European Commission

Proceedings of the 9th international conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL '17)

Part III

Bertoldi, Paolo

2017

EEDAL
Energy Efficiency in Domestic Appliances and Lighting

Joint Research Centre

EUR 28961 EN

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JRC109209

EUR 28961 EN

PDF	ISBN 978-92-79-77174-3	ISSN 1831-9424	doi:10.2760/113534
Print	ISBN 978-92-79-77173-6	ISSN 1018-5593	doi:10.2760/68449

Luxembourg: Publications Office of the European Union, 2017

How to cite this report: P. Bertoldi, *Proceedings of the 9th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL '17) - Part III*, EUR 28961 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-77174-3, doi:10.2760/113534, JRC109209.

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13 HEATING, COOLING AND WATER HEATING

Measured Performance of a High-Efficiency Solar-Assisted Heat Pump Water Heater

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Abstract

This paper describes a novel solar photovoltaic-assisted heat pump water heater (PV-HPWH). The system uses two 310 W_p PV modules, micro-inverters and innovative controls to produce and store daily hot water. The system likely costs half that of solar thermal systems, with greater reliability, no freeze protection and potentially superior performance in cloudy locations. Moreover, no net metering is needed for the PV, which with two modules makes for a simple installation.

The HPWH controls have been modified through experimentation such that higher tank temperatures are achieved during the day when solar availability is high while avoiding triggering the compressor during early morning hot water draws. When tank temperatures are satisfied, the remaining PV electricity is stored in the tank using staged electric resistance elements. Typical performance sees hot water storage greater than 65ºC at sunset. A mixing valve provides hot water at the target temperature (52ºC). By altering tank temperature, an equivalent of ~2 kWh of electrical energy is stored for use during evening hours. Typically, there is no grid electricity demand during the utility summer peak demand window.

The system has been tested for twelve months in a laboratory at the Florida Solar Energy Center. Realistic hot water draws were imposed with detailed data recorded on system performance. Long term COP, averaging 5.4, has been as high as 8.0 during sunny summer days. Average daily grid electricity consumption has been 1.2 kWh/day– less than many refrigerators. Prospects for further development and refinement are discussed.

Introduction

Reducing energy use for heating water remains a major challenge around the world. Field data shows that heat pump heat pump water heaters (HPWH) can significantly reduce electricity needs in warm climates. For instance, in eight Central Florida homes in 2013, comparison of one year pre and post-retrofit hot water energy after changing from electric resistance to HPWH showed 68% (5.3 kWh/day) sub-metered savings [1]. Effective COPs for 2012-generation HPWHs are approximately 1.5 – 2.5, depending on climate, location within a building, and machine characteristics [2]. Recent work has shown that HPWH interaction with space conditioning loads are potentially significant with interior locations—for instance, reducing cooling loads by more than 5% in warm climates [3].

For electric water heating to be an attractive substitute against efficient natural gas heating for reducing greenhouse gas emissions, seasonal system electrical COP must be greater than 3.0 at average emission rates for U.S. generation resources.[1] While solar thermal water heating systems have high COPs (often above 3.5), these systems are typically expensive and can have high maintenance needs [10]. At the November 2013 ACEEE Hot Water Forum in Atlanta, a thought-provoking presentation compared solar thermal water heating systems with heat pump water heaters (HPWH) powered by photovoltaic (PV) modules. [4] The simple premise was that with the introduction of high-efficiency HPWHs in the U.S. market coupled with rapidly falling PV prices, it was now more cost-effective to install a PV-driven HPWH rather than a conventional solar thermal system. Using an example of a 1.0 to 1.3 kW PV system powering a HPWH with an Energy Factor (EF) of 2.5, it was calculated that a PV-driven HPWH currently had a $5,000 to $8,500 installed cost before incentives, while the installation of a conventional solar water heating system cost $7,000 to $10,000 before incentives. In addition, the PV-driven HPWH saved more energy, was easier to install with no plumbing, used less space, required less maintenance, and could not leak, overheat, or freeze.

[1] This calculation assumes an emission rate of 681 g/kWh for average U.S. electrical generation against an emission rate of 227 g/kWh for natural gas at an energy factor of 0.80 for an efficient new natural gas hot water systems (condensing or tankless). https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Background

Water heating in residential and small commercial buildings continues to pose a challenge as the overall efficiency of buildings improves with minimum energy efficiency code requirements for air conditioning, lighting and building envelope occurred over the last decade. Although some improvement in the minimum energy efficiency for storage water heaters in the United States was implemented in 2015, energy efficiency improvements to other building components appear to provide significant potential energy savings compared to those applied to standard water heating appliances.

Over the last 10 years, PV has gained momentum in the U.S. with improvement in conversion efficiencies as well as decreased cost. The use of PV to heat potable water has been discussed by many researchers. Previously in 1998-99, direct resistance water heating using PV was first explored and tested at the Florida Solar Energy Center (FSEC) in a novel design by Dougherty and Fanney [6]. The system featured a 1060 W_p PV array with proprietary control algorithm to switch between a three-resistance capable heating element to maximize power transfer. In recent years, other PV system designs for dedicated water heating have evolved into the market.

While PV has been combined with heat pumps for solar-assisted space heating and air conditioning, there are not many instances where PV is used with a heat pump for water heating. In one of the few examples, Aguilar et al. [6] conducted an experimental year-long study of a PV-assisted split-system heat pump for water heating in Spain. The system consisted of two PV modules of 235 Watts each, a 189 liter storage tank, and a heat pump with a long-term coefficient of performance (COP) of 3.15. Under a typical residential hot water load, the annual solar contribution was greater than 60%.

Compared to standard electric resistance, residential heat pump water heaters provide considerable energy savings due to their high efficiency. Currently in the United States, HPWH's ranging from 189 to 303 liters are rated with an energy factor (EF) as high as 3.4 as indicated under the advanced product list published by the Northwest Energy Efficiency Alliance (NEEA). [7] The design and integration of PV and heat pump water heaters provide a synergistic combination to improve overall efficiency at a reasonable cost.

As part of the effort towards zero energy buildings and high efficiency water heating systems, the Florida Solar Energy Center (FSEC) -- working under contract with the National Renewable Energy Laboratory (NREL) -- has been developing a PV-assisted heat pump water heater (PV-HPWH) prototype (Figure 1). The system combines two 310 W_p solar photovoltaic (PV) modules and grid-tied microinverters with a commercially available 189-liter HPWH. Using the HPWH's integrated tank to store solar energy, the PV is used without any grid interconnection, thus avoiding potential net metering issues that have recently emerged in many U.S. states.

Figure 1: PV modules (310 Watts each) and 189–Liter HPWH shown with added insulation

The PV-assisted HPWH prototype began evaluation in February 2016 at the FSEC hot water systems laboratory in Cocoa, Florida. The testing utilized an automated hot water load schedule totaling 223 liters per day, typical of an average 3-4 person family. An average COP of 3.5 was obtained for the first month of February. (By subtracting the PV-generated electricity produced from the total electricity used by the system, the net grid electricity is used in the calculation of the PV-HPWH system COP.) Further analysis excluding the PV contribution indicated a HPWH-alone performance COP of 2.1 in February which is virtually identical to manufacturer claims for the unit [8]

The PV-HPWH prototype evolved with a series of automated control improvements through the spring and summer. Beginning on March 2016, the system was upgraded to autonomously change the thermostat setting from 52^{o}C (baseline) to 60^{o}C depending on the power produced by the PV and micro-inverters. The thermostat setting change was triggered by a minimum PV power threshold of 260 W averaged over one minute. Following that change, during the month of April, the factory-supplied 4500 Watt bottom heating element was removed and replaced with one of a lower wattage (750 W). The bottom heating element was then re-wired and independently activated via a controller board and software developed at FSEC.

System Description

A diagram of the PV-driven HPWH as tested at FSEC can be seen in Figure 2. The HPWH used in the study is rated at 600 Watts: however, depending on tank temperatures, data indicated that power draw changes between 490 and 700 Watts. A higher than rated power draw was routinely demonstrated as the compressor operated and heated water approaching the highest thermostat setting of 60⁰C. Furthermore, fix-mount PV modules facing south at a 24⁰ tilt produce the highest power during mid-day hours (11:00 am – 2:00 pm). On average, the power produced by the PV modules was 369 Watts during the mid-day period. The balance or net energy to operate the HPWH compressor is sourced from the grid.

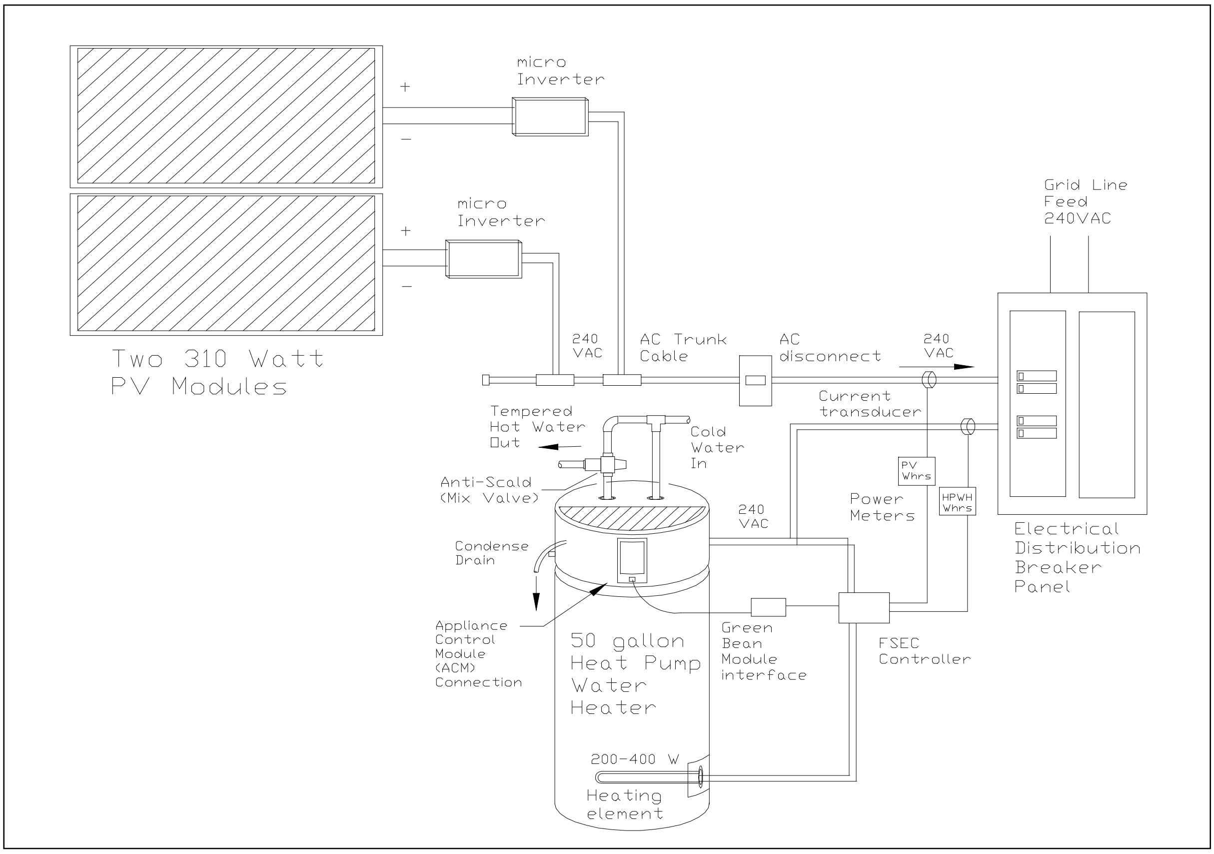

Figure 2: Schematic diagram of prototype PV-assisted HPWH.

To match the energy produced the PV modules to the electric resistance heating element load, power control circuitry using capacitive reactance was implemented, resulting in a two-stage resistance heating element (192 and 396 Watts). Further development of the FSEC-developed controller led to techniques to maximize the compressor operation efficiency and store most PV energy as hot water. Once a full tank of 60⁰C temperature water was reached and the compressor was shut-off by the HPWH thermostat, additional heat energy is transferred into storage via the two-stage electric resistance element. Hot water delivery temperatures were tempered by a mixing valve set at 52 ⁰C, enabling the HPWH tank to act as thermal storage for the PV-generated energy.

Increasing temperatures in a 189-liter tank from the 52 ⁰C baseline upwards to 60⁰C is the thermal storage equivalent of 1.7 kWh. By adding extra energy past 60 ⁰C into the tank, the system was able to store an additional 0.5 kWh per day. Therefore, additional thermal storage in the tank from raising the thermostat setting is equivalent to approximately 2.2 kWh (neglecting standby losses.) Data indicated that thermal storage levels above 60⁰C appear during 75% of the days analyzed. Peak hot water temperatures reached past 65⁰C in May and August as measured at the hot water outlet port during the 3:49 pm hot water draw and average 62⁰C in late afternoons.

On a daily basis, tank heating in response to early morning hot water draws (83 liters) before 7:45 am was begun typically around 7:30 am, but the heating process was interrupted at 8:30 am by a thermostat setback to 46⁰C. Hot water recovery using the HPWH compressor is then completed at a later time in the morning -- 10:30 am when solar resources are typically higher -- by resuming a 52⁰C thermostat setting. This process is illustrated in Figure 3 showing data recorded on August 23, 2016. The compressor turns on at 7:38 am for only 10 minutes, due to previous day storage and the 49ºC thermostat setting, and then is followed by 192 Watts of electric resistance heating. The compressor resumes heating again at 9:07 am due to its thermostat setback of 46ºC: and completes recovery by 11:30 am. The operation of the two-stage electric resistance heating operation is visible in the afternoon indicating extra energy being stored at a rate of 396 and 192 Watts, respectively.

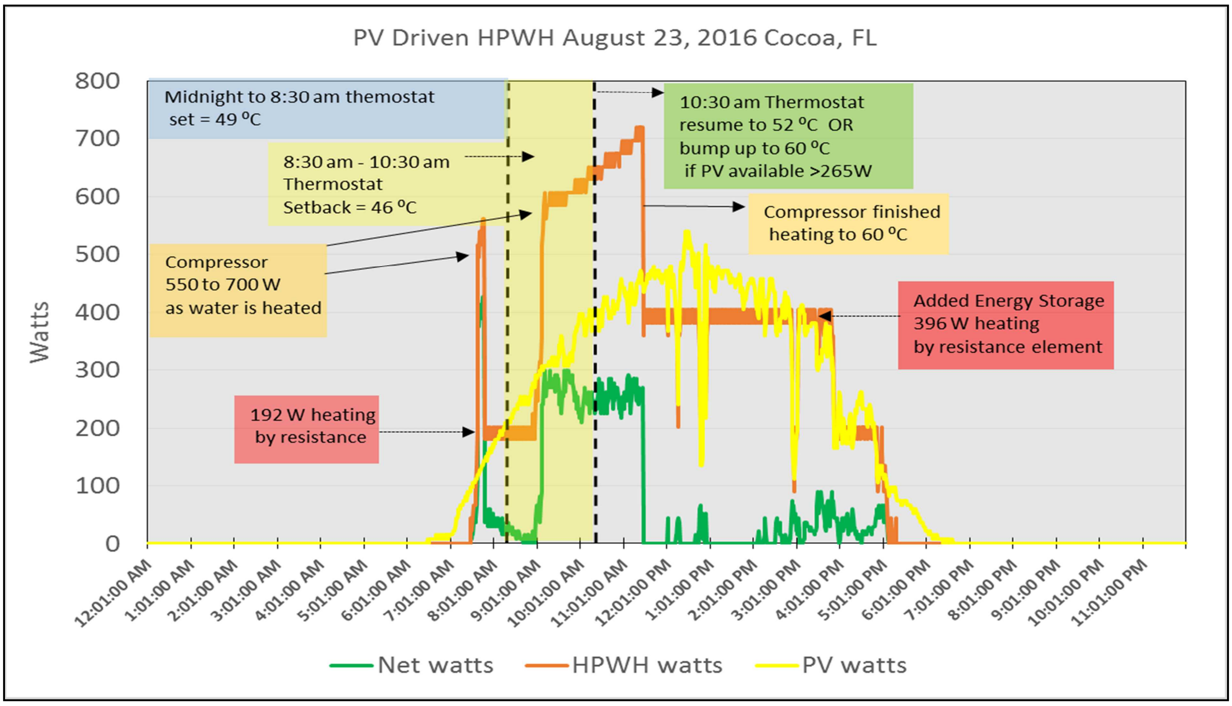

Figure 3: Example PV production and HPWH power usage in the prototype PV- HPWH

Results

Figure 4 displays recent results from testing the prototype PV-assisted HPWH in Central Florida. The bar graph shows the daily coefficient of performance (COP) of the overall system for the month of September 2016 as defined by the relationship:

$$\text{COP} = \frac{\text{Hot water energy out}}{\text{Grid electrical energy in}}$$

Figure 4 also shows the daily solar radiation on the two PV modules (dotted line) in Watt-hours per square meter per day on the right axis. It is apparent from the figure that COPs above 4.0 are typically possible on days with daily plane of array solar radiation above 4 kWh per square meter. Variation in the COP on any particular day is not only affected by the solar irradiance, but also by its distribution against loads on that particular day. Efficiency is also influenced by the solar irradiance on the preceding day as this influences the stored thermal energy over evening hours. Overnight tank thermal storage is particularly important for the efficiency with which early morning hot water draws are served.

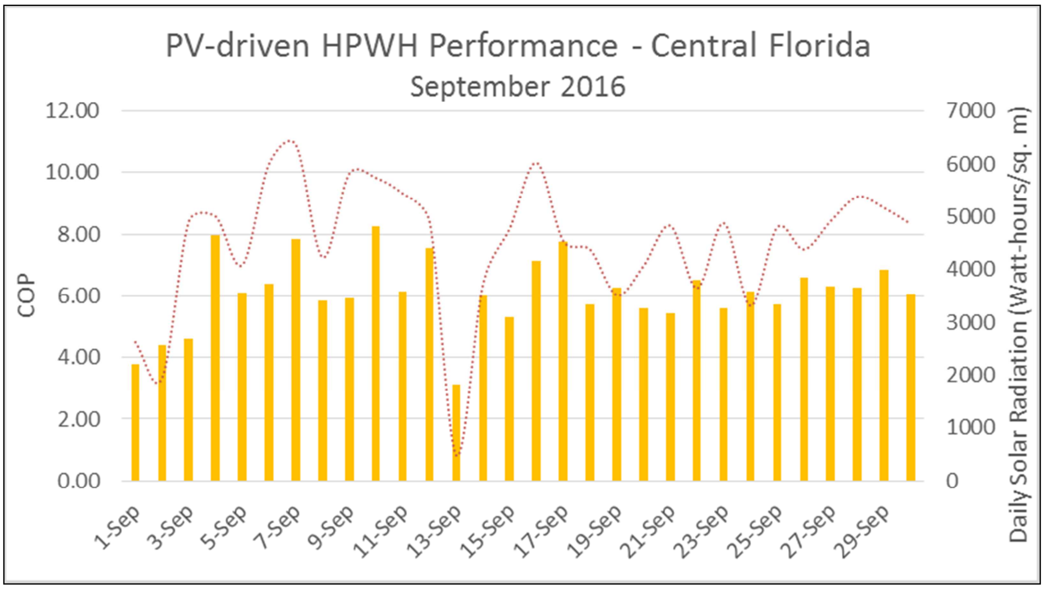

Figure 4: Prototype PV-assisted HPWH Performance in September 2016 in Central Florida

Measured long-term performance recorded through January 2017 can be seen in Figure 5. The plot shows the average monthly COP (left y-axis) and kWh per day of electricity consumption (right y-axis). Performance of the PV-driven HPWH has been exceptional, demonstrating average monthly COP's as high as 6.6 and 7.0 for the months of May and July. COP's leveled off at around 6.0 for the months of August thru October and declining in November. Further improvement could be realized by utilizing a portion of the 18% of total energy produced by the PV/micro-inverters that is unused and is fed back into the grid during early mornings and late afternoon hours. Future development work is planned to maximize PV-supplied energy to be used by the system.

Performance data for the months of December and January 2017 reveals COPs of 5.1 and 4.8 respectively which are consistently higher than during February 2016 when controls optimization and the two-stage heating element was not in place.

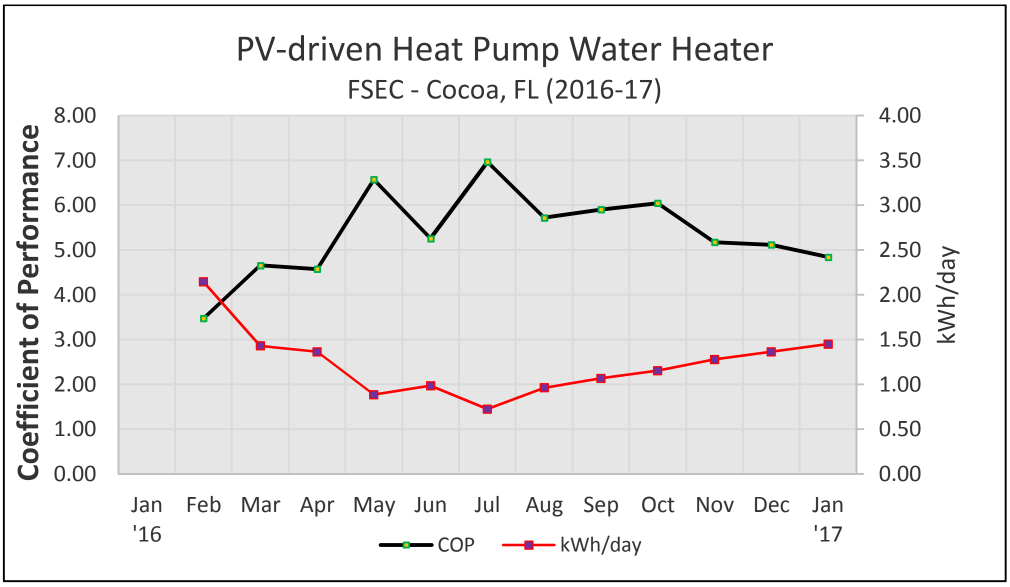

Figure 5: PV-HPWH monthly average COP and kWh per day (February 2016 – January 2017)

A time-of-day analysis was also performed to determine the hourly peak demand reduction potential of the PV-HPWH against standard electric resistance water heating. Figure 6 presents the hourly demand as compared to a 189-Liter standard electric water heater (red line) that was operated simultaneously in the laboratory.

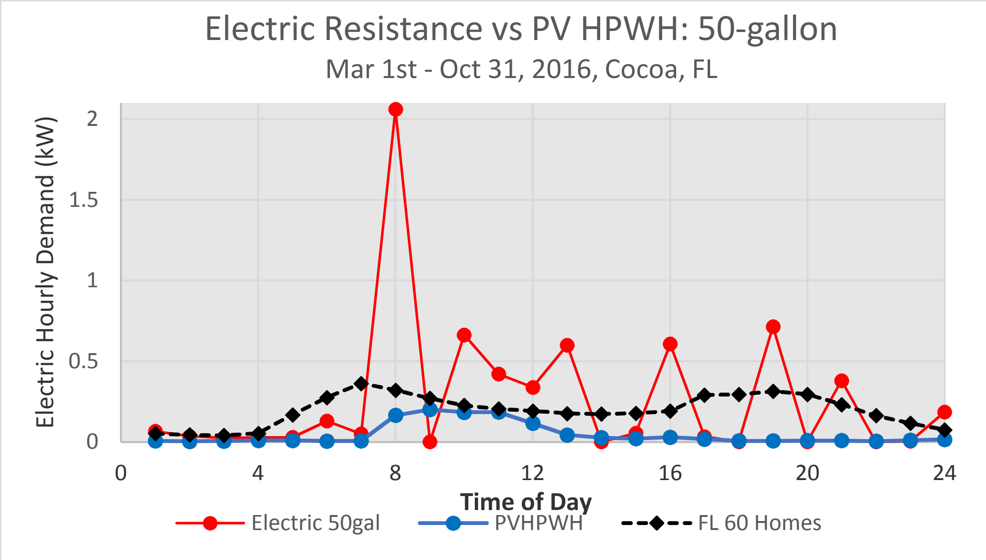

Figure 6: Time of day load profile of PV-HPWH compared to a single 189-Liter electric water heater and the load profile of 60 Florida homes with electric resistance water heaters

The plot also shows the diversified demand profile (black dashed line) of 60 residential electric water heaters operating in Florida homes, recently monitored in 2013 as part of the U.S. DOE Building America Phased Deep Retrofit (PDR) study. [9] Because of the extra thermal energy storage (~2.2 kWh), the PV-HPWH would not increase the late afternoon ramp-up demand on utility generation caused by conventional PV's decreasing electricity production.

The PV-HPWH has demonstrated impressive performance by integrating photovoltaics with compressor-based refrigerant water heating, smart controls, and added energy storage. Table 1 provides a summary of its 12-month performance since February 2016. Analysis performed on the data after May 2016, when the auxiliary heating by electric resistance was implemented for additional heat storage, indicated that the solar contribution from the PV and micro-inverters averaged 65.6% of the total electricity used by the system. The average long term COP of 5.4 was exceptional.

Table 1: Summary of PV-HPWH performance (February 2016 -- January 2017)

Average Monthly Daily Electric consumption		**Average Monthly COP (min /max)**	**Average PV Energy Generated**	**Added storage above 52^{0}C**	**Average Hot water Max Temp Stored**	**Average Daily Hot Water Delivered (w/ 52^{0}C mix valve setting)**		
kWh/day	**Min-Max kWh/day**		**kWh/day**	**kWh/day**		**L**	**kJ**	**kWh**
1.2	0.7 – 2.1	5.4 (4.5 / 7.0)	2.3	2.1	62^{0}C	215	21,868	6.1

Performance data collected from the PV-HPWH to date also indicates it is the highest efficiency electric water heating system ever tested under FSEC's hot water system evaluation program, conducted under the Building America Partnership for Improved Residential Construction thru 2016. [10] Figure 7 places the PV-HPWH at the top of the chart with an average grid electricity use of 1.2 kWh/day. Note that the conventional 189 L electric resistance tank used about 7.6 kWh per day with a typical COP of approximately 0.8. Accordingly the prototype PV-HPWH saved 84% of the energy typically needed for conventional electric resistance water heaters.

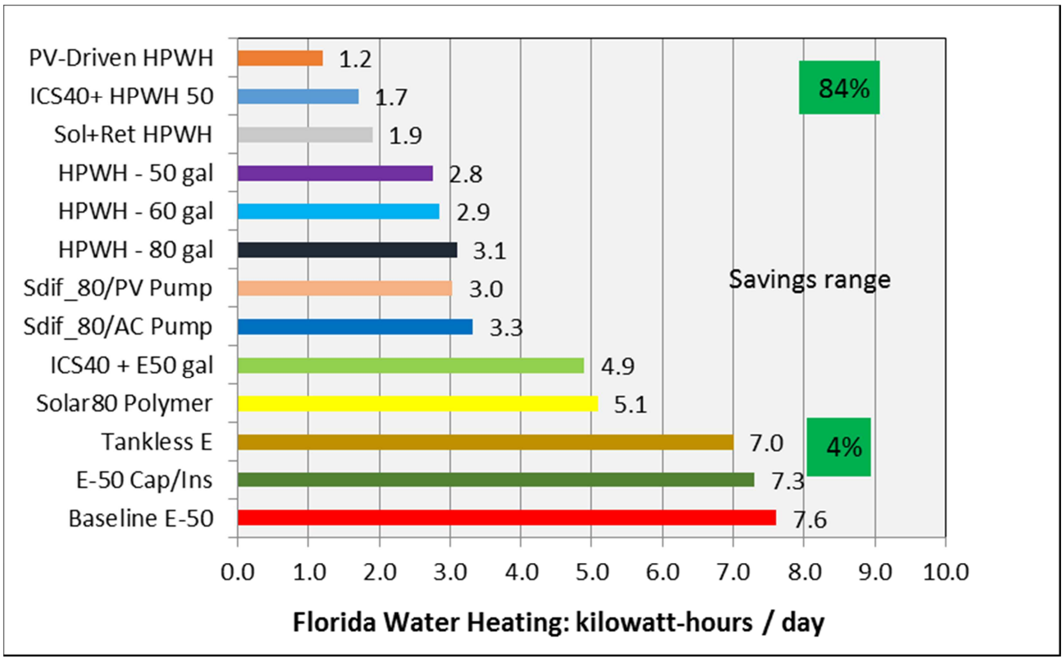

Figure 7: Representation of various electric water heating systems daily electric use compared to a baseline (standard 189 L electric) and the potential for energy savings (4%-84%)[2]

Conclusions

The prototype PV-HPWH showcases innovative strategies for distributed PV systems that limit grid interaction and provide increased thermal energy storage. The system utilizes a custom appliance control module (ACM) interface to vary thermostat settings (46ºC to 60ºC) depending on time of day and solar radiation levels. It also prioritizes thermostat setbacks on a time of day basis. By setting the thermostat down to 46°C during early morning draws, it can disrupt compressor heating recovery normally set to 52°C and shift the remainder of recovery to times where higher solar resources are available (i.e., after 10:30 am). Long-term COPs through January 2017 have averaged 5.4 requiring grid power of only 1.2 kWh per day for a typical residential hot water load. The total daily grid electricity use is less than that for many household refrigerators.

This level of efficiency improvement represents approximately an 84% reduction in electric power for heating hot water compared with a simultaneously monitored electric resistance system. The total PV-HPWH system equipment assembled had retail cost of $2053 for the prototype (including the HPWH) fares very well compared to traditional solar thermal systems. Other key advantages of the PV-HPWH technology:

- Simplified installation likely to further reduce installed costs
- No plumbing or pumps associated with the PV assisted system
- No need for freeze protection
- PV output at given irradiance higher under cold conditions when water heating loads higher
- Solid state components likely yield greater long term reliability

[2] Key: ICS40: Integrated collector storage solar system (40 gal); Sol+Ret: Solar heating of HPWH tank; HPWH: heat pump water heater of various sizes (40,60,80 gal); Sdif: Solar differential with PV or AC pumping; E-50: Electric resistance 50 gal tank; Solar80 Polymer: unglazed solar collector w/80 gal storage; Tankless E: tankless electric resistance; E-50 Cap/Ins: E50 tank w/ insulated cap and tank cover; Baseline E-50: Electric resistance baseline system. (EF=0.9).

- PV to thermal storage strategy typically produces 2.2 kWh of evening load shift relative to standard electric resistance systems.

FSEC continues to collect data on the PV-HPWH in order to characterize performance of the latest control techniques for a full year. Various improvements along with smart controls have been created and demonstrated in this project which will likely continue to show performance improvement over the 2017 spring season (the final improvements were not fully implemented until summer).

The system will undergo further refinement in order to be demonstrated in a residential water heating field project. HPWH manufacturers show the latest generation of compressors operate at 50 watts less compared to the HPWH unit used in the PV-HPWH demonstration [11]. In northern climates, larger storage (303-Liter) HPWH's could also be utilized along with additional PV modules, which simulation analysis indicates likely have further performance advantages [2,8]. However, both of these promising potential improvements are yet to be tested.

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Intelligent control of domestic and commercial point of use water heating and cooling applications

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ABSTRACT

Point-of-use water heating and cooling dispensing devices include coffee makers, bottled and bottle-less hot and cold water dispensers, and plug load counter top hot water "hot pot" dispensers. Many devices in this category use substantial energy maintaining water temperatures at a level that enables immediate. Additionally, many of these devices maintain the temperature at this level 24 hours a day, reducing the temperature during long unused periods would save considerable energy. In this study we evaluate the savings potential of a novel thermal control methodology, Active Thermal Observation and Management (ATOM), which uses a self-learning, probabilistic approach to observe occupancy and assess the probability of short-term occupancy. In this approach, the set-point holding temperature of the hot or cold water is actively adjusted to reduce thermal loss. With system knowledge of the required warm-up time to the user's set point, a balance is struck between user convenience and energy savings. Device-mounted sensors provide observational capability of the device to sense user interaction and user involvement. The correlation of events over time and patterns of device interaction are used to improve future predictive models for thermal set points. Thus, extended device usage leads to improved energy savings and improved convenience for the user. This algorithm can be applied to food-safe serving applications. The implications of this work are far reaching and can have substantial savings impact on many residential and commercial devices that use temperature-hold features.

INTRODUCTION

Recent improvements in lighting and indoor climate control efficiency have left plug loads as a growing challenge for improving total household and building energy efficiency. Countertop water heaters, water dispensers (supplying hot and cold or cold water alone), and commercial coffee brewers are major energy use plug load appliances.[1-3] For example, bottle type hot and cold water dispensers, specifically have a US EPA/DOE ENERGYSTAR standard (version 2.0) setting the maximum standby energy draw for this type at 0.87 kWh/day – representing an annual energy usage of 318 kWh (see Figure 1).[4] In comparison, the energy use value for this single device is on-par with the total for an entertainment system area - the most concentrated plug load center in most homes.[5] For devices that are used intermittently, such as residential coffee makers, manufacturers have used simple inactivity or daily timers to turn off major appliance operations after an allotted time, a time of day, or a designated operation (such as brewing) is complete. Comparatively, for on-demand water dispensing devices, similar savings controls are not commonly used as these devices are expected to stay ready to dispense on demand at an arbitrary time (see Figure 1). The majority of energy use for these type of devices is used by heating and cooling (if equipped) functions rather than any additional electronics functions such as interfaces or controls. This brings thermodynamic factors as major efficiency limiters. With the exception to some operational dynamics of refrigeration systems (in devices that cool liquids), [6-10] minimal efficiency improvement other than insulation is possible for low cost resistive water heating systems.[11-13] This leaves operational control of these functions as a major direction to improve energy efficiency without impacting the lifestyle and habits of users. The California Plug Load Research Center (CalPlug) is currently investigating controls for this class or devices. CalPlug is an academic research center based at the University of California, Irvine which focuses on energy for commercial and household plug load devices. In the current reported work, we investigate plug load, counter-top, point of use water heaters (commonly referred to as electric "hot pots") and the impact on energy savings an intelligent control device could have with lessons to be drawn for additional similar devices.

BACKGROUND

CalPlug has previously investigated intelligent controls for set top box (STB) power management. The control system developed used sensors to determine user schedule and from this investigation we demonstrated 57.9% savings by enabling lower power operating modes when users were not present or not imminently ready to begin using the set top box under control.[14]. User detection from fused sensor feedback with time correlation permits self-learning to continually improve energy efficiency without impacting users.

Point-of-use water dispensers provide the capability to scale energy usage by reducing the temperature set points to a lower energy settings when usage is not eminently expected. Knowledge of past schedules of device interaction permits the generation of a probability-based likelihood map of device interaction with respect to time. A period of time where hot water is unlikely dispensed (say 3 AM), and with no prior history of dispensing for a particular unit, the set points for hold temperature can be placed in a lower energy position. For periods of time where interaction is more likely (say 6 PM on a weekday) the set point can be altered to save energy, yet the required warmup period should be reduced to avoid user frustration, limiting energy savings potential during this period, but enabling the solution as viable. There are multiple human use factors that come into play regarding interaction triggers and warmup time tolerances to avoid frustration. These points are currently under investigation. This sensor mediates a dynamic balance between user-convenience against potential energy savings and is the key benefit to the Active Thermal Observation and Management (ATOM) system being investigated.

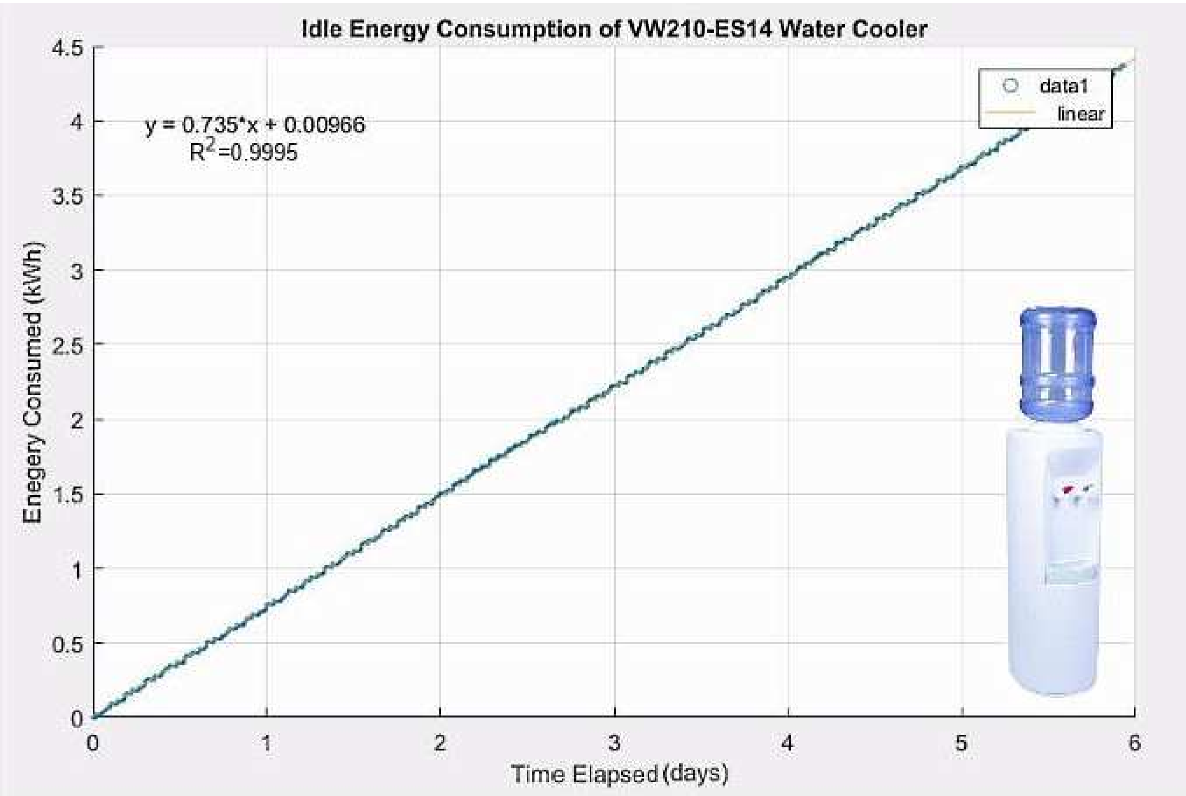

Figure 1: Energy consumption for a hot and cold bottled water dispenser measured by CalPlug. Energy usage is constant to hold temperature set points at all times of the day and night– even in periods where device usage is extremely unlikely.

For a water heater, if the device is not used for a given period, the standby temperature can be lowered to reduce heat loss. Reducing liquid temperature reduces heat flow, yet increases the time period required to reheat the device when water is requested. A dynamic balance between energy savings and user satisfaction must be met.

Thermal flow is approximated for an insulated water heater by Fourier's law of thermal conduction (shown in Equation 1(1)), effectively an insulated vessel assuming no mass loss, and no fluid convection, where heat loss is only via conduction through the insulator. Correspondingly, the temperature of the liquid with respect to time is explicitly shown in Equation 1(4).

$$\frac{\Delta Q}{\Delta t} = \frac{-KA}{d}\left(T_{Liquid} - T_{Ambient}\right) \qquad (1)$$

$$\text{where } Q = mc_h\left(T_{Liquid} - T_{Ambient}\right) \qquad (2)$$

$$mc_h\frac{dT_{Liquid}}{dt} = \frac{-KA}{d}\left(T_{Liquid} - T_{Ambient}\right) \qquad (3)$$

$$T_{Liquid}(t) = T_{Ambient} + \left(T_{Liquid\ @t=0} - T_{Ambient}\right)e^{-\frac{kAt}{dmc_h}} \qquad (4)$$

Equation 1(1-4): Solution of Fourier's law of thermal conduction applied to an insulated vessel: An illustrative one dimensional solution is shown, where Q represents heat flow, t represents time, k is the conductivity of the insulator, d is thickness of the insulator, A is cross sectional area of the insulator, c_h represents the liquid heat capacity, m is liquid mass. In (3) the final differential equation is solved for time in the form: $U(t)=Be^{-t/\tau}+C$. This relationship is effectively similar to the electrical analogy of a RC series circuit.

The rapid addition of heat occurs at a timescale substantially greater than loss. For this reason, heating can be modeled by considering specific heat without considering heat loss. Accordingly, liquid temperature is linearly proportional to added heat (Q) if $Q_{heating}>>Q_{loss}$ and constant, per Equation 1(2).

The presented heat model Equation 1(4) provides a reasonable approximation for temperature change due to bulk heat loss. The effects of convection (in the liquid and vapor phase), and liquid loss due to evaporation do play a role in real-world systems yet are not taken into account in Equation 1. Consideration of these factors requires knowledge of system design for model acuity. Alternatively, knowledge of the governing first principles allows empirical fitting of experimentally collected data into simplified empirical models based on first principles. This semi-empirical approach provides a balance between simplicity, flexibility, and first-principle model rigor. In this presentation, goodness-of-fit is shown using Pearson's R^2 value as a simple and conventional comparative metric. Unless otherwise noted, reduction of residuals as opposed to first principle fitting with constraints from known values was primarily used. This approach is used in this investigation to frame data analysis.

MATERIALS AND METHODS

A countertop water heater (hot pot) from a major manufacturer was filled with 1.0 L of water for all studies presented. All studies were performed at 20 °C ambient temperature. A calibrated K-type thermocouple was used to measure liquid temperature and provide thermal control. The internal thermal controller on the countertop water heater device was bypassed for all reported studies. A PC based thermal controller constructed by the authors provided negative feedback direct control with 1.5 °C of hysteresis to prevent rapid thermal cycling and match real-world control approaches for similar devices. For control of refrigeration systems, rapid cycling of compressors can cause mechanical failure due to successive starts with excessive refrigerant backpressure. Energy usage was measured and recorded using a calibrated Onset HOBO UX-120-018 plug load logger.

Passive Cooling

Heat loss was assessed (via change in liquid temperature) by measuring a free decay in temperature from 98°C to 45°C. A temperature of 98°C was chosen as this was the highest temperature where phase change was not observed as free visible bubbles in the liquid. A fitting of Equation 1(4) was performed using a data analysis package, OriginLab Origin 9.0. This measurement was performed to assess both thermal loss and the temporal period a hold temperature varies for optimal ATOM controller thermal scheduling.

Active Heating

Heating rate was assessed (via change in liquid temperature) by measuring a change in temperature while applying continuous, maximum power (686 W) to the heating element from 28°C to 99°C. Temperature change was measured against time. Assuming a high rate of energy addition versus energy loss, a linear relationship was regressed.

Holding Temperature Energy Consumption

The energy required to hold a set point temperature within the set 1.5°C hysteresis limits was assessed by a 30 minute power consumption test that was started once the initial set point was met. This was repeated for all evaluated set points. During the heating phase, a constant maximum power (686 W) to the heating element was applied. A period of 30 minutes was chosen to balance sufficient cycles while minimizing evaporation to improve extrapolation. Set points between 40°C to 95°C were chosen. Measured energy values from the 30 minute periods values were extrapolated to kWh/day. Energy usage was plotted against set point temperature. Assuming the required energy to maintain temperature is equaled to loss, the fitting of Equation 1(4) was performed similar to the passive cooling measurement evaluation.

RESULTS

Passive Cooling

As shown in Figure 2, a clear exponential cooling relationship is observed between temperature and time elapsed. A strong fit is observed regressing Equation 1(4) with no physical fitting constraints. If the first principle form of Equation 1(4) is used, the following regression is found: $y = 20(°C) + 79(°C) * \exp(\frac{-x}{164.3348})$ with R^2=0.996 using $T_{ambient}$ and initial liquid temperatures. The differentiation of this expression combined with Equation 1(2) results in the heat loss (Q) in watts represented as: $Q(t\ in\ min) = \frac{-2500 * e^{-\frac{2500t}{410837}}}{410837} * 1kg * 4186(J/kgC)$. The average rate of heat loss in the measured range above 50°C is 23W.

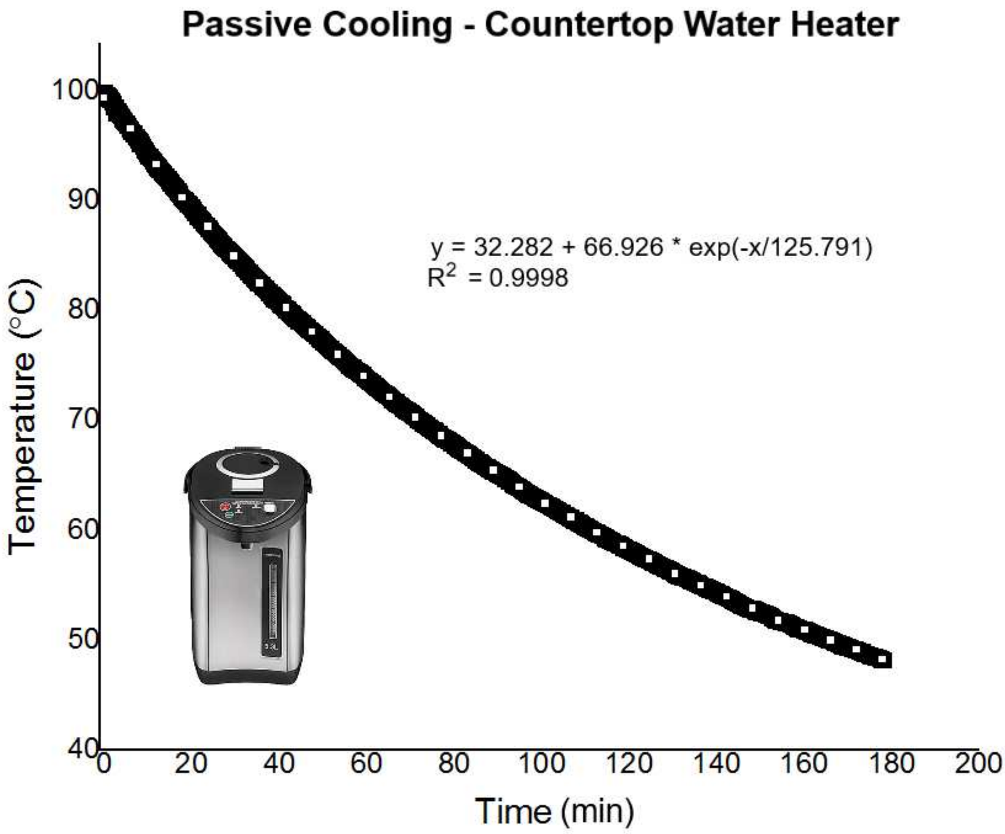

Figure 2: Passive cooling of 1.0L of water in the closed countertop water heater from 98°C to 45°C.

As shown in Figure 3, an approximately linear relationship is observed between temperature and time elapsed. A linear regression provided: $y = 0.1551\mathrm{x} + 25.23$ with R^2=0.9957. It is worthwhile to note a strong fit is observed when regressing the same data with an exponential polynomial function: $y = \exp(-3.7102 * 10^{-6}\mathrm{x}^2 + 0.00451\mathrm{x} + 3.27095)$ with R^2=0.9985. The R^2 value from this fit is deceptively high as substantial residual error is balanced between positive and negative residual differences – an all too common source of issue when using R^2 as a goodness-of-fit metric.

The breakdown of a strongly linear relationship between heat added and temperature shown in Figure 3, is likely due to both liquid and vapor phase convection and evaporative cooling effects. During heating, at around 75℃ the appearance of small surface-attached bubbles and the increasing water vapor pressure (trending towards atmospheric at boiling point) lend credence to this speculation. A secondary effect of thermal mass of the vessel creating a temporal lag in heating likely explains the delay to heating after the element is activated. Both of these factors, in addition to conductive cooling add additional and potentially non-negligible error to the linear heating model.

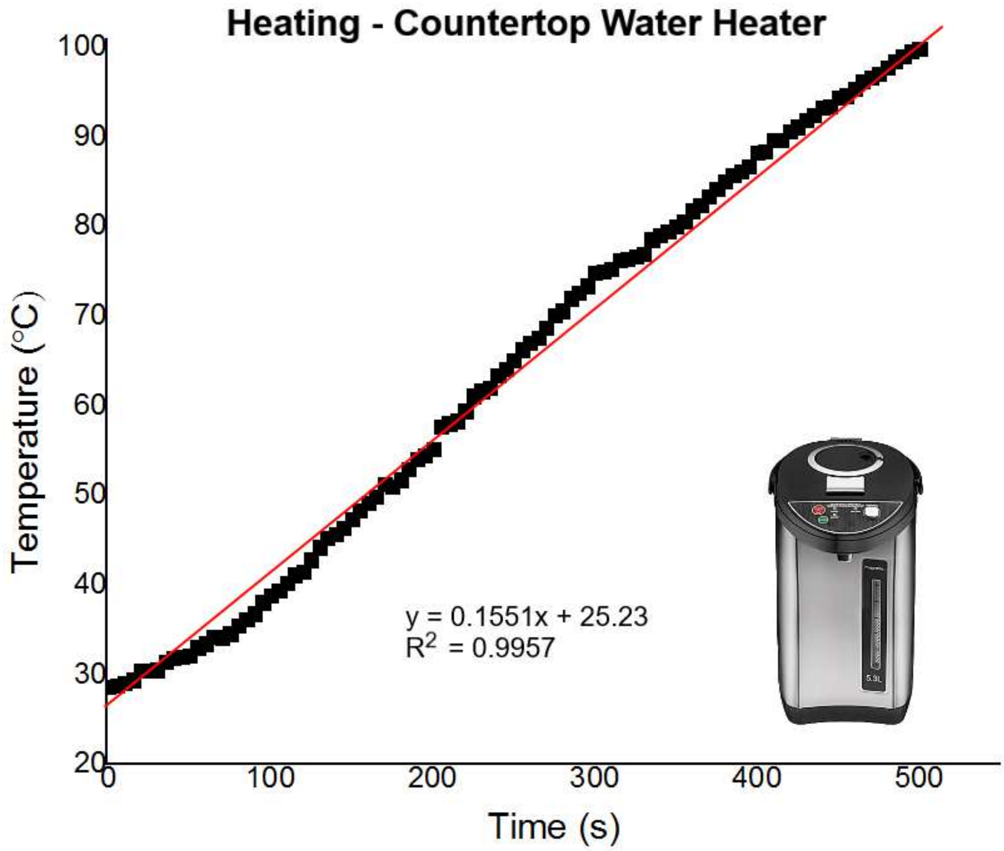

Figure 3: Active heating of 1.0L of water in the closed countertop water heater from 28°C to 99°C.

As shown in Figure 4, a non-linear relationship is observed between energy consumed at multiple holding temperatures. This is expected as Q_{in} = Q_{out} when the temperature is constant, hence a relationship similar to that expressed in Equation 1(4) is not surprising. The following relationship was found from an unconstrained regression: $y = -1.3307 + \exp(\frac{-x}{104.45517})$ with R^2=0.9996.

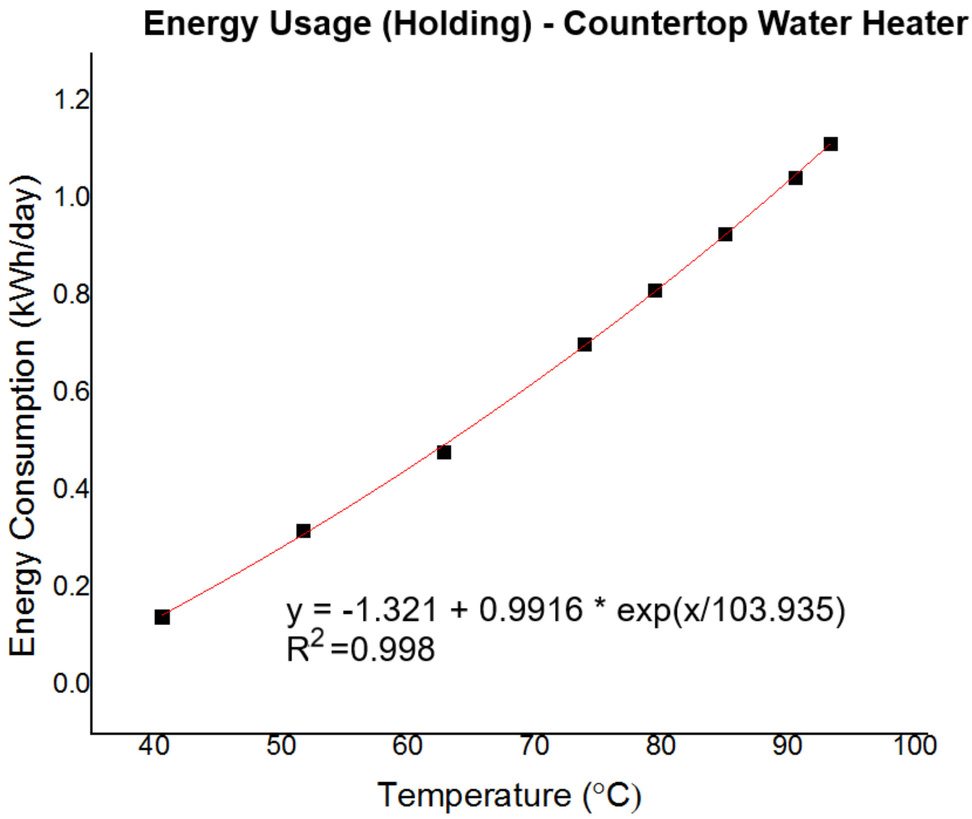

Figure 4: Energy required to maintain (hold) a set temperature within 1.5°C hysteresis bands of a given multiple set temperature values.

DISCUSSION

Dynamic temperature control can save substantial energy. In Figure 1, we present the required energy for a hot and cold bottled water dispenser in a commercial building. From the period of 6PM until 8AM, there is no usage of this device – this is 13 hours of a 24 hour day. A CalPlug study showed that 0.18 kWh of energy was required to bring this water cooler from ambient temperature (75°C) to the hot and cold set points. If typical daily usage of this device requires 0.746 kWh, a revised operation schedule with 7 hours requires 0.34 kWh. If the overhead (pick up load) for reaching the set-point is added, this new daily energy requirement is 0.53 kWh. This results in a 29% decrease in energy usage.

For the counter top water heater, heat loss ranges between 25W and 8.5W between 98°C to 45°C, respectively. This heat loss rate is substantially less than the heater supplying 686W of thermal energy when heating. The ideal heating relationship expanded from Equation 1(4) is y(t) = 0.1626x + 28 for a starting temperature of 28°C degrees (Figure 3). Heat balance based on addition and loss can be calculated at any arbitrary temperature and time from a given staring point based on the presented information. A single heating event requires 0.095 kWh to return the water to 95°C from an ambient equilibrium temperature of 20°C.

As the behavioral control factors of the ATOM system are still in experimental determination, only the savings potential is calculated assuming the operation of the ATOM system can reach these performance goals. We provided multiple simplified scenarios illustrating potential application:

1. *A household uses the countertop water heater daily with no usage from 9AM to 5PM, occasional usage during the period of 6 PM to 8 PM, and rare usage from 9 PM to 12 AM, with no normal usage from 12AM to 6 AM.* In normal use with a set point of 95°C, daily energy usage is 1.1 kWh. If in the new schedule, 95°C is maintained between 6 PM and 8 PM, 50°C is maintained between 9 PM and 12 AM, and ambient is maintained during the

balance of the time, the new daily energy usage is 0.53 kWh after the energy for the heating events are added. This results in a comparative energy savings of 51.8%.

2. *An office kitchen uses the countertop water heater from 8 AM until 5 PM for tea, followed by no usage over the evening period.* As before, the daily, baseline usage is 1.1 kWh to maintain a 95°C holding temperature. No intermediate holding temperature is assumed in this case. The new daily energy usage after intervention is 0.233 kWh. This results in a comparative energy savings of 79%.

3. *A residential user with a high tolerance for waiting for water to reheat to the set point uses the countertop water heater intermittently from 7 AM to 8 AM for preparing instant coffee and makes tea in the evening intermittently from 6 PM until 12 PM. During the remaining period the device is unused.* As before, the daily, baseline usage is 1.1 kWh to maintain a 95°C holding temperature. As this user is more willing to tolerate longer warmup savings, deeper energy savings approaches can be applied. The ATOM system can search for periods of time where usage is possible but unlikely and progressively lower or raise the temperature to automatically match usage based on past models of usage. In simplified form, for 6 hours at night, there is no usage and the set point is reduced to ambient. In the morning, the set-point is raised to 95°C. In the evening, deep energy savings are applied based on the artificial intelligence algorithm of the ATOM system. Effectively 2 hours are maintained at 50°C, 2 hours at 70°C, and 2 hours at 95°C. – a summarized simplification of the usage schedule. The resulting daily energy use from this schedule would be 0.654 kWh considering intermediate warmup power requirements. This results in a comparative energy savings of 40.5%.

Beyond what has been presented, other considerations must be taken into account. For energy calculations, the authors use energy required to maintain the temperature at a holding point as a major calculation figure. If water is dispensed, depending on the type of dispenser, the energy used is higher. This case equally affects both the baseline and intervention scenarios, so it was not included in calculations. Every user has a different threshold to waiting for reheating from a reduced set-point. This programing aspect is key to making the solution practically successful. Long wait times for reheating will cause user frustration which could result in discontinuation of this solution entirely. A healthy balance between energy usage and user satisfaction is critical for successful application. The overhead energy usage of the implementation of the ATOM system is expected to be under 1.0 watt (0.024 kWh daily), yet this must be factored in for calculation of true energy savings for a complete system.

CONCLUSION

The work presented describes the foundation for a new type of dynamic energy management system for plug load device control. Water heating and cooling applications have largely been overlooked within the broad scope of plug loads. However, they do have an impact on the rising plug load burdens for residences and commercial buildings. The ATOM system's occupancy and interaction based control system extends upon CalPlug's previous work in power management of STBs. Continued work on the behavioral and sensing aspects of the learning control system is required to achieve the savings potentials presented in this report. Adaptive, behavioral based control provides the next major horizon in plug load energy savings to help users save energy without adversely affecting their lifestyle.

ACKNOWLEDGEMENTS

This research was sponsored by support from the California Energy Commission, Southern California Edison, and the University of California, Irvine. The authors would like to thank Jason Luo, Omair Farooqui, Sid Kasat, Binh Nguyen, Duy Nguyen, Hugh Dang and Phat Quach for their experimental assistance to this study.

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Green on-site power generation: Environmental considerations on small-scale biomass gasifier fuel-cell CHP systems for the residential sector

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Abstract

Contemporary combined heat and power (CHP) systems are often based on fossil fuels, such as natural gas or heating oil. Thereby, small-scale cogeneration systems are intended to replace or complement traditional heating equipment in residential buildings. In addition to space heating or domestic hot water supply, electricity is generated for the own consumption of the building or to be sold to the electric power grid.

The adaptation of CHP-systems to renewable energy sources, such as solid biomass applications is challenging, because of feedstock composition and heat integration. Nevertheless, in particular small-scale CHP technologies based on biomass gasification and solid oxide fuel cells (SOFCs) offer significant potentials, also regarding important co-benefits, such as security of energy supply as well as emission reductions in terms of greenhouse gases or air pollutants. Besides emission or air quality regulations, the development of CHP technologies for clean on-site small-scale power generation is also strongly incentivised by energy efficiency policies for residential appliances, such as e.g. Ecodesign and Energy Labelling in the European Union (EU). Furthermore, solid residual biomass as renewable local energy source is best suited for decentralised operations such as micro-grids, also to reduce long-haul fuel transports. By this means such distributed energy resource technology can become an essential part of a forward-looking strategy for net zero energy or even smart plus energy buildings.

In this context, this paper presents preliminary impact assessment results and most recent environmental considerations from the EU Horizon 2020 project 'FlexiFuel-SOFC' (Grant Agreement n° 641229), which aims at the development of a novel CHP system, consisting of a fuel flexible small-scale fixed-bed updraft gasifier technology, a compact gas cleaning concept and an SOFC for electricity generation. Besides sole system efficiencies, in particular resource and emission aspects of solid fuel combustion and net electricity effects need to be considered. The latter means that vastly less emission intensive gasifier-fuel cell CHP technologies cause significant less fuel related emissions than traditional heating systems, an effect which is further strengthened by avoided emissions from more emission intensive traditional grid electricity generation. As promising result, operation 'net' emissions of such on-site generation installations may be virtually zero or even negative. Additionally, this paper scopes central regulatory instruments for small-scale CHP systems in the EU to discuss ways to improve the framework for system deployment.

Introduction

Traditionally, combined heat and power (CHP) systems are often based on fossil fuels, such as natural gas or heating oil, but the transition to efficient energy systems using renewable energy sources is urgently needed in particular in the heating sector to achieve world-wide sustainability targets. Based on EU classifications, combustion plants are rated >50 MW_{th} for large systems and <1 MW_{th} for small appliances (residential heaters and boilers), with medium combustion plants (MCP) in between. Today, CHP is still mainly realised in the medium and large-scale sector, especially for renewable biomass fuels. However, the applied traditional technologies have restrictions regarding fuel flexibility and electric efficiencies.

In contrast, dedicated biomass integrated gasification fuel cell systems (B-IGFCs), are deemed to achieve much higher efficiency levels [1]. Thereby, adaptation to small scale generation applications based on renewable energy sources (such as solid biomass) is specifically challenging, because of feedstock compositions and heat integration. Small-scale cogeneration systems are thereby typically intended to replace or complement traditional heating equipment in residential buildings. In addition to space heating or domestic hot water supply, a part of the fuel energy is used to generate electricity for the own consumption of the building or to be sold to the electric power grid. In addition to efficiency potentials, B-IGFCs also offer further important co-benefits, such as security of energy supply as well as emission reductions in terms of greenhouse gases (GHG) or air pollutants. In particular, solid residual biomass as renewable local energy source is also best suited for decentralised operations such as micro-grids to avoid inefficient long-haul fuel transports to centralized power plants.

Against this background the EU Horizon 2020 project ‘FlexiFuel-SOFC’ (Grant Agreement n° 641229, see also http://flexifuelsofc.eu) aims at the development of a new, innovative, highly efficient and fuel-flexible biomass CHP technology integrating a small-scale fixed-bed updraft gasifier, a novel and compact gas cleaning concept (covering particle precipitation, removal of HCl, H_2S and other sulphur compounds as well as tar cracking) and a high temperature solid oxide fuel cell (SOFC) for electricity generation. The technology shall be developed for the residential sector with a capacity range of 25 to 150 kW (fuel power) and shall allow the utilisation of cost efficient residual biomass feedstocks to enlarge the applicable fuel spectrum. Overall the new system shall achieve an equal-zero emission operation (regarding CO, OGC, NO_x, HCl, SO_x, PAH and PM and due to the utilisation of biomass also regarding CO_2), in combination with high electric and overall efficiencies. A two-phase approach for the construction of testing plants, the performance of test runs and accompanying assessments shall result in a significant increase of the technology performance of small-scale biomass based CHP systems.

The presented paper provides an overview of environmental aspects relevant for biomass gasifier fuel cell systems in general and presents also a generic approach for assessing related impacts. All given results are based on the work performed in the first phase of the ‘FlexiFuel-SOFC’ (‘FF-SOFC’) project. Following the opportunities and challenges to be addressed, the development of respective technologies for clean on-site heat and power generation is also strongly linked to sufficient incentives. Besides technology aspects, a well-aligned and comprehensive energy efficiency and environmental policy framework is crucial. Accordingly, the obtained results are set into relation with the EU major policy framework and recommendations are portrayed for aligning technical and policy evolution to harness environmental and overall benefits.

Environmental considerations on small scale biomass CHP

In advance of any large-scale future deployment of new technologies, such as efficient CHP systems fostered e.g. by polices and measures, the potential environmental impacts have to be adequately assessed. Accordingly, a systematic approach is needed to evaluate the specific environmental and policy implications. The following chapter describes a generic assessment method, typically used e.g. before the implementation of polices and measures for the EU or other markets, as well as the most relevant parameters and effects to be considered. The described approach is applied by Wuppertal Institute for small-scale biomass gasifier fuel-cell CHP systems for the residential sector and respective findings of the preliminary environmental impact analysis from the EU Horizon 2020 project ‘FlexiFuel-SOFC’ are presented, based on the data inputs by all project partners.

Assessing environmental impacts

Based typically on consecutive results from comprehensive market studies (provided for the FlexiFuel -SOFC project by partner Utrecht University) and data from techno-economic analyses (provided for the FlexiFuel-SOFC project by partner BIOS in cooperation with all other partners), the subsequent environmental impact assessments (IA) also need to follow a well-defined inherent structure. Prototypical structures for such analyses can be derived from various sources. For the presented exemplary IA, main aspects as defined by the Impact Assessment Guidelines of the European Commission [2] are used as basis. However, for assessing the deployment of innovative technologies still under development, some modifications are necessary since the context is not the same, as e.g. for the purposes of dedicated EU Ecodesign and Energy Labelling Directive Impact Assessments. Therefore a holistic method is described based on different steps as follows:

Step 1: Problem Definition → Step 2: Define Objectives → Step 3: Develop Options →
Step 4: Impact Analysis → Step 5: Comparison of Options

Step 1: Problem definition – Energy and resource efficiency

Besides general objectives of world-wide sustainability targets, such as mitigating global warming by reducing greenhouse gas and air pollutant emissions as well as the dependence on fossil fuels, also other technology specific aspects have to be tackled. For CHP using renewable energy sources, this applies especially also for constrains regarding the availability of biomass feedstocks.

Global trends concerning population, crop yields, diet, climate change, etc. usually suggest an expansion of cropland – if at all – only for the purpose to feed the world population. Further land requirements for dedicated energy crops would come on top, whereby the sustainable availability of arable land is definitely the essential limiting factor. If land is converted from natural habitats to agricultural areas, there is significant risk for severe biodiversity loss as well as other negative environmental impacts. For example, if major carbon sinks, such as forests, grass- and peatlands, are destroyed to provide space for cultivation, further negative consequences on greenhouse gas balances are the inevitable effect. As long as the overall demand for cropland grows for the needs of food production, any land use for crop production for material or energy purposes will lead to additional direct and indirect land use change [3]. If not strictly controlled, this might also lead to unintended and inefficient long-haul fuel transports, e.g. from tropical countries, where conditions for cheap feedstock production are most favourable.

Availability of water is another limiting factor for growing biomass feedstocks, both in terms of quality and quantity, as agriculture already uses about 70% of fresh water globally [3]. Any expansion of intensive energy crop cultivation would be adding to this. In particular in water scarce regions, this may lead to another form of competition with food production. Thereby, extreme weather events due to climate change might further increase uncertainties in terms of available water resources.

The above-mentioned exemplary environmental impacts related to the ‘water, energy and food nexus’ apply to many ‘first generation biofuels’. However, there are also new pathways for more sustainable production and alternative use of biomass for energy purposes that can help to reduce potential pressures on the environment.

Step 2: Define objectives – Efficiency first

Overall, demand side energy efficiency should provide the ‘first fuel’ for any future economic development [4]. Secondly, on the supply side any use of fuel, also for renewable biomass, should be as efficient as possible. In this context, in particular energy recovery from waste and residual biomass can save significant GHG emissions without requiring additional land use change. Specifically, the inevitable part of municipal organic waste and residues from agriculture as well as forestry provide significant energy potentials, which are still largely untapped worldwide. In the same vein, the cascading use of biomass to produce (construction) material first, then recovering the energy content of the resulting waste, can further maximize the CO_2 mitigation potential of biomass.

Thereby, comprehensive further research is still required, especially concerning the proper balance of residues remaining on-site for soil fertility and removal for energy provision, as well as with regard to nutrient recycling e.g. by ash utilization. Nevertheless, promising approaches exist or are under development to maximize benefits and to minimise negative environmental effects. In this context, the presented specific results from the 'FlexiFuel-SOFC' project concentrate on the principles for efficient use of solid biomass fuels from agricultural or forestry residues in small-scale CHP systems based on B-IGFCs during the operation phase, when energy efficiency and pollution control during energy recovery has to be addressed.

Step 3: Develop options – System application cases

Before starting an impact assessment, framework conditions have to be established, in particular the geographical scope (e.g. the EU-28) and time horizon (e.g. 2050) of the analysis. Furthermore, based on market studies and techno-economic analyses the most promising fields of application for the new technology need to be defined. For the analysed systems, decentralised operation close to fuel feedstocks is envisaged to avoid increasing levels of transportation of biomass with market penetration, which could otherwise offset emissions reduction benefits. Accordingly, based on the preliminary results of the 'FlexiFuel-SOFC' project, the following specific application cases have been identified for the European market (with focus on Central Europe):

- Application A is a system with about 70 kW_{th} nominal heat output and 20 kW_{el} electric power at nominal load to be used typically for base load heat and electricity production for small district heating networks (micro grids). It can be also applied e.g. for hotels, hospitals, or enterprises with permanent electricity and heat demand over the whole year. It uses bulk agro pellets as non-woody biomass solid fuel, and is characterized by 8,000 effective full load hours annually for electricity generation.

- Application B is a system with about 21 kW_{th} nominal heat output and 6 kW_{el} electric power at nominal load, to be used typically for space and process heating as well as domestic hot water supply for farms, large apartment buildings, public buildings, small enterprises or micro grids. As biomass solid fuel traditional wood chips are used. The system is optimized for heat-controlled operation (electricity and heat production in winter and transitional period; heat supply without electricity production in summer). It is characterized by 4,000 effective full load hours annually for the electricity generation part.

- Application C is a system with about 40 kW_{th} nominal heat output and 6 kW_{el} electric power at nominal load, to be used typically for heat and domestic hot water (DHW) supply for residential buildings such as multi family houses or apartment buildings. It is optimized for heat-controlled operation (electricity and heat production in winter; DHW supply without electricity production in transitional period and summer). Wood chips are used as biomass solid fuel and 2,500 effective full load hours annually are assumed for the electricity generation part.

Furthermore, for each of the application cases, three basic technology performance levels have been evaluated, which cover the most likely alternative technologies for the addressed market segment in Europe (focus on Central Europe/Austria, e.g. for operating hours and PV sunlight availability). Due to the envisaged decentralised operation and consumption strategy no general limitations in terms of electricity grid feed-in capacities are assumed.

- Base Case (BC) or 'Business as usual (BAU)' assumes that a standard biomass boiler generates the necessary thermal output for heat supply, while electricity needs of the application case are covered with grid electricity.

- Best Available Technology (BAT) assumes a state of the art biomass boiler (the highly efficient Windhager PuroWIN ultra low emission boiler, on the EU market since 2016) to generate the necessary thermal output, combined with a photovoltaic (PV) system to cover the electricity needs of the application case. The system is also connected to the grid to feed in potential excess PV electricity production or to cover electricity demand surpassing PV electricity output.

- Best Not yet Available Technology (BNAT) represents the newly developed 'FlexiFuel-SOFC' system. The needs for both, heat and electricity, in each application case are covered by the CHP system, which is also connected to the grid to feed in potential excess fuel cell electricity production or to cover electricity demand surpassing the CHP electricity output.

The environmental performance parameters from the first phase of the FlexiFuel-SOFC project have been compared within a preliminary environmental performance analysis with respective data from other state-of-the-art systems in order to evaluate and quantify the relative performance and improvement potentials of the new technology on a single product level. Preliminary results for TSP (Total Suspended Particles, also referred to as 'total dust') and energy efficiency (%, based on fuel input in terms of net calorific value 'NCV' / lower heating value (LHV) / lower calorific value (LCV), as well as combined useful heat and electricity output) are presented in Figure 1.

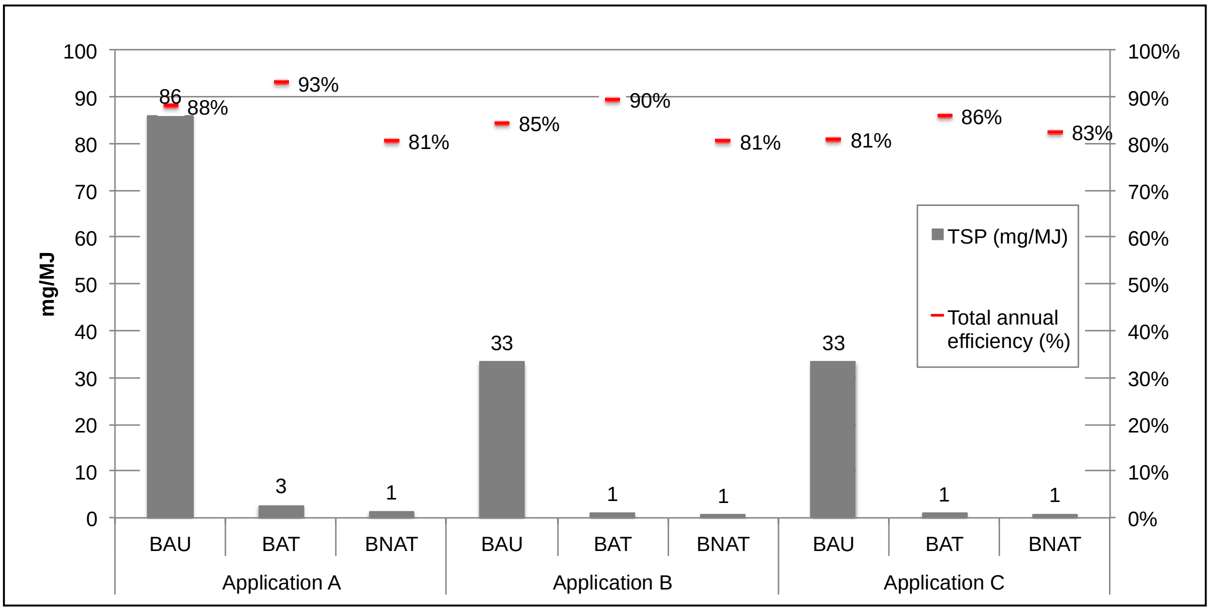


Figure 1: Preliminary TSP emission factors and energy efficiency compared

Source: Own illustration

Taking the available results from the FF-SOFC project into account, the preliminary environmental performance analysis revealed significant technical emission saving potentials of BAT and BNAT compared to BAU standard systems. Thereby TSP (total suspended particles) and (not illustrated) OGC (organic gaseous compounds) and CO (carbon monoxide) show similar reduction trends.

Following this, BAT and BNAT technologies have the potential to reach large on-site emission reductions in a short time period if broad market diffusion rates can be achieved in the future. Based on the current results and input data it can also be concluded that even stringent future Emission Limit Values (ELVs) in the EU for new installations (e.g. as part of a future revision of the EU Ecodesign Lot15 regulation on solid fuel boilers), should be no constraint for the much better new BAT and BNAT systems. The preliminary environmental performance analysis also revealed that in contrast to the very low emission levels, there remains a further technical optimisation potential especially for the total annual efficiency levels of BNAT FF-SOFC technologies compared e.g. to the highly efficient PuroWIN BAT system. This can be explained mainly by the current status of the FF-SOFC technology being still under development (e.g. no final insulation applied), the more complex CHP system operation (compared to heat only operation for BAU and BAT) as well as the technically more challenging usage of agro pellet fuel for Application A. Consequently, these aspects will be further addressed in the final phase of the FF-SOFC project.

Based on the previous definitions and findings, for the macro-scale EU wide impact assessment, the following three basic technology scenarios have been considered for each application case and the analysed specific market segment for heating and CHP systems:

- BC scenario as 'Business as usual' (BAU) development: sales and stock consist of Base Case standard appliances throughout the simulation period.

- BAT scenario: Sales are switched to assumed 100% Best Available Technology from the given reference date 2020 onwards.

- BNAT scenario: Sales switch to assumed 100% Best Not yet Available Technology from the given date 2020 onwards.

It has to be noted that such scenarios provide insights into ‘extreme’ pathways with 100% of sales switch to a given technology performance level within the analysed market segment at a given date while also providing a baseline, which assumes no changes besides the continuation of current trends. The result is a corridor showing the range of available technical potentials that can be addressed by a variable deployment of the new technology, e.g. as result of different polices and measures. This approach with ‘extreme’ pathways has the advantage to require solely total sales and stock data for each application case, and no market share split is required at this level. This provides upper and lower limits for the available corridor, which is especially relevant for new technologies that are still under development, and for which only very preliminary data is available.

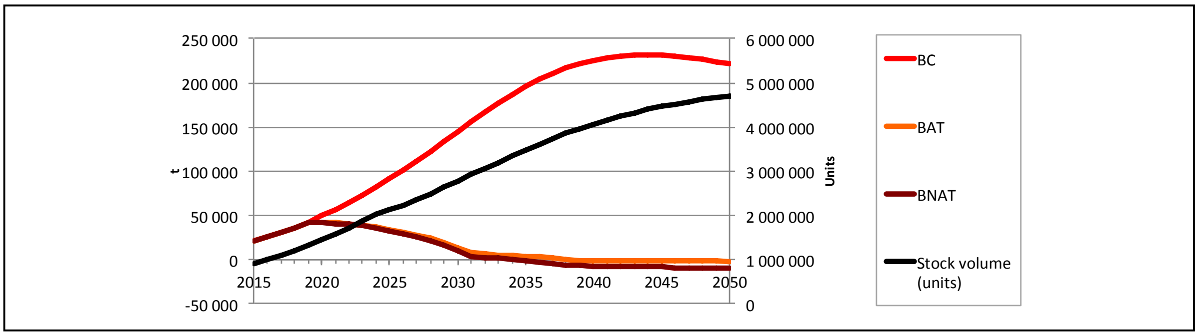
As essential part of this step, the application of a dynamic stock model is needed to calculate scenarios for the development of future stock sizes for the different technologies. Generally, based on market study data, stock data can be computed with a sales-driven model combining the last known or reconstructed stock volume data for applications, historical and expected total sales, and average lifespans for the different applications and system components. Stock data are calculated successively for each year of the simulation period, using classical stock dynamics model equations. Accordingly, as relying on preliminary values for several key parameters (such as emission intensities) of technologies still under development, this preliminary assessment does not seek to dwell into every last detail regarding absolute amounts, e.g. of emitted pollutants. At such an early stage emphasis is laid more on comparing the general dynamics of different options and explaining results for model calibration with the aim to give recommendations regarding the general future technical or policy evolution. As technology development progresses, later iterations of the assessment (after final development of the FF-SOFC technology) will address the relevant parameters more in detail.

Step 4: Impact Analysis

The analysis in step 4 evaluates quantitatively the operation-related impacts of the options identified in the previous step. Each option needs to be analysed on its own: first the baseline, that is one BAU scenario per application case; and next, also the BAT and BNAT scenarios respectively. Following this approach, the most relevant impact categories and associated indicators for the analysis are presented.

The most pertinent use-phase environmental indicators for B-IGFCs concern air emissions, including carbon dioxide (CO_2) as the relevant greenhouse gas. Regarding harmful emissions, particulate matter (PM, given in this paper as ‘Total Suspended Particles’ or TSP), organic gaseous compounds (OGC) and carbon monoxide (CO) are parameters typically addressed for biomass combustion systems as well as by related standards and regulations. The derived absolute emission levels depend on assumed stock volumes and product lifetimes, which dictate the pace of (re-)investment cycles. Total annual efficiencies determine fuel requirements for a given energy output. Also the used fuel type is an important influencing factor in terms of combustion processes and technology requirements, e.g. for Application A using a much more challenging non-woody biomass solid fuel (agro-pellets), compared to Applications B and C using traditional woody biomass fuels (wood-chips).

As peculiarity for CHP systems, emissions need to be treated as combined result of direct on-site fuel combustion and grid electricity effects. Taking into account also avoided emissions from off-site grid electricity generation, resulting CHP net emissions may be virtually even negative. Based on basic emission values per fuel type for solid fuel combustion and average emission intensities per type of electricity generation of conventional power generation in Europe [5][6] (for GHG emission rates,



including also LCA aspects for fuel processing and transportation), this applies for BAT and BNAT scenarios with less emission intensive on-site technologies in combination with avoided emission-intensive off-site grid electricity generation (see Figure 2 and Figure 3). For the defined application cases, BNAT net emissions decrease further mainly because FF-SOFC devices require less grid electricity consumption (contrary to BAT devices and their intermittent PV systems), hence their gross electrical output (the same as for BAT devices) is more avoided grid electricity which results also in more virtually 'negative emissions'.

Figure 2: Total net TSP emissions (t) and stock volume (units), EU-28, Applications A, B & C

Source: Own illustration

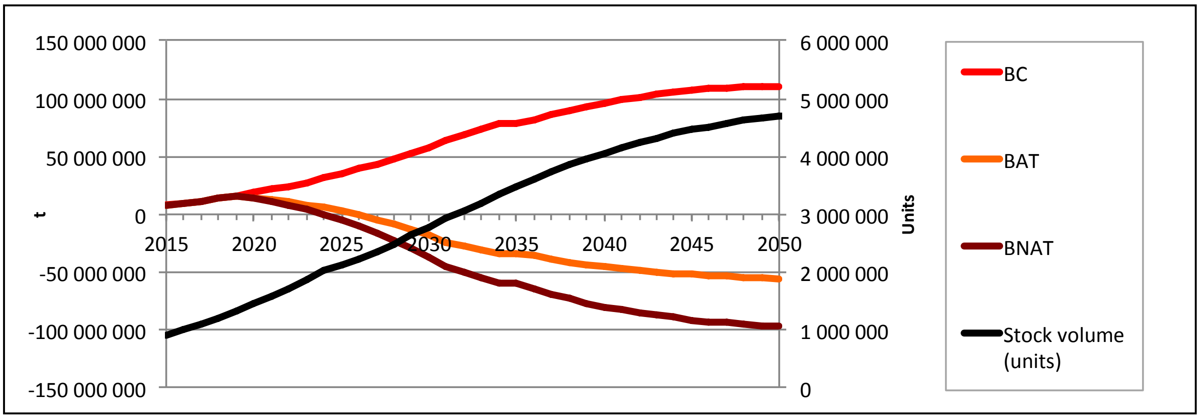


Figure 3: Total net GHG emissions (t) and stock volume (units), EU-28, Applications A, B & C

Source: Own illustration

Further important drivers are the assumptions made regarding the dynamics of key parameters such as the future energy demand per building. E.g. presuming all other aspects being equal, total stock emissions may decrease in the long run even in BAU although the stock still increases. The reason lies in the assumption that the typically required nominal output of heating appliances will decrease as expected effect of improved insulation and energy performance of buildings (e.g. in Europe, based on the European Performance of Buildings Directive 'EPBD' [7]). Consequently, this would mean that less fuel input per unit is required, resulting directly in less fuel related emissions.

Step 5: Comparison of options

Based on the defined operation parameters, total emission saving potentials from Application A are expected to dwarf those of the other two applications, especially due to the larger nominal system capacity, the high number of annual full load operating hours and the more challenging non-woody biomass fuel. Application B is a smaller device with much lower thermal output (less required fuel input), less operating hours per year, and uses 'cleaner' woody biomass fuel. Application C runs even less full load operating hours than Application B, generates more heat, but less electricity, i.e. relies more on grid electricity for BC systems.

In general, net grid electricity effects are most relevant regarding the total GHG emissions for BAU, BAT, and BNAT devices. Net GHG emissions in the BAU scenarios are particularly higher due to higher EU traditional power grid emission intensities while both BAT and BNAT GHG net emissions may even virtually decrease below zero due to lower emission intensities combined with the avoided grid electricity. This is also the case even with decreasing future power grid electricity emission intensities (according to current trends) taken into account.

Regarding non-GHG emissions, on-site solid fuel combustion is by far the main driver in baseline scenarios while emissions from fuel combustion and net grid electricity emissions also tend to (over)-compensate each other in BAT and BNAT scenarios. Table 1 compares qualitatively the gained results for the preliminary assessment of the different application cases. Subsequently, during the final phase of the FF-SOFC project, the preliminary environmental performance analysis and impact assessments will be updated and further refined as soon as final measurement data from the technology development will be available.

Table 1: BNAT (FF-SOFC) saving potentials compared to BAU scenarios

Impact indicator	Application A	Application B	Application C
Net electricity effects	+++	++	+
GHG emissions	+++	++	+
Non-GHG emissions	+++	++	+

Note: (+) more absolute saving potentials

As result of the preliminary analysis, especially BNAT for Application A and B systems appear highly relevant for available saving potentials, but also regarding derived non-environmental parameters, e.g. for large potential energy costs savings (solid fuel costs minus avoided grid electricity costs). Intensive use to maximise full load operation hours and electricity generation may even further increase economic attractiveness, which needs however to be adequately balanced e.g. with repair and maintenance costs and the lifetime of system components. Besides the environmental aspect, (fuel) efficiency is also economically a very important parameter, as there is on the other side currently no general financial rewarding for the superior emission reduction performance of the ultra low emission FF-SOFC technologies.

Furthermore, efficiency is typically also the most relevant ranking criteria when regulators implement Minimum Energy Performance Standards (MEPS). The same applies to product energy labels, which allow a better visibility and the active promotion of very innovative technologies. Related to this, also the selection for product-specific incentive programmes to foster e.g. a voluntary early retrofit or replacement of old installations with much better new products depend usually on (very) high efficiency levels. The high relevance of such policies and measures for CHP is therefore also further addressed in the following section.

Environmental policy aspects for CHP

In the last 20 years, much has been done to support cogeneration, i.e. an environmentally friendly way to generate electricity and useful heat. In Europe, several policies on EU and Member States (MS) level were introduced to foster the technology. At the same time, the aim was to increase the overall energy efficiency of the technology and to reduce harmful emissions to the environment, giving directly or indirectly general incentives also for the development of innovative B-IGFCs.

In 1997, a strategy to promote CHP and to dismantle barriers to its development was published [8]. From that time, the way was open for an accelerated development towards cogeneration. The next Figure 4 illustrates the relevant main EU policies on a timeline. The Directives, which are written in bold are key policies that have a strong influence on CHP, the other measures have an indirect effect. All together, they form a comprehensive policy package including clear targets, taxes, minimum standards, capacity building and financial incentives. In addition, it is important to consider that EU level measures are complemented by EU Member State's national policies. Some MS, like Germany, Belgium and the Netherlands have already introduced ambitious plans that go far beyond the requirements of the EU. The relevant EU policies with implications also for small-scale systems are described below.

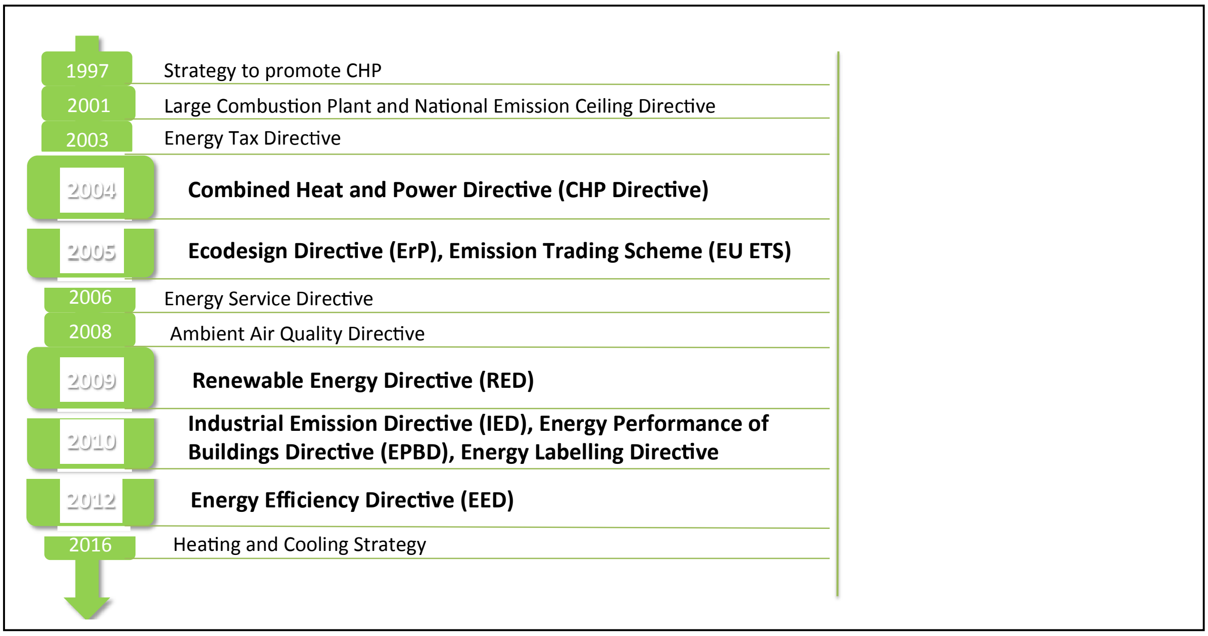


Figure 4: Evolution of the EU legislative regime on cogeneration

Source: Own illustration

In 2004, the CHP Directive 2004/8/EC [9] was published with the aim to 'increase energy efficiency and improve security of supply by creating a framework for promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings'. This was the first Directive with a focus only on cogeneration technologies. In 2012, this Directive was repealed by the Energy Efficiency Directive (EED) 2012/27/EU [10] and forms today the basis for the CHP development on EU level.

In contrast to the EED, the Ecodesign Directive 2009/125/EC [11] (also referred to as 'Energy related Products' or ErP Directive) forms a framework to set minimum performance requirements for specific product groups. Several Ecodesign implementing measures address cogeneration, e.g. regulation 2015/1189 applies to solid fuel systems with a nominal heat output of 500 kW_{th} or less as well as to solid fuel cogeneration boilers with an electrical capacity of less than 50 kW_{el}. The regulation sets MEPS and emission limit values (ELVs) for particulate matter, organic gaseous compounds, carbon monoxide and nitrogen oxides. Manufacturers have to meet these requirements, valid as of January 2020, to put products on the EU single market.The minimum requirements of the Ecodesign Directive go hand in hand with the Energy Labelling Directive 2010/30/EU [12], which provides depicted information to consumers on the efficiency of energy-related products. Respective information is provided for many product groups through a label, which is attached to each covered product to be sold on the European market. Due to this increased transparency, consumers and investors, which are the main target group, shall opt for more efficient products. In the wake of increased demand for energy-efficient technologies, manufacturers are, in turn, incentivised to develop more innovative products. For this purpose the European Commission determined for the current regulation that energy classes A++ and A+ rated heating appliances, which indicate the most energy-efficient technologies in this product group, are reserved for cogeneration as well as renewable energy sources. Hence, the EC deliberately decided to direct investment decisions of consumers and investors towards low-carbon cogeneration technologies.

Besides cogeneration-specific Directives, the Renewable Energy Directive (RED), and the Energy Performance of Buildings Directive (EPBD) build a general policy framework. These framework

Directives do not affect CHP specifically but have a strong influence in fostering the market. Thereby, the Renewable Energy Directive 2009/28/EC [13] has also an indirect role in influencing cogeneration applications with its specific role for biomass. Besides other aspects, the Directive establishes objectives to expand the share of renewable energy in the energy mix of the MS.

Even though the RED does not include a specific target on the expansion of cogeneration, in particular, MS can meet EU renewable energy objectives, among others (e.g. cofiring), also by biomass cogeneration. In addition, the Directive requests annual National Renewable Energy Action Plans (NREAPs), which shall provide planning security for investors.

Another relevant regulation is the Energy Performance of Buildings Directive 2010/31/EU [7] by stipulating in a holistic way that buildings become more energy-efficient. Existing buildings are supposed to meet energetic standards (Article 7) and all new buildings will have to be 'Nearly Zero-Energy Buildings' (NZEB) by the beginning of 2021. Furthermore, for new buildings, the Directive instructs that 'the technical, environmental and economic feasibility of high-efficiency alternative systems' should be taken into account. This also includes cogeneration as well as district heating or cooling systems, especially those that rely on energy from renewable sources. Hence, the EPBD requests MS to factor in CHP and district heating for providing building energy, which may have a positive effect on the demand for respective systems. However, given that the EPBD facilitates the reduction of energy demand in buildings, it should be acknowledged that buildings would also require less absolute energy for space heating. If net zero-energy buildings are achieved, the demand for CHP may alter and e.g. several building owners or settlements may have to team up so that heat energy demand is suitable for an economically feasible operation of a single joint CHP system.

Overall, the existing EU policy package for cogeneration has a strong influence on the potential market share of B-IGFC systems. The high number of policies demonstrates the relevance of CHP technology and the envisaged role in the coming years, and among others, EED, EPBD and the Ecodesign Directive/Labelling Directives are currently also under review to further enhance their future effectiveness. The next Figure 5 summarizes CHP relevant policies and differentiates between the nominal power range of the affected systems and the type of fuel.

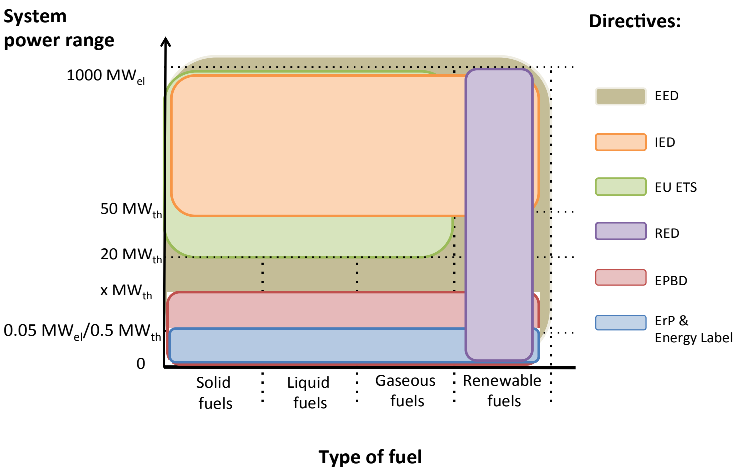


Figure 5: EU policies relevant for CHP, depending on fuel and nominal power range

Source: Own illustration (based on [14])

Conclusions and outlook

This paper provides insights into the most essential environmental aspects of small-scale gasifier fuel cell CHP systems, based on preliminary environmental impact assessment results for the technology developed in the EU Horizon 2020 project 'FlexiFuel-SOFC'.

Three specific application cases were investigated, which represent the most promising fields of application for the new technology on the European market: Application A for hotels, enterprises, small district heating networks; Application B for farms, small enterprises, micro grids as well as Application C for smaller residential buildings. Furthermore, for each of the application cases, the new FF-SOFC systems as 'Best Not yet Available Technology' (BNAT) were compared to traditional biomass boilers (Base Case or BC) and to state of the art biomass boilers associated with a PV system (Best Available Technology or BAT), which represent the most likely alternative technologies to be replaced on the European market. Thereby, on-site air emissions as well as grid electricity consumption effects have been jointly taken into account. Most relevant was for the preliminary impact assessment of the FlexiFuel-SOFC project to demonstrate general dynamics of different application cases and their sensitivities to technical parameters and other modelling assumptions. This kind of reasoning will inform how to use environmental impact assessment approaches to support directly decision-making processes regarding the general direction of the technology development and for policy making.

The presented results clearly identify the main emission drivers for the different technologies considered. In all scenarios, greenhouse gas (GHG) emissions are driven by grid electricity consumption effects. Since BAT and BNAT technologies generate their own electricity, avoided off-site grid electricity emissions quickly overcompensate direct on-site emissions from fuel usage in these scenarios, meaning that net GHG emissions are virtually negative. Regarding non-GHG emissions, on-site solid fuel combustion is by far the main driver in baseline scenarios while emissions from fuel combustion and net grid electricity emissions even tend to (over)-compensate each other in BAT and BNAT scenarios. BNAT scenarios show significant technical emission saving potentials compared to BC and even BAT systems, mainly because vastly less emission intensive BNAT devices consistently help to avoid more grid electricity consumption than intermittent BAT PV systems. It has to be mentioned that such results are sensitive to several crucial (preliminary) technical parameters of the FF-SOFC technologies that are still under development, such as e.g. emission intensities of the different solid fuels used by the application cases. Further assumptions regarding the future development of EU grid electricity emission intensities and heat energy demand (driving thermal output, hence fuel requirements) are also very relevant for the overall behaviour of the modelling.

Considered together, the gained insights give some meaningful indications on the most prominent environmental aspects to be considered for the further long-range system design within the FlexiFuel-SOFC project. The maximisation of electricity full load operation makes BNAT systems - with the current set of assumptions - most attractive, due to relevant on-site and grid electricity emission reductions (displaced EU grid electricity generation by own electricity production). Therefore, Applications A and B have overall saving potentials much larger than Application C, which make them most relevant for closer scrutiny. Of the two, Application A has by far the larger impact, especially due to significantly higher nominal heating and electric capacities, longer operating hours and the used agro-pellet non-woody biomass fuel.

Additionally, the gained results have to be set into relation with policy developments addressing the CHP sector. Especially for smaller CHP systems targeting at the residential sector, policies that address the typically required size of heating appliances may affect considerably the development and usage profiles of such systems. Most prominently, e.g. in Europe, based on the European Performance of Buildings Directive 'EPBD', the expected effect is that heat requirements of buildings will decrease significantly as consequence of improved insulation and energy performance of buildings. Accordingly, this may lead especially in the residential sector to altered system requirements, causing a shift from single dwelling heating systems towards micro-grids supplying several dwelling units to allow economically attractive annual operation hours. Additionally, very specific regulations for appliances, such as Ecodesign and Energy Labelling may further incentivise the market of residential scale B-IGFC systems. Overall, in this context FF-SOFC systems may provide one of the essential key technologies for efficient decentralised power and heat generation based on renewable energy sources to pave the way towards a decarbonized energysystem.

Acknowledgements

The research leading to the presented results has received funding from the European Union Horizon2020 Programme (H2020/2014-2020) under Grant Agreement n° 641229.

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US HPWH Market Transformation: Where We've Been and Where to Go Next

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Abstract

Water heating is the second largest energy end use in the US residential sector, accounting for approximately 17% of US residential energy consumption. Heat pump water heaters (HPWH) consume 60% less energy than conventional electric-resistance water heaters. However, HPWHs presently make up just 1% of all electric water heaters sold in the residential sector. If market penetration doesn't increase, there is a possibility that major water heater manufacturers will decrease investment in their HPWH product lines and eventually discontinue their HPWH models. Both market barriers and technology limitations have prevented market adoption in the past. However, technological barriers have been diminished through cooperation between manufacturers and the energy efficiency community. This paper will serve as an important historical reference on HPWH commercialization and market transformation efforts in the US, as well as provide a detailed analysis of market opportunities and offer next steps to increase market adoption.

Introduction

Water heating is the second largest energy end use in the US residential sector, behind only space heating. It accounts for approximately 17 percent, or 1.87 exajoules (1.77 quadrillion BTUs), of national residential energy consumption.[3] The EIA currently projects US household energy use to increase from 11.2 exajoules (10.62 quadrillion BTUs) in 2016 to 11.39 exajoules (10.8 quadrillion BTUs) in 2050, including an increase in water heating energy use from 1.87 exajoules (1.77 quadrillion BTUs) to 1.95 exajoules (1.85 quadrillion BTUs). [1]

Approximately 47 million US households have electric water heaters, and an average of 4.2 million electric water heaters are sold annually into the residential sector. [2] Nearly all electric water heaters in the US installed base and sold in the market use electric-resistance technology, which converts electrical energy into heat by running electrical current through resistors (i.e., electric water heater elements). This technology has nearly maximized its efficiency potential in electric water heaters.

HPWHs are an energy-efficient alternative to electric resistance water heaters. HPWHs use a vapor-compression refrigerant cycle (similar to air conditioners and refrigerators) to transfer heat from the surrounding air to the water in the tank. HPWHs use up to 60-70% less energy than electric-resistance water heaters. The typical 189-liter (50-gallon) electric-resistance residential water heater in the US consumes 4,650 kilowatt-hours (kWh) per year, costing more than US$580 annually to operate. In comparison, the typical 189-liter (50-gallon) HPWH consumes 1,910 kWh per year, costing US$240 to operate. On average, a US household will save more than US$340 and 1,740 kWh annually if using a HPWH instead of an electric-resistance water heater.[4]

Currently, major water heater manufacturers[5] offer more than 180 HPWH models in the US market, but HPWHs only make up about 1% of the annual US electric water heater sales, and considerably less than 1% of the installed base. [3] A moderate displacement of electric-resistance water heater installations with HPWHs would lead to significant national energy savings. There are 37 million households with electric water heaters having a tank size of 117 liters (31 gallons) or greater. [4] If just 15% of these households replaced their electric-resistance water heaters with HPWHs, it would amount to more than 15.7 terawatt-hours saved annually. The greenhouse gas emissions avoided would be the equivalent of removing 2.3 million cars from the road each year.

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[3] For 2016, water heating is 16.7% of delivered energy consumption by end use. Energy Information Administration, 2017 Annual Energy Outlook.

[4] Average US electric rate of ($0.1255 per kWh) from November 2015 through October 2016. Average kWh savings of 2,740 annually based on a 2.3 Energy Factor HPWH, 0.945 Energy Factor electric resistance water heater, 242 liters (64 gallons) per day of hot water use, inlet water temperature of 14.5 °C (58 °F), set point temperature of 57 °C (135 °F) and ambient air temperature of 19.5 °C (67.5 °F).

[5] Manufacturers include A.O. Smith, Bradford White, GE Appliances, Rheem, Stiebel Eltron, and Vaughn, among others.

Technological Considerations

HPWHs can achieve efficiencies greater than 100% because more than one unit of heat energy can be extracted from the surrounding air and transferred to the water for each unit of electrical energy used by the HPWH. However, since HPWHs must extract heat from the surrounding air, the temperature of the ambient air impacts the ability of the HPWH to heat water, and thus its efficiency. This is an important consideration when installing HPWHs in cold, unconditioned spaces (e.g., a garage in a northern climate). Identifying the HPWH's compressor cut off temperature is an important consideration in these circumstances. In addition to ambient air temperature, air volume is an important consideration for HPWHs. There must be 21 to 28 cubic meters (750 to 1,000 cubic feet) of air available to the unit so it has a sufficient supply of warm air for the evaporator. For this reason, a small closet, particularly one with a solid door, is an unsuitable location for a HPWH. [5] As the surrounding air is drawn across the HPWH's evaporator and cooled, moisture in the air will condense on the coil. This condensed water must be drained appropriately to protect the HPWH from damage.

In some circumstances HPWHs may not have adequate capacity to meet household hot water demand using only the heat pump. When the ambient air temperature is low, inlet water temperature is low, and/or hot water draw is high, HPWHs may automatically switch to electric-resistance mode to maintain the set point temperature of the stored water. Most HPWHs include resistance electric heating elements and are often referred to as hybrid water heaters in the water heating industry.

HPWHs typically have three to four manual settings to ensure operation meets user expectations:

- Heat Pump Only Mode, which maximizes energy efficiency during active use
- Default/Hybrid Mode, which automatically switches between heat pump and electric-resistance heating, as needed, to manage the tank's set point temperature.
- Electric-resistance Mode, which uses the electric elements to heat water and is least efficient
- Vacation Mode, which adjusts operational settings for extended periods of inactivity. [6]

When electricity generation and demand are in a period of imbalance on the distribution grid, the hybrid control of HPWHs offers flexibility for demand response. Electric water heaters are good candidates to balance the grid during these periods of imbalance since they can store electricity in the form of hot water, and can curtail electricity consumption to decrease demand on the grid with little or no impact on the user. While the HPWH is switched off, households need enough hot water in the tank to satisfy their hot water demand.

When using a HPWH for curtailing peak electricity load, a high set-point temperature (e.g., 65.5 °C or greater, or 150 °F or greater) combined with a thermostatic mixing valve can potentially ensure a larger supply of hot water during peak curtailment periods as well as provide a safe hot water delivery temperature (e.g., 49 °C, or 120 °F) for users. In addition, large tank HPWHs (e.g., 303-liter, or 80-gallon capacity) can ensure adequate hot water supply during peak curtailment periods for households with high hot water demand. [7] [8]

HPWHs installed within a home's thermal envelope can impact the home's space conditioning loads. The HPWH will provide a minor reduction in the home's cooling load during the summer, whereas it will cause a minor increase in the heating load in the winter. For a given home, the specific impact on space conditioning energy use depends on the climate, home's size/configuration, location of the HPWH in relation to the HVAC system's thermostat, and space conditioning systems used. One way to minimize the impact on heating and cooling loads is to install intake and exhaust ducting that allow the HPWH to draw exterior air from the outside, and expel cold exhaust air outdoors. Many HPWH models available in the market have connections available for aftermarket duct kits. Ducting can also ensure there's an adequate supply of air for HPWHs installed in confined spaces. [5]

The HPWH's fan and compressor emit between 45 and 65 decibels of sound while operating (depending on the model). This is roughly the amount of noise from a room air conditioner, dishwasher or refrigerator. For this reason HPWHs should not be located near bed rooms. Areas of the home that are not frequently occupied, such as garages or basements, are good locations for HPWHs to limit the potential for noise disruption.

Technology Timeline

The HPWH has gone through a number of technological phases since it was first introduced to the US market. Much of the development resulted from collaboration among the US Department of Energy (DOE), state agencies, efficiency programs, non-profit associations and manufacturers.

First Generation

The Hotpoint Company, which later became the Hotpoint Division of General Electric Company, designed and developed the first HPWH model for mass production in the 1950s. While this HPWH worked well, low electric rates limited its appeal and development was halted. [9]

In the mid-1970s, a spike in energy prices renewed interest in HPWHs. The National Rural Electric Cooperative Association (NRECA) and DOE funded the development of a HPWH prototype, selecting Energy Utilization Systems as the manufacturer. This led to the development of both integrated and add-on models. The integrated design combines the heat pump and tank into one unit whereas the add-on design is a split system, separating the hot water tank from the heat pump, for the purpose of retrofitting existing electric-resistance water heaters. In an expanded study in which 85 integrated and 15 add-on units were tested by 20 utilities, the integrated model performed well, revealing annual HPWH energy and operating cost savings of about 50% and useful life of 10 years. [9]

During the early 1980s, at least sixteen HPWH models were available in the US market, resulting in 10,000 shipments per year. In addition, a number of electric utilities were offering incentives and zero-interest loans to stimulate the purchase of HPWHs. However, the US HPWH market soon collapsed. While HPWHs were twice as energy efficient as electric-resistance water heaters, they were three to five times more expensive. Electricity prices declined, impacting cost effectiveness. In addition, reliability and quality control were below consumer expectations. For regions with moderately hard water, scale build-up on the heat exchanger combined with poor componentry led to early equipment failure. This issue was exacerbated by the lack of HPWH repair expertise among mechanical contractors and plumbers. As a result, a number of manufacturers (an estimated ten of twelve) removed their HPWH models from the market by 1995, and market penetration remained low at approximately 2,000 shipments of add-on HPWHs per year. [10] [11]

Market-Optimized Integrated HPWH

In the late 1990s, DOE, California Energy Commission (CEC), and the New York State Energy Research & Development Authority (NYSERDA) sponsored an R&D project to develop a “market optimized” HPWH. The primary objective of this project was to develop a “drop-in” or integrated HPWH that could serve as an immediate replacement for an electric-resistance water heater that had reached the end of its life, thereby facilitating quick and easy installation.[6] The “market-optimized”, integrated HPWH model was intended to relieve certain installation challenges (e.g. circulation pump, additional piping and wiring) and engineering weaknesses that caused reliability issues for the add-on HPWH. The consulting company Arthur D. Little Co. patented the concept with technical assistance from the Oak Ridge National Laboratory. The EnviroMaster International (EMI) Division of ECR International was selected as the manufacturing partner. In 2002, ECR International (via EMI) released the Watter$aver drop-in HPWH model. This model achieved an Energy Factor of 2.47 in accordance with the DOE test procedure, indicating energy savings of more than 60% compared to the typical electric-resistance water heater. [12]

While ECR International’s (ECR) drop-in HPWH model was a significant improvement over previous integrated and add-on models, it still experienced reliability and quality control issues stemming from control board and temperature sensor failure. To compound these reliability issues, ECR didn’t have the marketing budget or supply chain relationships to overcome market barriers. In particular, ECR lacked a network of technicians to install, service and repair units in the field. As a result, ECR discontinued the Watter$aver within five years of product launch and HPWH market penetration continued to be dormant.

[6] The majority of water heater installations are in response to failure of the existing water heater, calling for an emergency replacement to maintain hot water service.

Current Generation

In late 2005, ENERGY STAR, a voluntary labeling program for energy efficient products, focused its water heater strategy on working with major manufacturers to introduce integrated HPWH models to the US market, similar to the successful strategy used to introduce the front-load clothes washer in 1998. In 2009, after collaborating with manufacturers, trade associations, efficiency programs, utilities and retailers for four years, ENERGY STAR launched the residential water heater program, which featured the integrated HPWH. In six months, three manufacturers (GE Appliances, A.O. Smith and Rheem) released eight drop-in HPWH models (189- and 303-liter models, or 50- and 80-gallon models), all of which qualified for the label.

Concurrently with the launch of the ENERGY STAR water heater program, DOE initiated a rulemaking to update to US national, mandatory minimum energy efficiency standards for residential water heaters. In April 2010, less than a year from the introduction of HPWHs to the market, DOE ruled that all 208-liter (55-gallon) or greater electric water heaters would have to meet an efficiency level that only HPWHs could attain.[7] This rule went into effect in April 2015. [13]

After the launch of the ENERGY STAR water heater program and while DOE was finalizing its rule for water heater standards, the Northwest Energy Efficiency Alliance (NEEA) released its Northern Climate Specification for HPWHs in October of 2009. This voluntary specification calls for manufacturers to meet certain performance requirements (e.g., freeze protection, compressor cut-off temperature, condensate management, sound levels) that enable better HPWH performance, especially in colder climates. Many electric utilities and energy efficiency programs located in colder climates have adopted the NEEA specification as a requirement for their HPWH incentive programs. In response, manufacturers introduced new, improved HPWHs to the market.

The latest HPWH models can achieve an Energy Factor of 3.5 while operating in heat pump only mode with ambient air as cold as 1.5 °C (35 °F) or as hot as 63 °C (145 °F). They are duct ready with eight-inch diameter connections at the HPWH, capable of adapting down to five-inch diameter intake and exhaust ducting that can extend as far as 38 meters (125 feet). An important consideration for consumers is they operate at noise levels of 45 decibels. NEEA updated the title of this initiative to the Advanced Water Heater Specification in May 2016, introducing two new tiers of specifications, including demand response, intended to guide manufacturer HPWH development further. [14]

Emerging Technology

An emerging technology in the US market is the carbon dioxide (CO_2) HPWH, which uses CO_2 as the refrigerant. This technology has been in the Japanese market since 2001, when more than five manufacturers started selling the EcoCute design, initially developed through a partnership between Tokyo Electric Power Company, Denso Corporation and the Central Research Institute of Electric Power Industry (CRIEPI). The CO_2 HPWH has the unique ability to achieve a Coefficient of Performance (COP) greater than 3.0, while also maintaining 90 °C (194 °F) set point temperature at an ambient air temperature of -15 °C (5 °F). [15]

The Japanese manufacturer Sanden has introduced both integrated and split-system CO_2 HPWH models to the US market. The integrated model has a 163-liter (43-gallon) tank, achieves an Energy Factor (EF) of 2.65, First-hour Rating (FHR) of 261 liters (69 gallons), and can be fully ducted. The split system model has its compressor and evaporator located in an outdoor unit whereas the 314-liter (83-gallon) tank is located indoors. It achieves an EF of 3.35, FHR of 97 and operating noise level of 38 decibels for the outdoor unit. Both Sanden HPWH models are validated as capable of implementing demand response if equipped with the necessary software and hardware to initiate utility-generated DR signals. [16]

Market Dynamics

Understanding the state of the HPWH market involves understanding current HPWH market share, market actors, consumer decision-making factors and market barriers.

[7] The minimum mandatory Energy Factor as of April 15, 2015 for residential electric water heaters with a rated volume of 208 liters (55 gallons) or greater was determined by the volume of the water heater using the formula: minimum Energy Factor = 2.057 – (0.00113 x Rated Storage Volume in gallons).

Market Share

Currently in the US, both the installed base of HPWHs and the number of HPWHs sold annually are small in comparison to the overall residential water heater market. The majority of residential water heaters sold annually in the US, as well as the majority of the installed base, are natural gas-fired units.[8] ENERGY STAR started tracking the number of qualified HPWH shipments in the US in 2010. Since then, approximately 260,000 HPWHs have been shipped domestically out of a total of 23.5 million domestic electric storage water heater shipments. In addition, there are approximately 46.8 million electric water heaters in the US installed base. This means that the estimated HPWH average annual share of the US electric water heater market is only 1.1%, and the HPWH share of the installed base of electric water heaters is 0.5%. [3] [2]

Table: Shipment Data for Electric Water Heaters and ENERGY STAR qualified HPWHs

Year	ENERGY STAR HPWH Shipments	Electric Water Heater Shipments	HPWH Market Share
2010[9]	59,000	3,736,597	1.6%
2011	23,000	3,738,882	0.6%
2012	34,000	3,733,988	0.9%
2013	43,000	4,008,478	1.1%
2014	46,000	4,277,329	1.1%
2015	55,000	4,027,067	1.4%
Total	260,000	23,522,341	1.1%

The updated US mandatory minimum energy efficiency standards for residential water heaters took effect in April 2015. These standards require all 208-liter (55-gallon) or greater electric water heaters meet an efficiency level that only HPWHs can attain.[10] It is now clear that these standards have not had the expected effect of significantly increasing the market adoption of HPWHs. There is evidence that installers have found multiple ways to work around the standards, such as installing two smaller electric-resistance water heaters or installing an electric-resistance water heater in combination with an electric tankless "booster" water heater. [17]

Market Actors

Water heaters move through a few different market channels from manufacturers to consumers. Three manufacturers, A.O. Smith, Rheem and Bradford White, produce an estimated 95% of residential water heaters sold on the US market. The remaining 5% are manufactured by dozens of smaller companies. Manufacturers distribute water heaters to wholesalers (also referred to as distributors) and retailers (e.g., Lowe's, The Home Depot, etc.). Wholesalers and retailers each account for approximately half of domestic water heater shipments. Retailers tend to sell more electric water heaters whereas wholesalers tend to sell more gas water heaters, both at approximately a 60/40 split. Plumbers and mechanical contractors sell and install 60% of all water heaters whereas consumers install 26% as Do-It-Yourself projects. Remodelers, builders and property owners account for the remaining 14% of shipments. [18] [19]

[8] According to the 2009 Residential Energy Consumption Survey (RECS), 58.3 million US homes have natural gas-fired water heaters compared to 46.8 million homes with electric water heaters. According to the Air-Conditioning, Heating and Refrigeration Institute (AHRI), there were 4.4 million natural gas-fired water heaters shipped in the US in 2015 compared to 4 million electric water heaters.

[9] 2010 ENERGY STAR HPWH shipment data include shipment data from 2009 since qualified HPWHs entered the market part way into the year. 2009 ENERGY STAR HPWH shipments were not reported, but added to 2010 shipments.

[10] The minimum mandatory Energy Factor as of April 15, 2015 for residential electric water heaters with a rated volume of 208 liters (55 gallons) or greater was determined by the volume of the water heater using the formula: minimum Energy Factor = 2.057 – (0.00113 x Rated Storage Volume in gallons).

Electric water heaters are more likely to move through the retailer market channel and undergo a consumer DIY installation. HPWHs reflect this trend with 50% of HPWHs purchased at a retailer and installed by the consumer as a DIY installation. [17]

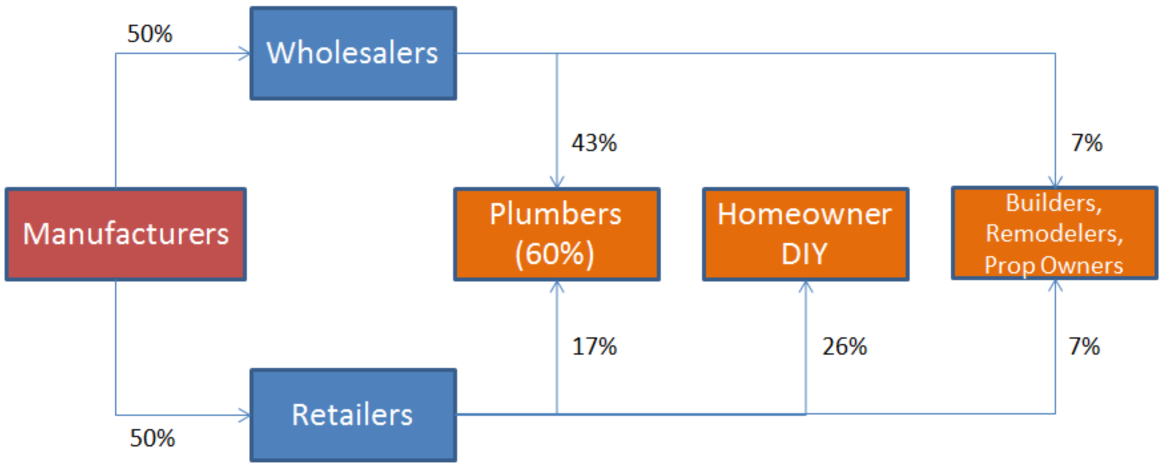

Figure: Water Heater Distribution Channels and Shares

Organizations that promote energy efficiency, such as for-profit electric utilities, municipalities, electric cooperatives, state energy offices and regional energy efficiency alliances, are not typically a part of the residential water heater distribution chain. Energy efficiency programs run by these entities tend to have subprograms emphasizing the market adoption of specific energy efficient technologies, such as HPWHs. The long-term objectives of these programs can include offsetting the need for electricity generation, decreasing peak load, decreasing greenhouse gas emissions, decoupling of revenue and profit generation, and meeting a clean energy portfolio standard. Energy efficiency programs intervene in the market to overcome barriers to technology adoption in order to achieve efficiency resources. Program strategies may target each market actor in the distribution chain to facilitate increased market adoption by consumers. The longest-running HPWH efficiency programs have been in existence since 2009.

Consumer Decision-Making Factors

Research by the NEEA suggests that the primary reason consumers purchase new water heaters is due to failure of the existing unit. Emergency water heater replacements account for an estimated 85-90% of water heater purchases. In these instances, it's typical for consumers to purchase the water heater model suggested by the installer, who either recommends installation of the same water heater model as the failed unit, or a model that is similar in its specifications. While the majority of consumers consider energy efficiency important, they do not perceive it as important enough to justify early replacement of a functional water heater. The other reasons consumers purchase new water heaters are the lack of hot water production, energy efficiency, leaks (i.e., near failure) and high operating cost. [17]

NEEA's research also suggests that current HPWH owners purchased a HPWH over alternatives to save energy, receive utility rebates, and decrease water heating operating costs. The majority of current HPWH owners planned their water heater replacement rather than waiting for the previous unit to fail. While these consumers previously had operational water heaters, they went forward with the planned HPWH replacements primarily due to the old age of the previous water heater and secondarily to upgrade to a more efficient water heater. These consumers considered at least one alternative to a HPWH, which is an advantage that planned replacements have over emergency replacements due to the lack of a time constraint. In addition, they came to the conclusion to purchase a HPWH on their own, not due to the suggestion of a contractor or installer. All of this suggests that current HPWH owners are not representative of typical water heater owners, who account for the majority of the market. [17]

Consumers who are aware of HPWHs but currently own electric-resistance water heaters claim to have three main drivers that could entice them to purchase a HPWH: decline in first cost, failure of the current water heater, and increased utility rebates. [17]

Market Barriers

A combination of barriers is inhibiting HPWHs from realizing their market potential. These barriers have evolved with economic, market and technological circumstances over time. Market barriers remain a significant challenge whereas technological barriers, through incremental innovation, have been diminishing. Key barriers are those considered most influential to inhibiting HPWH market transformation.

Table: Key Barriers to HPWH Market Adoption

Barrier	**Description**
First Cost	High upfront cost compared to the standard electric-resistance water heater. Consumers encounter “sticker shock” when discovering that the purchase and installation of a HPWH is 2-3 times more expensive.
Consumer Awareness and Education	Lack of awareness of HPWHs as a purchase option, its value proposition and what to do to facilitate a HPWH installation.
Availability	Lack of consumer access to HPWHs, particularly when in need of an urgent replacement due to the failure of the existing water heater.
Installer Expertise	Lack of trained and engaged installers. Lack of clarity on HPWH sizing to meet household hot water needs. Lack of interest or understanding in promoting HPWHs to consumers and resolving installation barriers.
Performance	Confusion over climate suitability and parasitic losses to heating systems. Dissatisfaction with hot water delivery in heat pump mode. Displeasure with the compressor noise level and cool air exhaust.
Installation Constraints	Lack of space at the current water heater footprint to accommodate a HPWH, inability to accommodate ventilation requirements, ducting and/or condensate drainage.

First cost is still the primary barrier to HPWH market adoption. The installed cost of a HPWH can run US$1,500 to US$3,500, depending on the model and installation circumstances. In comparison, an electric-resistance water heater tends to have an installed cost of US$600 to US$1,000. As a result, HPWHs typically have an incremental installed cost of US$1,000 to US$2,500. [20] Manufacturers, retailers, distributors and installers recognize this as a critical issue, particularly in the replacement market. Consumers who need an urgent water heater replacement often don’t consider the lifecycle cost effectiveness of their purchase. They often don’t have the time to research water heater options such as a HPWH and find incentives decreasing the first cost of a HPWH. In addition, they may not have the money readily available to make a purchase. [17]

Most US consumers are still unfamiliar with HPWHs, particularly the value proposition and whether their household is a good candidate for HPWH installation. Consumers will choose an incumbent water heater technology by default in absence of understanding the existence and benefits of owning a HPWH. The value proposition of purchasing a HPWH lies in its annual energy and cost savings. However, this is often not of interest to consumers unless their current water heater fails and they’ve been made aware of the cost savings benefit by their installer or retail sales associate at the point of sale. Water heaters are typically installed in obscure locations in a household and receive little to no attention until they break or don’t provide enough hot water during a peak consumption period. The majority of consumers do not know how much energy their water heater consumes and/or how much it costs them to operate. [20]

Depending on the region, consumers may not have access to HPWHs, particularly when in need of an emergency replacement. Wholesalers and retailers may have few, if any, HPWHs in inventory. They may ask the consumer to put in a special order to receive the appropriate HPWH model for the household's hot water use and installation circumstances. It can take days, or even a week, for the HPWH unit to arrive for installation. Installers may not have HPWHs on the truck when an emergency replacement is needed. In certain regions, installers depend entirely on wholesalers or retailers for inventory and do not keep a stock of water heaters at their place of business.

Depending on the region, installers may have inadequate expertise in installing and promoting HPWHs to consumers. They may need different licenses to conduct the plumbing, maintain the heat pump and maintain the electronics (e.g., control board). They also may have a limited understanding of how to accommodate HPWH installations across various household scenarios. In these situations, consumers may not have the patience for the installer to conduct the due diligence needed to resolve complications such as HPWH size, ventilation, ducting and condensate drainage. Installers may also have issues with sizing the HPWH for the household hot water load. Last but not least, installers may have little interest in promoting HPWHs to consumers, particularly due to their fear of potential "call backs" if the HPWH has a maintenance issue.

Improvements in HPWH technology have lowered certain barriers. Over the past five years, manufacturers have decreased the noise level of HPWH compressors by roughly 15 decibels. They have also improved heat pump efficiency in cooler ambient temperatures by lowering the cut-off temperature for compressor operation. Most HPWHs in the market come with connections to fully duct (intake and exhaust) the unit using an aftermarket kit. This provides a solution to consumer displeasure with cool air exhaust and addresses concerns about parasitic losses to heating systems. Manufacturers have also increased the reliability of HPWHs by improving design and construction, which is reflected in longer warranties.

In certain instances, HPWH installation can be cost prohibitive if major renovations are necessary to accommodate the unit. This is more common for installing HPWHs in multifamily buildings, which may not have the space for a HPWH or may not have a way to drain condensate. In these instances, consumers may not have the option of relocating the HPWH or renovating the existing footprint to accommodate the HPWH.

Best Practices

Best practices can help improve HPWH market adoption at the national, regional or local level in target markets. Overcoming market barriers effectively calls for the involvement of multiple market actors to coordinate activities. When market actors partner, their initiative is stronger than if each had conducted its own effort. Co-marketing partnerships leverage the brand, relationships, and financial resources of each participating market actor involved. These partnerships can arise between all market actor types, but are more common through a retailer, manufacturer and efficiency program effort. [21]

Energy efficiency programs and market actors use a number of tactics to address critical HPWH barriers in an effort to increase market adoption.

Table: Best Practices for Overcoming Market Barriers

Barrier	Best Practices
First Cost	• Mail-in rebates • Instant rebates or buy downs • Low-interest loans • On-bill financing • State tax credits • Federal tax credit • Leasing • Consumer awareness
Consumer Awareness and Education	• Compelling consumer messaging • Bill inserts

	• Point-of-purchase displays and informational brochures • Web presence and mass emails • Advertisements • Press releases • Journal and newsletter articles • Live events • Social media campaigns • Sales training for installers and retail sales associates
Availability	• Wholesaler incentives • Installer incentives • Manufacturer influence • Promotion guidance • Business case research and analysis
Installer Expertise	• Trainings • Competitions • Certification, credential and marketing • Installation guidance • Sales guidance • Incentives
Performance	• Testing • Consumer feedback • Specification requirements • Tiered incentives • Golden Carrot competitions

The first cost market barrier offers a variety of options for reducing its impact on consumer purchase decisions. The most common tactic for reducing first cost is offering consumer incentives, such as mail-in or instant rebates (purchase subsidies). Low- or no-interest loans and on-bill financing are other ways to provide funding relief for consumers who pay a premium when purchasing HPWHs upfront. A potential way of addressing first cost is for efficiency programs to lease HPWHs to consumers at a discounted monthly cost for the HPWH, maintenance and repair over the unit's lifetime. In this case, consumers have zero upfront cost and receive immediate cost savings through decreased energy use. [22] Federal and state tax credits are another method of reducing first cost. It's important for market actors to promote all options available to consumers to relieve first cost. In combination, these options can have a substantial impact at reducing the incremental cost of a HPWH purchase.

Improving consumer awareness and education involves developing compelling consumer messaging and spreading this message through multiple avenues and market actors to impress upon target consumers. Messaging should clearly communicate the value proposition for HPWHs, call on consumers to plan their HPWH replacement, and catch attention (e.g., through vivid imagery or expression). Involving each market actor in the consumer awareness strategy improves its effectiveness. Installers and retail sales associates have direct engagement with consumers and can provide education and guidance in a one-on-one setting. Training and guidance can improve their ability to communicate the value proposition of HPWHs. Retailer promotions and discounts, often in partnership with manufacturers and/or efficiency programs, are a sizable driver of consumer purchases. Point-of-purchase materials and displays can introduce a call to action for consumers to purchase a HPWH and start saving energy and money right away. [17]

Increasing availability begins with motivating wholesalers and retailers to keep a sufficient inventory of HPWHs and then motivating installers and retail sales associates to drive HPWH installations and sales. Manufacturers and efficiency programs can offer incentives, such as rebates or commissions, to these market actors for selling HPWHs. Providing training or promotional guidance can help these market actors with consumer messaging and targeting. Furthermore, communicating how HPWH sales benefit their business case is important, particularly for independent wholesalers, retailers and installers, since they may not fully appreciate the higher margins of HPWH sales and how HPWHs diversify their product portfolio. [20]

Establishing an experienced and engaged base of HPWH installers calls for a combination of activities. Trainings are a good way to improve installer expertise. They provide live instruction and offer tips for navigating complicated installation scenarios. They can also offer an opportunity to equip installers with the information and messaging to influence HPWH purchases. Written guidance can be provided via instruction manuals or smartphone applications, which can offer a resource for both routine and unique installation scenarios. Once trained, efficiency programs can certify and brand installers so they receive exclusive access to incentives and can have their expertise marketed to consumers. A unique method of increasing installer engagement is to offer instant rebates on each HPWH installed. Efficiency Vermont has increased market share considerably in its region using this approach. [23] Another unique method is to offer incentives to installers for reaching certain milestones for HPWH installations. NEEA has been successful using this approach to increase HPWH installations in its territory. [24]

While these best practices are relatively straight forward, there are opportunities for implementing innovative or unprecedented strategies. Other industries employ a myriad of strategies to address similar market barriers to those faced in HPWH market adoption. Solar developers conduct power purchase agreements to relieve market barriers, such as first cost, for installing solar panels. There is an opportunity to conduct efficiency purchase agreements for HPWHs with the emergence of wireless low-cost submeters and connected HPWHs. In this case, an efficiency program can purchase, install and maintain the HPWH at the cost of purchasing and installing an electric-resistance water heater to the customer. An efficiency program can use an algorithm to calculate the expected energy use of an electric-resistance water heater, given the home's metered hot water loads using the HPWH. The expected cost savings on energy bills could be allocated between the efficiency program and customer at a predetermined distribution. This would effectively be a pay-for-performance approach. Using a connected HPWH under this approach could also be an opportunity for demand response programs interested in peak load management. Efficiency programs, manufacturers, retailers, wholesalers and installers may discover that applying innovative methods can be more effective than the time-tested methods currently considered best practices.

Market Assessment

Approximately 46.8 million, or 41%, of occupied US homes have an electric-resistance water heater. However, not all of these homes are a good fit for a HPWH. Among the HPWH models in the market, the smallest tank size is 189 liters (50 gallons) and lowest FHR is 193 liters (51 gallons) of hot water delivery. [25] Electric-resistance water heater models with 114 liters (30 gallons) of storage have a maximum FHR of 185 liters (49 gallons) of hot water delivery. [26] Thus, homes currently using an electric-resistance water heater with 114 liters (30 gallons) or less of storage are not a good candidate for a HPWH replacement. Of homes with an electric-resistance water heater with storage of 117 liters (31 gallons) or more of storage, 68% are single-family homes, 23% are in multifamily homes and 9% are in mobile homes (small, prefabricated single-family homes – also called manufactured homes). [4]

Table: US Homes with Electric Water Heaters with 31-49 and 50+ Gallons of Storage

Residence Type	117-188 liters (31-49 gallons)	189+ liters (50+ gallons)	Total	Percent
Mobile Home	2,716,219	694,391	3,410,610	9%
Single-family: detached	14,184,598	9,358,231	23,542,829	63%
Single-family: attached	1,303,569	504,343	1,807,912	5%
Multifamily: 2-4 units	1,566,804	903,468	2,470,272	7%
Multifamily: 5+ units	3,753,591	2,290,839	6,044,430	16%
Total	23,524,781	13,751,272	37,276,053	100%

Based on data from Energy Information Administration's 2009 Residential Energy Consumption Survey

Mobile homes and multifamily homes tend to have HPWH installation complications due to space constraints, condensate drainage, and ducting. Multifamily homes are also more likely to be rented than owned, which causes a split incentive issue between the owner and renter for the investment in energy efficient upgrades. This makes these types of homes inferior candidates compared to single-family homes for replacing existing electric-resistance water heaters with HPWHs. However, the high hot water loads in multi-family buildings offer an opportunity for the installation of CO_2 HPWH technology combined with commercial-size tanks, where the equipment cost can be split among multiple housing units.

Target Household Profile

Based on market share, HPWH technology is in the early stages of the adoption curve. Consumers who fall in this range of the adoption curve are innovators and early adopters who tend to have above average financial resources and education levels. [27] The target household profile for a HPWH purchase is a single-family home with hot water usage suitable for an electric-resistance water heater with 117 liters (31 gallons) or more of storage, a household gross income of US$50,000 or greater, and householder education level of an Associate Degree or higher. [17] Using data from the US Energy Information Administration's 2009 Residential Energy Consumption Survey (RECS), there are approximately 6.9 million households in the US that fit this profile, making up approximately 14.8% of US households with electric water heaters. [4]

In addition to existing homes, new homes are continually constructed that also fit the target household profile. Based on US Census building permit data, the US has an annual average growth rate of 7.7% in new construction of single-family homes since 2012, meaning growth of new home construction has been accelerating over the past five years. Assuming this average growth continues, the US should add approximately 795,000 new single-family homes in 2017.[11] If new single-family home construction reflects existing stock, then 217,000 of these households fit the profile of needing a water heater with 117 liters (31 gallons) or more of storage (regardless of fuel type), a household gross income of US$50,000 or greater, and householder education level of an Associate Degree or higher. These households indicate the maximum HPWH installations in target households in the new construction market if fuel type were not a consideration. Assuming water heater fuel type for new single-family home construction reflects existing housing stock, then 76,800 of these households fit the profile of needing an electric water heater with 117 liters (31 gallons) or more of storage, a household gross income of US$50,000 or greater, and a householder education level of an Associate Degree or greater. These households indicate the expected target household HPWH purchases in the new construction market. [28]

Based on US Census building permit data, the US has an annual average growth rate of 7.85% in new construction of all household types since 2012. Assuming average annual growth continues, the US should add 1,264,000 new households in 2017. If new household construction reflects the existing stock, then 41.2%, or 520,400 households, are expected to install electric storage water heaters. Assuming one electric water heater is installed per household, this represents the annual US new construction market for electric water heaters. Total US electric water heater shipments have fluctuated between 3.7 million and 4.8 million annually over the past 20 years with an average of 4.2 million electric water heater shipments per year. Removing the electric water heater shipments destined for the new construction market results in a replacement market of 3.67 million electric water heaters annually. Given that the target household represents 14.8% of all US households with electric water heaters, approximately 542,000 of annual electric water heater shipments in the replacement market are purchased by target households.

[11] According to the US Census, actual single-family household new construction "starts" are 2.5% greater than building permits issued due to reclassification of multifamily households to single-family attached households as well as housing starts that do not require a building permit. However, actual single-family household new construction "completions" are 3.5% less due to household construction abandoned. Thus, building permits reflect a net decrease of 1% of actual single-family household new construction. Analysis reflects these data corrections.

Table: Target Household Profile in US Installed Base and Market

US	Target Household Profile	Households with Electric Water Heaters	Total Households with Water Heaters*
Installed Base	6,904,188	46,759,338	110,729,440
Annual Replacement Market	542,097	3,671,406	7,450,689
Expected Annual New Construction Market	76,836	520,377	1,264,416
Expected Total Annual Market	618,932	4,191,783	8,715,105
Potential Annual New Construction Market	216,726	-	-
Potential Total Annual Market	758,823	-	-

* Based on RECS 2009 data, there are 113.6 million total US households of which approximately 2.9 million do not have a water heater.

Target Region Profile

The ideal target region for HPWH market penetration should have a high saturation of target households. It should also have incentives and financing available for consumers to leverage in their purchase. For the purpose of a HPWH value proposition that resonates even better with consumers, it should also have comparatively high electric rates, improving the cost effectiveness of a HPWH purchase.

Assessing regional HPWH market adoption opportunities begins with identifying states or regions with a high saturation of target households. The methodology applied to RECS 2009 data to determine characteristics of the US housing stock, water heater installed base, and water heater market can also be applied to the RECS reportable domains, which are the states or groups of states by which EIA designs and conducts the survey sample for RECS. These states and regions provide the most detailed or disaggregated analysis using the RECS data. Total expected shipments per year for the target household profile offer a basis for determining which states or regions are better candidates for HPWH market adoption than others, assuming the fuel type selected in new construction reflects the state or region's disposition for electric water heating in the installed base. Total potential shipments per year for the target household profile provide a basis for determining which states or regions are better candidates if the new construction market were not disposed to a specific water heater fuel type and all target households selected electric HPWHs. This represents the potential shipments to target households if market actors influenced the new construction market to install electric HPWHs rather than the typical fuel installed in the region or state (e.g., natural gas).

States in the Southeast and Mid-Atlantic have the greatest number of projected annual 31+ gallon water heater shipments to target households, both expected and potential. These states also have strong new construction markets and hot/humid ambient temperatures that are favorable for HPWH operation.

Table: Target Household Projected Annual Shipments of Electric Water Heaters by RECS 2009 Reportable Domain

RECS Reportable Domains	Expected Shipments/year			Potential Shipments/year		
	Replace	NC	Total	Replace	NC	Total
FL	76,067	16,779	92,847	76,067	21,513	97,581
TX	42,098	9,313	51,411	42,098	32,498	74,596
SC, NC	38,818	9,594	48,412	38,818	15,669	54,487
DC, DE, MD, WV	38,236	3,582	41,818	38,236	6,171	44,407
OH, IN	33,855	2,327	36,182	33,855	7,955	41,810
PA	32,525	1,615	34,140	32,525	4,098	36,623
AZ	27,463	5,610	33,073	27,463	8,892	36,355
VA	28,745	3,655	32,400	28,745	9,029	37,774
AL, KY, MS	27,649	2,330	29,979	27,649	4,718	32,367
WA, OR, HI, AK	24,097	3,584	27,681	24,097	10,876	34,973
IA, MN, ND, SD	21,821	2,466	24,286	21,821	8,642	30,462
GA	20,026	3,611	23,637	20,026	10,598	30,624
TN	13,949	2,909	16,858	13,949	6,255	20,204
CA	14,114	1,168	15,282	14,114	17,721	31,835
WI	12,391	1,055	13,446	12,391	3,882	16,273
CT, ME, NH, RI, VT	11,367	745	12,112	11,367	3,202	14,569
MI	10,392	729	11,121	10,392	4,211	14,603
IL	9,426	378	9,804	9,426	2,892	12,318
AR, LA, OK	8,581	974	9,554	8,581	3,854	12,434
NY	9,135	360	9,495	9,135	3,501	12,636
MO	8,694	660	9,353	8,694	2,791	11,485
MA	8,627	625	9,252	8,627	2,736	11,362
NJ	7,898	417	8,316	7,898	3,573	11,471
NM, NV	6,194	886	7,080	6,194	4,367	10,561
KS, NE	5,281	493	5,774	5,281	2,448	7,729
ID, MT, UT, WY	2,494	540	3,035	2,494	7,032	9,526
CO	2,155	429	2,584	2,155	7,603	9,758
US Total	542,097	76,836	618,932	542,097	216,726	758,823

Table notes: Individual values may not sum to the total values due to rounding. “Replace” refers to the shipments in the replacement market and “NC” refers to shipments in the new construction market.

Based on data in the Database of State Incentives for Renewables & Efficiency (DSIRE) and ENERGY STAR Rebate Finder, there are more than 130 major efficiency programs offering HPWH incentives to households covered by efficiency programs and most of these incentives are mail-in rebates. These programs are accessible to more than 57 million electric utility households nationally. Rebate values range from US$50 to US$1,500 per HPWH, depending on the circumstances of the

HPWH installation.[12] States with a high number of households with access to HPWH rebates as well as high average rebate values are better candidates for market adoption than those with a low or no households with access to rebates. Active rebates provide an immediate opportunity for increased HPWH market adoption if combined with other best practices. [29] [30] [31]

Table: Rebate Programs by State (Minimum of 1,000,000 Customers Covered)

State	Total Electric Utility Households Covered	Weighted Average Rebate
California	11,200,000	$310
New York	4,500,000	$525
Massachusetts	3,000,000	$260
Wisconsin	3,000,000	$300
New Jersey	3,000,000	$500
Tennessee	2,900,000	$200
North Carolina	2,800,000	$350
Pennsylvania	2,800,000	$330
Georgia	2,300,000	$540
Washington	2,100,000	$520
Missouri	1,700,000	$500
Maryland	1,600,000	$500
Illinois	1,600,000	$475
Oregon	1,400,000	$250
Ohio	1,200,000	$440
Arizona	1,100,000	$220
Iowa	1,000,000	$310

The cost effectiveness of owning a HPWH is better for target households with high electric rates. The average US residential electric rate is $0.13 per kilowatt-hour (kWh).[13] The state with the highest electric rate is Hawaii with $0.27 per kWh whereas the state with the lowest electric rate is Louisiana with $0.09 per kWh. The Northeast, Mid-Atlantic and Pacific Non-contiguous regions, as well as the state of California, have electric rates greater than the average US rate, making the cost effectiveness of HPWH ownership even better in those areas. [32]

[12] Rebate requirements often include thresholds for tank size, efficiency rating and length of warranty. Installation by an approved or certified installer is typically required to ensure proper operation. In certain regions of the US, locating the HPWH in an unconditioned space, such as a garage or unconditioned basement, is a requirement. It is also not uncommon for programs to require the new HPWH to replace an electric water heater exclusively, or a gas water heater exclusively.

[13] Annual electric rates calculated based on average from November 2015 through October 2016. US average electric rate is a weighted average based on state occupied households.

Table: Electric Rates by Region

Region	States	Weighted Average Electric Rate ($/kWh)
Southeast	AL, FL, GA, KY, MS, NC, SC, TN	$0.112
Mid-Atlantic	DC, DE, MD, NJ, PA, VA, WV	$0.144
Northeast	CT, MA, ME, NH, NY, RI, VT	$0.182
Midwest	IA, IL, IN, MI, MN, MO, OH, WI	$0.128
South Central	AR, LA, OK, TX	$0.106
Mountain Plains	AZ, CO, KS, ND, NE, NM, NV, SD, UT, WY	$0.118
Pacific Northwest	ID, MT, OR, WA	$0.100
California	CA	$0.171
Pacific Non-Contiguous	AK, HI	$0.248

The cost effectiveness of owning a HPWH is also better for target households in regions with demand response programs. By enrolling in a demand response program, households can take advantage of time-of-use electric rates or other financial incentives to enable utilities, municipalities, and electric cooperatives to decrease peak load. Regions with peak load or grid congestion issues often have a larger need for demand response programs. The Mid-Atlantic and Southeast (particularly Florida) are two regions featuring demand response programs intended to relieve grid congestion.

Where to Go Next: National Strategy

An example of a national strategy for HPWH market adoption could consist of helping launch or improve HPWH efficiency programs in target regions through the implementation of best practices in combination with a national promotional campaign to spread HPWH awareness, education, and enthusiasm to program developers, manufacturers, wholesalers, retailers, installers, and consumers.

A national promotional campaign could utilize social media to generate interest in the awareness and education messages through the sharing of photos, videos, and consumer and installer experiences. It would leverage manufacturer incentives, HPWH program incentives and/or Federal tax credits, if/when available. Market actors would be invited to co-brand and collaborate on all initiatives. Awareness activities could include advertising (online and print), press releases, and point-of-purchase displays and puzzles (online and in-store) to emphasize the monetary savings, energy savings and technological advancement of HPWHs. Education activities could include site selection checklists, online installation trainings (targeting do-it-yourself consumers and installers), and installation competitions (video contests and live events).

Region-specific activities could focus on facilitating both the launch of new and improvement of existing HPWH energy efficiency and demand response programs in regions that have a strong target market opportunity. Launching new programs would involve providing research studies, case studies, testimonials, and other information to regional energy offices, utilities, municipalities, electric cooperatives, and non-profit organizations interested in pursuing objectives achievable through HPWH energy efficiency and demand response programs. In particular, existing studies could be analyzed to forecast the impacts of a successful HPWH energy efficiency program on a region's electric load (especially peak load) along with potential impacts on infrastructure, electric rates, carbon emissions, and clean energy portfolios for the target region. Once an organization decides to launch a new program, resources (e.g., marketing messages, drop-in web content, online tools and applications, online forms, bill inserts, images, etc.) would be available to ease the process. These materials could be made available on the national promotional campaign website.

Improving existing HPWH energy efficiency and demand response programs involves updating the program tactics and resources to the latest best practices and developing stronger partnerships with market actors in the regions. Programs could offer on-bill financing to households that qualify. Programs could partner with manufacturers to secure HPWH inventory equipped with a CTA-2045 port for the region's wholesalers and retailers, offering the potential to conduct demand response. [33] Manufacturers could collaborate with programs to co-host trainings for installers, their call center representatives and big box retail sales associates.

To help existing programs boost HPWH market adoption for emergency replacements, installers would receive instruction on how to expedite routine installations and overcome unique installation challenges. Installer call center representatives and big box retail sales associates would receive training on how to determine site selection for a HPWH installation as well as how to make HPWHs the first offer to consumers using region-specific savings figures in the sales process. Trained installers would receive program certification, branding, marketing support, and exclusive incentive offers for installing HPWHs in the program's region. Programs would partner with wholesalers to present HPWH point-of-purchase displays at the sales counter and implement instant rebates for HPWHs purchased by certified installers.

To help existing programs boost HPWH market adoption for both planned and emergency do-it-yourself replacements, programs would partner with retailers to present point-of-purchase displays along with both mail-in and online rebate forms (via sales associate with a tablet/smartphone and security passcode provided by the program). Retailers would receive program certification and trained sales associates would receive exclusive incentive offers, such as commissions, for HPWH sales headed to homes in the region.

To increase HPWH market adoption in the new construction market, programs could partner with new home production builders in the region. Programs could work with manufacturer partners to offer bulk procurement of HPWHs that meet program requirements. Builder partners could receive program certification, branding, marketing support, and exclusive incentive offers for installing HPWHs in their projects. Case studies could demonstrate how installing HPWHs in new homes has a positive impact on the business model for general contractors and builders. These case studies would be used in the recruitment of new partners operating in the new construction market.

Target Regions for Market Adoption Activities

A number of states have a combination of characteristics indicative of a strong opportunity for market adoption. Certain states have a high number of target households with access to rebates, combined with high expected shipments to target households in the replacement market and relatively high expected and potential shipments to target households in the new construction market. In the Southeast, North Carolina, South Carolina, Georgia and Tennessee fit this profile. In the Northwest, Washington and Oregon fit this profile.[14] In the Southwest, Arizona is a fit. HPWH programs in these states should focus their efforts on adopting best practices that overcome market adoption barriers in both replacement and new construction markets.

In the Mid-Atlantic, Pennsylvania, Maryland and DC have high expected shipments to target households in the replacement market combined with a high number of target households with access to rebates and relatively high electric rates. In the Midwest, Ohio has the same profile of having high expected shipments to target households in the replacement market combined with a high number of target households with access to rebates. HPWH programs in these states should focus on overcoming market adoption barriers in the replacement market through best practices.

California is unique since it has high potential shipments to target households in the new construction market, high number of households with access to rebates and high electric rates. Efficiency programs in California should focus on influencing and collaborating with market actors in the new construction market. Given the state's goals for decarbonization, efficiency programs should also pursue electrification of hot water loads using HPWHs to reduce carbon in the fuel cycle for water heating. The primary barrier for electrifying hot water loads is the potential for electric upgrades. While

[14] The Northwest has the strongest regional HPWH program (i.e., NEEA) in the US and has achieved the highest rate of market adoption of any US region.

adding a circuit in an existing panel can be relatively inexpensive, upgrading an electric panel can be costly.

Florida and Texas have the highest number of expected and potential shipments to target households in the replacement and new construction markets. These states are the ultimate opportunity in HPWH market adoption. However, they have a relatively low number of target households with access to rebates and their electric rates are low. Establishing more efficiency programs in these states is needed, along with engaging market actors in activities that overcome barriers to market adoption in both replacement and new construction markets.

Conclusion

The large-scale market adoption of HPWHs would achieve significant energy savings and peak load reductions nationally. While HPWH technology has advanced considerably over the past two decades, market share still remains very low. A number of market barriers have inhibited widespread market adoption, particularly first cost, installer expertise, availability, and consumer awareness and education. If market adoption doesn't increase, there is a possibility that major water heater manufacturers decrease investment in their HPWH product lines and eventually discontinue their HPWH models.

A national HPWH strategy would improve existing HPWH energy efficiency and demand response programs in target regions through the coordination of market actors and integration of best practices. It would recruit organizations in target regions to meet their objectives by launching new HPWH programs or improving existing their existing HPWH programs. It would complement these initiatives with a national awareness and education campaign, co-branded through partnerships with market actors. Through these focused efforts, the US has the potential to achieve a HPWH market share of 15%, which would save more than 15.7 terawatt-hours and 11 million metric tons of carbon dioxide annually.

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Demand-Response Performance of Electric Resistance and CO_2 Refrigerant Heat Pump Water Heater

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Abstract

The use of heat pump water heaters (HPWH) in the residential sector could provide energy savings in excess of 63% per water heater over a typical electric resistance water heater (ERWH) [1]. However, from a utility perspective, it is also important to consider the demand-response (DR) capabilities of such energy efficient technologies. This paper will discuss the DR performance of a carbon dioxide refrigerant HPWH (CO_2 HPWH) compared to an ERWH as demonstrated by experiments using the side-by-side PNNL Lab Homes; as well as evaluate the impact of other key variables, such as tank size and tank set point temperature, on the ability of water heaters to provide grid services. The experiments evaluated the total dispatchable power and resulting energy shift that the water heaters could provide during a peak shift or balancing reserve type of DR event. The results indicated that the CO_2 HPWH can respond to the scheduled DR events and provide a similar level of service as the ERWH. The study also demonstrated how increasing thermal mass, through a larger water tank size, can increase the ability of the water heater to respond to DR events for long periods of time (e.g., peak shifting), but will reduce the availability and responsiveness of the water heater for shorter duration DR events (e.g., frequency regulation).

Introduction

Water heating represents ~19% of residential energy consumption, amounting to 1.803 Quads annually [2]. Efficient water heater options are needed in the market to achieve significant energy savings in the residential sector. Heat pump water heaters (HPWH), which offer a savings of 63% or greater according to the DOE test procedure, are a viable option for improving energy efficiency in the 41% of homes that currently use electric resistance water heaters (ERWH).[15]

The National Renewable Energy Laboratory (NREL) has reviewed the energy savings and performance advantage associated with ERWH and HPWH technologies through a number of studies. Given the higher coefficient of performance (COP) (i.e., the ratio of the useful energy transferred to the electrical energy consumed), NREL has estimated COPs for HPWHs to be between 1.21 and 3.55, compared to estimated COPs of nearly 1.0 for ERWHs [3]. As expected, this is very dependent on the refrigerant type and ambient air temperature. The NREL research focusses on HPWHs using R-134a and R-410a, which are the most common refrigerants. In general, the inherent energy efficiency savings of an HPWH using R-134a refrigerant, as measured in Pacific Northwest National Laboratory (PNNL) Lab Homes, is 61.7 ±1.7% compared to an ERWH and will result in permanent peak energy demand savings as well [1].

Evaluation of new HPWHs using R-744 refrigerant (carbon dioxide; CO_2) was conducted to quantify the operating conditions and determine the COP of these types of water heaters. The CO_2 refrigerant is advantageous because it offers a large reduction in global warming potential (GWP) and higher efficiency than conventional refrigerants. CO_2 has a GWP of 1 compared to other refrigerants like R-410a (with a GWP of 2,000) and R-134a (with a GWP of 1,302). Such low-GWP refrigerants will be increasingly important to meet the goals of the United States Environmental Protection Agency's Significant New Alternatives Policy (SNAP) Program, which calls for the removal and slowly phase out refrigerants that have been shown to cause harm to the environment.[16] In addition, CO_2 can operate over a wider band of temperatures than R-124a and R-410a refrigerants. This beneficial property allows heat to be extracted from ambient air temperatures as low as -8.3°C (17°F). The research

[15] Based on U.S. Department of Energy (DOE) test procedure (10 CFR 430.32(d)) and comparison of an ERWH (energy factor, EF = 0.90) versus a HPWH (EF = 2.4).
[16] For more information, see: https://www.epa.gov/snap

conducted by Ecotope estimated the COP of CO_2 HPWHs to be 2.1 at -8.3°C (17°F) and 5.0 at 95°C (95°F)[17] [4].

One potential barrier to the widespread implementation of HPWHs is their impact on demand-response (DR) programs. Demand response programs are most commonly used to turn off loads (i.e., reduce demand) when demand is higher than supply (i.e., during peak times). However, more advanced demand response programs are being envisioned that turn on and off loads more dynamically in response to variable generation availability. Effective demand response programs are an important tool to enable more widespread implementation of intermittent renewable generation and can also serve to increase system reliability, defray cost of new infrastructure investment, improve system efficiency. Through these impacts, demand response has the potential to enable reduced costs and environmental impacts associated with operation of the electricity grid [5]. The performance of HPWHs across associated DR events is currently under investigation, especially for new technology designs, such as CO_2 HPWHs. While the improving the energy efficiency of water heaters is important, improvements in efficiency should also consider the impact on DR capabilities.

In a residential environment, loads with high thermal inertia, such as water heaters, air conditioners, and refrigerators, are the best candidates for DR programs because their electrical energy input can be changed with minimal impact on the customer or the utility of the appliance [6]. Specifically, residential ERWHs have been identified as ideal candidates for DR for the following reasons:

1. They contain significant thermal storage.
2. They contribute the second largest residential load, behind heating equipment.
3. They have relatively high power consumption and a large installed base.
4. They follow a consistent load pattern that is often coincident with utility peak power periods [7,8].

Many utilities currently employ ERWHs to reduce peak load by turning off the water heater during times of peak demand, also called peak shifting. Some utilities are also considering the potential of using ERWHs to strategically increase load during times of high renewable generation (e.g., solar bulge or excess wind resource) and to provide additional balancing and ancillary services (*e.g.,* voltage regulation) [9]. In this way, water heaters can act as a battery for the grid, charging when power is most readily available and storing the energy to use when it is needed.

While HPWHs offer inherent peak load reduction benefits due to their increased energy efficiency,[18] the DR performance characteristics of HPWHs, particularly how their performance differs from ERWHs, has not been well demonstrated when responding to demand signals. Previous research has evaluated the DR capabilities of traditional, integrated HPWHs and found that due to the larger capacity of ERWH's electrical elements, a greater load shift can occur when compared to the small draw of the HPWH compressor during heat pump-only mode. However, the run time of the HPWH compressor greatly influences the probability of the HPWH being able to shift load during the DR event. That is, because the compressor runs longer than the standard electrical elements to serve the same load, it has a greater potential to be on when the DR signal is received and, therefore, is more available to respond to the request to shift the load [1].

The research described in this paper builds on previous studies by comparing an emerging HPWH technology employing a remote compressor design (i.e., split-system) using CO_2 as the refrigerant to a 190 liter (50 gallon) ERWH reference case. The DR performance of the CO_2 HPWH, which features a larger thermal capacity and improved efficiency, is compared to a traditional 190 liter (50 gallon) ERWH reference case, which is representative of typical residential installations and current practice today. In particular, this research focuses on the ability of emerging CO2 HPWH technology to provide DR services, as well as the impact of key variables, such as tank size and tank set point temperature, on the characteristics of the response, which are applicable to both ERWHs and HPWHs.

[17] The maximum ambient air temperature the CO_2 HPWH is capable of operating at is 43.3°C (110°F), as advertised by the manufacturer, although the water heater has not been experimentally evaluated at that temperature.

[18] The power consumption of HPWHs is typically 50-75% less than a traditional ERWH; therefore the HPWH will contribute 50-75% less to periods of peak consumption.

5. Theory

To evaluate the DR capabilities of the split-system CO_2 HPWH and reference-case ERWH, a set of controlled experiments were undertaken in a matched pair of unoccupied laboratory homes (Lab Home A and Lab Home B) located on the campus of PNNL in Richland, Washington. The PNNL Lab Homes offer unique facilities for testing residential equipment. The Lab Homes consist of two 139.4 m^2 (1500 ft^2) identical manufactured homes that have been modified to represent dwellings in the Pacific Northwest. Equipped with extensive temperature and power monitoring equipment, energy efficiency equipment can be integrated into an Experimental Lab Home (i.e., variable), and its performance compared to a Baseline Lab Home (i.e., control or reference case). Energy reduction demonstrated within the Experimental Lab Home can be attributed to the installation of differing energy efficient equipment [1,9].

The DR experiments were conducted using a split system CO_2 HPWH with a 315 liter (83 gal) tank that was recently introduced to the U.S. market. In addition to the enhanced energy efficiency of the CO_2-driven compressor, the CO_2 HPWH also does not feature back-up electric resistance elements. The performance of the CO_2 HPWH unit was compared to the performance of a 190 liter (50 gal) ERWH, which is representative of the existing ERWH stock and the majority of water heaters that are currently participating in existing DR programs today [10]. In addition, this reference case makes the results comparable to the results of integrated HPWHs discussed previously [1]. The reference case 190 liter (50 gal) ERWH was installed in the water heater closet of Lab Home A and an 315 liter (83 gal) HPWH was located in the Lab Home B water heater closet plumbed to an outdoor compressor. In addition to the difference in water tank size, the evaluated HPWH also differed from the ERWH in terms of the water set point temperature. The ERWH temperature was set to be representative of a typical household operating temperature [11]. The HPWH nominal operating temperature, however, was pre-set by the manufacturer to 65.6°C (150°F), further exaggerating the difference in thermal capacity between the “typical” ERWH and the evaluated HPWH. Although the tank set points differed, the HPWH was equipped with a mixing valve that allowed the same 48.9°C (120°F) water temperature to be delivered in all experiments.

The variation in tank size and tank set point prevent an “apples-to-apples” comparison of the two systems, but the ERWH represents the “typical” case and, in this way, the performance of the emerging CO_2 HPWH technology is evaluated against a market reference case that is representative of what utilities are currently using in current DR programs. Specification details of each water heater within this research are shown in Table 1.

Table 1. Summary of Characteristics of HPWH and ERWH

	ERWH	HPWH
Tank Size (liter)	190	315
Set point (°C)	48.9	65.6
Energy Factor (d’less)	0.93	3.35 [4]
COP (d’less)	1	2.1-5.0; depending on outdoor air temperature [4]
Compressor location	NA	Outside conditioned space
Refrigerant	NA	R-744 (CO_2)

Demand Response Experiments and Explanation

When considering grid stability, reliability, and economics, two types of DR are of particular interest and were evaluated in these experiments: 1) peak shifting/oversupply mitigation and 2) balancing reserves.

6. *Peak Shifting/Oversupply Mitigation* is typically used to shift the residential water heating loads out of the peak demand period, most often in the afternoon/evening hours, to hours when there is low demand and possibly excess generation. For example, oversupply mitigation is used in the Pacific Northwest during spring when wind energy is frequently available at night. Shifting of load to the hours when wind-generated electricity is available allows capture and storage of this energy for use during peak load hours. In preparation for thermal storage, the water heater may be

turned off, typically at night, to create future capacity for storing energy as hot water. Once heated with oversupply energy (i.e., raising the set point temperature to 150 F), this hot water is then delivered at a time when it has value the following day. Peak shaving, which simply reduces the daily peak demand period, is also a common DR practice for capacity-constrained utilities. This results in a similar operational scheme although the focus is turning the water heater off during the peak as opposed to turning the water heater on during the period of oversupply.

7. *Balancing Reserves* are used as a response to hourly or sub-hourly changes in generation capacity either because of 1) inherent variability in the generation resource or 2) large disturbances in the grid (e.g., transmission fault) [12]. As increasing amounts of power from wind and solar resources are introduced into the grid, balancing reserves are needed to respond to fluctuations in wind speed or insolation [14]. Using DR for balancing reserves also can increase overall grid efficiency and decrease stress on mechanical generators from frequent ramping [14]. Balancing reserves can be implemented for either a generation shortage or surplus. These two types of balancing reserves (generation shortage or generation surplus) are called INC and DEC, respectively. For INC events, electricity demand is greater than supply and load shedding is required (or *increased* generation). For DEC events, generation is outpacing electricity demand and increasing load (or *decreasing* generation) will help to stabilize the grid. Balancing DEC DR events were not evaluated in this experiment.[19]

A DR schedule was developed to simulate and test peak shift DR event to simultaneously evaluate: 1) the duration of "peak shifting" that could be tolerated by the water heater without sacrificing customer utility (i.e., still providing hot water) and 2) the related capacity of the water heater to absorb excess generation in response to an oversupply event. The schedule for the HPWH was implemented over 7 days and consisted of increasing the time step that the unit is off, beginning at 6 hours, to a total of 12 hours by the seventh day. This increased daily strain on the water heater was imposed to determine the maximum duration of time the unit could be off and still deliver the desired water temperature during the daily draw schedule.

The schedule followed for the ERWHs was previously developed and implemented, and focused on 3-hour DR peak shifting events with one event per day. The peak shifting schedules are shown in Table 2 and Table 3 for the ERWH and the HPWH, respectively. Due to the large tank size of the HPWH, a larger peak shift and balancing INC interval duration was chosen. This is to ensure that both systems are adequately stressed over time when attempting to quantify the load shift and the amount of time the unit can maintain the delivered water set point temperature. In Tables 2 through 5, the "DR Event Duration" represents the period of time the water heater was turned off.

Table 2. ERWH Peak Shifting DR Schedule

Day	Start Time	End Time	DR Event Duration
1	7:00 AM	10:00 AM	3 hours
2	2:00 PM	5:00 PM	3 hours
3	6:00 PM	7:00 PM	1 hours

Table 3. HPWH Peak Shifting DR Schedule

Day	Start Time	End Time	DR Event Duration
1	6:00 PM	12:00 AM	6 hours
2	5:00 PM	12:00 AM	7 hours
3	4:00 PM	12:00 AM	8 hours
4	3:00 PM	12:00 AM	9 hours
5	2:00 PM	12:00 AM	10 hours
6	1:00 PM	12:00 AM	11 hours
7	12:00 PM	12:00 AM	12 hours

[19] More information on Balancing DEC, see Widder, S. 2013. *Demand Response Performance of GE Hybrid Heat Pump Water Heater. PNNL-22642, Pacific Northwest National Laboratory, Richland, Washington.*

The Balancing INC protocol was applied to determine the ability of the water heaters to respond to a balancing reserve call, while not adversely affecting the occupants. By their nature, Balancing INC calls can come at typical or random times during a day depending on grid resources and utility operating characteristics. As such, the Balancing INC schedule was spread over the day with relatively short 1-hour requirements. Table 4 and Table 5 present the Balancing INC schedule for the ERWH and the HPWH, respectively.

Table 4. ERWH Balancing INC DR Schedule

Day	Start Time	End Time	Balancing INC Event Duration
1	8:00 AM	9:00 AM	1 hour
	8:00 PM	9:00 PM	1 hour
2	2:00 PM	3:00 PM	1 hour
	2:00 AM	3:00 AM	1 hour

Table 5. HPWH Balancing INC DR Schedule

Day	Start Time	End Time	Balancing INC Event Duration
1	2:00 PM	3:00 PM	1 hour
2	2:00 PM	3:00 PM	1 hour
3	2:00 PM	3:00 PM	1 hour
4	8:00 AM	9:00 AM	1 hour
	2:00 PM	3:00 PM	1 hour
	8:00 PM	9:00 PM	1 hour
5	8:00 AM	9:00 AM	1 hour
	2:00 PM	3:00 PM	1 hour
	8:00 PM	9:00 PM	1 hour
6	8:00 AM	9:00 AM	1 hour
	2:00 PM	3:00 PM	1 hour
	8:00 PM	9:00 PM	1 hour

Water Heater Draw Profile

To simulate water usage within a residential home, water draws are done periodically throughout the experimental day. A draw profile is developed to simulate high and low water usage scenarios. The water flow rate is tuned through the use of the needle valve and fixed at about 5.67 liter/min (1.5 gal/min). A solenoid connected to the data logging system cycles off and on according to a pre-defined schedule. For this comparison of ERWH and HPWH DR performance, PNNL elected to simulate a “high” usage scenario and a water draw profile based on the Building America House Simulation Protocol [16]. A high draw volume was chosen to create a worst-case scenario to evaluate the potential for customer impact from decreased hot-water delivery temperatures and the ability of the water heaters to meet DR and load demands from the hot-water draw profile. Thus, for the HPWH and ERWH experiment, the daily hot-water draw was adjusted by increasing the number of bedrooms in the Building America House Simulation Protocol calculations to five bedrooms, which results in hot-water use of approximately 492 liter/day (130 gal/day) at the 48.9°C (120°F) set point. While extreme, evaluating the DR performance and hot-water delivery characteristics on a “very high” usage draw profile ensures that the results are conservative and representative of the worst-case customer impact, where many homeowners will be impacted much less than the experiments demonstrate. In this way, the results from this experiment can be easily extrapolated to smaller, more representative draws because the operational limits of the water heaters have been evaluated.

Discussion and Results

Prior to the experiments, a full system baseline was implemented for both the ERWH and the HPWH to represent typical operation of the evaluated equipment under the scheduled load profile without DR events. This allowed for direct determination of the impact of the DR events on water heater performance, hot-water delivery, and daily energy use.

ERWH and HPWH Baseline

The baseline period for the ERWH was June 2013. Data collected during a 5-day test series were analyzed to confirm proper operation and to serve as the control for comparison to the performance when DR events were implemented. Figure 1 presents the power profile of the ERWH (blue line) along with the hourly average outdoor air temperature (red dashed line). As expected, the ERWH has a very consistent wattage profile, and the peaks generally align with the automated hot-water draws. Across the daily draw pattern, the average energy use per water heater power draw event was 0.89 kWh.

The baseline period for the split-system CO_2 HPWH DR experiment was implemented in the Lab Homes during August 2014. Figure 2 highlights one day of the power profile during the baseline period when no DR events were implemented.

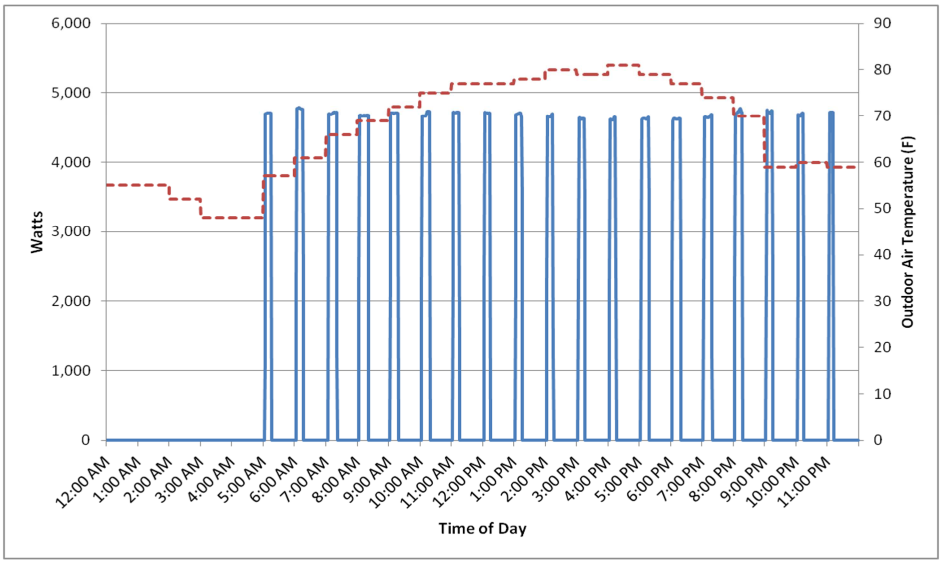

Figure.5. ERWH Baseline Power Profile, June 3, 2013

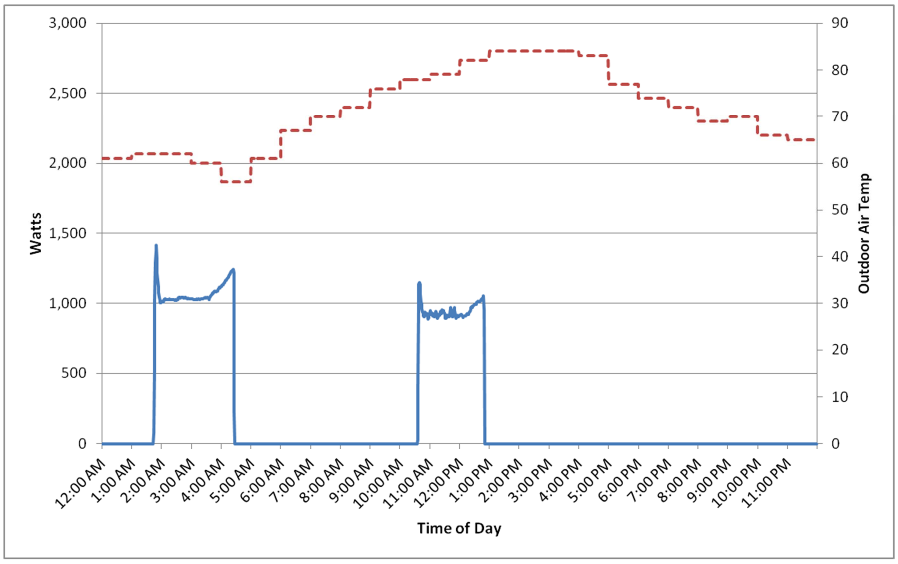

Figure 2. Split-System HPWH Baseline Power Profile, August 22, 2014

In responding to the hot-water draw, the split-system CO_2 HPWH delivered a relatively consistent power profile across the baseline period, both in magnitude and duration. As shown in Figure 2, the HPWH uses 25% of the power used by the ERWH (approximately 1 kW). In contrast to the ERWH, the HPWH has fewer, but longer, electric load events associated with the water draws. The trend of longer operation also was observed in previous work in which 190 liter (50 gal) integrated HPWHs were evaluated, demonstrating that some of the increased duration is due to the decreased compressor output capacity, as compared to the 4.5-kW heating elements in the ERWHs [1]. However, the split-system CO_2 HPWH evaluated in this research showed longer duration and more infrequent operation even than the 190 liter (50 gal) HPWH evaluated in Widder et al [1]. This is a result of the higher set-point temperature and the large tank capacity (315 liter (83 gal)) of the evaluated HPWH. Table 6 highlights the daily energy usage between the HPWH and ERWH during the baseline period. The HPWH is an estimated 75% more efficient than the standard ERWH. Recall that, as mentioned previously, conventional integrated HPWHs with tranditional refrigerants offer up to 63% savings as compared to the standard ERWH [1]. This highlights the advantage of the CO_2 HPWH when compared to R-134a and R-410a refrigerants, where the CO_2 HPWH can offer up to an additional 10% of energy savings compared to other refrigerants.

Table 6. Energy Use of the HPWH Compared to the ERWH during the Baseline Period

Experiment	Split System CO_2 HPWH	Electric Resistance Water Heater
Baseline Period	4.99 ±0. 992 kWh/day	20.2 ±0. 348 kWh/day
% reduction over ERWH	75%	0%

ERWH peak shifting demand response results

The schedule for the ERWH peak shifting testing included three 3-hour off periods that occurred at 7:00 AM, 2:00 PM, and 8:00 PM over the course of 3 days. Figure 3 presents the power profile with outdoor air temperature for one of the days when the 2:00 PM schedule was implemented. The blue line show the water heater power draw throughout the day (in Watts) on the left axis; the red dashed line shows the outdoor air temperature for that day (in °F) on the right axis; the red bars indicate the period when the DR schedule was implemented and the water heater was powered down.

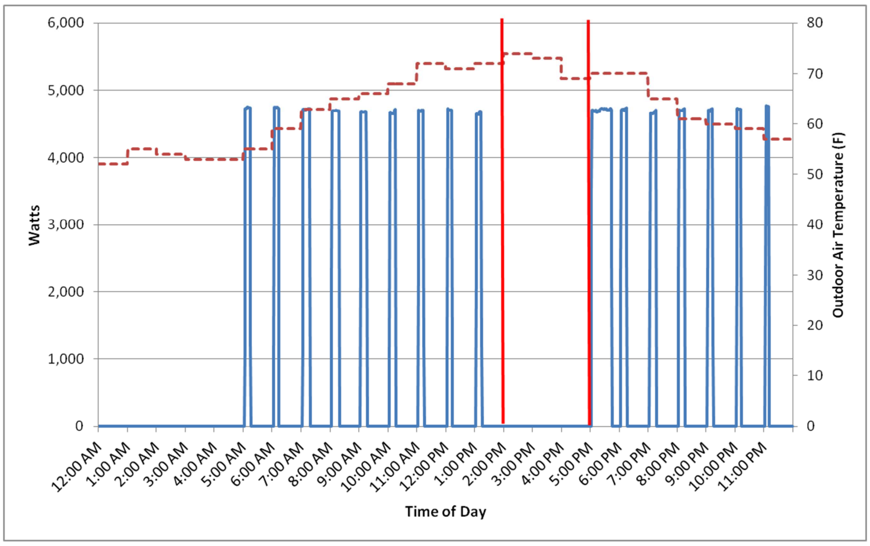

Figure 3. ERWH Peak Shift Power Profile: 2:00 PM to 5:00 PM Powered-Down Protocol, 6-13-13

In comparison with the ERHW baseline (Figure 1), the peak shifting DR power profile highlights a demand shift of 4.6 kW during the DR period for the ERWH. That is, during the DR event, 4.6 kW of power may be shifted off of peak periods. However, the 4.6kW load is only "available" for approximately 32 minutes of the peak shift period even at this very high water draw [1]. After the DR event, at 5:00 PM, the ERWH goes into recovery mode during which it draws the same 4.6 kW of power but over a longer duration. The recovery energy use for this 3-hour DR event was 2.69 kWh, and represents the amount of future energy able to be stored by implementing this DR protocol. This recovery, and its associated impact, should be fully understood and managed (timing and duration) for a successful real-world DR implementation. Three hours was the longest time the 190 liter (50 gal)ERWH could be shifted without significantly affecting the hot-water delivery temperature at the large, 492- liters/day draw profile. Hot-water delivery temperatures at the end of the 3-hour peak shift decreased to as low as 48.9°C (120°F) [9].

Split-System HPWH peak shifting experiment

Peak shifting of the split-system CO_2 HPWH is presented in Figure 4, which highlights the longest DR event of 12 hours and the resulting implications. By comparing Figure 4 to Figure 2 above, one can see that the peak shifting DR event resulted in a portion of one of the typical baseline activation events (the event normally beginning at about 11:00 AM) being terminated early and moved to after the DR period (12:00 AM to 2:00 AM). The HPWH provided a demand shift of between 1.1 kW and 1.2 kW. Figure 4 also illustrates how, after the DR event when the HPWH cycles back on, the HPWH is on for a longer period of time in the evening and early morning hours, affording opportunity to absorb potential excess generation during this typical low-demand "trough." Although the internal tank temperature decreased over the 12 hour event, the delivered temperature to the Lab Home remained above the experimental set-point of 48.9°C (120°F) [9].

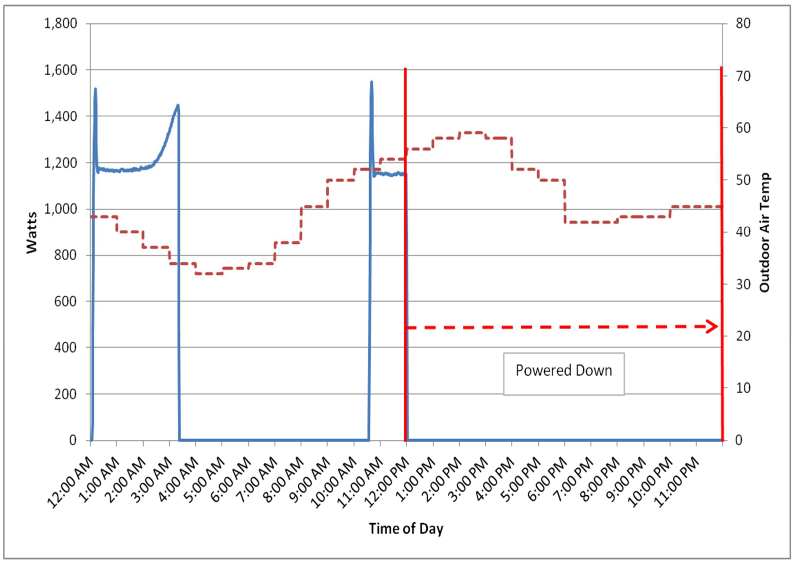

Figure 4. Split-System Peak Shift Power Profile: Longest DR Event (12 hours powered down), 10-27-14

Table 7 presents the DR summary for the peak shifting protocols enacted. In the table, Dispatchable Watts describes the peak Watts available to be shifted through implementing a peak shifting DR event, both reduced during times of peak demand and increased during times of oversupply mitigation. Note that the "Dispatchable Watts" is equivalent to the power draw of the equipment. The Recovery Energy Shift is the quantity of energy (kWh) that is shifted to the post-DR period. The Peak Shift Duration indicates the number of hours the protocol was enacted while still affording appropriate water temperature deliveries. Notably, the large thermal storage capacity inherent in the design of the split-system CO_2 HPWH allows for significant peak shifting ability, such that all of the energy necessary to heat water can be shifted to off-peak times. Operating the HPWH in such a manner offers the same Recovery Energy Shift, or ability of the water heater to absorb load at off-peak times, but at 64% of the daily energy consumption. Increasing the thermal capacity of the ERWH by increasing one or both of the tank size and/or raising set point temperature would similarly increase the available "Peak Shift Duration," but also further reduce the energy efficiency of the ERWH and accomplish a similar service at significantly higher overall energy use.

Table 7. Peak Shift DR Protocol Summary Findings

Experiment Metric	ERWH	HPWH
Peak Shift Experiment		
Dispatchable Watts (kW)	4.6	1.2
Recovery Energy Shift (kWh)[1]	2.69	2.95
Peak Shift Duration (hours)	3	6

Maximum Off Period While Delivered Water Temperature Met (hours)	3	12
Daily Energy Consumption (kWh)	8.87	5.90[2]

1 The Recovery Energy Shift is the water heater energy use at the conclusion of the Peak Shift period.

2 Dependent on outdoor air and supply water temperature

ERWH balancing INC experiment

The schedule for the ERWH Balancing INC testing included two 1-hour periods when the water heater was turned off at 8:00 AM and 8:00 PM over the course of a week. Figure 5 presents the power profile with outdoor air temperature for one of the days when the 8:00 AM and 8:00 PM schedules were implemented.

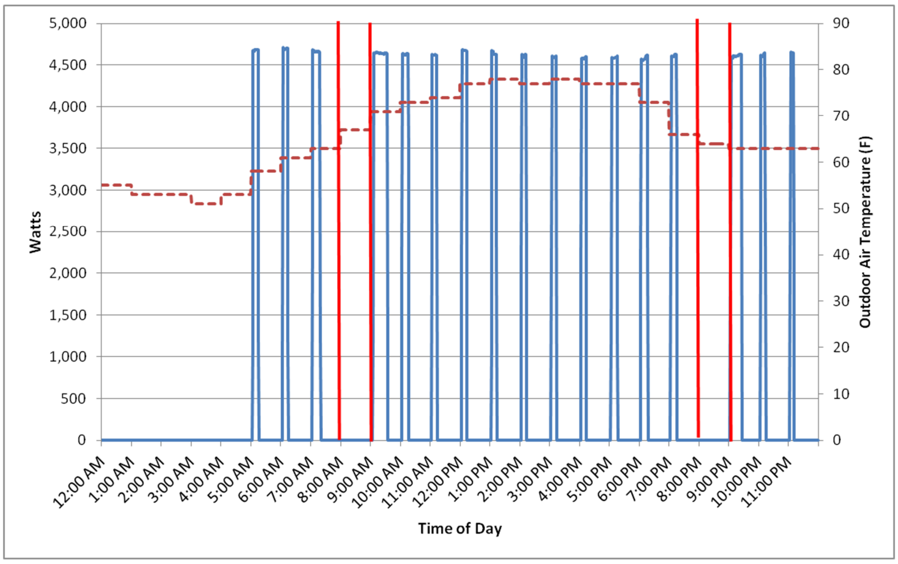

Figure 5. ERWH Balancing INC Power Profile 8:00 AM and 8:00 PM (1 hour powered down), 6-23-13

In comparison with the ERWH baseline shown in Figure 1, the ERWH Balancing INC DR profile provides a possible 4.6 kW that can be dropped (i.e., dispatched) during the 1-hour events, for each of the two displaced water heater activation events. However, similar to the peak shift DR event, the ERWH is only "available" for approximately 25% of the hour, on average, depending on the draw pattern and the load placed on the water heater during the hour. Following the Balancing INC events, at 9:00 AM and 9:00 PM, the ERWH goes into recovery mode in which it draws the same 4.6 kW of power but over a longer duration. This recovery, and its associated impact, should be fully understood and managed for a successful DR implementation. These DR events had no effect on the delivered water temperature to the Lab Homes [9].

Split-system CO_2 HPWH Balancing INC experiment

Split-System Balancing INC testing included two separate tests. The schedules were presented in Table 6. The first protocol implemented was a 1-hour off period starting at 2:00 PM. The second protocol expanded the off periods to three 1-hour periods, powering down the HPWH at 2:00 AM, 8:00 AM, and 8:00 PM. Figure 6 and Figure 7 present the demand profiles of the single-hour and then the three, 1-hour periods, respectively. These experiments did not result in an appreciable drop in delivered water temperature [9].

For this experiment, based on the water draw profile implemented, the HPWH was only available to respond and drop load during the 8:00 PM Balancing INC DR event. During the other Balancing INC DR event, the HPWH was not on and, therefore, was not able to respond to the call to drop load. The infrequent operation of the HPWH, which results in a lack of availability of the HPWH for these short-duration Balancing INC events, is primarily due to the thermally massive water heater tank. The large tank with a high temperature set point was beneficial in the peak shifting DR events since it allowed the water heater to be turned off or on for long periods of time in response to long (≥3 hour) duration events. However, the high thermal mass is detrimental for more frequent DR events, such as Balancing INC, because the HPWH is on much less frequently and, therefore, is much less responsive. As this is a function of the tank size and set point temperature, and not the water heating mechanism, the same would be the case for an ERWH with a large tank and/or higher set point temperatures.

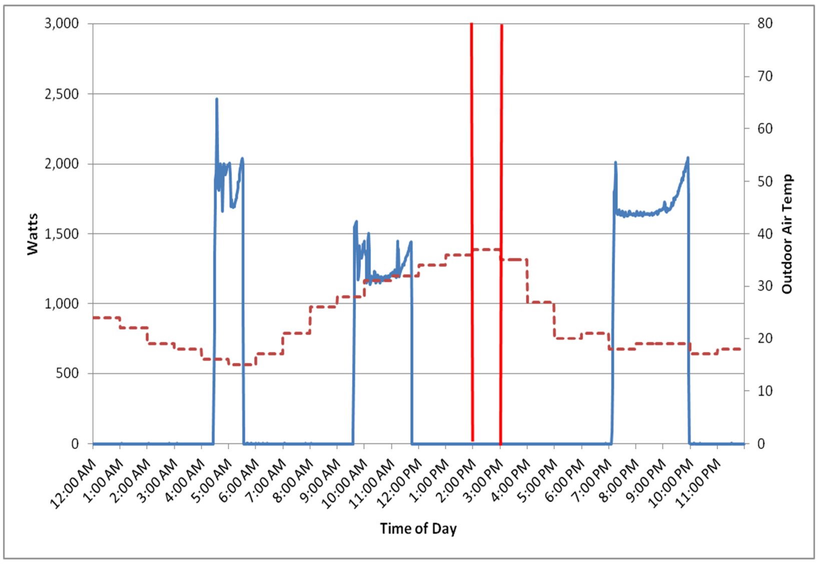

Figure 6. Split-System Balancing INC Power Profile: 2:00 PM (1 hour powered-down-protocol), 11-12-14

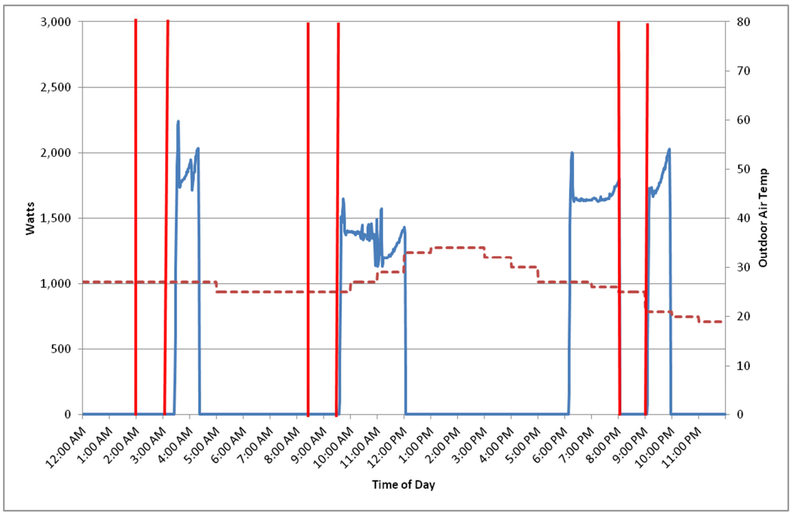

Figure 7. Split-System Balancing INC Power Profile: 2:00 AM, 8:00 AM, and 8:00 PM (1 hour powered-down protocol), 11-14-14

Table 8 presents the DR summary finding for the Balancing INC protocols enacted. In the table, the Dispatchable Watts describes the peak Watts available to be shifted through Balancing INC implementation. That is, as described previously, the "Dispatchable Watts" is equivalent to the power draw of the equipment, which can be manipulated during the DR event. For the HPWH, these Dispatchable Watts are greater than for the peak shift DR event (presented in Table 6) since the outdoor air and source water temperatures were lower. The Recovery Energy Shift is the value of energy (kWh) that is shifted to the post-Balancing INC period. The Balancing INC Duration indicates the number of hours the protocol was enacted. Because the HPWH is on for more of the hour when the Balancing INC event occurs, it can shift a greater amount of energy despite the lower power draw, In addition, the HPWH is sensitive to outdoor air and water supply temperatures.

Table 8. Balancing INC DR Protocol Summary Findings

Experiment Metric	ERWH	HPWH
Balancing INC Experiment		
Dispatchable Watts (kW)[1]	4.6	1.6
Recovery Energy Shift (kWh)[2]	0.86	1.6
Daily Energy Consumption (kWh)	21.1	10.1[3]
Balancing INC Duration (hours)	1	1

[1] The increase in HPWH Dispatchable Watts for the Balancing INC experiments results from the cooler source air and supply water during this period.
[2] The Balancing INC Recovery Energy Shift is reported assuming the protocol period aligns with a water heater activation event. Assuming alignment and the 1-hour event, the values listed are the maximum energy shifts.
[3] Larger energy consumption compared to the baseline period due to decreased outdoor air and supply water temperatures.

8. Conclusion

To encourage widespread market penetration of efficient water heating systems, such as HPWHs, it is important to understand and quantify both the energy savings and DR characteristic of differing types of water heaters. The CO_2 HPWH evaluated in this study reduced daily energy consumption by up to 75 percent compared to the ERWH, as evaluated during the baseline experimental period. Thus, the HPWH offers significant potential to reduce energy consumption associated with residential water heating [9]. However, actual percent savings from an HPWH will vary depending on outdoor air and supply water temperatures, as well as actual hot water demand. Table 7 details the percent demand reduction between the HPWH and ERWH technologies.

Regarding DR performance, both water heater technologies tested are capable of implementing both DR protocols and, therefore, theoretically are capable of participating in DR programs. Comparing the response of the ERWH with the HPWH, the inherent efficiency of the CO_2 HPWH results in lower dispatchable power available to the utility to turn on or off in response to DR events. Although the HPWH has a lower dispatchable power (kW) draw, it remains on for a longer time. This increases the likelihood that a given water heater will be available to respond to the DR event when necessary. Although not evaluated directly in this work, extrapolating this performance to a population of water heaters responding in a typical DR program, a reduction in Dispatchable Watts would translate to a larger number of water heaters being enrolled and required to respond to a given event to achieve the same magnitude of decrease or increase. However, since HPWHs are, in general, on more frequently and, therefore, more available to respond, this balances the decreased “Dispatchable Watts” to some extent. In addition, a population of HPWHs will, through their improved efficiency, inherently lower demand and potentially inherently reduce the need for peak shaving and some INC balancing events. Further modeling work or field studies are needed to more quantitatively understand and compare the performance of populations of ERWHs and HPWHs.

In addition, the experiments demonstrated that the larger thermal mass contained in the 65.6°C (150°F), 315 liter (83 gal) tank of the CO_2 HPWH significantly increased the possible duration of DR events that the water heater could accommodate without adversely affecting the occupants. However, for more frequent DR events, like Balancing INC, the larger thermal mass meant the HPWH operated less frequently and, therefore, was often unavailable to drop load when the DR event was scheduled. This impact of thermal mass is applicable to all water heaters, regardless of heating technology, and should be considered when selecting water heaters to provide both efficiency and DR services. Depending on the nature of the required DR services, water heaters with larger or smaller thermal masses may be more beneficial.

Table 9 details the specific findings of these experiments.

Table 9. Specific findings of Experiments

Water Heater	ERWH	Split System HPWH
Dispatchable Watts	4.6kW	1.2-1.6kW*
Total Off Period While Delivered Water Temperature Met	3 Hours	12 Hours
Baseline Average Daily Minutes of Operation	4.51 Hours	4.96 Hours

* Dependent on outdoor air and supply water temperature

In conclusion, depending on the DR event initialized, an HPWH can provide similar DR services as an ERWH, but more efficiently. However, the characteristics of response are different (lower Dispatchable Watts), so utility programs should be designed with these characteristics in mind. In addition, the thermal capacity and size of the storage tank will need to be matched to the specific DR event to ensure adequate operation and implementation of the event.

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Advanced MOF-Water Adsorption Heat Pumps for Space Cooling and Heating

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Abstract

A new adsorption heat pump system is presented that is capable of improving energy efficiency of cooling systems through a novel multi-bed system configuration, use of a new class of metal organic framework (MOF) sorbent material, and unique sorption beds that are scalable and make use of well-established manufacturing processes. Sorption heat pumps represent an important alternative to mechanical vapor compression cooling systems because they use primarily heat instead of power, which enables opportunities for producing cooling using waste heat such as in combined heat and power (CHP) systems, solar heat, or even conventional fuels sources such as natural gas. In addition, heat pumps can significantly improve energy efficiency of heating systems, such as water heaters or space heating. Attaining competitive energy efficiencies and reducing system size have been two principal challenges with sorption heat pump technologies. Here, these challenges are being met with materials that exhibit unprecedented uptake capacities, such as a super hydrophilic MOF that exceeds the water sorption capacity of silica gel by a factor of two to three. Coefficients of performance (COP) exceeding 1.0 are achievable through a novel multi-bed configuration that enhances internal heat recuperation. Isotherm data for a MOF sorbent material are presented, along with test data obtained from demonstrator sorbent beds used for characterizing bed productivity and heat and mass transfer performance. The test data are used to validate system models that are used to generate trade-off curves between COP and system size.

Introduction

Adsorption heat pumps utilize heat to drive thermodynamic cycles that transfer heat from a lower temperature to a higher temperature for applications such as space cooling and refrigeration or for improving energy efficiency of space heating or water heating [1, 2]. Conceptually, the mechanical compressor of a vapor compression machine is replaced with a thermochemical compressor that sorbs the refrigerant into a solid sorbent media. Heat used to desorb refrigerant at high pressure—above the operating pressure of the condenser—thereby replacing the power demand of the compressor. Although some power is still needed for valves and fans, heat-driven technologies are able to use waste heat and alternative energy sources, such as exhaust heat [3] or solar [4, 5], and thereby substantially reduce power demand. The challenges are attaining competitive energy efficiencies and minimizing system costs by reducing system size and complexity.

Considerable research has been conducted to develop adsorption heat pump concepts, including solar-powered and waste-heat combined cooling heating and power (CCPH) systems [6]. A major challenge has been the requirement for extremely large beds associated with long cycle times, and relatively low energy efficiency caused by thermodynamic losses. The losses are largely attributed to the temperature gaps between the cycle and the external sources and sinks [7]. Thermal mass of the sorbent media and the hardware also contribute to efficiency losses, and the sorbent capacity and ratio of hardware mass to sorbent mass are key factors [3, 8]. Reducing the size and cost of the sorbent beds requires shortening the thermal cycle times, which is limited by heat transfer. Advancements have been made in improving thermal conductivity of monolithic sorbent media [9] and adding high conductivity fillers [10, 11], as well as through advanced bed designs that reduce overall thermal resistance [12].

Additional challenges occur with heat pumps in extreme operating environments, such as cold weather when temperatures drop below 0°C [13] or very hot temperatures. The target application for this development effort is forward operating bases, where the U.S. Department of Defense operating requirements can reach 52°C. The objective is to exceed a coefficient of performance of at least 0.3 for cooling air from 32°C to 20°C. To meet these significant challenges, a unique high efficiency system concept has been adopted, along with novel sorbent materials and innovative sorbent bed technology.

Multi-bed Adsorption Heat Pump System

Adsorption heat pumps typically suffer from low efficiency caused by parasitic thermal loads associated with the sorbent and bed thermal masses. Many approaches have been developed to improve efficiency including multi-bed regenerative [14], thermal wave [15, 16], and cascading [17] cycles. In this work, high energy efficiency is achieved through a unique multi-bed concept depicted in the schematic in Figure 1 that is designed to recuperate heat from the beds being cooled to the beds being heated [1, 18-20]. Four beds are shown in Figure 1, but any even number of beds can be used. The condenser, evaporator, and throttle valve serve the same functions as in a conventional vapor compression refrigeration cycle, but the mechanical compressor is replaced with a sorption compressor. Refrigerant is adsorbed onto solid sorbent at low temperature and pressure in Bed 1 in Figure 1, and desorbed at high temperature and pressure in Bed 3.

The beds are heated and cooled using a closed-loop heat transfer loop. Any number of potential heat sources can be used to heat the oil to its highest temperature, such as waste heat, solar, geothermal, or burning a fuel. The hot oil from the heat source sequentially heats half of the beds before being cooled to its lowest temperature. After rejecting heat to ambient or some other heat sink, cold oil cools the other half of the beds. To thermally cycle the beds, each bed sequentially occupies each of the positions in the system for one quarter of a cycle, and the sequence is indicated by the dashed arrows in Figure 1. Bed positions are changed using a system of valves used to change the path of the heat transfer fluid stream.

The sorbent in Bed 1 is adsorbing refrigerant from the evaporator at low pressure while being cooled. When it moves to position 2, the bed is closed and starts being heated which builds pressure as refrigerant desorbs from the sorbent. As soon as it reaches the condenser pressure, it opens to the condenser and begins producing refrigerant vapor while it remains in positions 2 and 3. This bed is closed again when it is first moved to position 4, where cooling causes the pressure to drop as refrigerant vapor is adsorbed. Once pressure reaches the evaporator pressure, it is opened to receive refrigerant vapor from the evaporator. This cycle continues with each bed occupying each position for one fourth of each complete cycle.

High efficiency is achieved because heat is effectively recuperated from beds being cooled to beds being heated. For example, Bed 3 is at its highest average temperature when it moves to position 4. Heat transfer fluid flowing through Bed 4 is heated, which reduces the amount of heat needed from the heat source. This heat recuperation scheme increases the coefficient of performance of the heat pump.

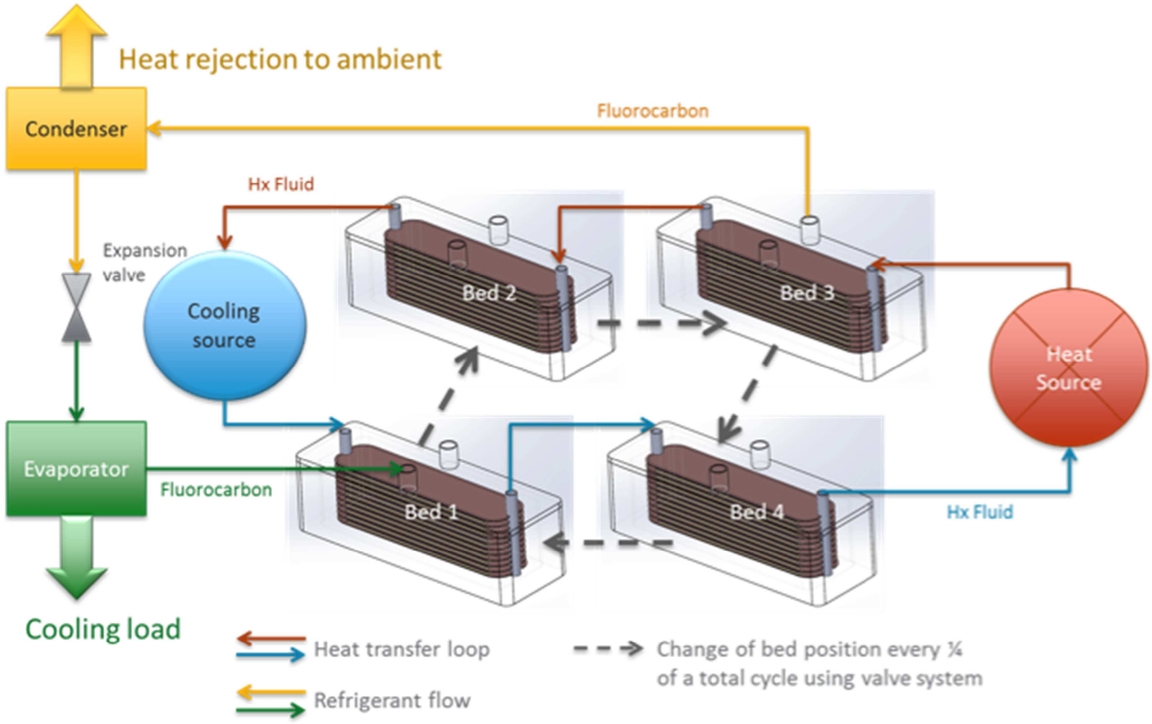

Figure 1. Schematic of the multi-bed adsorption heat pump.

This concept can achieve high efficiency for both space heating and cooling. In heating mode, all of the rejected intermediate heat is used for space heating, which by heat balance is the sum of the heat source duty and the low temperature heat recovered from the cold sink—outdoor air or ground source, as examples. This means that the heating COP can be greater than 1, which is not possible with conventional gas furnaces. Displacing natural gas furnaces that now dominate residential space heating in the U.S. is a route to substantial building energy savings [21].

In cooling mode, low temperature heat is removed from the living space and the intermediate temperature heat is rejected outdoors. System model results indicate that this innovative AdHP concept can feasibly achieve energy efficiencies that are comparable to vapor compression air conditioners when compared on a primary energy basis [1]. The ability to offload compressor power used for space cooling from the power grid peak demand in the summer impacts the U.S. energy landscape. This would extend power generation capacity by flattening the demand, thereby reducing the need for additional peaking capacity and the need to expand the transmission system to satisfy peak demands for air conditioning.

Sorbent Selection

A working system consisting of sorbent media and refrigerant is suitable if it provides adequate working capacity—the difference in the equilibrium loading between the adsorbing and desorbing conditions. Silica-gel and water is predominantly used in adsorption systems for space cooling, and several heat pump systems have been advanced using this working system [22-25]. Metal organic frameworks (MOF) are a class of nanoporous materials that exhibit very high pore volumes and surface areas [26], and have been recently considered for adsorption cooling [27-30]. An enormous number of MOF materials and architectures can be generated because of the wide selection of building blocks of transition and lanthanide metals in combination with organic linkers [31, 32].

A Ni-MOF-74 [33] material was selected for this application of space cooling in extremely hot environments with ambient temperatures up to 52°C. In addition to being stable with repeated cycles of water loading and unloading, this MOF was selected because of the steepness of isotherm curves shown in Figure 2 that yields better working capacity than silica gel. The example depicted in Figure 2 shows a doubling of working capacity from 8 wt% for silica gel to 16 wt% for Ni-MOF-74 at an ambient temperature of about 25°C. The difference becomes more significant as the ambient temperature increases until the silica gel becomes impractical.

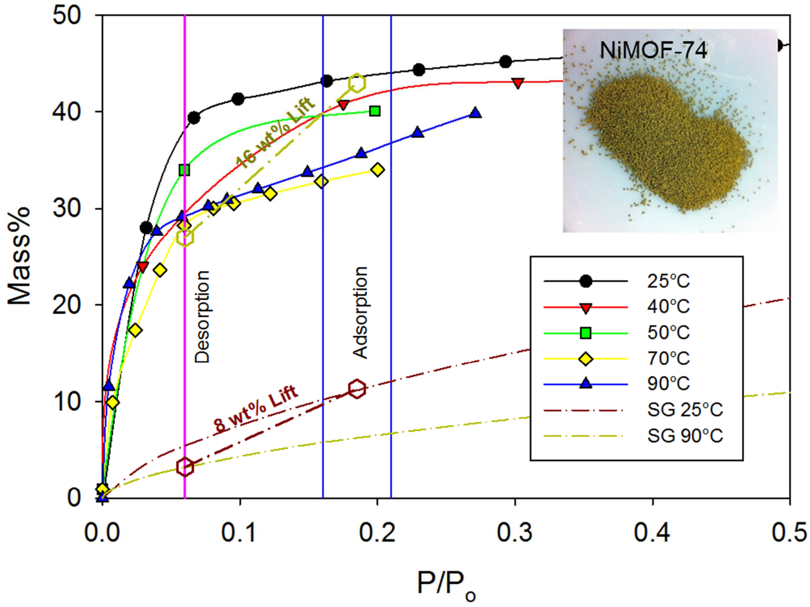

Figure 2. Water loading isotherms for Silica Gel and NiMOF-74 showing mass uptake versus pressure divided by saturation pressure, P_0.

Bed Development

Heating and cooling sorbent beds is typically a slow process due to low thermal conductivity of particulate beds and the length-scale for heat transfer. Slow heating and cooling implies long cycle times and poor bed productivity, which drives up system size and cost. Plate-fin heat exchangers, such as those used for vehicle radiators, were adopted as an effective sorbent bed platform for this application. An example is shown schematically in Figure 3. The MOF adsorbent is loaded into the interstices between the fins and held in place using containment screens. Heat transfer fluid flows through the tubes to thermally cycle the sorbent media. Optimization of the plate-fin heat exchanger is a trade-off between heat transfer coefficient to enable faster cycling and thermal mass that impacts system efficiency. An effort to optimize the design for Ni-MOF-74 identified a fin structure made of 0.1 mm thick aluminum folded into a corrugated structure 1.5 cm tall and 1.5 mm fin spacing. The design for aluminum tubes called for heat transfer channels 1 mm tall and tube walls 0.3 mm thick. The heat transfer coefficient was calculated to be 690 W/K-m^2 and had a thermal mass ratio—heat exchanger thermal mass divided by sorbent thermal mass—of 0.55. In contrast, an off-the-shelf motorcycle radiator was measured to have 0.18 mm thick fins at 1.7 mm spacing and 0.8 cm height, and the tubes had 1.5 mm channels and 0.3 mm walls. Analysis of this structure predicted a 460 W/K-m^2 heat transfer coefficient and a thermal mass ratio of 0.98. While off-the-shelf heat exchangers are feasible, bed size and system performance benefits from customization of the heat exchanger design.

Using water as the refrigerant for this application causes bed pressures to alternate between about 10 Torr and 150 Torr absolute pressure, so the beds must be contained within housings that can support vacuum. Figure 3 shows CAD drawings of one concept for a single plate-fin heat exchanger contained in a stainless-steel housing. Scale-up to higher cooling capacity involves increasing the size or adding more heat exchangers. High thermal conductivity of the heat exchanger is desirable, but the housing represents parasitic thermal mass, so low thermal conductivity is desired to reduce the amount of heating and cooling of the housing. The housing is equipped with 4 ports, two for heat transfer flow into and out of the heat exchanger and two ports on the housing for refrigerant flow. Refrigerant flows into the housing from the evaporator at very low pressure and high volumetric flow, so a larger port is used. Refrigerant flows to the condenser at higher pressure, so a smaller pipe size can be used.

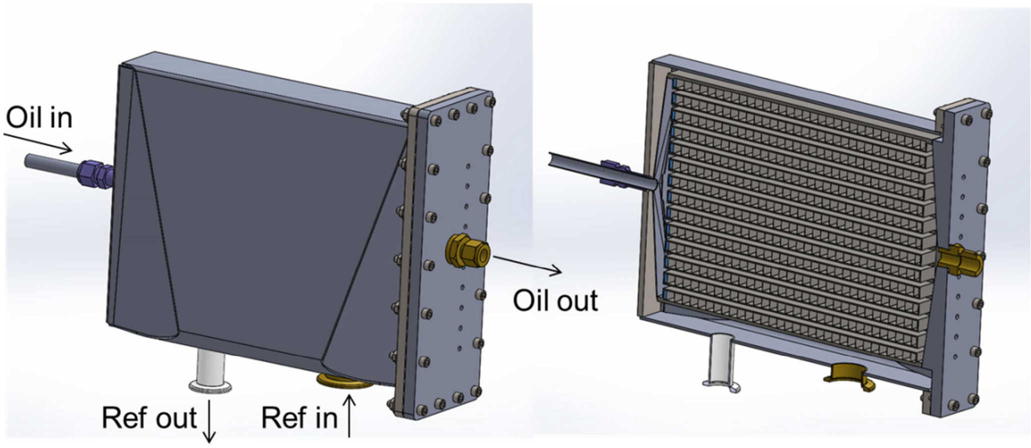

Figure 3. CAD drawing of a sorption bed consisting of a housing (left) containing a single plate-fin heat exchanger coil (right).

Smaller devices that represent unit cells of the larger plate-fin heat exchangers were used to test thermal cycling and measure water production rates. The unit cell consisted of a single corrugated fin structure with heat transfer plates attached to the top and bottom, as shown in Figure 4. The unit cell structure represents a worse case test for heat transfer performance because convective heat transfer within the tubes improves in the stacked structure when sorbent media is on both sides. Nevertheless, heat transfer tends to be dominated by the thermal conductivity of the sorbent media, so the unit cell was an adequate measurement for thermal and mass transfer dynamics leading to valid design of the scaled-up beds.

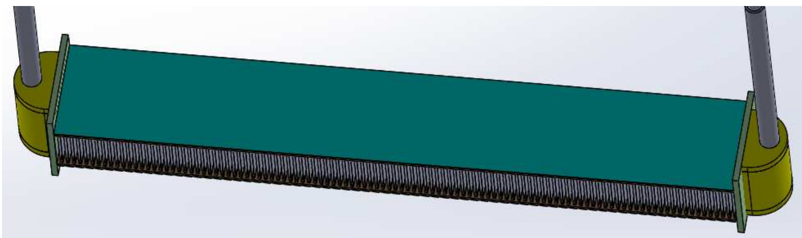

Figure 4. Unit cell for testing heat and mass transfer performance.

Unit Cell Testing

An open loop heat pump system was created for thermal cycling unit cells and measuring average water production rates. Figure 5 shows a process and instrumentation diagram (P&ID) for part of the test system. Unit cells were installed in a housing with multiple ports for heat transfer lines, refrigerant flow, and other instrumentation, including pressure transducers and thermocouples. Thermocouples were inserted into the MOF beds at locations along the length to monitor thermal profiles within the beds. Two temperature control baths containing Paratherm NF heat transfer fluid were blanketed with nitrogen to limit oxidation of the oil at elevated temperatures. Automated control valves were used to alternate hot and cold oil flow to the unit cell for thermal cycling at regular frequency. Tests were performed with hot oil between 150°C and 200°C. The cold oil temperature was varied between about 35°C and 60°C, the latter representing the hot climate conditions of the target application.

Water was loaded into the unit cell bed from an evaporator that was a water-jacketed vessel and temperature controlled using a third bath. The objective was to maintain a constant pressure source at about 10 Torr, but typically the pressure drop from the evaporator to the bed was 2-3 Torr, so actual bed pressure during adsorption was about 8 Torr. During the desorption half of the cycle, water refrigerant flowed from the bed to a condenser that was also temperature controlled to maintain a constant back pressure. Like the evaporator line, pressure drop from water vapor flow caused an increase in back pressure that could be initially several Torr but would diminish as the desorption rate and flow diminished.

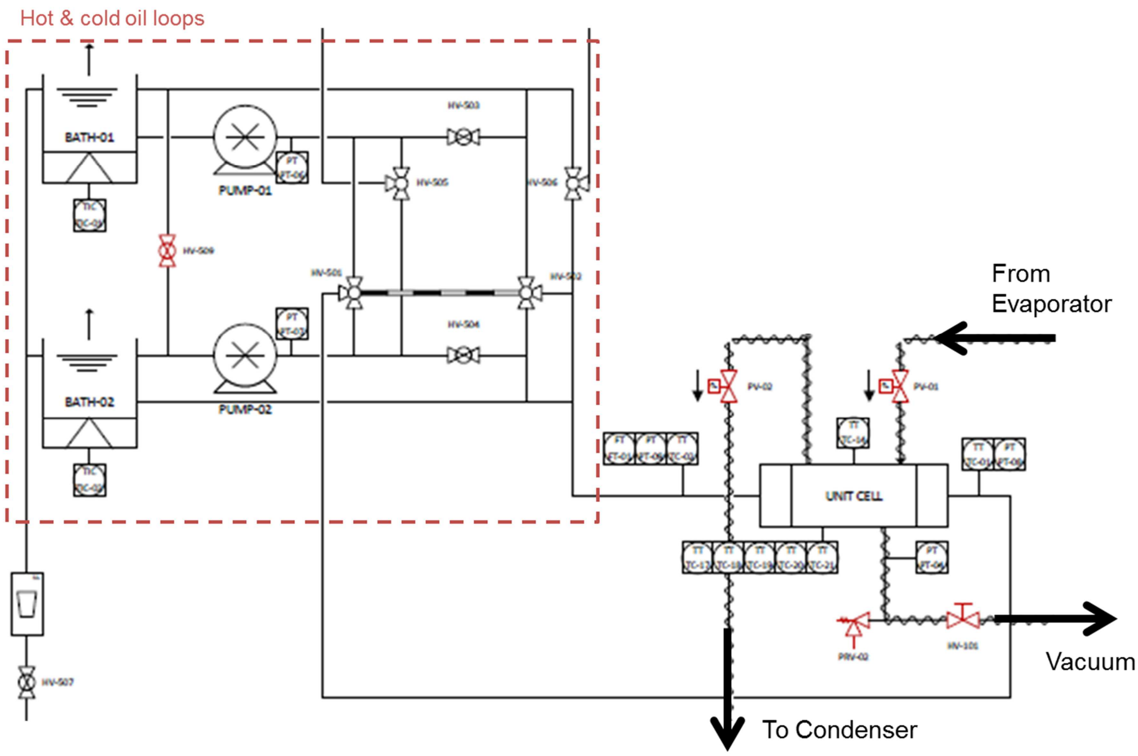

Figure 5. Process and instrumentation diagram for part of the unit cell test stand.

The test stand was operated automatically for a given number of thermal cycles while collecting condensate water from the condenser. At the end of the last cycle, the collected water was weighed, and the average water production rate was determined by dividing the mass by the cycle length and number of cycles. The condenser capacity was about 24 g and the number of cycles varied between 4 and 20. All refrigerant lines were heat traced to maintain all surfaces contacted by refrigerant above the condenser temperature in order to prevent inadvertent condensation elsewhere in the system.

Results are presented in Figure 6 for a third generation aluminum unit cell that was fabricated according to the optimized design presented above. The mass of Ni-MOF-74 loaded into the unit cell was 40.8 g, and the empty bed weight was 78.0 g, giving a metal to sorbent thermal mass ratio of 0.85. The thermal mass ratio was higher than designed because of the extra heat transfer plate in the unit cell and also due to the headers and tubing attached to the ends. The unit cell was loaded into a housing fabricated from PEEK weighing 375 g and having a thermal mass of 675 J/K compared to 85 J/K for the unit cell and MOF. The large thermal mass of the housing potentially dominates the heating and cooling duties, which was mitigated by using low thermal conductivity PEEK polymer for the housing.

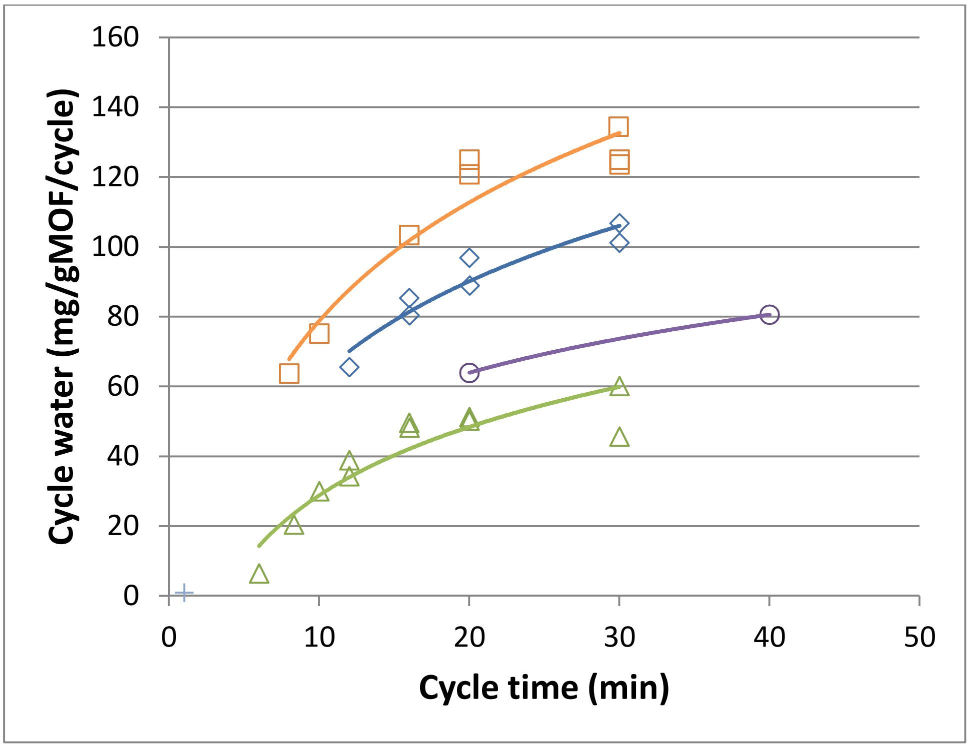

Figure 6. Unit cell test results with 17.8 g of Ni-MOF-74, 140°C hot oil, 60°C cold oil, 11 Torr evaporator pressure, and condenser pressures of 31 Torr (□), 56 Torr (◇), 92 Torr (○), and 149 Torr (△).

The data in Figure 6 shows the amount of water produced per cycle with the evaporator set for 11 Torr static pressure and with hot and cold oil baths set to 140°C and 60°C, respectively. The latter temperature enables operation in hot climates in excess of 50°C. As expected, water production rate increased with longer cycle times because the average bed temperature change was greater, and longer times facilitated interparticle mass transfer, which can be significant with nanoporous materials like MOFs. The different curves in Figure 6 represent different condenser pressures corresponding to 30-60°C condenser temperature range. Water production rates were still increasing at cycle times of 30 minutes. However, longer cycle times reduce bed productivity and require larger beds, so cycle times in an actual system would likely be less than 20 minutes.

Sorption System Modeling

A lumped parameter system model (LPM) [1] was used to interpret unit cell test data. The dynamic model solves for the average pressure, temperature, and loading of the beds, heat transfer fluid temperatures, and ammonia flow rates. Lumped parameters represent average bed temperature and sorbent loading in lieu of profiles within the beds that would require detailed modeling of the geometry, such as by using finite element analysis. The simplified LPM model was developed in MATLAB and uses built-in differential equation solvers. In addition to overall heat and mass balance equations, the model solves heat and mass transfer equations that use overall heat and mass transfer coefficients. The fifth differential that is solved simultaneously with the other four either maintains constant pressure (first derivative set to zero) when a bed is open to the evaporator or condenser, or sets the ammonia flow rate to zero when the beds are closed. The four steps in a thermal cycle—pressurization, desorption, depressurization, and adsorption—are modeled sequentially and is solved iteratively until the final conditions match the initial conditions within a specified tolerance. While the model is simplified, it is a useful tool for analyzing data, designing beds and systems, and optimizing operating conditions.

Metal Organic Framework Sorption Isotherm

The LPM model requires a sorption isotherm equation for the working system of water and Ni-MOF-74 sorbent. The isotherm equation was developed by fitting sorption data obtained from thermogravimetric analysis (TGA) over the temperature range of 25°C to 70°C. However, the TGA instrument is limited to pressures up to the saturation vapor pressure of water at room temperature.

Therefore, an isotherm model fit to the available TGA data would be extrapolated well beyond the measured data to hot oil temperatures and condenser pressures.

To mitigate potential extrapolation errors, the isotherm model was simultaneously fit to data obtained from unit cell testing. In the limit of very long cycle times, bed loadings asymptote to equilibrium loadings at the end of the adsorption and desorption cycles. Therefore, water produced from long thermal cycles represents the difference in equilibrium loading between the adsorbing conditions (evaporator pressure and cold oil temperature) and the desorbing conditions (condenser pressure and hot oil temperature). The difference in equilibrium loading between two state points were obtained by extrapolating curves like those in Figure 6, and the data were added to the TGA data in fitting the isotherm equation. Figure 7 shows the TGA data (filled symbols) and the unit cell data at 130°C hot oil temperature (empty symbols). The curves correspond to the Langmuir isotherm equation fit to all the data simultaneously. As before, P is the pressure and P_o is the saturation pressure at the isotherm temperature. This isotherm model was then used in the LPM system model.

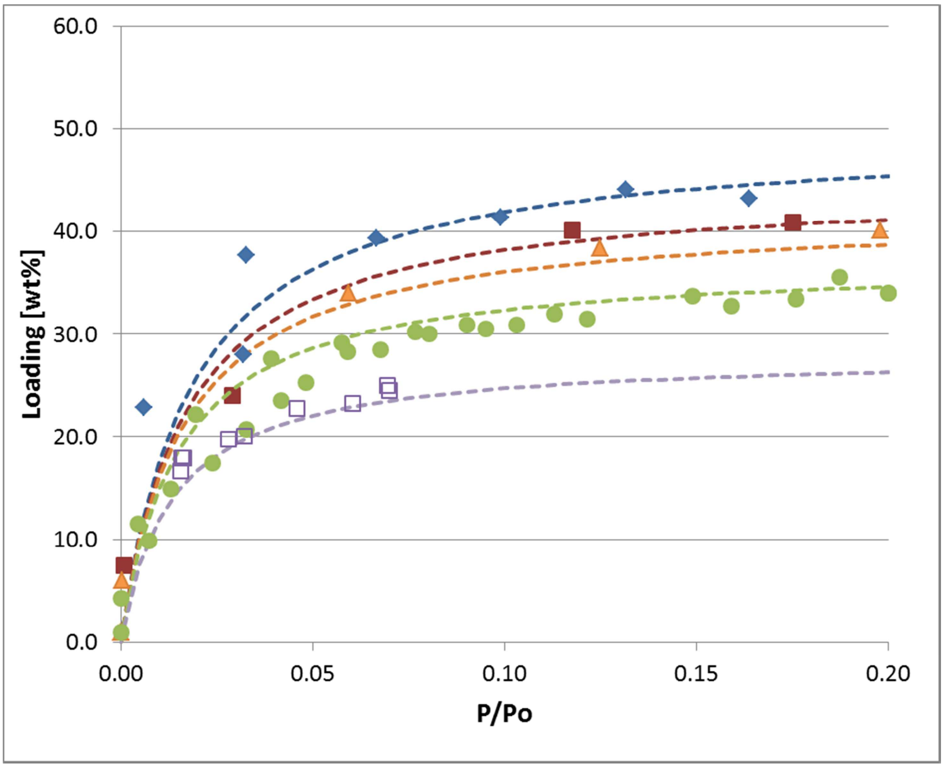

Figure 7. Isotherm data for water and Ni-MOF-74 for 25°C (◆), 40°C (■) , 50°C (▲) , and 70°C (●), along with unit cell test data at 130°C (□) and dashed lines representing the Langmuir fit.

LPM Model Calibration

The unit cell data were used to calibrate the overall heat and mass transfer coefficients of a 2-bed LPM model. For each of the unit cell tests used for the calibration, the LPM parameters were set to the conditions of the test, including temperatures, pressures, heat transfer flow rate, and cycle times. Physical parameters, including sorbent mass, heat and mass transfer areas, and thermal masses were based on the unit cell configuration. The overall heat transfer coefficient was estimated for the unit cell geometry using a series resistance model that included a convective heat transfer coefficient for the oil, estimates of wall conduction resistance that included a fin efficiency for the corrugations, and conduction resistance for the sorbent loaded between the fins. The estimated mass transfer coefficient accounted only for the pressure drop through the bed, and intraparticle mass transfer was assumed to be negligible.

Three parameters were added to the model for calibration. Multipliers were applied to the heat and mass transfer coefficients and the structural thermal mass. The latter was an adjustment for the thermal mass of the housing that added an unknown parasitic thermal load. Four sets of data were used to calibrate the three parameters. The datasets included varying cycle times, 100 and 250 Lpm oil flow, 140°C or 160°C hot oil, and condenser pressures of 31 Torr and 150 Torr. The consistent parameters were the evaporator pressure at nominally 10 Torr and cold oil temperature of 60°C. The best fit of these 4 datasets used a multiplier of 1 on the heat transfer coefficient, 0.75 on the mass transfer coefficient, and 1 on the structural thermal mass. The results of the fit are shown in Figure 8 as the predicted versus measured water production per thermal cycle. The 0.75 multiplier on the mass transfer coefficient is attributed to predominantly intraparticle diffusion. As a result of this calibration, the mass transfer coefficient multiplier of 0.75 was used in subsequent models, including the 4-bed model used for design and performance predictions.

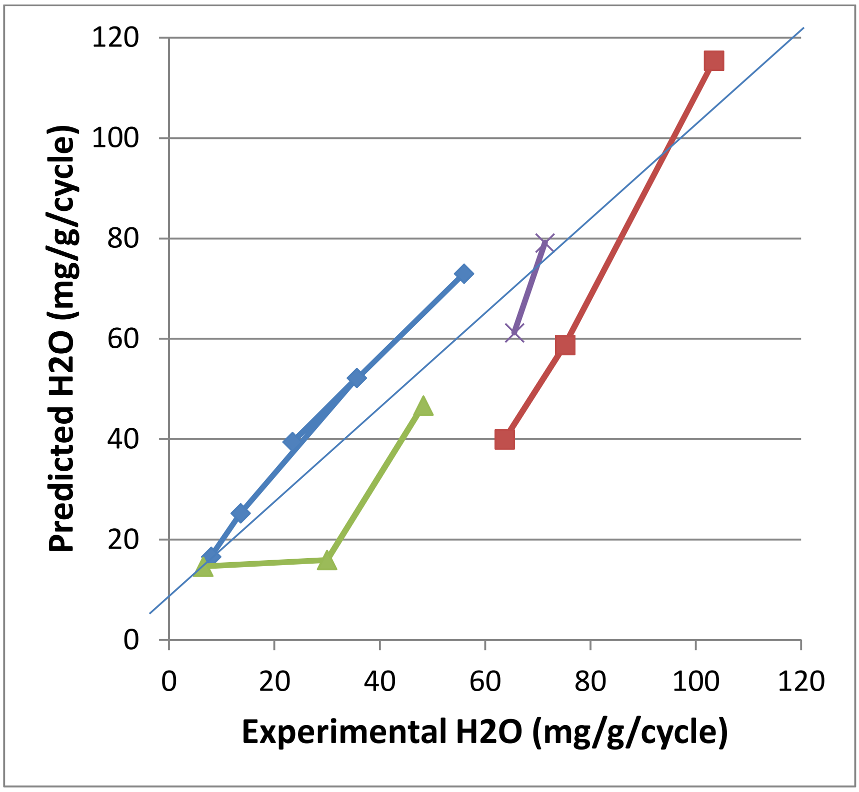

Figure 8. Comparison of water production rate from unit cell testing and a fit of the 2-bed LPM system model.

Design of a 4-Bed Heat Pump

The calibrated LPM model is finally used to design a 4-bed adsorption heat pump with water refrigerant and Ni-MOF-74 as the sorbent. The target application of hot climates with outside air temperatures above 50°C dictates that cold oil and condensing temperatures are higher than 50°C to facilitate heat rejection. The specifications call for cooling the return air to 19.5°C, so the evaporating temperature must be lower for the evaporator coil heat transfer. Translating from outside temperature and cooling targets to condensing and evaporating temperatures involves an overall system design including specifying balance-of-plant items. The hot oil temperature depends on the available heat source, but with an outside temperature above 50°, the hot oil is preferably at least 150°C. The working capacity of the sorbent increases and the size of the beds decrease if the hot oil can be heated to 200°C. Working capacity diminishes above 200°C hot oil temperatures, because the Ni-MOF-74 is nearly unloaded at the condenser pressure, and further heating recovers minimal additional water. Ideally, the adsorption heat pump is operated using waste heat instead of burning fuels. Engine exhaust heat, such as from auxiliary generator exhaust, can reach temperatures of 200°C making this a viable alternative.

In lieu of a full system design with balance-of-plant components, performance curves of the 4-bed system were generated for varying condenser and evaporator pressures, as shown in Figure 9. Coefficient of performance for cooling is the ratio of the average cooling duty to the average heating duty from the hot oil. The original target call for a minimum COP of 0.3, and Figure 9 indicates about 10 kg of Ni-MOF-74 is required for a 0.75 RT portable cooling unit at the desired conditions and using

200°C hot oil. The highest curve is a best case scenario of 51°C condensing temperature and 14.5°C evaporator temperature. The middle curve is more reasonable with 5°C driving force for heat transfer in both the evaporator and condenser. Those heat exchangers would be smaller with more heat transfer driving force represented by the lowest curve. Nevertheless, this very challenging application of air conditioning in desert-like conditions is viable with this technology and the amount of sorbent needed is not unreasonable.

Each point in Figure 9 represents the highest COP achievable with that mass of sorbent producing 0.75 RT of cooling. Each maximum COP was obtained from approximately 400 simulations of the 4-bed LPM model over a range of heat transfer flow rates and cycle times, which was made practical by the simplified LPM model.

As expected, there is a trade-off between the size of the system and the achievable COP. The minimum COP of 0.3 is readily achievable and can be increased further to over 0.6 with larger beds. In more temperate environments at temperatures closer to 35°C, even higher COPs greater than 1 are achievable, as has been explored for an alternative working system [1].

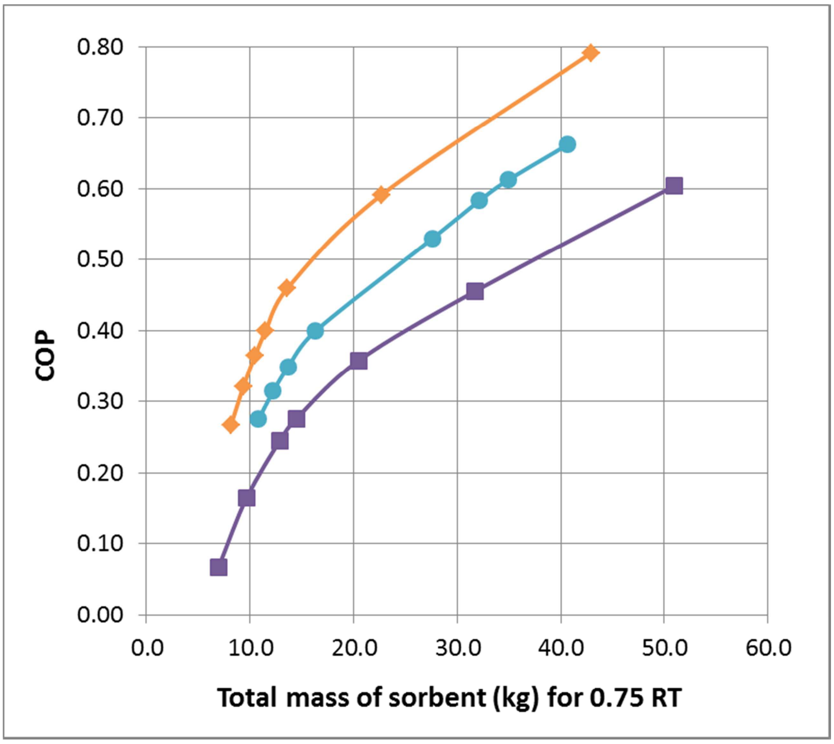

Figure 9. Trade-off between coefficient of performance (COP) and total sorbent mass for a 4-bed Ni-MOF-74 adsorption heat pump system operating with 200°C hot oil at 51°C and 14.5°C (◆), 57°C and 14.5°C (●), and 60°C and 12.8°C (■) condensing and evaporator temperatures, respectively.

Conclusions

A novel adsorption heat pump has been designed to provide space cooling in extreme climates in excess of 50°C outside temperature. A coefficient-of-performance greater than 0.3 is viable with approximately 10 kg of Ni-MOF-74, and even higher COPs greater than 0.6 are possible with larger beds of over 40 kg. This is made possible by a combination of MOFs—a class of emerging nanoporous sorbents—a novel high-efficiency multi-bed system concept, and low thermal mass sorbent beds that can provide excellent heat transfer for thermal cycling. A technology development protocol was followed that included building and testing unit cells of the larger bed architecture. The data were useful for also improving the isotherm model equation and validating a simplified lumped-parameter system model. The validated system model was subsequently used to optimize performance curves for a 0.75 RT adsorption heat pump. The system model can be used in the future to complete an overall system design including balance-of-plant heat exchanger and mechanical components.

This work was focused on developing technology for extremely hot environments. Alternative working systems may be optimal for other operating environments, such as lower temperature refrigerants with other MOFs for freezing temperatures [30]. However, the same protocol can be repeated for other operating specifications. It has been demonstrated that the high efficiency system concept can reach COPs over 1 for residential cooling applications [1], and this is expected with optimized MOF-refrigerant systems.

Acknowledgements

This work was performed for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830. Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy. The work was funded by the U.S. Department of the Navy in conjunction with the U.S. Department of Energy, ARPA-E.

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14 SMART APPLIANCES

Smart appliances and smart homes: recent progresses in the EU

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Abstract

The EU energy system is facing rapid changes due to the full market liberalization and the high share of renewable energy sources. These trends have resulted in the installation of renewable energy generation in buildings (heat pumps, PV, etc.). The high penetration of renewable energy has also increased the interest for demand response activities in the residential sector and the adoption of energy storage solutions. This transformation will be further boosted with the penetration of plug-in hybrid and electric vehicles. Residential consumers will become prosumers and will have a much more active role in the energy markets. In addition to these trends, the fast penetration of internet in buildings and in mobile devices, and new communication protocols between equipment, appliances and home gateways has offered new opportunity for traditional appliances to offer demand response, flexibility and storage capabilities, as well as to respond to price and other external signals. The paper focuses on the role that "smart" appliances and devices play in the new European energy transition towards low carbon impact, digitalization and smartness. The paper looks at the current European definitions of smart appliances, the development of standards and test protocols, the technologies development and the common communication protocols. Finally the paper analyses the potential benefits for end-users and the energy system by a large penetration of smart appliances and the policies that can foster this penetration.

Introduction

Among the policy priorities of the European Commission in order to boost the European economy and growth while taking care of the impact on climate change are the creation of a Digital Single market and of the Energy Union.

EU policies for the Digital Society

Among the EU priorities for 2020 the European Commission has proposed the Digital Agenda [1] in 2010 and more recently the Digital Single Market [2] in 2015 which aims for to:

- Offer a better access for consumers to digital goods and services across Europe;
- Create the right conditions and a level playing field for digital networks and innovative services to flourish;
- Maximize the growth potential of the digital economy;

The lack of Interoperability and absence of standards are seen by the Commission as a hurdle for the development of the Digital Single Market. ICT standardization is seen as essential for the interoperability within the Digital Single Market, allowing for the steering of the development of new technologies like 5G wireless communications, data-driven services, cloud services, intelligent transport systems and the Internet of Things.

The digitization in basic sectors are seen as crucial in the strategy namely for e-Energy as it is seen as an important sector where it is acknowledged a radical change in the energy sector where "*citizens, industries and commerce will engage in active management of their energy, first as consumers who adjust their consumption, but also as producers of electricity from residential, industrial or community-based renewable sources. Users and companies will be able to optimize their demand or supply of energy through different vectors and local storage, under a new energy market design as addressed in the Energy Union.*"

According with the Digital Single Market [2] strategy the three interrelated areas where ICT is expected to have an impact on the efficiency of energy systems are:

1) ICT in buildings - in the form of building management systems and sensor networks;

2) ICT in Energy Grids (Smart Grids) – In order to reduce peak demand and facilitate integration of renewable sources;

3) ICT in households – With the introduction of smart meters and smart appliances, making consumers aware of their energy consumption and trigger potential behavioral changes.

The deployment of smart meters, smart appliances and other elements of smart grids are foreseen to generate massive amounts of data, allowing for new players in the sector such as aggregators for demand response or decentralized energy productions and new energy services companies.

The European Commission's published in September 2016 a strategy on Connectivity for a European Gigabit Society (COM(2016)587). The strategy sets a vision of Europe where availability and take-up of very high capacity networks enable the widespread use of products, services and applications in the Digital Single Market. This vision is based on three main objectives for the year 2025:

- Gigabit connectivity for all main of socio-economic drivers,
- Uninterrupted 5G coverage for all urban areas and major terrestrial transport paths,
- Access to connectivity offering at least 100 Mbps for all European households

EU Energy policies

The need to increase energy efficiency progress in the EU was reinforced in the Conclusions of the European Council meeting of 8-9 March 2007, and based on agreements made in June 2010, the EU set a target of 20 % reduction in the EU primary energy consumption by 2020. This target results in a consumption levels of 1474 Moe in 2020, which is reduction of 368 Mtoe compared to 2007 primary energy consumption projections of 1842 Mtoe in 2020. This target is part of the EU energy and climate targets for 2020, which also contain a reduction of GHG by 20% in 2020 compared to 1990 and 20% of final EU energy consumption to be covered by renewable energy

The Energy Efficiency Directive [4] (EED), adopted in 2012, laid down the foundation for more actions to be taken in order to put the EU on track. The Directive, which is a key part of the EU's overall climate and energy legislative package, requires EU Member States to set indicative national energy efficiency targets and legally binding measures to help the EU reach its 20% energy efficiency target by 2020. In particular, all EU Member States are required to implement policy measures that improve energy efficiency at all stages of the energy chain from production to final consumption.

In particular the EED articles 9-11 on Metering outline that Member States when deploying smart meters in their territory provide information on actual time of use and that their information and the access to their smart meters may be accessed by third parties acting in the market.

The EED's article 15 on Energy transformation, transmission and distribution outlines that Member States shall ensure the removal of tariff incentives that are detrimental to energy efficiency and that may obstruct Demand Response activities. Member States should also guarantee that demand side resources such as Demand Response should participate alongside supply in wholesale and retail markets and that demand response providers, including aggregators, are treated in a non-discriminatory manner, on the basis of their capabilities.

More recently EU leaders adopted in October 2014 [5] the 2030 climate and energy framework, which sets three key targets for the year 2030:

At least 40% cuts in **greenhouse gas emissions** (from 1990 levels)

At least 27% share for **renewable energy**

At least 27% improvement in **energy efficiency.**

The energy efficiency target is expressed as a 27% reduction from the 2007 projections for primary and final consumption in 2030. Most recently the European Commission has proposed a reduction of 30%, this target is currently under discussion between the 3 EU institutions.

Another relevent policy action in the EU is the liberalisation of th electrcity and gas market and the creation of a single internal market.

The Directives 2009/72/EC [6] and 2009/73/EC [7] concerning the common rules for the internal market in electricity and gas outline the need for Member States to encourage the modernization of distribution networks through the introduction of smart grids, smart meters, and developing innovative pricing formulas.

Member States were required, by 2012, to assess the long-term costs and benefits to the market and the individual consumers of the roll-out of smart metering systems. In the case of this assessment resulting positive, at least 80% of the consumers should be equipped with smart meters by 2020.

The European Commission produced a recommendation for the preparations for the roll-out of smart metering strategies (2012/148/EU) [8] which follows the above mentioned directives concerning the common rules for the internal market in electricity and gas. In this recommendation, data protection and security considerations are outlined, along with the proposal for a methodology for the Cost-Benefit-Analysis that Member States should perform for the roll-out of smart meters. The recommendation also outlines the common minimum functional requirements that smart meters should present.

For the costumer, the meters should provide readings directly to the costumer since direct consumer feedback is seen as essential to ensure energy savings on the demand side. There also the reference for standardized interfaces which should enable energy management solutions in real time like home automation and demand response schemes. In terms of reading updates, these should be of at least every 15 minutes. On the metering operator side the meters should allow remote reading, provide two-way communication between the smart meter and external networks and allow frequent readings so that the information can be used for network planning. Other requirements on the functionalities of smart meters are the provision of secure data communication, fraud prevention and detection and the provision for import/export and reactive metering to allow renewable and local micro-generation.

Another important development in relation to the energy transition and a competitive energy market with a high degree of renewable energy is demand response. Demand Response is seen as a crucial technology on the Strategy for the Energy Union, by allowing the full participation of consumers in the market. The 2013 Staff Working Document on Demand Response (SWD (2013) 442) [9] explains the importance of demand side participation, demand response in particular. With the full transposition of the Energy Efficiency Directive and Electricity Directive, it allows for the right conditions being created for policy-makers, regulators, network operators and energy businesses to trigger more demand side participation in the energy market. The document estimates that the volume of controllable load by smart appliances in the EU is of at least 60 GW, of which 40 GW would be economically viable. The shift of this load from peak times to other periods is expected to reduce peak-generation in the EU by 10%. In terms of accelerating Demand Response in the residential sector, the promotion of household appliances that are able to modulate temporarily their energy use, smart metering systems and energy storage possibilities are seen as solutions for an effective adoption of Demand Response in the European market.

Definitions of smart appliances and smart homes

1. The preparatory study for Smart Appliances [10] promoted by the European Commission under the Ecodesign directive defines Smart Appliances as "an appliance that supports Demand Side Flexibility that is able to automatically respond to external stimuli e.g. price information, direct control signals, and/or local measurements (mainly voltage and frequency); The response is a change of the appliance's electricity consumption pattern."

2. This definition does not necessarily meet eye to eye to the definition of "smart" that is commonly used, not only in smart appliances, but in other fields like Smart devices, smart homes or smart cities. Usually, the term smart is used when a service or a product is somehow connected or connectable to other services or products through a network of some kind enabled by ICT services or goods. For the purpose of this report, smart or connected devices are devices with embedded ICT and that can be connected to other devices or systems via a cable or wirelessly.

In the report from 2015, Karlin, B. [proposes distinct products aggregated into three groups, under a common nomenclature of Home Energy Management Systems (HEMS),that fit into the Smart Home/Connected Appliances ecosystem under study in this paper:

In this section a brief summary is presented outlining the main characteristics of the Smart Home Systems components in terms of user interfaces, smart hardware and software platforms.

Energy Portal

Energy portals are informatics based applications that presents energy consumption information which was usually imperceptible to the consumer in a more user friendly way with the information being explained in an easy to understand display of information.

This type of applications provides a more detailed and direct feedback than traditional bills and are usually provided as a service from energy utilities.

Energy Portal	
Main Functionality	Energy data collection and transmission for the final consumer
Specific Functionalities	Receives energy consumption information from smart meters, smart appliances and other smart products within the household. Allows more detailed and almost real-time energy consumption information than traditional bills Allows users to act on the information given and remotely control appliances Provides immediate feedback on actions, suggestions on potential savings and comparisons with similar consumers
Interface	Smartphones, Web based applications, computer software
Communication	Wi-Fi, LAN
Interaction	Bi-directional. Allows for interaction with other smart home products

In-Home Displays

In-Home Displays are simple interfaces that provide immediate energy use feedback for the consumer also having the ability to send pricing signals. The type of information given is usually very simple and direct. These devices are connected to the home energy network via a traditional normal meter and communicate with other peripheral devices through a home area network.

In-Home Displays	
Main Functionality	Immediate energy data collection and real-time transmission for the final consumer.
Specific Functionalities	Receives energy consumption information from traditional meters, usually through the clamping of current transformers to the home electrical network. Gives real-time energy consumption information Programmable to send energy pricing signals
Interface	Device display, peripheral displays
Communication	Wireless communication
Interaction	Uni-directional from the device to the user

Load Monitors

Load Monitors give a simple piece of energy consumption information of an energy consumption device. These are connected between the power outlet and the actual device and give the energy consumption of the device.

The type of information given by Load Monitors is usually limited to the energy consumption and eventually a calculation of costs associated with this consumption, if these parameters are imputed by the user.

Load Monitors	
Main Functionality	Immediate energy data collection of individual appliances
Specific Functionalities	Installed between energy plugs and the appliances Receives real-time energy consumption information directly from individual appliances More complex models also give simple price information
Interface	Device display
Communication	Usually only visual information from the display
Interaction	Uni-directional from the device to the user

Smart Appliances

Smart Appliances are defined in the Ecodesign Preparatory Study for Smart Appliances as appliances that are communication enabled. This communication platform can be used to offer multiple classes of functionalities like demand side flexibility.

On the energy aspect of smart appliances, these have the capability to receive, interpret and act on a signal received from an energy provider and adjust its operation according with the settings chosen by the energy consumer.

Smart Appliances	
Main Functionality	Home appliances with the capability to communicate both with the user and other platforms and services
Specific Functionalities	Communication between the smart meter, providing information to the energy utility Ability to change the appliance's consumption pattern Possibility to adapt its consumption to energy produced on-site Ability to support variable pricing based on day-ahead energy market
Interface	Device display, peripheral displays, web applications, energy portals
Communication	Wire and wireless communication
Interaction	bi-directional between the user and energy utilities

Smart Thermostats

Smart Thermostats ultimately have the same main functionality of traditional thermostats that is to control the temperature from a HVAC system. The added features of these devices in comparison with traditional ones are the added programming allowed, using self-learning algorithms of the consumption patterns and intuitive interfaces with an easy user experience.

Smart Thermostats	
Main Functionality	Temperature control with variable consumption parameters
Specific Functionalities	Self-learning of consumption patterns Geo-fencing activation/deactivation Presence detection Communication with user and possibility for remote control through other devices Interaction with other smart home connected devices
Interface	Device display, peripheral displays, web applications
Communication	Wi-Fi

Interaction	bi-directional

Smart Lights

Smart lights are lighting devices that incorporate normal lighting with embedded technology that allow for automatic control. These products are doted with sensors and microprocessors that can detect environmental light or occupancy and act upon prompts defined by the user.

Smart lights allow users to adjust its lighting need by scheduling times and reduce over illumination, thus reducing the energy consumption associated with lighting.

Due to its smart features, smart lights can be remotely controlled and even support demand response programs in response to inputs from energy utilities.

Smart lights	
Main Functionality	Lighting devices with connected features
Specific Functionalities	Lighting sensor Dimming possibility Presence detection Demand response readiness Lighting scheduling Communication with user Remotely controlled Interaction with smart home hubs Color changing
Interface	Web and smartphone applications
Communication	Wi-Fi
Interaction	bi-directional

Smart Plugs

Smart plugs are devices that come between an energy plug and an energy consumption appliance. These devices have a characteristic to turn non-smart appliances into smart ones due to its incorporated intelligent features.

A Smart plug allows for appliances connected to it to be remotely controlled and provide feedback of the energy consumption of the appliance.

Smart plugs	
Main Functionality	Control and feedback of energy consuming appliances
Specific Functionalities	Remote control of appliances Turn non-smart appliances into “smart” ones

	Communication with user Interaction with smart home hubs
Interface	Web and smartphone applications
Communication	Wi-Fi
Interaction	bi-directional

Smart Hubs

Smart Hubs are devices that aggregate several smart connected devices within the smart home environment. The main objective of smart hubs is to integrate the functionalities of all these devices and communicate with all in a concerted way within a home network.

Smart Hubs	
Main Functionality	Connection and integration of smart home connected devices
Specific Functionalities	Remote control of connected devices Association of connected devices making them able to communicate among themselves Internet access Entertainment features
Interface	Hub display, Web and smartphone applications
Communication	Wi-Fi
Interaction	bi-directional

Status of the enabling factors

Smart Appliances and connected devices within the Smart Home are intrinsically linked with external conditions like the access to a fast internet, possibility to offer Demand Response to final consumers through aggregators, etc.. This section gives an overview on the status of the European Market in terms of the current adoption of universal access to fast internet, the roll-out of smart meters or the readiness of Member States to allow to Demand Response through aggregators.

Internet Access

In terms of internet access, according to Eurostat, in the year 2016, the great majority of households have internet access, with some Member States reaching up to 100% of access in their territories. As can be seen in **Error! Reference source not found.**. Member States like AT, BE, CZ, DE, DK, EE, ES, FI, FR, HU, IE, LU, MT, NL, PL, SE, SK and the UK have all a level of internet access within households of 80% or above. In terms of the overall EU28 population, 85% of all Europeans have internet access in their households. In terms of the broadband coverage, all the EU28 had, in 2015 broadband coverage, with 68% over 30Mbps and a nearly 50% broadband coverage of over 100 Mbps. On a Member State level, BE, DK, EE, LT, LY, LV, MT, NL, PT, SI, SK and the UK have more that 80% of broadband coverage higher than 30Mbps and BE, DK, LT, LU, LV, MT, NL and PT having 80% or more of its territory covered by broadband speeds of 100 Mbps or higher.

Smart Meter Roll-out

The deployment of a smart meter is a starting point for an advanced control of the energy consumption within the household. The final consumers can benefit from almost real-time information on their consumption patterns and be able to act on it.

EU Member States needed to perform, by 2012, a Cost-Benefit-Analysis for the roll-out of smart meters across its territory until 2020. The European Commission's Joint Research Centre (JRC), along with DG Energy has produced, in 2014, a report on the benchmarking of smart meter deployment in the EU, with a focus on electricity. This report performs a benchmark of the Cost-Benefit-Analysis performed by Member States (27 at the time), in order to evaluate the feasibility of the global deployment of smart meters around Member States territory.

The conclusions of this benchmark are summarized in the figure below:

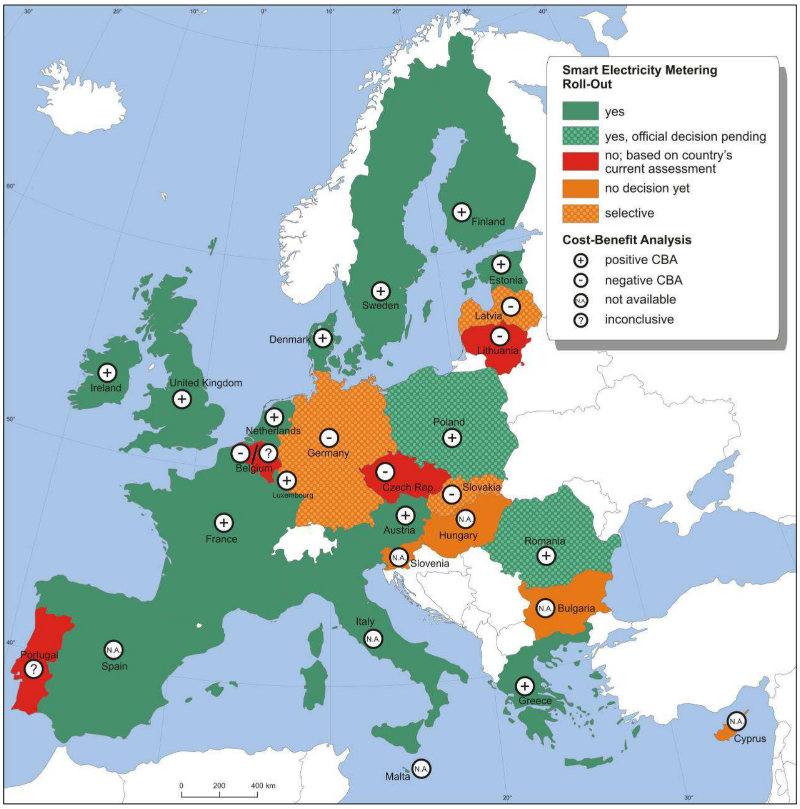

Figure 1 - Smart Electricity Metering Roll-Out (2014). Source: European Commission

16 Member States (Austria, Denmark, Estonia, Finland, France, Greece, Ireland, Italy, Luxemburg, Malta, Netherlands, Poland, Romania, Spain, Sweden and the UK) will proceed with large-scale roll-out of smart meters by 2020 or earlier, or have already done so. In two of them, namely in Poland and Romania, the Cost Benefit Analysis yielded positive results but official decisions on roll-out are still pending;

In seven Member States (Belgium, the Czech Republic, Germany, Latvia, Lithuania, Portugal, and Slovakia), the Cost Benefit Analysis for large-scale roll-out by 2020 were negative or inconclusive, but in Germany, Latvia and Slovakia smart metering was found to be economically justified for particular groups of customers;

For four Member States (Bulgaria, Cyprus, Hungary and Slovenia), the CBAs or roll-out plans were not available at the time of writing;

Legislation for electricity smart meters is in place in the majority of Member States, providing for a legal framework for deployment and/or regulating specific matters such as timeline of the roll-out, or setting technical specifications for the meters, etc. Only five Member States (Belgium, Bulgaria, Hungary, Latvia and Lithuania), have no such legislation in place.

Demand Response

As outlined in the Staff Working document on Demand Response (DR) [9], Demand Response is an asset for both the retail and the wholesale market. The value of demand response for the wholesale and balancing markets, at various time scales (i.e. including the day-ahead, intraday and forward markets) is far from being tapped. Demand response is an integral part of a consumer-centric retail market vision in the energy sector. Its role is foreseen in the design of the EU internal energy market calling for consumer empowerment. In both wholesale and retail, demand response is centered on fair reward to consumers for demand flexibility and relies on available technical solutions.

Consumers today have the chance to participate in Demand Response programmes in multiple Member States in accordance with the requirements of the Energy Efficiency Directive, something that did not fully occur in the past.

The Joint Research Centre (JRC) on its report on “Demand Response status in EU Member States” [13] gives an overview on the state of Demand Response in the EU-28 and provides a review on the readiness of Member States in terms of the establishment of a legal framework and market readiness for the use of Demand Response in the energy market, thus having the ability to potentiate the deployment of smart homes as active partners in the energy infrastructure.

Some key elements for a successful development of Demand Response programmes outlined are: 1) the definition of independent aggregators that can ensure the consumer’s right to choose their energy service provider and allow full aggregation of consumer’s loads; 2) market design should enable the participation of Demand Response and other distributed resources like Virtual Power Plants and 3) Technical modalities enabling Demand Response should be defined by standardization and replication throughout whole Europe.

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In the JRC report it is possible to realize a three-speed-Europe in terms of the status of Member States regulation concerning Demand Response.

First, there are the Member States that have yet to actively create a Demand Response policy. Member States like Portugal, Spain, Italy, Croatia, the Czech Republic, Bulgaria, Slovakia, Hungary, Cyprus, Greece, Poland or Malta had not yet adjusted their regulatory structures to enable demand side resources to participate in the markets, begun the process of defining the role of an independent aggregator and DR service provider, or adjusted critical technical modalities.

The second group of Member States more advanced on the enablement of Demand Response are Austria, Finland, Denmark, Germany, the Netherlands and Sweden by enabling Demand Response through the energy retailer. Rather than leaving to independent aggregators to offer demand response solutions for consumers in a more transparent way, the retailers in these Member States have their demand side solutions offers as a bundle with their electricity bill, leaving to consumers the choice to accept the entire package or refuse it entirely, making it hard for them to know what they are rejecting/accepting as they will hardly have a fully transparent offer.

The third group of Member States enables both Demand Response and independent aggregation. This includes Belgium, France, Ireland and the UK. Belgium and France have both defined the roles and responsibilities around independent aggregation.

Although there are some shy signs that Demand Response is taking off in several European Member States, there is still a long way for the whole Europe to be ready to offer sound Demand Response solutions for energy consumers, which ultimately will also impact in the development of the smart home environment in general and smart appliances and connected devices in particular.

Smart Appliances and Connected devices market

In what concerns the market share of Smart Appliances and connected devices in the EU, there is still a gap in terms of information, mainly due to simply being still a relatively new market. Although there are some studies on the amount of smart appliances being sold, a more in-depth study to the whole connected devices market would be welcome.

In the IHS Markit evaluation of the Home Appliance Market [14], a forecast on the smart appliance market estimates for a growth from less than 1 million units in 2014 to over 223 million units worldwide as shown in the figure below. This forecast is considered conservative by IHS, with more space to grow.

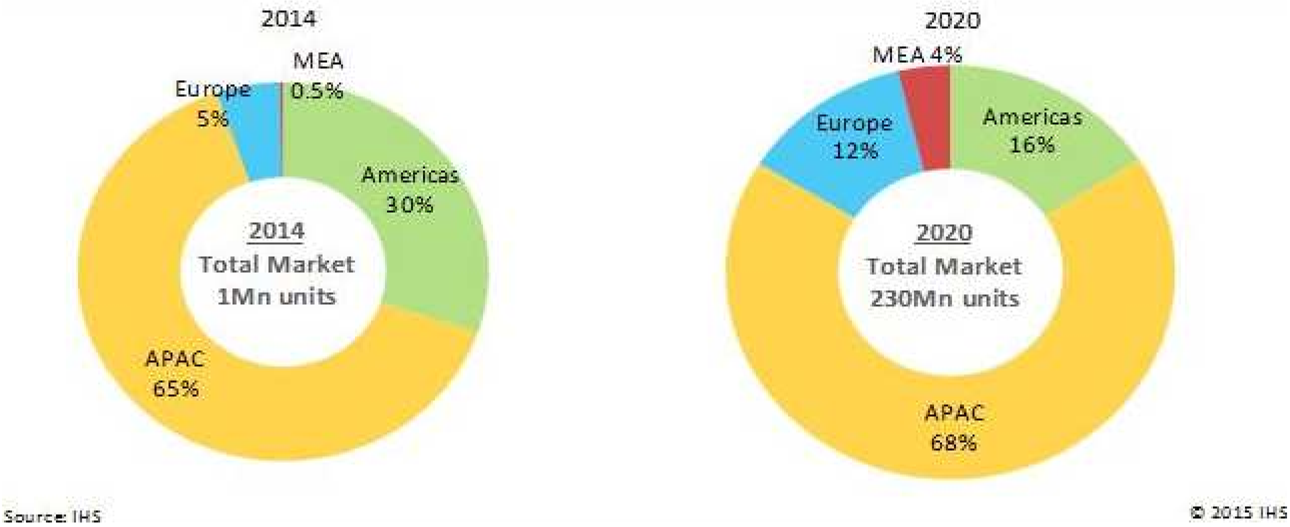

Figure 6 - World market for smart connected major home appliances in 2014 and 2020. Source: IHS

The penetration of these smart connected appliances is projected to grow from an estimated 0.2% in 2014 to 31.3% in 2020, with that of smart room air-conditioners reaching 52% and smart washing machines 42% in 2020. China is projected to be the leading market for smart connected major home appliances, followed by the United States. As demand for smart connected appliances develops in other countries, the share of Americas is projected to drop from an estimated 30% in 2014 to 16% in 2020.

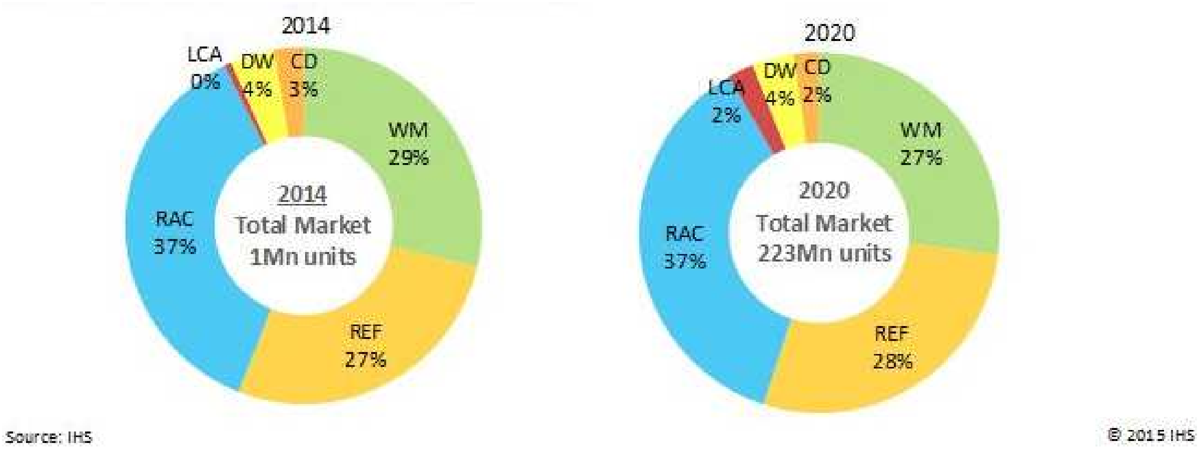

Figure 7 - Worldwide market for smart connected major home appliances in 2014 and 2020. Source: IHS

Although the smart home market is still a relatively small one, according with the Deloitte consumer review of 2016 “Switch on to the connected home!” [15] there are some signals of change that will reflect in an increase of the consumption of smart home devices, greatly due to a generational change. The report highlights that younger generations find more value in smart home devices, with UK consumers under 34 years old being more likely than older generations to purchase connected devices with the conviction that these would make their lives easier. In this study, 48% of the respondents said they think smart home devices are too expensive, while 26% refer to think that the technology needs to evolve further before they buy a smart device. Older consumers are more worried about the device's long replacement cycles than the price.

While in some categories such as entertainment, consumers are already purchasing connected devices, fewer people own devices in other areas of the smart home ecosystem, with only two or three percent of the consumers having purchased smart security systems, smart thermostats and lighting systems.

The majority of people within this study (70%) do not plan to buy any connected devices in the near future, and only plan to replace lighting and thermostats with connected devices once they need to.

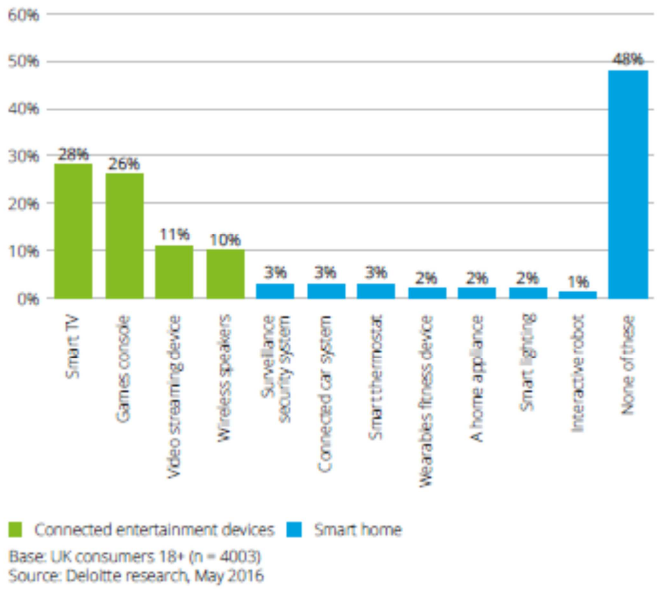

Figure 8 - Consumer ownership of connected devices. Source Deloitte (2016)

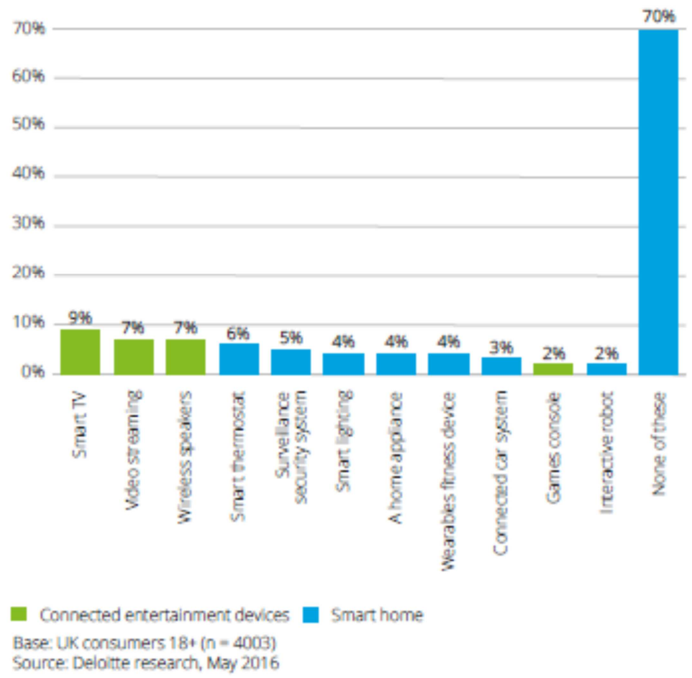

Figure 9 - Intent to purchase within 12 months. Source: Deloitte (2016)

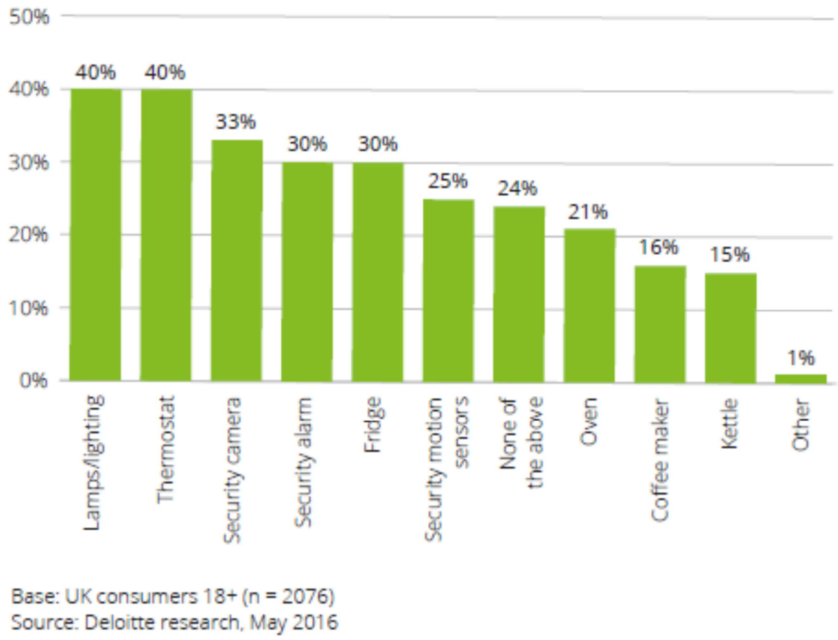

Figure 10 - Appliances consumers are most likely to replace with a connected device. Source: Deloitte (2016)

Although encouraging, the forecasts of development of the smart home market are to be taken cautiously. It is natural that an evolution in the consumption patterns should occur. However, this market will need to be supported by a global ecosystem that can support its developments by advances in telecommunication networks and energy systems and above all a common vision between all the agents present in this ecosystem.

Discussion and conclusions

As in the case of other new emerging technologies such as smart phones, smart meters, etc. it is important that common definitions of smart appliances are adopted, including the minimum functionality. The authors propose that the communication capability with other devices and the access to internet is of the key and qualifying features of smart appliances. It is also important that the definition allows to differentiate between smart appliances and other smart devices in the smart home environment, for example smart meters, smart thermostats, and other devices that are connected (e.g. complex set top boxes, home gateways).

The second important step is to establish test methods to assess the performances of the additional features and the energy consumption of the appliances. As the additional communication equipment will add to the normal appliance energy consumption (i.e. the energy consumption to carry out the main tasks, e.g. washing, cooling, cooking, etc.), it is important to identify induced energy savings and other energy system benefits resulting from the smart appliances, e.g. enabling demand response or storage of energy, or self-consumption of renewable energy, etc.

The third important area of standardization are communication protocols possibly based open standards, which would allow the interconnection of different types of smart appliances, by different manufacturers, with other smart devices (e.g. smart set top boxes, home gateways, smart meters).

Finally beside the energy or environmental benefits, the smart appliances shall be appealing for the consumers in the different age segments, i.e. offer additional benefits and services, such as controlling the appliances from remote, enhanced durability though self-diagnostic and enhanced maintenance, facilitation of tasks (e.g. automatic detection of wash cycle, etc.)

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Thermostats in Residential Buildings: How Updated are They? What's the "Smart" Penetration, Turnover Rates, and the Remaining Savings Potential?

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ABSTRACT

This study examines the penetration of digital thermostats in residences in five states around the US, and the rate of turnover of older thermostats – based on lifetimes and thermostat ages. The natural or market outflow of thermostats was computed to provide estimates of the annual opportunities for installation of new models. We discuss the energy savings available, user satisfaction, advantages and disadvantages associated with new models.

This paper assembles information from five similar studies conducted by the author. The study examines results from surveys in five different states with responses from a total of more than 3,000 homes, that gathered data on:

- The number of thermostats on the walls in houses and apartments;
- The types of thermostats in place (by age and technology type); ;
- Replacement patterns, and
- Satisfaction and usage information.

The data were used to develop statistical estimates of thermostat lifetimes and replacement rates.. The data let us draw conclusions about the energy savings that might be realized from thermostat replacement programs and interventions, using information on the current stock of thermostat technologies in place. We provide implications including:

- The penetration of new smart / wifi models (as well as programmables) in the residential sector, with variations by state. From a smaller sample of follow-up work, we provide information on the influence utilities have had in the installation of new models, vs. the "natural" uptake of the models.
- The energy savings potential that could be achieved in the sector from programs is calculated using secondary data on savings, and information from the surveys on the remaining potential for replacing older non-programmable and non-"smart" programmable models with updated models – using natural replacement rates (derived from EULs and ages of cohorts) as the baseline.

The study uses a combination of data collection methods and modelling. We present conclusions regarding:

- the rates of ownership and replacement of thermostats in the residential sector,
- variations by US state,
- the energy savings that could be achieved by replacement of older models by more capable new models, and
- the potential for utility programs to influence replacement rates.

This study shows the potential for utility programs to increase household's comfort, control, and savings through accelerated thermostat replacement programs with ''digital'' or ''smart'' models. The presentation also discusses elements underlying the results, including measure life, mercury, and behavioral issues.

Introduction

Smart (wifi-enabled / WE) thermostats – and even programmables in a number of cases – provide an significant opportunity for delivering energy savings in homes and businesses across the US[20], with fairly minimal disruption in homes. The size of the *total* potential depends on the number of older-type thermostats still in use, and the size of the *annual* potential depends on two things:

- Natural marketplace turnover, and
- The aggressiveness of utilities in encouraging – or implementing – replacement with upgraded models.

To estimate this potential, SERA conducted detailed surveys with more than 3,000 single family and multi-family (SF, MF) households in five states around the US (California, Illinois, Rhode Island, New York, and Maine), gathering detailed data on the number, types, ages, replacement, and satisfaction with and use of the thermostats. We used the data to conduct statistical analyses to:

- Estimate the total number of older-type thermostats in use
- Estimate the natural lifetimes of older thermostats, to develop estimates of the number of thermostats naturally available to be replaced with upgraded models on an annual basis
- Estimate the penetration of Wi-Fi Enabled thermostats (by type) in the US and customer feedback on satisfaction and use; and,
- Draw conclusions about the potential for energy savings from thermostat rebate and replacement programs and implications for market interventions from public and private sector organizations.

We specifically gathered information on thermostats that were:

- Non-programmable, asking about the different thermostat types that did and did not contain mercury;
- Programmable, but non-communicating (none of which contain mercury), and
- Programmable, with communication, learning capabilities, and other features (none of which contain mercury.

Motivations for the Study

The work on this project began with a recycling industry client who was interested in determining the amount of mercury contained in thermostats on the walls of American homes and businesses. The original study estimated the metric tons of mercury on walls, the annual outflow of thermostats available for recovery and recycling, and recommendations for legislative goal-setting for mercury recovery.

SERA saw an opportunity to undertake some tangential research at our own cost, on the uptake, turnover, and residential energy savings potential, and the program and policy implications. The study would allow us to estimate the potential energy savings in this market, which could determine the priority of thermostat measure incentive or replacement programs.

Another reason for our energy-related tangential work was to pilot test a non-standard method of developing estimates of the thermostat service lifetimes used in assigning energy savings from thermostat-related energy efficiency programs. Across-the-board, lifetimes for energy efficiency measures have not been updated very regularly, and most are more than 20 years old. Statistical studies have been scarce, perhaps because traditional studies take a long time. Traditional studies track failures of measures installed by a program in one or two program years – and waiting for sufficient failures to identify the decay function. This can mean waiting 7-9 or more years after installation, and tracking failures one or more times in the interim – a potentially expensive study. This project tested the feasibility of estimating measure lifetimes by tracking failures of measures installed over a longer period of time. Using after-the-fact data from participants over many years may eliminate the need for multi-year tracking; however it requires greater recall on the part of households than does the traditional study. We were concerned about recall and home tenure issues; this test of methods was partly to see if the recall could be good enough to support this type of measure lifetime work. We took an extreme case – asking about measures that could have been

[20] Note the authors conducted a parallel study of thermostats in commercial buildings.

installed decades ago, and seeing if the recalled data on failures and ages could provide sufficient failures to provide a sensible estimate.[21] The study was successful in supporting development of a lifetime estimates for traditional thermostats. We are in the process of developing lifetime estimates for digital models. This is not to say that the traditional real-time study method might not have advantages (being less dependent on recall), but given that these measure life studies are not being conducted, our approach may provide an inexpensive alternative for certain types of measures:

- those that are singular and easily recalled (e.g. thermostats, water heaters, furnaces, etc., but not light bulbs);
- those that have been installed over a period of time (not the latest high tech heat pump model);
- those with long lifetimes, for which the near-term failure rates would be expected to be too low to “identify” the function quickly.

Methodology Options from the Literature

To conduct the work, we needed data on the number of thermostats, the types, ages, and other information. A core element is a count of existing thermostats on walls. Before starting the research, we reviewed the existing literature on estimating thermostats[22] in buildings, and assessed the main advantages and disadvantages (Figure 3.1).

- **Rule of Thumb Method:** This method computes an average of the number of thermostats per household that have been previously published, and applying those to the states included in our studies. An example includes a study by NEWMOA (2001)[2].
- **On-site Data Collection**: Auditors could be sent to a statistically-selected sample of homes to count the number and type of thermostats on walls in a sample of homes (single-family and multi-family). A study conducting this work in the business sector[23] is represented by King County (2005) [4]
- **Contractor / Stakeholder Interviews or Tracking**: Contractors could be asked to count and track the removal of thermostats by type and month, and provide the data to researchers. See studies by PSI (2010), [3] for ACCA and PHCC. .
- **Stock Turnover**: Using national sales data, a statistical stock turnover model can be developed to estimate measure purchase, extract new vs. replacement, and estimate counts and lifetimes. See Welch & Rodgers (ACEEE 2010).[7]

[21] If a similar approach is used to study cohorts of homeowners that received measures over multiple program years, that study will have an advantage – the installation years will generally be known. Our project was a much harder case, and was exploratory.

[22] and particularly mercury thermostats, given the genesis of the study

[23] Recall that our underlying initial studies included both residential and commercial thermostats.

Method	Advantages	Disadvantages
Rule of Thumb / Use Available Estimates	Simple, inexpensive	Uncertain study accuracy Few studies Doesn't reflect potentially-significant variations by state or sub-sector (SF and MF)
On-site data collection	Accurate, verified	Expensive to achieve statistical sample Especially expensive to achieve accuracy at a widespread state level (travel costs)
Contractor Data collection	Involves relevant experts Gathers data from entities involved in replacement process Gathers data from fewer entities than households	Several pilot tests and studies indicate response rates are very poor, even if encouraged by their industry association[24] Responses are potentially biased Expensive to gain responses
Statistical stock turnover	Uses existing data Statistical, defensible	Large measure categories, not only including energy efficient measures Can be difficult to sort out by state

Figure 3.1: Advantages and Disadvantages of Methods for Estimating Counts of Thermostats in Buildings

One or more of these methods may be appropriate for estimating counts of some measure types, but none were well-suited for application to thermostats. Furthermore, none would address the range of other data needs for this project – the types of thermostats, and data on ages and lifetimes (and for the initial client, the number of thermostats that would contain mercury). The methods we developed for each step of this project are outlined briefly below.

SERA Research Approach: Summary of Occupant Survey & Analysis Method

SERA developed an "Occupant Survey & Analysis" methodology tailored for this assignment. We initially developed and tested the approach in 2009 for a legislative mercury thermostat study required by the State of California (Skumatz, 2009).[5] The approach was deemed successful by the State, and was directly used to set statewide goals for thermostat legislation. When we conducted the work for additional states (starting in 2013, including [6]), we implemented several enhancements, but the underlying method did not change substantially.

The core of the method was a detailed web survey, asking the array of questions necessary to support our statistical analysis work. Without this survey, we might have had to use data from an array of sources, none of which would be perfectly compatible, and might require after-the-fact *ad hoc* translations and assumptions. We decided a consistent data source – even though it would mean a long survey -- would be easiest and most consistent for our analytical purposes.

The data collection and analysis steps are described below. All steps of this methodology are displayed in Figure 4.1.

[24] This confirms the difficulties found in very expensive studies in the 1990s in California that worked with retail stores for years to try to track sales of energy efficient equipment including refrigerators, hot water heaters, and other measures.

Methodology Step	SERA Technique
Survey Instrument	Web survey (surveymonkey.com). A web version was needed because we needed to be able to show pictures of thermostat types.
Questionnaire Content	Thermostat counts, types[25], ages, replacement patterns, satisfaction information, demographics. Demographic questions mirrored census questions for comparison purposes.
Sampling	Purchased random samples[26] for two separate sectors (SF & MF), with data to be weighted based on their ratio within the underlying population; included oversampling for MF because of poorer response rates. Goals of 386 responses for each subsector.
Soliciting Responses	Postcard and phone outreach (SF & MF), and offered raffle prize. Initial postcards provided survey link and toll-free phone number. Then mailed second round of postcards to a sample of non-respondents after 2-4 weeks. Followed up with phone outreach in cases (state, sub-sector) for which the responses were too low. A Spanish sentence on the postcard gave a phone number and we conducted an abbreviated version of the survey in Spanish, limited to core questions.
Validation Work on survey count & types – On-site	Selected a sample of respondents, geographically clustered, sampling to include a variety of thermostats but oversampling on non-digital models. Sent trained staff / technicians to the selected participant homes to 1) re-count / verify number of thermostats, 2) verify types of thermostats, and 3) open thermostats to inspect to see if the thermostat contained mercury.[27] Data were used to help develop correction factors for the survey responses regarding thermostat counts and types, and as the basis for estimating the percent of different types of thermostats that contained mercury.
Validation of survey counts & types & mercury content – Participants	Selected a sample of respondents randomly across the state, asking them to photograph each thermostat in their home with their cell phone[28] and email it to our offices. Each of these verification respondents was provided with a Starbucks Gift Certificate. These responses were used to help develop correction factors for the survey responses on thermostat counts and types.
Weighting and Bias Mitigation	The responses were weighted by sampling criteria and the demographic data (primarily age of head of household and county) were compared to census. If significant deviations were found, the sample weights were adjusted accordingly.
Later Follow-Up Survey	Email/Phone survey of sample of respondents to confirm initial results, and obtain updated information on deaths/removals, ask about interim replacements with new (WE) thermostat models, and ask about satisfaction and usage. Used for energy–related analyses.
Analysis	Organize and clean data; estimate average number of existing thermostats and percentages by type, applying the correction factors dictated by the validation work. Code ages of thermostats in homes by types. Code dates of removals / replacements by types and prepare the censored database for analysis of lifetimes using 'hazard functions' and comparing results by distribution type; Weibull-based models generally performed best. Used results to estimate median measure lifetimes. Applied entire measure life function, which maps percent of thermostats removed/failing to function at each thermostat age, along with the counts of cohorts of thermostat ages to compute annual outflows of estimates of thermostats under "natural market" outflow conditions.[29]
Results	Estimated average thermostats per SF and MF household; computed total thermostats in the states by type (and estimated number containing mercury). Estimated annual natural market turnover and thermostats available for replacement under "baseline" conditions. Developed estimates of mercury on walls, and applied data on potential savings of WE thermostats over traditional models to estimate savings potential. Conducted policy-related analyses

[25] Information on the "types" of thermostats we asked about are presented in a later section of this paper.
[26] Purchased from InfoUSA, a well-known vendor.
[27] For liability purposes, no survey respondents were asked to open thermostats
[28] In fact, one of the main changes in methodology was the fact that the earlier California study used disposable cameras, sent out and returned to our office, because cell phone cameras were not yet prevalent!
[29] Additional steps were needed to identify the mercury-related conclusions, including assigning mercury percentages by type and age cohort, and computing annual outflows with a focus on thermostats containing mercury.

Methodology Step	SERA Technique
	regarding program potential for energy-efficient measures.

Figure 4.1: Description of SERA 'Occupant Survey and Analysis' Steps

Major Types of Thermostats

Thermostat types and technologies have changed many times, and our study includes examples of nearly all types that have been manufactured over the decades. The types were initially important because only certain types have the potential to include mercury. However, the categorization also came in handy for the energy-related re-analysis because it allowed us to examine the percent of models that were, essentially, pre-programmable / old mechanical types, programmable types, and smart / wifi-enabled (WE) types. WE. The thermostat types households were asked to identify are shown below;

Wi-Fi Enabled: Wi-Fi Enabled (WE) Thermostats are unique in their ability to connect to the internet for both sending and receiving data. The sending and receiving of data allows these 'smart' devices to learn a user's behavior in order to optimize their heating and cooling regimen offering the potential to save energy and money. These measures typically have an associated mobile app or computer program that can be used to alter a home's climate control or to visualize and compare energy use. Some of most common brands identified by SERA's research (in our study areas) were Nest, Ecobee, Honeywell, and Sensi. See Figure 5.1 for illustrations.

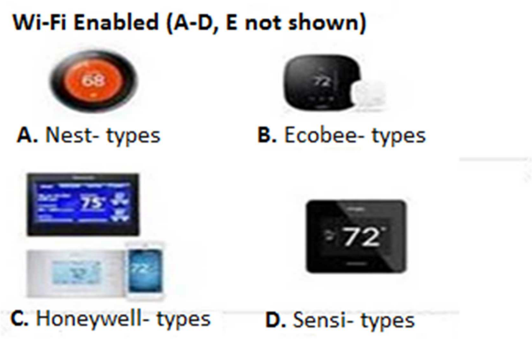

Figure 5.1: Communicating Thermostats

NON Wi-Fi Enabled Digitals: The Digital, but non-WE, thermostat category includes thermostats that have at the bare minimum a small digital display. These devices cannot connect to the internet in order to send or receive data, but some can be programmed using the controls on the measure itself. This category was split into two groups: programmable thermostats and non-programmable thermostats. See Figure 5.2 for illustrations.

Figure 5.2: NON-WE Digital Thermostats

NON-Programmable (Digital / Mechanical): The last category of thermostats is also the oldest. The Non-Digital group is composed of the many different types of thermostats developed before the integration of consumer electronics. These measures have NO digital technology whatsoever and certain models rely on hazardous mercury for measuring the air temperature.[30] The major model types SERA identified and separated for the Non-Digital thermostat category were: Rectangular/Square, Round, Small SNAP, and Pneumatic (found mostly in large commercial spaces). See Figure 5.3 for illustrations.

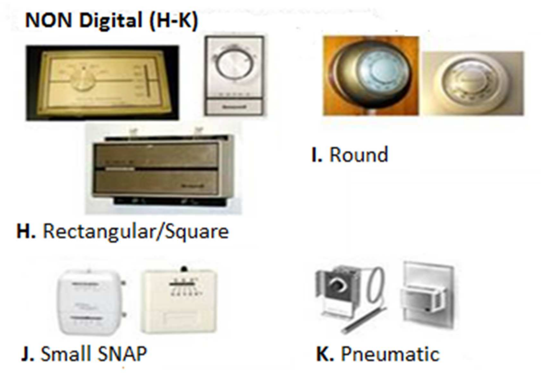

Figure 5.3: Non-Digital / Mechanical Thermostats

Study Results

The study provided an array of component results, culminating in estimates of savings and related policy implications. Figure 6.1 illustrates the steps.

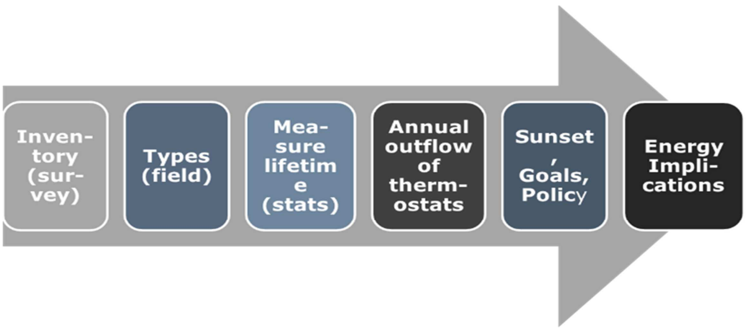

Figure 6.1: Study Outputs

Number of Residential Thermostats: The average number of thermostats in the different states varied from a low of 1.15 per residential household (in Illinois) to a high of 2.08 per household in Maine. As a consequence, the total estimated number of thermostats on walls in the states are shown in Figure 6.5.

Distribution of Residential Thermostat Types: On average, about half the thermostats are digital or wifi-enabled in the states studied. The data for the distribution of thermostats by type in California is not presented because this study was conducted too early types to be comparable. Among the four states presented, the penetration of digitals and WE is lowest in Rhode Island (a little less than 40%) and greatest in Illinois (more than 60%). Figure 6.2 shows SF thermostat composition by type for each state. The cool colors (purple, blue, green) at the bottom of each bar are the relatively more efficient digital model types, purple being the most efficient WE group. The hot colors (yellow, orange, reds) on top of each bar are non-digital, less energy-efficient models that are most 'ready' for upgrades.

[30] Specifically, a large majority of the older round models, and a small percent of the SNAP types.

In each state except Illinois, where the penetration in both sectors is highest, the penetration of non-mechanical thermostats in MF homes is lower – as low as about 25% in Maine and Rhode Island. See Figure 6.3 for the breakdown by thermostat types in MF homes.

Differences between the states in their percentages by type are due to variations in industry standards at the time the homes were constructed (which varies by state), the aggressiveness of utility companies in their thermostat (and HVAC) replacement and incentive programs, and to some degree, the advertising by thermostat manufacturers to upgrade. Higher penetrations of newer type thermostats in SF homes may be driven by utility programs, and homeowner computations of savings they may achieve. We assume that the lower MF numbers indicate that owners are put off by costs for replacement of multiple units, and will also be influenced by the share of heating bills paid by the occupants (e.g. baseboard, wall units, etc.) vs. by the building owner (central boilers, etc.).[31] Utility programs may also not have focused as aggressively on this sector.

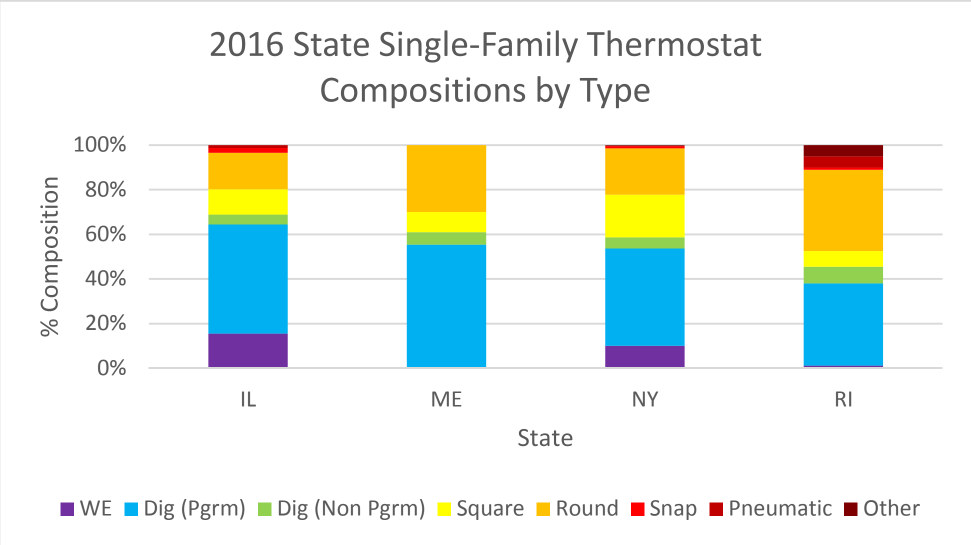

Figure 6.2: Single-Family Home Thermostat Composition by Type and by State
Source: SERA Research

[31] These HVAC system questions were not asked in the survey.

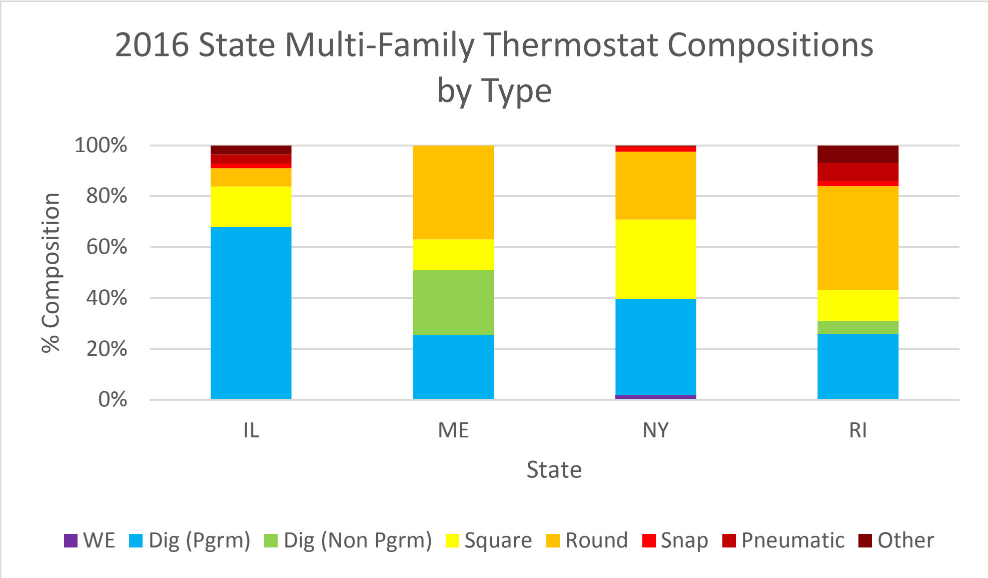

Figure 6.3: Multi-Family Home Thermostat Composition by Type and by State
Source: SERA Research

Measure Lifetime for Non-Digital Thermostats: The data used for measure lifetime computations includes two groups: the age of the existing *in-situ* thermostat and the service life of the previous thermostat. The estimation technique combines information for both groups, and it is called censored data, because the total years the existing thermostat will be on the walls before failure is not (yet) known; however the statistical method allows the censored data to add to the analysis. The median lifetimes for non-digital models was estimated to be about 25-32 years for the various states.[32] A typical lifetime curve is presented as Figure 6.4. This lifetime estimate may be longer than commonly published in lifetime tables for digital models, as most readers will be more familiar with the utility tables of accepted lifetimes for digital models. The author conducted a literature search for studies identifying lifetimes for non-digital models.[33] The results presented in this paper are consistent with the values presented in tense non-statistical reports covering older models.

Certainly, the estimate may suffer from the fact that it is based on recall data collected via survey; in addition, some data were not available when occupants did not live in the home at replacement time. However, the actual lifetime figure is difficult to determine, because most lifetime values energy efficiency experts would be familiar with would be for newer, energy efficient digital models, and this number is based on lifetimes of non-digital models. If the number is biased upward, however, then we know we are being conservative about the natural outflow of thermostats annually, and the natural outflows might be somewhat faster than estimated in Figure 6.5.

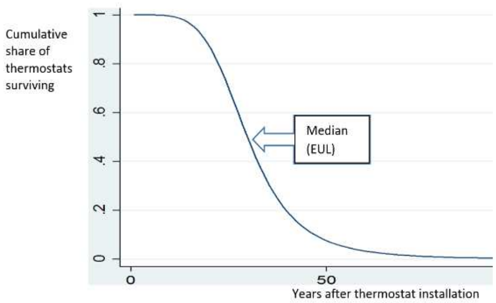

Figure 6.4: Non-Digital Thermostat Lifetime Curve, Estimated

Estimated Annual Outflows of Thermostats: Combining information from the measure lifetime curve and the age cohorts of non-digital (mechanical) thermostats still on the walls, we estimate approximate "market-based" annual outflows of thermostats –indicating the number of thermostats that would easily be available for replacement with new, more efficient wifi-enabled (or programmable) models. These estimates are included in Figure 6.5.

Savings Potential from Replacement of Non-Digital Thermostats: We examined the web for estimates of savings from new Wifi-enabled thermostats.[34] Manufacturer literature provided numbers on the order of 585 kWh/yr per home for electricity (labeled as 17.5% of HVAC use), and 56 therms/yr per home, portrayed as 9.6% of HVAC). A review of non-industry national sources, and discussions with various experts in the field indicated that a figure closer to 8-10% of HVAC savings may be more realistic. To keep our estimates more conservative, we used these lower estimates (about 290 kWh and 30 therms per thermostat) in our calculations in Figure 6.5. We applied this estimate to all the residential non-digital thermostats we estimated for each state to compute the total potential, regardless of timing of replacement.[35]

[32] Note that multiple survey respondents stated they had replaced their HVAC system several times but requested that it should be wired into the same thermostat; they liked the familiarity and they "knew how to use it". This was not an uncommon response among phone interviewees (who, of course, tended to be older).

[33] These studies were generally non-statistical and based on interviews, and were often non-specially-defined "typical lifespans" (if there were statistical estimates we might not have needed to conduct our study). The lifespans cited for these older model types are typically 20-40 years, with the most common values in the 30-35 year range. See Appendix F, Skumatz New York Study [6].

[34] Note, this study is not at all focused on how these thermostats save energy. We are only interested in estimating the potential that the saturation of older models represents as an energy saving opportunity.

[35] Obviously there are baseline issues in counting the savings attributable to any program. This calculation provides the estimates if all the thermostats were installed immediately, and does apply a lifetime – it is annual savings. The user may determine how many years should be counted toward early replacement or other issues. That was not the

Policy / Program Implications: There are said to be substantial savings available from replacing existing non-digital thermostats in homes and apartments with smart thermostat. Only a small share of those savings will be achieved in the near term if utilities do not undertake incentive programs for early replacement. Under "natural replacement" outflows, only about 30% of the total achievable savings would be realized in the next 10 years. Given the direction for lighting, thermostat replacements might be a target measure, as it doesn't require the cost or disruption associated with replacement of the HVAC system.

We note that these are not the total savings available.

- First, our follow-up interviews indicate that perhaps 30% (and perhaps as many as 50%) of households with digital thermostats do not use the programmable features. Therefore, replacement of a significant share of traditional programmables with new WE models might achieve savings levels similar to those achieved relative to non-programmable mechanical models.
- Second, this paper does not include the results and savings potential for commercial thermostats.

Residential Thermostats - Estimates (All units in thousands unless otherwise noted). Excludes Commercial Thermostats	IL	ME	NY	RI	CA*	National Est (based on simple weighted average)
Average Thermostats per HH (number)	1.15	2.08	1.23	1.23	1.17	1.20
Population	12,900	1,328	19,651	1,051	38,000	321,400
Total Residential Thermostats on Walls	5,700	1,100	9,300	500	17,100	148,300
Estimated Non-Digital Thermostats - Residential	2,200	600	4,900	300	6,700	64,000
Median Thermostat Age, Non-Digital T-Stats (Years)	30	28	26	28		
Annual Outflows Non-Digital T-Stats 2015-2024	80	20	100	10	180	1680
Annual Outflows Non-Digital T-Stats 2025-2034	50	10	140	10	180	1680
Annual Outflows Non-Digital T-Stats2035-2044	40	10	140	0	160	1520
Annual Outflows Non-Digital T-Stats 2045-2054	10	10	60	0	70	640
Percent Outflow 2015-2024	36%	33%	20%	33%	27%	26%
MWh/yr Savings Available if all residential non-digitals replaced (assume 290 kWh savings / thermostat); 1 relevant Thermostat per home	554,800	83,700	1,155,300	70,700	1,660,700	15,465,800
Therms of Gas Savings if 25 Therms/Thermostat	47,800	7,200	99,600	6,100	143,200	1,333,300
Table Note: (*) California numbers uses approximate updates of the older data gathered in this study.						

Figure 6.5: Summary of Results for Residential Thermostat Counts and Savings Potential

The remainder of this paper provides the information we gathered on WE thermostat satisfaction and gathered in our follow-up survey.

purpose of this study. There are also nuances in the computations based on whether the model being replaced is an old non-programmable model, or programmable model, and whether the programmable model's programmable features are being used. We used the most conservative assumptions, excluding all programmables from this "savings potential" computation. Later we note that substantial savings may also be obtained from some programmable digitals because a substantial number of households never use the programmable features.

Focus on Wi-Fi Enabled (WE) Thermostats: Follow-up Survey Results

The follow-up survey focused on WE thermostats, gathering information on market adoption, , reasons for installing these measures, customer satisfaction, impact on utility bill, and some qualitative consumer feedback. California was not included in the follow-up survey.

Growth in Market Adoption: The market adoption of WE thermostats has been occurring only recently. SERA began this study in California in 2009, then added Illinois, Maine, New York, and Rhode Island to the study area in 2013-early 2015. The follow-up survey was conducted in late 2016, and indicated that about 71% of households with WE thermostats installed them in 2016, 14% in 2015, and 14% in 2014. The survey indicated that the adoption was higher in Illinois and New York than in the other states. Note that some of the respondents in Illinois specifically mentioned rebate programs from ComEd (Illinois), and others mentioned rebates at DIY stores. Individuals with WE measures considered themselves early adopters and many referred to themselves as “techies” on the survey.

The survey found that three brands dominated the market. In our survey, Honeywell’s percent exceeded 40% of the WE thermostats in place; Ecobee and Nest each had about 30%.

Reasons for Installing: Nearly half the respondents reported the reason for installing a WE thermostat was their relative ease of use and increased control compared to their non-WE alternatives. About a quarter chose the WE model because it came with an upgraded HVAC system or it was required for some other type of home installation. About one-fifth installed the WE model because the old thermostat broke or simply didn’t work well. Fewer than 10% stated they were incentivized to install a WE thermostat through some kind of energy program or rebate. This last response may indicate a significant opportunity for increased utility and stakeholder program activity.

Customer Satisfaction: WE owners were very satisfied with their new thermostats; every respondent was either very or somewhat satisfied, and the average satisfaction was 1.3 out of 5 (1 = Very Satisfied, 5 = Very Unsatisfied).

Impact on Utility Bill: Given the short time the WE equipment has been in place, most respondents stated it was simply too soon to be able to confirm whether or not they had been able to save money on their utility by switching to a WE thermostat. However, just under one third of respondents who reported upgrading to a WE thermostat AND had been using it long enough to comment on its impact reported saving money on their utility bill. In addition, there were many WE thermostat owners who did not know if they had saved at all on bills, but reported that ‘they feel like they’re saving money’ and that makes them feel good. The WE thermostats appear to support the ‘feel good’ effect associate with many energy-efficient or other eco-friendly measures.

Likes and Dislikes about WE Thermostats: For the most part, respondents said they enjoy the mobile functionality, which allows them to alter their home temperature from anywhere, and they noted the adaptive ability as well. Other respondents liked how their thermostat mobile app integrated with other home control apps, like home security systems. Some of these integrations include additional sensors to be placed throughout a home that pick-up differences between rooms or indoor vs outdoor conditions, and others offer the same service for multiple properties. Another interesting integration that was reported was the ability to connect a WE thermostat and a home entertainment in order to voice adjust temperature settings. Multi-functionality and integration with other home systems seem to be the most-praised features by consumers.

The main complaint received about WE thermostats was “the app is not perfect” or the app interface is too confusing. In some cases, respondents stated frustration with the inability to integrate their thermostat with other ‘smart’ devices (i.e. smart refrigerator, other appliances). This is a fairly vague complaint, but it should be kept in mind that many thermostat owners have little to no technical expertise and are intimidated by ‘High-Tech’ devices.

Summary & Conclusions

SERA was able to successfully determine the distribution of thermostats by type on residential walls for the five states studied. We were able to demonstrate an approach that may be a useful tool as a back-up for computing measure lifetimes.[36] The results indicate that old, energy-inefficient, mechanical thermostat models tend to have long lifetimes, typically in the high-20 to low-30 year range. The correction factors estimated by SERA validation work were fairly small for the "count" and "type" data, indicating the methodology developed by SERA worked fairly well for a low-cost, accessible approach. Note that this approach may also be applicable to measures beyond just thermostats.

Most importantly, the results show that there are a substantial number of older thermostats on walls – thermostats that could bring significant energy savings if they were replaced with models with programming capabilities, and even greater savings if they had wifi or other communications capabilities.

If the replacement with upgraded models is left to the rate of natural replacement it is possible only 30 percent of the potential savings would be achieved within 10 years – even if contractors and residents replaced 100% of retiring thermostats with higher-functioning models. There is substantial opportunity for utilities and stakeholders to intervene (programs and incentives) and achieve energy savings with far less disruption than would occur with HVAC equipment replacement or other retrofits. To achieve this it would be necessary to move the customer base for WE models beyond early adopter and 'techee' consumers. It may be that thermostats should be one of the next program priorities, especially given the reduced ability for utilities to rely on lighting (CFL and LED) programs as the core of residential programs.

[36] For thermostats and potentially other equipment that is singular, easily identified, and has other features amenable to this type of identification, recall, and analysis (e.g. water heaters, furnaces, etc.).

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A Luke-Warm Reception: Why Consumers Aren't Hot for Smart Thermostats

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Abstract

Technological advances have led to new offerings in home heating systems and to a market that is becoming saturated with variants of "smart" thermostats. But does this seemingly growing market have a growing audience? This paper presents quantitative and qualitative data from a large scale survey (N=1007) that investigates the appeal of smart thermostats to prospective consumers in the United Kingdom. Findings from the survey indicate confusion about what "smart" means and a general apathy towards smart thermostats. Survey respondents expressed resistance to the idea of "technology for technology's sake" and were reluctant to pay for something they failed to see the benefit of. Given this luke-warm reception, the paper proposes marketing strategies that may prove effective in bolstering the allure of smart thermostats.

Introduction

The worldwide roll out of smart meters represents a window of opportunity for new offerings in smart energy products that can further enhance consumer choice and control [1]. Indeed, the "strong growth" of the home energy management sector is one of the anticipated benefits noted by the UK government in their initial business case for the mandated smart meter roll out [2]. However, for this benefit to be realized, product demand must match product development. Yet, it's unclear whether consumers have appetite for these smart energy technologies. In this paper, survey data is presented that examines consumers' responses to one product that is increasingly prevalent in the "smart energy arena" – the smart thermostat. In particular, this paper focuses on consumers understanding of smart thermostats and their appraisals of "smart" as a concept and the drivers and barrier that may influence smart thermostat adoption.

Smart thermostats: A lucrative market?

A smart thermostat is a digital programmable heating system controller with internet connectivity that, among other functions[37], enables end-users to adjust their heating remotely. They are widely anticipated to be *the next big thing*. Indeed, over the last 5 or so years, the market place has seen an increase in smart thermostat offerings with contenders such as Honeywell, Nest, and Tado all competing for a share of the lucrative global market, anticipated to be worth $4.4 billion globally by 2025 [3]. Despite these promising forecasts, uptake appears to have been relatively slow with 1.4 million homes across Europe owning a smart thermostat [4]. Similarly, in the UK one of the largest energy providers has sold its own brand of smart thermostat to 2.6% of its 14 million customers over the past 4 years. This seems a small uptake given that British Gas' brand of smart thermostat (the Hive) is widely recognized as a strong contender in the British market place [5]. This disparity between forecasted growth and uptake is further mirrored in the commentary surrounding smart thermostats, with observations that smart thermostats are "the latest trend in home heating" [6] but "lack the instant appeal of Instagram" [7] and are seen as "an unsexy consumer technology" [8]. All of this suggests that smart thermostats have failed to cross the technological chasm and lure in those beyond the early adopters.

Existing research: what do we already know about the appeal of smart thermostats?

Current research examining the direct appeal of smart thermostats to consumers is fairly sparse, with much of the academic literature focusing more generally on consumers' responses to smart home technologies [e.g., 9,10,11]. However, some initial insights into the drivers and barriers are revealed by the market research agency Navigant who report that that while awareness of prospective benefits of smart thermostats is growing among tech enthusiasts and early adopters,

[37] E.g., 'learning' heating patterns to optimize pre-heating and zoning, responding to dynamic energy prices changes etc. Remote adjustment may be the valuable function.

many consumers are ill informed or simply not motivated enough to part with the cash needed to purchase a smart thermostat [1].

Further insights are yielded by Ahn, Kang, and Hustvedt [12] who examined several factors theorized to explain intentions to adopt sustainable household technology. They found that US participants' intentions to adopt the smart thermostat "iControl" were predicted by compatibility expectations (i.e, perceptions that the product would fit with their existing heating and cooling systems), performance expectations (i.e., that it would help increase their productivity around the home) and hedonic expectations (i.e., that it would be fun and enjoyable to use). In addition, the extent to which consumers reported a keenness for being amongst the first of their friends to adopt sustainable products also emerged as a significant predictor.

The present research: exploring consumer's readiness to adopt smart thermostats

There appear to be only a few research papers that directly address consumer receptivity to smart thermostats. Yet such knowledge appears important to acquire given the anticipated market growth of this product and may prove fruitful in helping understand how to market smart thermostats to prospective end-users. Given this, the present research reported below sought to examine the extent to which smart thermostats may appeal to prospective end-users.

Method

A survey was developed to ascertain a better understanding of the extent to which smart thermostats may appeal to prospective end-users. It targeted prospective end-users to gather both quantitative data to gauge levels of interest in smart thermostats and their features, but also qualitative data to ascertain the perceived barriers and drivers to smart thermostat adoption. Questions focused on ascertaining consumers understanding of smart thermostats; attitudes towards the concept of "smart"; the appeal of different smart thermostat features; and willingness to adopt a smart thermostat.

Data collection

Data was collected during October 2016 using the market research company Survey Sampling International (SSI) who have readily available access to a large respondent panel that have previously agreed to participate in online surveys in return for incentives (e.g., points which can be converted to vouchers for Amazon, PayPal, iTunes etc). SSI recruited a sample of over 1000 respondents with the following specified characteristics: They had to be (i) homeowners (ii) in the UK (iii) over the age of 18 (iv) whose household had a central heating system that could be controlled by a thermostat (V) not currently own a smart thermostat.

Sample

A total of 1007 respondents completed the online survey. Details of their characteristics, including gender age, and annual household income are displayed below.

Table 1: Sample Characteristics

Characteristics	Category	Percentage of Sample
Gender	Female	45.6%
	Male	55.3%
	Transgender	.1%
Respondent Age	Under 35	12.2%
	35 – 44	19.9%

	45 – 54	35.1%
	54 – 64	31.7%
	Over 65	.2%
Characteristics	**Category**	**Percentage of Sample**
Annual Household Income	Under £30,000	37.5%
	£30,000 to £49,999	30.1%
	£50,000 to £74,999	15.5%
	Over £75,000	8.9%
	Prefer not to say	7.9%

Survey Measures [continues]

Consumer understanding of smart thermostats

Respondents provided qualitative responses to the question "What does smart thermostat mean to you?"

Appeal of "smart" as a concept

Respondents were asked to "select the response that best describes how you feel towards the term "smart" (e.g., smart thermostat, smart tv , smart home)". The responses ranged from 1 ("Extremely negative") to 5 ("Extremely positive").

Appeal of smart thermostat features

Respondents were asked to indicate to what extent each smart thermostat feature appealed to them using a 7-point scale ranging from 1 ("Strongly unappealing") to 7 ("Strongly appealing"). Each smart thermostat feature was accompanied by a brief description. The smart thermostat features presented to participants were as follows:

> Remote Control; adjust your heating from your mobile, tablet, or laptop.
>
> Advanced Scheduling; more flexibility to program your heating to suit your home's routine.
>
> Portable; now you can move your thermostat around the house with you. Allows you to monitor your room's temperature and adjust it instantly.
>
> Integrated Heating & Hot Water Controls; switch your hot water on and off from a display inside your home and/or using your phone.
>
> Welcome Home; schedule your lights to come on when you arrive home.
>
> Multi-User - Multiple householders can use a smart phone app to control the heating. An activity feed will detail the changes made by users.
>
> Monthly Summary; personalized summary of your smart thermostat usage (i.e., energy usage for heating)
>
> In-app Notifications; alerts that appear inside the app and as a badge on the app icon when it's not in use
>
> Pipe Protection – prevents your pipes from freezing[38].

[38] Although this tends to be a standard feature in older or "dumb" thermostats it is marketed as a feature by some smart thermostat producers.

Self-Learning – the system learns your home's schedule and sets the heating accordingly.

Location Based Control – uses geo-tracking in occupant's phones to turn the heating off when the last person leaves and on again when the first person returns.

Zonal Heating – heat only the rooms you are using.

Willingness to adopt a smart thermostat

Participants were presented with an image and a basic description of a smart thermostat which they were asked to read carefully before continuing with the survey. To avoid participants responses being influenced by branding or prior product knowledge – a less well-known smart thermostat was selected that has been developed by a local small-medium sized enterprise and is referred to as "Cosy" (see appendix).

Following this presentation, participants were asked to indicate their agreement/disagreement with the following statement: "I would like this product in my home" using a 7 point scale ranging from 1("Strongly disagree) to 7 (strongly agree). After participants had responded to this question, qualitative data was elicited by asking participants to explain why they would like/would not like to have it in their home.

Data Analysis

Notably the survey resulted in both quantitative and qualitative response. Where qualitative responses were collected they were analyzed using the process of thematic analysis in which the analyst[39] (1) familiarizes themselves with the data, (2) codes it, (3) generates initial themes, (4) reviews these themes and (5) defines and names them (Braun & Clarke, 2006). An inductive approach was taken whereby the themes identified were strongly linked to the data. Hence, themes were largely identified at the semantic level.

Results

The following results are reported in the order in which participant's responded to measures.

Consumer understanding of smart thermostats

To investigate consumers' awareness of smart thermostats, participants were asked "What does the term smart thermostat mean to you?" The emerging categorizations are provided in Table 2. The wide-ranging responses given to this question are indicative of the divergence of knowledge that consumers have about smart thermostats. Just under a third of respondents (29%) admitted they were unsure or didn't know, while others simply described the features of a regular thermostat or erroneously confused the capabilities of smart thermostats with the capabilities of smart meters and/or in-home-displays (i.e., energy feedback).

Where consumers did appear to have some knowledge, their explanations of smart thermostats tended to emphasize the various features and capabilities of smart thermostats, most prominently 35% reported that smart thermostats would enable them to control their heating remotely or via their smart phone, while other respondents emphasized different features including automation/self-learning (6.75%), internet connectivity (4.97%), and enhanced programming capabilities (2.18%). These different emphases likely reflect participant's exposure to existing advertising of smart thermostats.

Table 2: What does "smart thermostat" mean to consumers? Categorization of responses.

[39] In this case the author of this paper.

Category	Example of participant response within category	Category frequency
Remote/smart phone control	*"One you can program away from the home"* *"Controllable by your smart phone"*	34.7%
Unsure	*"Bugger all" "Nothing" "I am unsure" "Don't know" "No idea"*	29%
Confusion of smart thermostat with smart meter and/or in home displays	*"Smart meter, you can easily see what you have used"* *"Display that shows you your energy use in real time and how much it costs"*	7.5%
Learning/Automation	*"It changes the temperature itself"* *"A thermostat that learns your patterns and automates some of your heating"*	6.7%
Internet/Wi-Fi control	*"It is connected through the internet"* *"Use wif-fi to control heating"* *"It can be controlled over the internet"*	5%
Control/Heating/Efficiency	*"Gives you more control of heating system"* *"Always in control" "Efficiency and control"* *"Makes life easier"*	4.8%
Describe thermostat	*"Turns heating on when the temperature lowers"* *"Senses the temperature in the room and adjusts accordingly"*	4.6%
Negative response	*"Nothing but more trouble"* *"I don't care either way - fed up with "smart" everything"*	2.3%
Programmable	*"Thermostat that can be programmed from outside the home"* *"Can be programmed to change heating levels whenever needed using a smartphone"*	2.2%
Money/Energy Saving	*"When it says smart – saves you money, I guess"* *"Controls your heating and helps to save you money"* *"Energy saving"*	1.6%
Misc (Positive, electronic/technical, branded product)	*"Sounds good" "Something technical" "like Nest"*	1.7%

The appeal of "smart"

Participants responses towards the term smart are best characterized as weakly positive or "luke-warm", with the largest proportion of respondents (48.6%), reporting that they felt neither positive/nor negative towards the term "smart" and the second largest proportion of respondents (31.1%) feeling somewhat positive towards it.

Table 3: Feelings towards "smart"

Which of these best describes how you feel towards the term smart (e.g., smart thermostat, smart home, smart TV)?	
Response options	**Percentage of sample**
Extremely positive	9.7
Somewhat positive	31.1
Neither positive nor negative	48.6
Somewhat negative	6.9
Extremely negative	3.8

The appeal of different smart thermostat features

This "luke-warm" response to smart thermostats continued to present itself in participant's responses to the appeal of different smart thermostat features (see figure 1, below) with "somewhat appeal" and "neither appealing nor unappealing" featuring as the predominant responses given by participants. Part of the reason for this may be because while brief explanations were provided about each of these features, it is probably difficult to report on their appeal to a group which has not experienced them. Nonetheless, the results provide an indication of the most and least appealing features of smart thermostats.

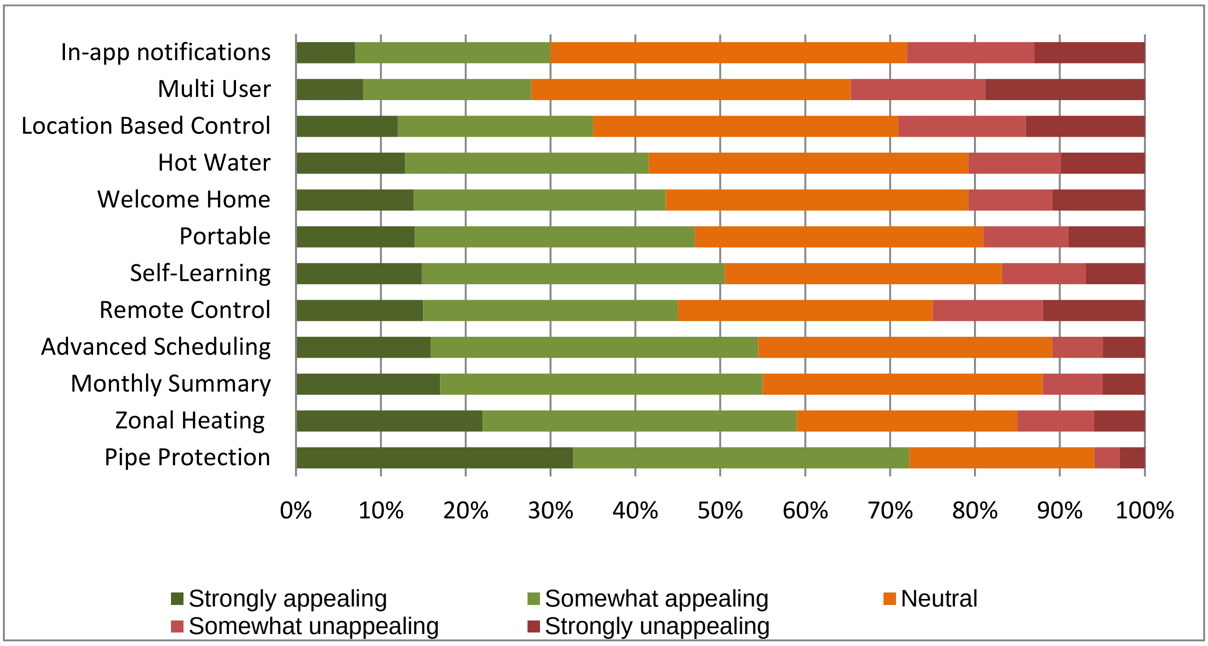

Figure 1: Reported appeal of different smart thermostat features

The features considered most appealing (i.e., those rated by over 50% of the sample as either somewhat or very appealing) were: Pipe protection, Zonal heating, Monthly summary, Advanced Scheduling, Self-learning.

The features considered most unappealing (i.e, those rated as either somewhat or strongly unappealing by 25% or more of the sample) were multi-user, location-based control, in-app notifications and remote control.

There is some indication in the preferences expressed for different smart thermostat features that prospective consumers find less technologically advanced features to be more appealing (e.g., 73% reported pipe protection was appealing compared to 35% that reported location based control was appealing). Indeed, the features that mostly strongly appealed to participants tend to already be available as standard functions in most new high end thermostats.

Consumer willingness to adopt the smart thermostat "Cosy"

As indicated in the figure 2, demand for the smart thermostat "Cosy" was somewhat lackluster with just 19% agreeing that they would like the product in their home. Approximately half of those surveyed (55%) said they would *not* like to have the product in their home, while just over a quarter (26%) of respondents had no opinion either way.

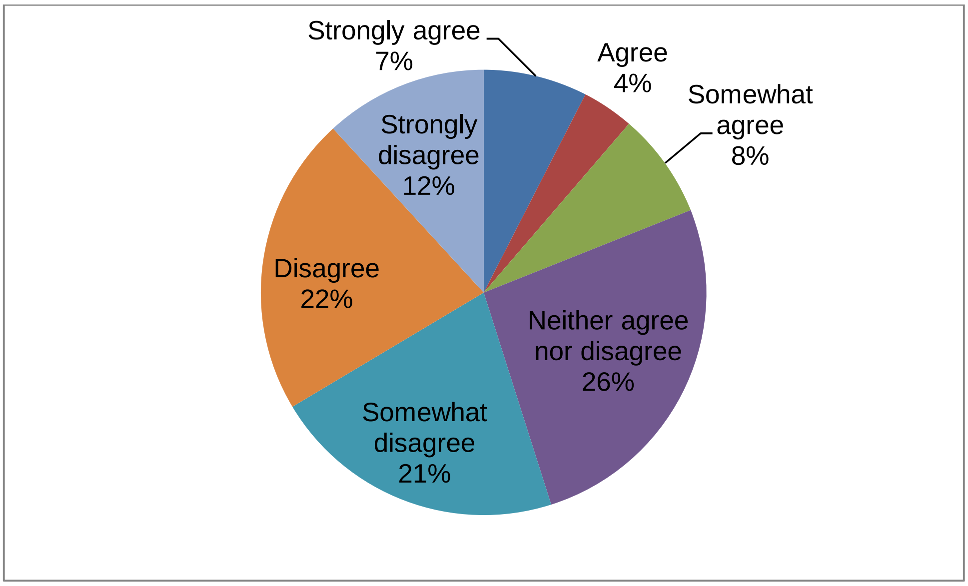

Figure 2. Responses to "I would like to have this smart thermostat in my home"

Investigation into the drivers and barriers for smart thermostat acquisition

The thematic analysis of the reasons participants gave for wanting/not wanting the smart thermostat in their homes are summarized below in Tables 4 and 5, with the major themes (i.e., those that were more predominant in the dataset) listed first. The frequency of these themes within the dataset is shown in Figure 3. These are reflected on further in the discussion section.

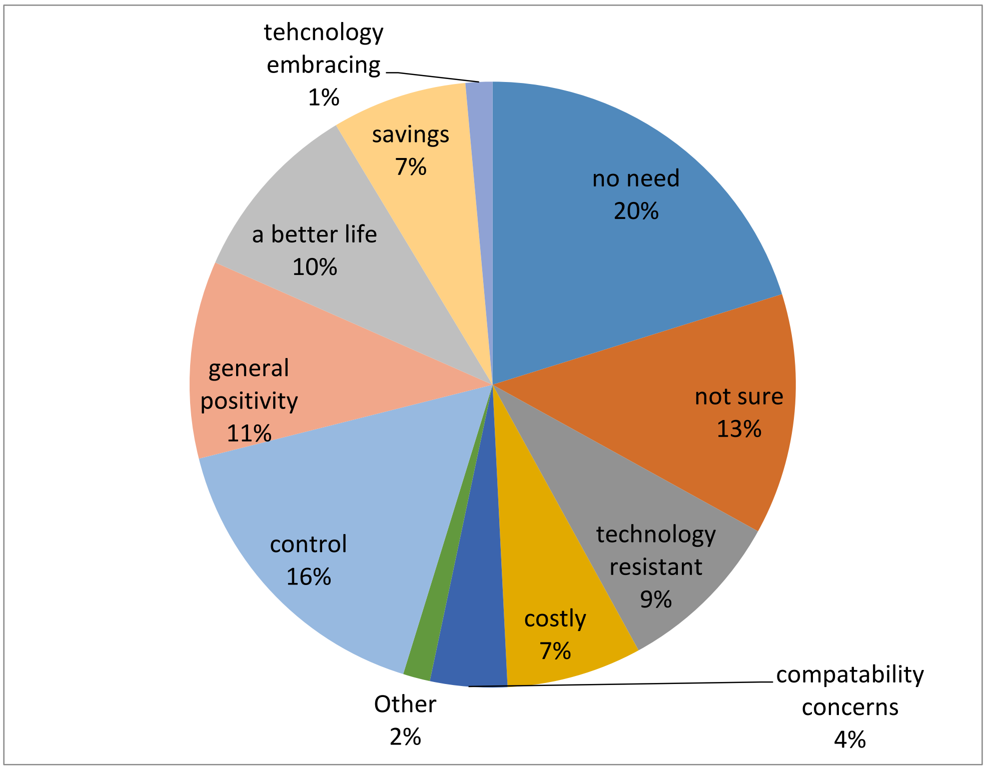

Figure 3: Frequency of reasons given for willingness (or not) to adopt smart thermostats

Table 4: Table of themes reflecting barriers to smart thermostat adoption

Themes for barriers to smart thermostat adoption	Illustrative Quotes
Superordinate theme 1: No need for it (n=182)	
Subtheme 1.1: No obvious advantages to it	*"Don't see the point"*
Subtheme 1.2: Satisfied with existing system	*"I can control my heating well enough already"*
Subtheme 1.3: Not relevant for my circumstances	*"I don't need it. I am here all the time, it is easy to tweak the thermostat if necessary"*
Subtheme 1.4:Does not fit with heating preferences	*"I would only turn on the heating when I am in the house and not before"*
Superordinate Theme 2: Nonspecific objection (n =116)	
Subtheme 2.1:No reason	*"Don't know" "No particular reason"*
Subtheme 2.2: Not sure	*"Unsure" "Undecided" "Not sure about it"*
2.2.1:Need further info	*"Don't know enough about it yet"*
2.2.2: Might not use it	*"Not sure I would use the functionality of it"*
Superordinate Theme 3: Technology resistant (n =81)	
Subtheme 3.1: Effortful/complex	*"It seems a lot of faff for something I already do"*
Subtheme 3.2: Gimmicky	*"Yawn...not needed. Another 21st century 'improvement'"*
Subtheme 3.3: Security/Privacy concerns	*"Don't want the risk of being hacked/burgled"*
	"Also I don't like the big brother aspect of the tracking"
Superordinate Theme 4:Cost (n =65)	
Subtheme 4.1:Affordability concerns	*"I could never afford it"*
	"I think it will cost a lot"
Subtheme 4.2: Cost/benefit justification unclear	*"Nobody in the house has a smart phone so the costs would be too high to make it worthwhile"*
	"May not save me any money"
Superordinate theme 5: Compatibility concerns (n=37)	
Subtheme 5.1: Won't fit with heating system	*"I don't think our system is able to use it – too old"*
Subtheme 5.2: No smart phone	*"Do not have or intend to have a smart phone so many features would be useless"*
Superordinate theme 6: Other (n =13)	
Subtheme 6.1: Aesthetically unpleasing	*"The unit itself is ugly"*
Subtheme 6.2: Domestic "discussions"	*"Could potentially create more conflict"* *"Each person would not agree on the settings"*
Subtheme 6.3: Dislikes "Cosy" concept	*"Loathe the name Cosy"* *"It seems a bit poncy"*

Themes for barriers to smart thermostat adoption	Illustrative Quotes
Subtheme 6.4: Not a home-owner	*“My home is rented, I can’t change anything”*

Table 5: Table of themes reflecting drivers to smart thermostat adoption

Themes for drivers for smart thermostat adoption	Illustrative Quotes
Superordinate theme 1: Control (n =147)	
Subtheme 1.1: Ease of use	"*Easy control of the temperature*"
Subtheme 1.2: Flexible Scheduling	"*Heating to suit us and our needs*"
Subtheme 1.3: Zonal heating	"*I like how you can have different zones*"
Subtheme 1.4: Remote control	"*My home takes time to heat up. I live alone so I could turn heating on remotely*"
Subtheme 1.5: Convenience	"*It would be nice to have at your fingertips rather than rummaging in the cupboards*"
Superordinate theme 2: General positivity (n =95)	
Subtheme 1.1: Perceived usefulness	"*Sounds like a good idea*" "*seems useful*"
	"*It seems like the ideal solution for home heating*"
Subtheme 2.1: Aesthetically pleasing	"*It looks stylish*" "*looks good*"
Themes for drivers for smart thermostat adoption	**Illustrative Quotes**
Superordinate theme 3: Quality of life (n =88)	
Subtheme 4.1: Warmer & happy	"*As it means I am happy if I am warm*". "*For general comfort and well-being*"
Subtheme 4.2: A simpler life	"*Would make life easier*". "*Easy to use and simple for a better home*"
Superordinate theme 4: Savings and efficiency (n =65)	
Subtheme 4.1: Money saving	"*It will save me cash!*"
Subtheme 4.2: Efficient	"*Looks an efficient system to use*"
Subtheme 4.3: Energy saving	"*Will save you energy*"
Superordinate theme 4: Technology embracing (n =13)	
	"*A clever piece of technology*"
	"*It looks to be modern and an intelligent device. Something I would like to try out*"

Discussion

Challenge 1: An apathy for "smart" and consumer confusion about what "smart" is

Interestingly almost half of the respondents surveyed indicated that they felt neither negative nor positive about the concept of "smart", indicating apathy. Moreover, perhaps unsurprisingly given the relative new entry of smart thermostats into the marketplace, approximately one third of our sample were unable to explain what the term means, while others explained the term incorrectly. There were also varying expectations in what "smart" might mean with some consumers presuming smart means self-learning and others anticipating monetary savings from improved efficiency. This indicates a lack of understanding about what smart thermostats are and what they can do. Indeed, this proposition is line with reports that consumers are still somewhat misinformed about smart thermostat capabilities [1], and statistics showing that 32.5% of people either have "no idea" (10.7%) or "a vague idea" (21.8%) about what smart home technologies are [11].

Solution 1: Rethinking "smart"

Evidently if the smart thermostat market is to continue growing there's a real need to communicate to prospective consumers what they are and what they can do. In communicating this, marketers should be aware of the wider context and how this might feed into confusion about their product's capabilities. For instance, in the present research some respondents confused smart thermostats with smart meters, presumably due to the wide spread advertising campaigns that are currently being run to support the UK government's mandated smart meter roll-out. This is problematic as it can lead to expectations that are not likely to be met (e.g., one respondent reported that a smart thermostat would stop him having to submit meter readings to his energy providers while another reported that that it would provide them with feedback about the cost of her energy consumption). This issue is further complicated by an increasing number of market competitors that offer home heating products with various functionalities but persist in labelling them as "smart thermostats". Not only may this pre-fix of smart lead to product confusion but it may not actually be that effective in appealing to consumers as indicated by consumer apathy towards the poorly defined term of "smart". Moreover, the findings suggest that the meaningless jargon of "smart thermostat" sounds cold and technical and may only appeal to early adopters. Worse, still it has the potential to alienate consumers with a growing resistance toward smart, as one respondent puts it they're "*fed up with 'smart' everything*", while another stated, "*smart is an over-used, generally meaningless PR term*". Given this, there appears to be a real need to consider dropping the industry jargon, and instead providing clear descriptions to customers about what the product is and what it can do for them.

Challenge 2: Getting consumers excited about smart thermostats

In a similar vein to challenge 1, there seemed to be a real lack of excitement around smart thermostats. While consumers did not vehemently oppose them, there seemed a real lack of urgency to acquire one with just 11% of those surveyed either agreeing or strongly agreeing that they would like to have a smart thermostat in their homes.

Closer investigation into why this was revealed that a major barrier is that people simply could not see the need for it or how it would benefit them ("*It would be nice to have but it's not essential*"). Many respondents reported that they were satisfied with their current heating systems and that it did not seem to fit with their existing heating requirements and/or preferences (e.g., "*Over the top for my needs*", "*I certainly wouldn't engage in the bizarre behavior of heating my home using an app when I'm not even at home*"). There was also a perception that smart thermostats would be costly and not worth it ("*I do not think it does much that I need that I cannot already achieve…It is probably far too expensive for the possible benefits*").

Another key factor that explained people's willingness to acquire a smart thermostat was their technology receptivity. Indeed 10% of reasons related to this with 9% attributable to technology resistance while 1% of reasons were indicative of a willingness to embrace technology. This is in line with findings that smart thermostats appeal to early adopters [1] and that early adopters are more likely to perceive stronger benefits of smart home technologies [11].

Where technology resistance was cited as a barrier this was due to concerns that it would be "*complex to learn*", "*effortful*" and a "*faff*". Others were more dismissive of it based on beliefs that "smart thermostats" were just another novelty gadget with a short life expectancy (e.g., "*It's a gimmick that will not last*"). Interestingly, perceptions that smart thermostats would be effortful to operate or a short-lived fad were often justified with explanations that it offered them no benefit in terms of functionality that they could not achieve themselves, again underpinning (e.g., "*It is technology for technologies sake, it is totally useless, it is not difficult to turn a thermostat up and down…*" "*Apps etc are just unnecessary hassle. If I'm cold, I'll turn it on, if I'm hot, I'll turn it off*", "*It seems a lot of faff for something I already do*")

Solution 2: Demonstrating the benefits

If consumers are to part with the cash needed to acquire a smart thermostat, then it needs to be clearer to them that they are not just a modern and bothersome fad, but that they offer tangible benefits that are relevant to them. At present this seems to be somewhat lacking with the largest barrier to smart thermostat emerging as a perceived lack of need. Given that most homes have some sort of heating or cooling system already installed – it's essential to demonstrate what additional benefits could be on offer to them. There are two strategies that can be pursued to accomplish this.

Strategy 1: Explicating and demonstrating the "universal" benefits

The more universal benefits that appeal to a wider range of the population need to be emphasized such as convenience, enhanced control, and a more comfortable home life. Indeed, these factors all emerged in the present research as drivers for smart thermostat adoption. In line with this, prior research has identified that UK households would value improved levels of control and convenience over the heating controls, in particular, "being able to control the temperature at different times in different rooms from one panel" and "being able to turn the heating on before getting home" [13]. In a similar vein, reducing effort, saving time, improving comfort and quality of life were amongst some of the main benefits perceived by end-users of smart home technologies [11]. If these benefits of smart home technologies are already perceived as desirable and feasible then it makes sense to promote them, but in such a way that they are concretely linked to how consumers may use or want to use heat in their home, rather than alluding to the benefits in a broader way (e.g., improved energy efficiency). Of course, efforts should be made to avoid promising consumers benefits they do not stand to realistically gain. For instance, caution should be exercised in promising consumers savings on their energy bills that they may not obtain, given that this is dependent on how the technology is used and implemented within the home environment. Indeed, smart thermostat NEST was reportedly facing a $350 million lawsuit through misleading buyers on savings [14].

Strategy 2: Spelling it out: who benefits and how?

An additional strategy that may be taken is to spell out to prospective end-users how a smart thermostat would work for them in their circumstances rather than relying on consumers to imagine prospective benefits. This may entail tailored advertising so that messaging is targeted to specific demographics (e.g., single households, family households etc) or occupations (e.g., shift workers) so that each segment of the population understands what exactly they stand to gain from adopting a smart thermostat. One way in which this could be achieved is using illustrative case studies that cover a diverse range of end-user scenarios. Using such a method it may be possible to shift end-users perceptions of the circumstances in which they may benefit from a smart thermostat. Indeed, in the present research perceptions of how a smart thermostat would benefit them varied, regardless of similar circumstances. For instance, two single respondents each living alone reported entirely different perceptions of whether a smart thermostat would benefit them (e.g., one respondent stated "*The idea is good if you have a busy household but I live on my own so don't have a problem sorting myself out*", while another noted "*I live alone so I could turn heating on remotely*").

In addition to spelling out who stands to benefit form a smart thermostat, marketing also needs to convey information about the compatibility of the product with various home/cooling systems as the present research and previous research identified this concern as a prospective barrier to adoption.

Conclusion

The present research contributes to the growing literature on the appeal of smart home technologies to prospective end users through exploring consumer receptivity to smart thermostats and identifying key drivers and barriers to smart thermostat acquisition. Overall, the findings from this research suggest a somewhat "luke-warm" response to the concept of smart and smart thermostats. While many of those surveyed did not actively reject the concept of "smart" or strongly object to the features that smart thermostats offer, there appeared to be a lack of appetite for having one in their own homes. The main reason for this appeared to be a lack of consumer awareness about what smart thermostats are and the benefits they offer. A potential caveat in this research may be that only one type of smart thermostat was presented to consumers with limited technological capabilities compared to other market competitors (e.g., Nest offers smart learning and automated heating in addition to remote control heating via an app). Nonetheless, this lack of appeal may be counteracted using marketing campaigns to demonstrate the universal appeal of smart thermostats through explicating the desirable (but also feasible) benefits that all consumers stand to gain. It should be clear from such campaigns what smart thermostats can do to improve on existing “non-smart” heating controls so that the increased functionality goes some way toward justifying the expense of replacing them. Another approach to marketing could be to demonstrate who stands to benefit from smart thermostats and how. In the latter case this may be achieved through using illustrative case studies and/or targeted advertising. With these strategies in hand, then there may be some hope that the market for smart thermostats can move from luke-warm to hot.

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Number references in the text in square bracket. Use "references" style here or Arial 10 justified single space. After each reference skip one line (inbuilt into style). See the examples below

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What is Cosy?

Cosy is a wireless home heating system that helps put temperature control in the palm of your hand. Using the Cosy app you and your family can control your home environment – whether you're at home, at work or away. Cosy lets you:

Have three temperature settings – Slumber for when you're asleep or out of the house, Comfy for normal living and Cosy for when you need that extra bit of comfort.

Easily select which setting you want – this can be done either from the portable Cosy display in your home or via your Cosy mobile app.

Create simple heating schedules – set daily temperature profiles to suit your life. You can create up to 7 of these. Cosy then automatically controls your heating for you.

The Radio Teleswitch: An historical perspective on the roll-out of domestic load control

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Abstract

In the mid-1990s, much like today, there was strong research interest in demand management in the built environment and its potential for mitigating electricity grid challenges. Tariffs, technologies and infrastructure required to enable it had been developed and were generally available. So what went wrong?

Since 1984 in Great Britain, the 'radio teleswitch' system had allowed for remote switching of meters and of loads such as electric heating in people's homes. Electrical engineers anticipated that this would usher in an era of improved load management and promote more even demand. But by 1996 the system was described as being 'significantly under utilised' [1] and, while hopes remained high, only a small percentage of British homes today have dynamically switched meters, heating or hot water [2].

This paper, based on historical desk research, outlines the development of the radio teleswitch system and compares it to discussions around smart grids and automation that are live today. It considers how dynamically switched systems were promoted and introduced to homes, how the landscape has now changed, and whether these changes might be enough to allow the systems being discussed now a greater chance of success. In this way it attempts to introduce a novel perspective to understanding both the deployment of load control technology in buildings and the limits on making efficient use of electricity infrastructure. It also hopes to inform current research and development by highlighting the rich track record of work in this area.

Introduction

Ever since the development of the first electricity networks, a key industry ambition has been to optimize (usually by maximizing) the use of assets such as generation and network infrastructure. In large part this has involved creating demand for electrical appliances, especially ones which operate in off-peak periods and therefore help improve the load factor of the system. [3] provides an insightful overview of the various efforts made to both build electricity demand in general and to promote shifting of demand to off-peak times, including government restrictions on use between specified times [4] and campaigns to exhort people to off-peak usage. Another key tool is the time-varying tariff, where different rates are charged for consuming electricity at different times with the aim of influencing people's usage patterns.

The ultimate ambition for generators and system operators, however, has been to exercise more direct forms control over the actual appliances whose use constitutes the load itself. While campaigns and tariff designs can be effective, they are indirect forms of influence that are mediated through householders' behaviour. This can be difficult to predict, and is almost impossible to influence reliably over the very short (i.e. seconds to minutes) intervals sometimes required by power systems. Introducing elements of automation can help, but can also exacerbate problems, such as the when timers are used to turn on appliances at the beginning of off-peak periods, creating rapid ramps in demand.

This paper is about the form of direct control that has been most widely used in Great Britain – the radio teleswitch (RTS). Introduced in the 1980s, it offered the exciting potential to reliably balance demand and supply of electricity, while working hand in hand with appliances that provided silent, smokeless comfort to consumers. In the paper I explore how the system works and track its development from the early days of optimism and growth to today, where it is largely the preserve of people disengaged with the energy market. I look at how the system was promoted and attempt to understand the reasons behind its ultimate stagnation. Finally I draw parallels with contemporary direct load control projects and consider which challenges still remain, and which may have been overcome.

System function and development

The radio teleswitch system in the UK is overseen by the Energy Networks Association, which provides basic information about its operation[40]. The system works by encoding data signals into radio broadcasts which in turn are decoded by teleswitch devices on consumer premises.

1. Distribution network operators (DNOs) have specific codes for teleswitches operating on their networks. The DNOs provide instructions to the Central Teleswitch Control Unit, which processes the instructions with the codes and passes them on to the British Broadcasting Corporation (BBC).
2. The data is sent out in the BBC Radio 4 long wave transmission (better known for its 'Test Match Special' full coverage of five-day-long cricket matches) produced at three different transmitters to cover the whole of the UK. The data streaming rate is 25 bits per second[41] (compared to the average broadband Internet speed in the UK of just under 23 million bits per second), and message are sent every two minutes.
3. The signals is received by the teleswitch (i.e. the devices installed on consumer premises).

Teleswitches have two main functions. One is to allow electricity meters to be switched between tariff rates – a function that is otherwise performed using a simple time switch. The other function is to allow the switching of electrical loads such as heaters. The teleswitch stores tariff or operating instructions until such time as a new message is received via the radio signal (with the appropriate code). In this way the radio teleswitch system can be used either to programme normal operation, or to provoke an immediate response (such as if load shedding is required). This paper focuses principally on the load control (rather than meter switching) functionality of the RTS.

Before the introduction of the RTS in the UK, tariff and load switching was accomplished by means of simple timer switches. These, however, had the problem of needing to be reset after power outages and lacking the ability to accommodate bi-annual transitions between Greenwich Mean Time (GMT) and British Summer Time (equivalent to GMT plus one hour) [1]. They also lacked the ability to respond in a dynamic way to demands on the grid or to easily accept new tariff structures. These reasons were key drivers of the development of the RTS.

The RTS was not the only contender to achieve such functionality, however, and it was by no means the first. As early as 1897, patents were taken out for systems which augmented the mains alternating or direct current with a signal to allow varying tariffs, or to remotely switch loads such as streetlamps [5]. Such 'ripple control' systems were identified by [5] as operating in many European countries as well as Australia, New Zealand and the African continent, with the combined capacity of systems subject to this control estimated at over 120 Gigawatts. The system is still widely used in New Zealand. Telephone line based systems had also been explored [6]. According to [6], a key benefit of the RTS system compared to others was its ability to be applied on a totally random basis over a large area without having to install a large number of new local transmitters (requiring an extended installation period).

Large scale trials of the RTS system began at the start of the 1980s, which 'proved the reliability of the system and excellent nationwide coverage' [7], p38. The system became fully operational in 1984[42], when local electricity boards began to place orders for teleswitches. The electricity boards were in charge of both networks and supply of electricity, meaning they were responsible for both local load management and customer billing (roles which are separated in the UK today). Teleswitches appealed to them because they allowed more reliable switching of meters, the ability to alter tariff times without having to physically visit the meter, and the possibility of offering interruptible tariffs [6].

Such innovative tariffs included *Budget Warmth*, where customers could pay a weekly fixed charge in return for having a storage heater in one room which is set to always provide a comfortable level of warmth and which is charged by the Central Electricity Generating Board (CEGB) depending on weather conditions and demand on the grid [8]. At the same time that such tariffs were being developed, the RTS system was awarded the Queen's Award for Technological

[40] http://www.radioteleswitch.org.uk/
[41] http://alancordwell.co.uk/Legacy/radio/teleswitch1.html
[42] http://www.radioteleswitch.org.uk/history.html

Achievement [8], and ‘prospects for innovative tariff and load control developments [were] a major source of favourable comment’ [6], p276.

Innovation continued in the years to follow, including systems which do not sound out of place even today. The CELECT heating system, for example, allowed customers to set desired temperatures for individual rooms in their house by day and time. The RTS was then used to convey outdoor temperature predictions and cost data to the system, allowing it to optimize charging and release of heat to match the temperature settings [9]. By this time the electricity industry in the UK had been privatized, with all electricity being bought and sold through the ‘Pool’, which was seeing substantial price fluctuation within and between days, with evidence that this was linked to domestic load [10]. Indeed, [10] (p5.27.1) state that ‘The logical conclusion … is the adoption of real-time tariffs for domestic consumers that change in response to the actual cost of supplying electricity’. The RTS seemed ideally placed to help respond to this challenge.

Potential unfulfilled

By the mid-1990s, however, optimism was waning. [1] described it as having be ‘significantly under utilised ever since … the widespread introduction of the system’ (p20). They argue that initial technical limitations on the number of Group Codes which were available (limiting the number of tariffs) could not be blamed, since even after these were expanded there was little development. Instead, looking forward to the imminent introduction of competition in the electricity supply market (in 1998), they highlight the difficulties in financial reconciliation – what is now known as settlement – between suppliers and the Pool as the most significant challenge. Specifically, the lack of half-hourly metering or statistical demand profiles adjusted for each supplier adjusted by dynamic switching patterns meant that there was no realistic prospect of suppliers being sufficiently rewarded for influencing load. This lack of incentive to influence for suppliers to influence load profile was also recognized by [11], who state (p290):

> *Since, with Profiling, a supplier's payments to the Pool in respect of a consumer will be independent of the actual load shape of that consumer, there will be no incentive for suppliers to pick out consumers with favourable actual load patterns. But other characteristics of consumers, such as payment method, total size of consumption and payment record will be of interest to suppliers.*

The same problem was also blamed for the lack of development of the CELECT heating system described above, as well as the additional challenge of the differing aims of suppliers and network operators in managing demand. Even though a trial in 100 homes had demonstrated a 25% reduction in peak demand reduction on the local network, and average reductions of 8% per customer in overall electricity use while, it is claimed, improving comfort, it did not progress beyond the trial stage [12].

Even if half-hourly settlement had been desired, it was difficult to see how it could be achieved given the technology available at the time. As [1] suggest, offering half-hourly settlement for small consumers would likely not be feasible since ‘A system that relies on recovering millions of data items … would seem doomed from the outset’ (p23). Instead, they suggest that much of the job of bill calculation should be devolved to the meter itself, which would store half-hourly data on usage tagged by time and tariff band, which would allow infrequent readings to provide for retrospective settlement. At the time, they asked: ‘Is such a system realistically achievable or just another pipe dream?’ (p23). While they recognize the potential benefits of systems with bi-directional communication, they see the established RTS system as at least complementary and still worthy of development.

By 2005 an estimated 4.5m customers had multi-rate tariffs [13], while by some counts around 1.5m had electric heating [14]. However, less than half a million meters were thought to be under contracts that permitted direct control via the RTS, and that some did not have ‘double’ meters which split out control of heating from other loads, meaning that remote control was likely to be unacceptable. Without the costly exercise of visiting homes to check, it was hard for suppliers to actually know what the specific contractual or metering arrangements in each home were. Compounding this, the cost for new suppliers of obtaining a new RTS Group Code and setting it up on relevant meters was high, and the inability to tie customers in to long-term contracts meant that the risk of committing to this cost was unlikely to be justified [13]. There was also the potential for conflict as certain codes were always reserved to distribution network operators to manage network constraints [13]. The combination of these factors is likely to have led to the continued lacklustre development of the RTS system.

An article in *Utility Week* in 2008 reflected on the RTS at 25 years old [15]. The experts interviewed in the piece, Geoffrey Hensman and Drew McGregor, raise a number of number of changes in the structure of the electricity industry related to the lack of take-up, including lack of vertical integration (leading to lack of shifting incentives alluded to above), and the move away from geographically defined supply regions (again, related to the split DNO/supplier incentive problem). However, they also re-emphasize some of the early promise of the scheme, such as its ability to make viable 'service' models of supply such as Budget Warmth – where heat or comfort are the product rather than energy. At that time, still preceding established plans for smart meter roll-outs, there was still some optimism for an enduring role for the RTS.

By the current decade, most thoughts had turned to how best to phase out the RTS. This was mainly driven by the anticipated transition to smart meters, which would perform the same function and more. There were also questions over the future of the Radio 4 LW transmission – as the technology required to broadcast it was no longer produced [2], leading to a shortage of spare parts[43].

Looking back over the life of the RTS, therefore, we see an initial period in the 70s and early 80s characterized by lots of research interest, leading to the introduction of the system amid high expectations. The technology was available to facilitate widespread direct load control, as was the technology which could create load worth controlling (in the form of electric heating systems). There were certainly some incentives in place to industry actors to undertake load control and flatten the load profile. However, while the system has functioned well since then, it did not have the transformative effect on the demand side that some in industry may have envisaged. Analysis at the time suggests this was mainly due to a combination of lack of incentive to shape load of individual customers and misalignment of aims between goals between different actors in the system. The next section considers the hopes alive now for the potential of smart appliances, including heating systems, to accomplish this transformation in the coming decades, and the extent to which these (and other) challenges faced by the RTS live on or have changed.

A new hope?

Prominent smart grid scenarios today envisage an electrified world with homes full of connected devices, heated electrically, and with electric vehicles in the driveway – all coordinated in harmony for the good of households and the overall network. Firstly, it is useful to consider what has changed since the time of the RTS which might bode well for the realization of this vision. Around the world, the introduction of smart meters provides a route by which price and direct load signals can be sent to smart appliances (although this is also possible simply over the Internet). Smart meters (depending on how advanced they are, which varies from country to country) or Internet-based systems afford substantial improvements over the RTS in providing features such as bidirectional communication and the ability to deal with 'millions of data items' [1]. As established above, the ability to transmit effective load control signals was not actually one of the major problems with the RTS – indeed, arguably it was a simpler system that, once it was turned on, was reliably accessible to pretty much everyone in the country using basic technology. The more advanced systems available today should permit a finer level of control, but this does not appear to have been a major barrier to the success of the RTS (although there may be indirect effects – see later paragraph).

One clear change in GB since the time of the RTS is the introduction of elective half-hourly settlement of small users. Up until recently, if suppliers wanted to settle customers on anything other than a standard profile they still had to use an agreed alternative profile – effectively introducing a new average profile for any new demand response tariff, and assuming that customers on the tariff followed that profile. With half-hourly settlement it is now possible to settle customers of the basis of when they actually use electricity. This provides a genuine incentive to suppliers to shift their customers' demand to times when the wholesale cost of electricity is cheaper, as they know that they will actually benefit from any such shift. This was highlighted

[43] As of today the signal is still being broadcast, and the most likely threat to its future now looks to be the shift from analogue to digital broadcasting.

above as a barrier to the success of the RTS, so does seem to be a significant positive shift for the prospect of doing domestic load control. Furthermore, it seems likely that half-hourly settlement will become mandatory, making it even more important for suppliers to consider when their customers are using power.

Another set of developments has occurred on the demand side. Falls in the price and size of computer components have led to the ability to incorporate advanced sensing, processing and connectivity into many more devices. This is the basis of the Internet of Things. As suggested above, combined with more advance communication networks, this affords the possibility of finer control of appliances, whether autonomously, by users, or remotely for the purposes of load control. In theory this permits subtler forms of load control, such as frequency response by fridges which is unnoticeable to the customer, or within-home balancing of different appliances within boundaries set by the user. However, one basic aspect of the situation has not changed a great deal in recent decades – that is that heating is still the dominant requirement for energy consumption in British homes. No matter what can be done with other new smart appliances (setting aside electric vehicles – see later), control of electric heating systems will be the key concern. And as described above, even in the mid-90s there had been successful test of 'smart' heating systems that offer many of the functions being touted today such as the capacity to learn the properties of the building, respond to weather and provide a comfortable level of warmth even while responding to load control signals.

Lingering challenges

Since the dwindling of the RTS, therefore, we have seen significant (although not necessarily transformative) progress in the 'smartness' of control and demand technologies, as well as increased incentives to suppliers to influence customer consumption (though half-hourly settlement). Where has there been less progress? Firstly, the electricity industry in GB is still characterized by vertical disintegration. As highlighted above, this means that, while half-hourly settlement may provide an incentive for suppliers (i.e. energy retailers) to shift demand, there is no reason to believe that such shift would align with the interests of transmission and distribution network operators or some generators. Clearly the different actors in the network will have different requirements whether or not they are part of the same organization, but the current situation means that there is no coordination where interests align, or discussion and compromise where they do not. Even if (as is the aim of the regulator, Ofgem), distribution network operators begin to take on the role of distribution system operators, this does not address the interest misalignment between sectors.

Perhaps the greatest uncertainty lies in the potential uptake by customers of the technologies most needed to make domestic load control feasible and worthwhile – electric heating systems and vehicles (EVs). For EVs at least, the future seems positive. In the latest National Grid Future Energy Scenarios report [16], even the 'slow progression' scenario as EVs accounting for more than 50 per cent of vehicles by 2050. EV sales in the UK are seeing exponential growth[44]. The picture for heating is less positive. Since middle of the last century, electric heating systems have been losing out to gas. Legal decarbonisation targets in the UK are driving the push towards electric heating using heat pumps (alongside district heating, and potentially other sources such as hydrogen). However, uptake has been low, and does not seem likely to hit even the minimum level the Committee on Climate Change has determined to be necessary to meet the UK's carbon reduction targets (2.5m homes by 2030) [45]. In this respect we are in a similar position to the early days of the RTS – that is, all the technology exists, and just the demand (in the form of electric heating systems) needs to be created. Arguably, however, we are now is a worse position to achieve this.

In the 1980s, the energy organizations with whom customers had a direct relationship (the electricity boards) were also in the business of selling electrical appliances, including heating systems. They had showrooms, used television advertising, and installed and maintained systems in people's homes. In a way this represented a further layer of vertical integration, taking in the actual demand technologies in homes as well as supply and transmission/distribution infrastructure. In this way, the electricity boards could both promote the use of electric heating in

[44] http://www.nextgreencar.com/electric-cars/statistics/
[45] https://www.theccc.org.uk/wp-content/uploads/2013/12/Frontier-Economics-Element-Energy-Pathways-to-high-penetration-of-heat-pumps.pdf

general, while also promoting systems which facilitated demand management – such as those open to RTS control. For example, electricity boards were reported to have purchased 170,000 teleswitches in 1986/7 to install in homes as a replacement for timeswitches [17]. They were therefore in an influential position to encourage adoption of demand responsive technologies.

Today, this level of integration with technology retail is comparatively very small as technology retail operations were sold off following privatization. While operations such as British Gas Connected Homes are active in the technologies such as smart thermostats, there are no major marketing drives for these to apply to electric heating in particular – they are rather about gaining traction in the connected home market in general. There is also little in the way of a marketplace where domestic demand response beneficiaries (such as DNOs) and providers (aggregators such as appliance manufacturers) can work together to achieve mutually beneficial impacts. Were such a marketplace to exist it could potentially foster the best of both worlds, where network actors could express clearly their demand response needs, with competition in the market for how best to meet them. More consideration is given to this market in the final section.

Focus on the user

A final important question for both the RTS and future smart heating systems is that of public demand and acceptability. While a number of the documents located as part of this work do touch on consumer perceptions, it tends to be blandly positive but with little detail. For example:

- 'There has been virtually no customer reaction to the use of radio teleswitches … where the Budget Warmth scheme is in operation, both customers and boards are pleased' [6]: 276.
- On the CELECT heating system: 'Initial feedback from these trials has been very good, with users experiencing enhanced levels of comfort and controllability' [9]: 6
- 'A survey of customers in Aberystwyth showed they viewed electricity more positively after moving to Menter [an RTS-based tariff]' [18] [Manweb's staff newspaper]

Set against this are reports of consumers being dissatisfied with electric and night storage heating technologies in general. For example, research previously conducted by me [19] (pp90-91) included some participants on a Cyclocontrol scheme, a now discontinued method of remotely controlling the floor heating in blocks of flats based on weather forecasts (conveyed through signals encoded in the network frequency, rather than the RTS). It found substantial dissatisfaction with the lack of control available to residents, with no option to affect the temperature other than opening the windows (p95). [20] reports the results of (now unavailable online) research by Consumer Focus showing 68% of people with storage heaters are happy with the system, compared to 91% of those with gas heating. [20] goes on to say that while 'storage heating is not wildly unpopular … it does have the reputation of being difficult to control' (p3).

As well as experience of the heating system, there is also the question of the extent to which people were aware, or had positive/negative views on, the external influence over RTS-controlled heating systems. A report for Ofgem on customers with dynamically switched meters found that, 'For the majority of customers, the idea of dynamically switching meters (and therefore the associated heating system) to control their electricity was … completely foreign' [21]: 11. Instances of people mentioning external control were described as 'relatively rare' (p13). The work found that most people had inherited their heating systems and learned to use them by trial and error, without having any 'official' guidance. If customers do want to discover details of the kind of external control they may be subject to, they have to dig into dense terms and conditions documents. For example, Scottish Power's T&Cs document 'Fixed Price Energy June 2016'[46] runs to 24 pages, and uses the following language (p11): 'The Controlled Circuit is energised for periods having an aggregate daily duration between 0 and 14 hours chosen by ScottishPower on the basis of forecast weather conditions', or 'The Controlled Circuit is energised for two or more periods with an aggregate daily duration of 8.5 hours'.

New smart control systems have been developed for both legacy storage heating systems [22] and heat pumps (e.g. [19], chapter 6) which place great emphasis on consumer controllability while also permitting external control for the purposes of demand response. Research such as [23] suggests that a substantial proportion of energy bill-payers are happy to accept some level of external control of heating. The indications from past experience and ongoing research is that

[46] https://www.scottishpower.co.uk/pdf/o201606_FixedPriceEnergy.pdf

external control of appliances is in principle acceptable to many people, and that it is the execution (such as the extent to which control impacts on comfort or performance) that will be critical.

Conclusions and future prospects for flexibility

In this article I have traced the rise and fall of the radio teleswitch system for directly controlling domestic heating in Great Britain. The system was born to an integrated, state-organized energy system with incentives to maximize overall electricity use while minimizing peaks. It soon found itself operating in a situation of misaligned incentives between privatised operators with domestic consumers who were deserting electric heating. I argue that despite great advances in technological capabilities, the structural issues which led to the aborted growth and slow demise of the radio teleswitch still largely exist today. Unless something changes, this has implications for the potential role of demand flexibility in the energy system.

There is one final significant trend not yet discussed that could be the salvation of flexibility in the future: decentralization. Distributed generation capacity in many countries has been growing rapidly for years, which together with falling battery costs for electric vehicles, home storage and grid-level storage promises to both increase the need for demand flexibility and make it easier to accomplish. However, the most important development may well be in the decentralization of markets for power. As [24] describes, the combination of distributed generation and storage with blockchain technology may herald a situation where transaction costs are low enough that individual households can deal directly with each other (peer-to-peer trading), form microgrids, or have direct relationships with a range of actors in the existing power industry [25]. Each actor can then offer a cost-reflective price directly to customers on an open market, helping to address the problem of misaligned incentives. More of the appliances people buy[47] have the innate ability to communicate with each other, and while energy trading is likely low in the list of priorities behind such purchases, this ability does permit market participation if the incentive (and cost, in effort and other ways) is right. It remains to be seen if these developments – which currently match the optimism seen in the early days of the radio teleswitch – can ultimately exceed it in delivery.

[47] http://www.gfk.com/insights/infographic/smart-major-domestic-appliances-are-connecting-with-households-globally/

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Interaction between Home Energy Management and Smart Appliances

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Abstract

Standardization Committees like CENELEC TC 59X ´Performance of household as well as similar electrical appliances´ and consortia are working on Smart Home and interoperability standards. It is the intention of CENELEC TC 59X /WG 07 to define a Smart Home/Smart Grid standard for Home Appliances, based on the scope

- *Standardization work to enable domestic appliances to improve functionality through the use of network communication.*
- *Examples of network communication include smart grid, smart home and home network.*

The main difference between Single Home Appliances and Smart Appliances in a Smart Home/Smart Grid environment is the dependency on networked systems with different stakeholders like Grid operators via Home and Building Managers realized by lots of different manufacturers.

This means that a Smart Appliance is not anymore a stand-alone device but embedded in a communication system with different other Smart Devices like Smart heating systems, Electric vehicles etc.

In this context interoperability is key to ensure the success of Smart Grid and Smart Home solutions. A customer of a Smart Appliance does not want to be confronted with technology, he needs solutions. Having this in mind, interoperability requires a kind of common architecture model to enable communication between different devices as well as neutral data model and messages to be understood by Smart Devices (like Smart Appliances) independent from different manufacturer.

As this target influences the requirements of the whole chain from the interface of the Grid into the premises, the home & building management and the Smart Devices, CLC/TC 59X/WG 07 ´Smart household appliances´ has liaisons with IEC/TC 57/WG 21 ´Interfaces and protocol profiles relevant to systems connected to the electrical grid´ which is dealing with the definition of the interface of the grid to the premises and CLC/TC 205/WG 18 ´Smart household appliances´ which is in charge with in-house distribution and management.

Furthermore, initiatives like EEBUS Initiative or Energy@home support international public standardization like IEC/TC 57, CLC/TC 205 and IEC/CLC/TC 59 together with international alliances like Open Interconnect Foundation (OCF), Thread, ETSI/one M2M and others.

This report describes the activities and results of work since the last report in 2015 towards one interoperable solution.

Opportunities and threats of billions of IP connections in a Smart Home

Wouldn't it be great if the car and the washing machine inform the Renewable Energy System at home about their need to charge or to wash? And wouldn't it be great if this is done on a flexible way to use the renewable power as efficient as possible?

This is the main target of Smart Homes or Buildings in the near future.

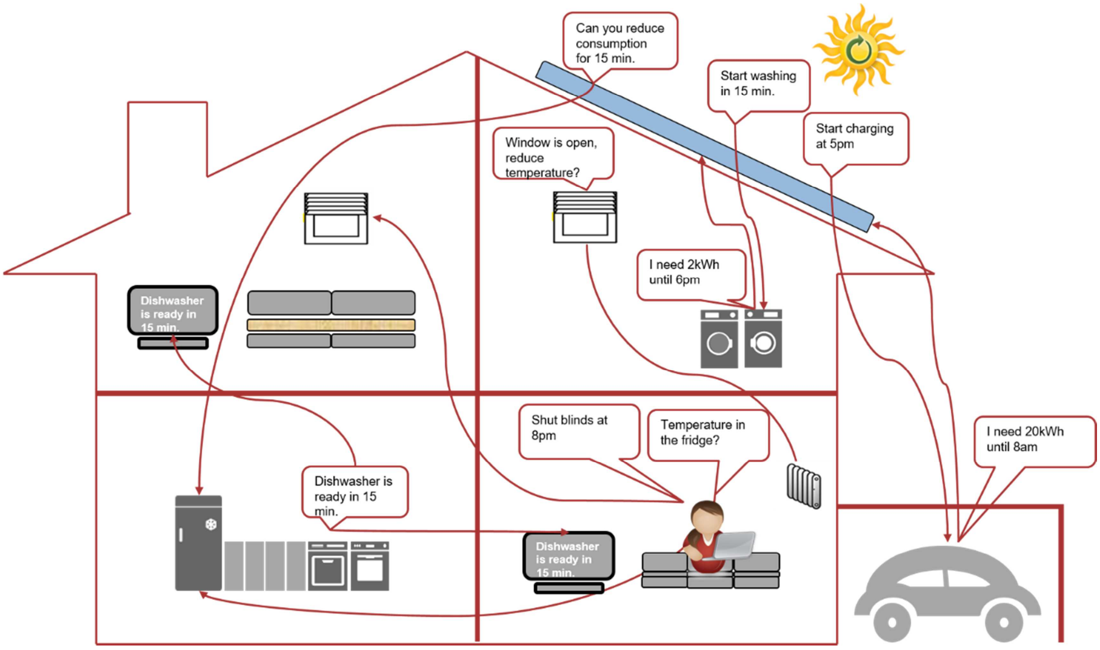

Figure 1: Interaction of Smart Devices within a Smart Home

This requires devices to be interoperable, which means to communicate with each other independent from manufacturer or technical platforms.

However, until today there are mainly proprietary solutions on the market with no capabilities to interop with others outside their platform. This is crucial for the success of a future Smart Home.

Interoperability, the major challenge

How to achieve interoperability?

A first answer is to agree on a common architecture model like SGAM (Smart Grid Architecture Model) [5] od HBAM (Home and Building Architecture Model)[14].

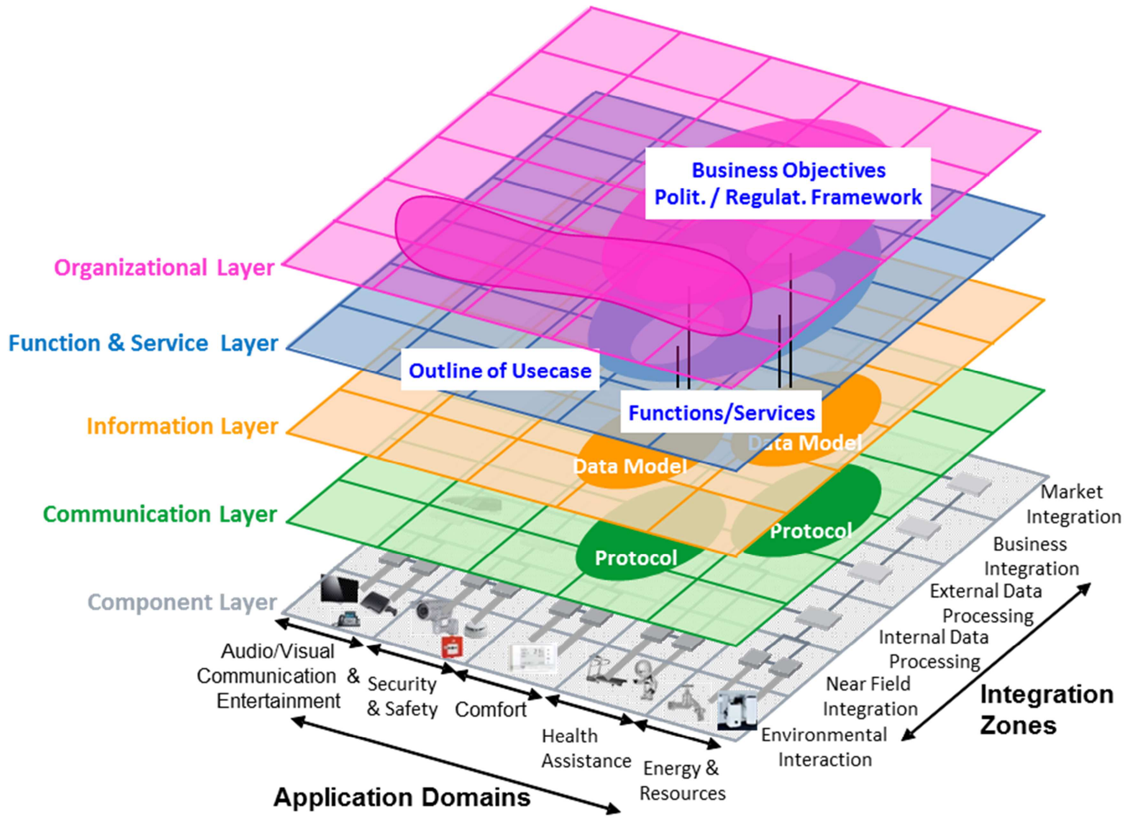

Figure 2: Home and Building Architecture Model (HBAM)

The Smart Grid Architecture Model or the one from the SGAM derived Home and Building Architecture Model clearly distinguishes different layers with corresponding responsibilities.

- Organizational Layer → Business Objectives and Business related user stories.
  - This layer represents the business objectives of a manufacturer like: I want to develop and offer a home manager with energy management, comfort features and audio streaming
- Function Layer → use cases and functions / services
  - This layer represents the relevant use cases / steps to achieve the business objectives
- Information Layer → Data Models
  - This layer contains the Data Models, the languages, messages and information to be exchanged between peers
- Communication Layer → communication / transportation protocols
  - This layer describes the way of how to transport the information between the peers
- Component Layer → physical components

A second answer is to agree on a common language. This common language is used to exchange information between devices like “I need 2 kW until 6pm” and needs to be completely independent from any kind of communication path like sending a letter, writing an E-Mail etc.

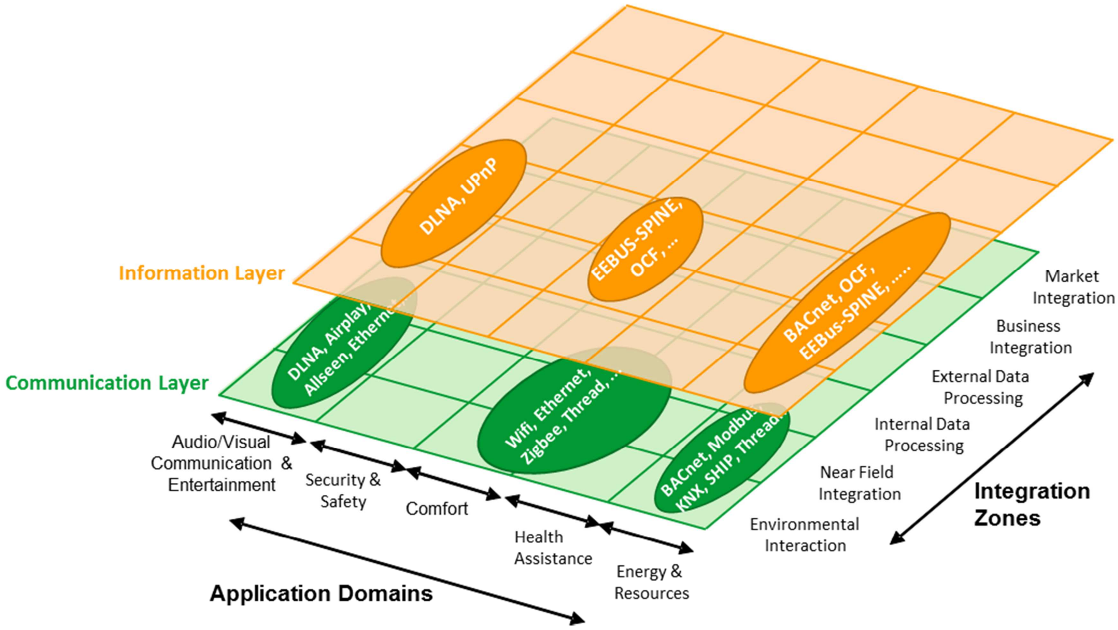

Figure 3: common language representation on information layer of HBAM

A language is (amongst other definitions) defined as a system of symbols and rules that serves as a means of understanding for a certain language community.

The information layer contains these languages in a manner of Data Models.

Furthermore, we need to consider different domains in a Smart Home & Building like

- Entertainment
- Health
- Energy Management
- Home Security
- and so forth

with different languages and vocabularies serving different targets.
Finally, different technological requirements need to be considered like

- Security levels of communication
- Bandwidth for data exchange
- Coverage
- Point to point or point to multipoint communication
- Broadcast solutions
- Low power driven solutions
- and so forth

But these requirements are not subject of this paper

This leads to a system that can allow management of Smart Home & Building applications with domain specific common languages. These languages are capable to be mapped onto suitable communication methods like verbal-, postcard- or email-communication and technology wise like Thread or SHIP (Smart Home IP). This is described later on.

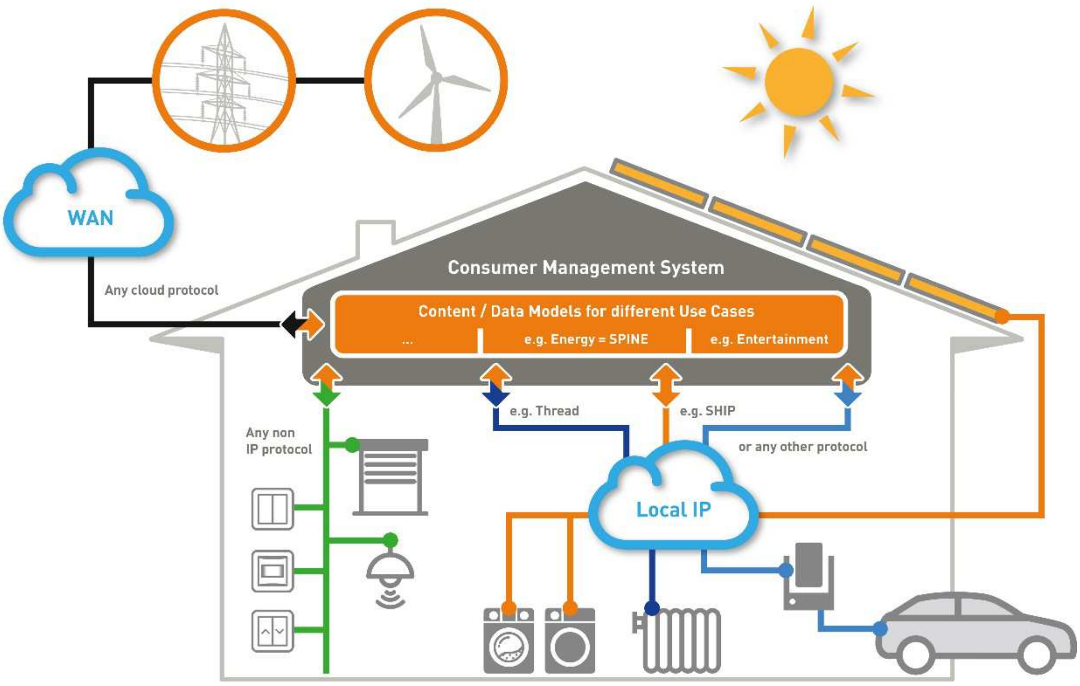

Figure 4: Consumer Management System for different use cases

SPINE, the language for Energy Management

As already mentioned, due to different requirements in various domains there is likely no single solution for a complete Smart Home. This is the reason why the EEBUS Initiative and Energy@home decided to focus on the domain Energy Management.

The corresponding language is called SPINE, **S**mart **P**remises **I**nteroperable **N**eutral message **E**xchange.

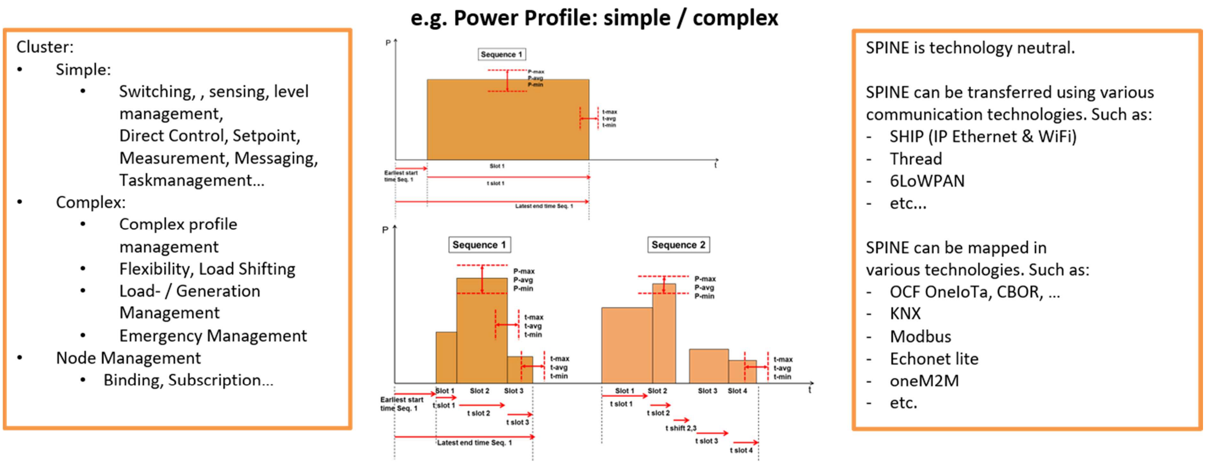

Figure 5: SPINE – the language for Energy Management

SPINE - General concepts

As stated above, SPINE itself is part of the Information Layer (see figure [3]) and does not define any layers below ISO-OSI layer 7. So, the SPINE data model and protocol specifications can be used with every technology that supports bi-directional communication with any payload.

The SPINE communication uses its own header and payload definitions within a SPINE message (hence within Information Layer or ISO-OSI layer 7).

A SPINE message is separated into header and payload as can be seen in figure [5]. The Protocol related aspects of SPINE (including structure of header and payload of messages) are described in the [ProtocolSpecification][12], together with some parts that occur in the payload. Most part of the payload (including the complete SPINE resource model) is specified within the [ResourceSpecification][12].

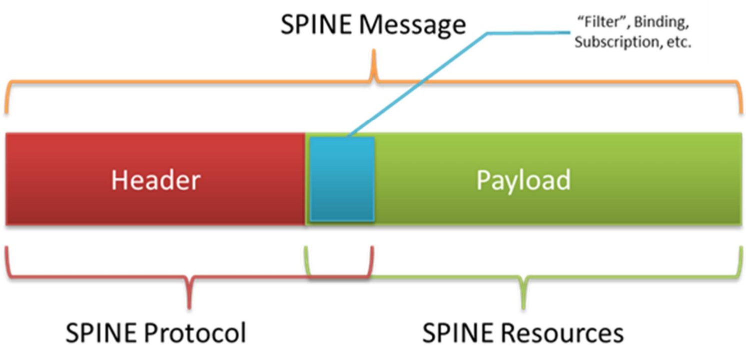

Figure 6: SPINE address levels

Messages can be transferred with different classifiers (e.g. read/reply/write), enabling polling-based communication as well as trigger or event based notifications.

The data model is very modular. For different use cases, the SPINE functions can be combined and used in different ways. This may seem more complex than just modelling each needed data as a separate element like it is common practice in most technologies. But in fact, the modularity enhances reusability and recognition of well-known definitions. Especially as the list of requirements grows, and so the list of different data points, the modular concept of SPINE shows its strength.

The SPINE device model helps finding appropriate communication partners. It consists of three layers: physical device, logical device (entity), functionality (feature).

The modularity requires the combination of “modules” into a single message for a specific purpose. A concept for combining several information in one atomic message is realized with the SPINE complex classes.

Each feature has a role: client or server (and, in some cases, special). The server provides information that may be read or (if allowed) written. The client requests information from a server or changes it.

Binding and subscription mechanisms enable an easy way to connect matching devices. The usage of binding is feature type specific (it may be used to determine which communication partner is permitted to change something on the device or where to send commands). Subscription is used wherever a client wants to receive updates from some server functionality automatically.

To be able to communicate with another device, one needs to know what functionality is implemented there. The device discovery concept delivers the relevant information about a device (including hierarchy levels device, entity and feature).

For every communication, it is essential to have some kind of address where the message shall be sent to. SPINE has its own addressing schema that has representatives for all three hierarchy levels.

In some cases, not the complete data of a resource is of interest. A filter may then be applied together with a read command, to cut down the payload to transmit. This concept is also used when a notification only includes changed data or together with a write command.

Further introductory sections with some more general information can be found in the following documents and sections:

SPINE device model (devices / entities / features)

A device model helps to find appropriate devices for communication as well as clustering information in a logical manner. The SPINE device model consists of three levels: device, entity and feature. Each level holds a type: *deviceType*, *entityType* and *featureType*.

- The device type denotes which physical device is described.
- The entity type states the logical device. A physical device may consist of more than one logical device.
- The feature type describes rules for exactly one class (simple or complex). In the device discovery, the feature type is stated together with a list of supported functions and the possible operations on each function.

The address levels of the described device-model parts are as depicted in the graphics below.

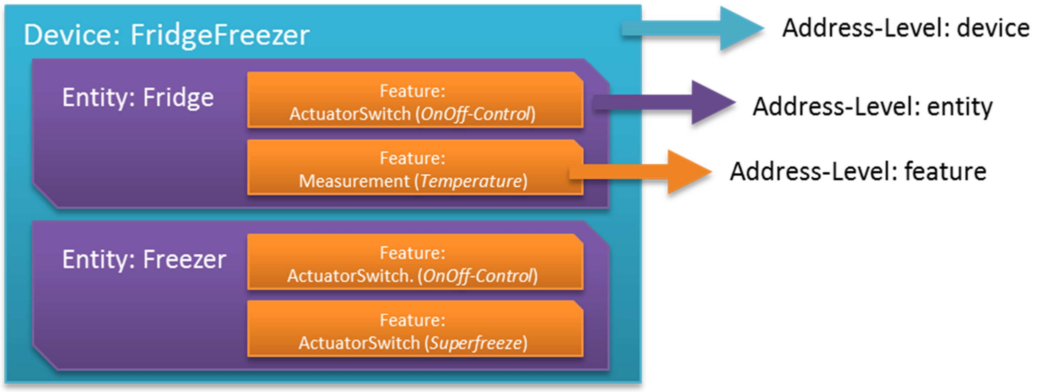

Figure 7: SPINE address levels

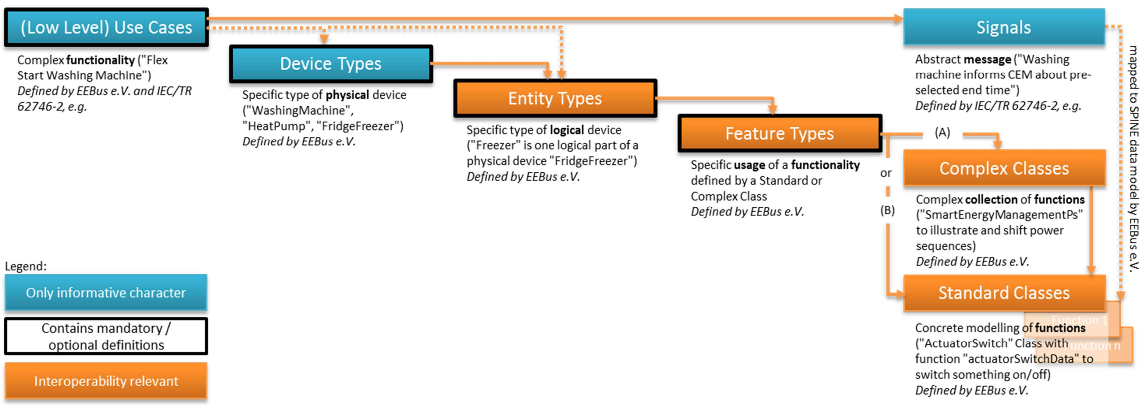

Figure 8: Dependencies of the standardized types and identifiers

SPINE classes, functions and elements

The SPINE data model is divided into classes. For each functional domain supported by SPINE, a related **standard class** is defined. For example, Measurement, Sensing, TimeInformation, etc. Additionally, **complex classes** exist that allow the combination of functionality defined by standard classes.

SPINE classes have a collection of functions that can be used for communication.

Functions contain elements. Each element represents a single information. E.g. a timestamp, a value, a unit, etc.

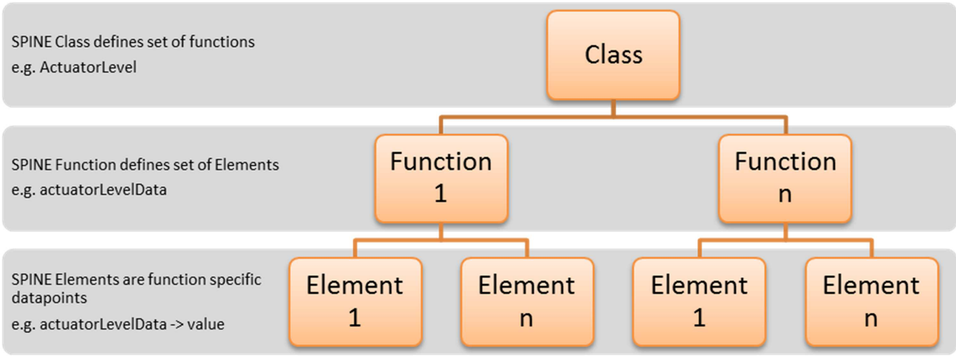

Figure 9: SPINE class hierarchy

Link between device and function vs. datagram and function

SPINE functions are, as already denoted earlier, the central component in all SPINE concepts. In the resource hierarchy, they are defined as the data containing part behind the lowest level ("FeatureType"). The following figure explains in a graphical way where the SPINE functions are "located" in the concepts. On the left side, the graphic starts with the entry-point to the typical SPINE message (element tag "datagram"). On the right side, the resource model is depicted (Device, Entity, Feature), together with the functions and the elements.

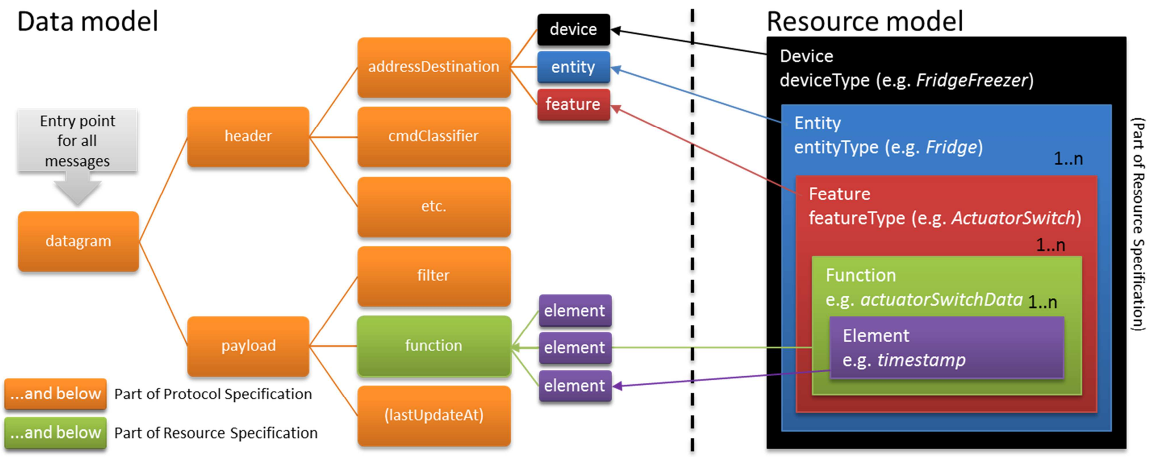

Figure 10: Link between datagram and function vs. device and function

SPINE- the interoperable language

As already explained, the SPINE data model is split consequently into a “resource” and “protocol” part. The “resource” describes the resource with its capabilities like a lamp with the capabilities to be “on”, “off” and possibly “dimmed”. The “protocol”, not to mix it up with communication protocol, describes the capabilities to address the lamp, to read the status or to write a new status and so forth.

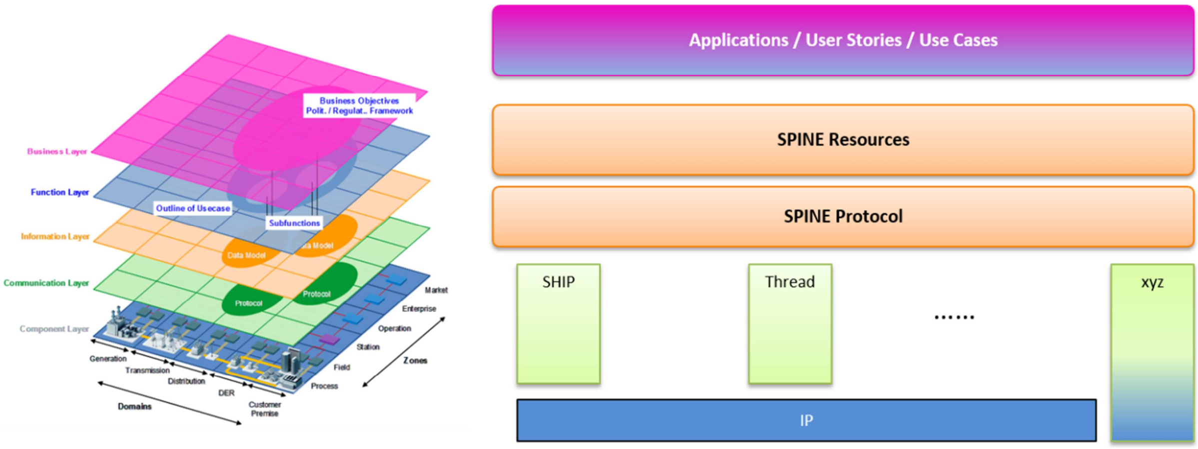

Figure 11: model SPINE – Information Layer within the HBAM model

Like figure [12] presents, typically each alliance tries to develop its own data model with resource and protocol model.

Typical further protocols are

- http (Hypertext Transfer Protocol)
- MQTT (Message Queue Telemetry Transport)
- RESTful (Representational state transfer)
- CoAP (Constrained Application Protocol)

Our intention is to make SPINE available to every meaningful solution like OCF, oneM2M, Thread etc.

The split between SPINE "resources" and "protocol" ensures to reuse the resources even if another system requests another "application-protocol". Only the protocol needs to be mapped but the context remains the same.

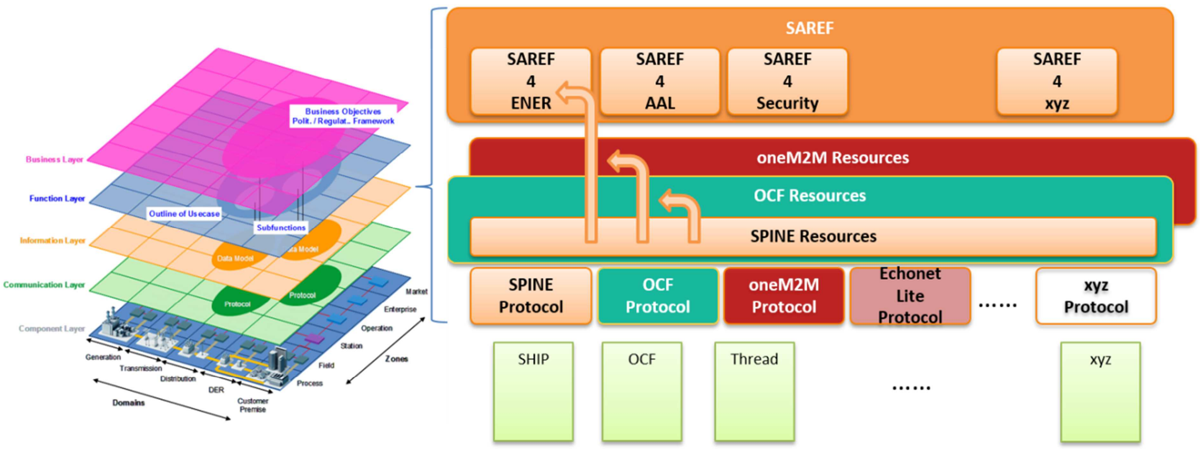

Figure 12: Alliance specific data models

The same applies to the mapping onto different communication protocols like SHIP (Smart Home IP) or Thread (see figure [13]).

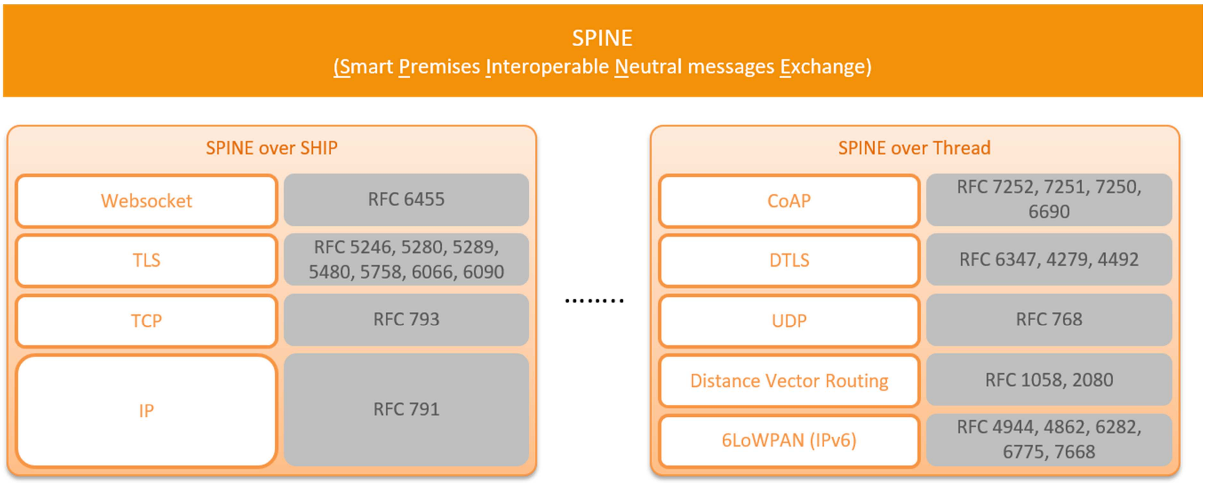

Figure 13: SPINE mapped onto various communication protocols

Partnershipment and liaisons to enlarge interoperability

A future Smart Home & Building is not realistic if every alliance and every manufacturer develop its own solution.

Since more than 3 years a few alliances together with International Standardization bodies started to closely work together and to harmonize their solutions.

One of these initiatives started with a collaboration between EEBUS Inititative e.V. in Germany and Energy@home in Italy. They harmonized their energy-related data models and created SPINE (**S**mart **P**remises **I**nteroperable **N**eutral message **E**xchange)r.

Together with support of the European Commission (DG-Energy and DG-Connect) they supported SPINE to become part of the European wide Smart Appliance Reference Framework SAREF, driven by ETSI / oneM2M.

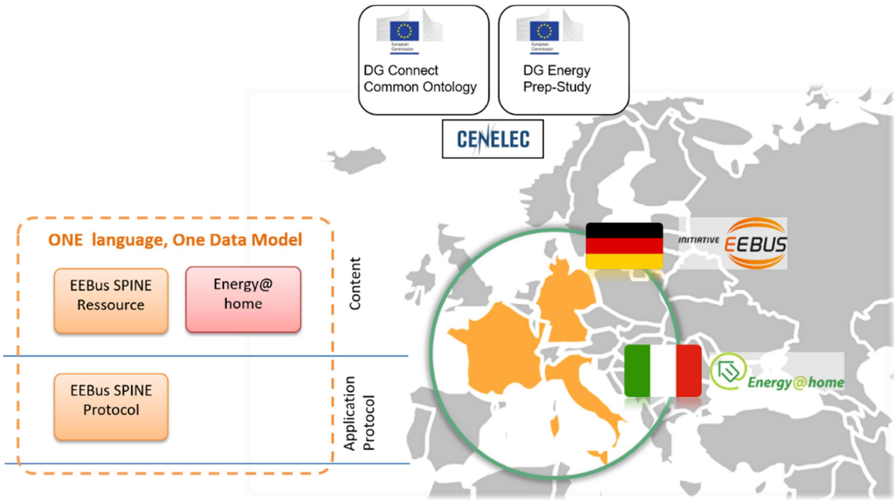

Figure 14: EEBUS Initiative and Energy@Home

Furthermore, the EEBUS Initiative started in 2014 to liaise with other alliances like OIC, today Open Connectivty Foundation (OCF, merger of OIC Alliance and Allseen Alliance in 2016) and Thread with the main intention to make SPINE available within these Smart Home solutions.

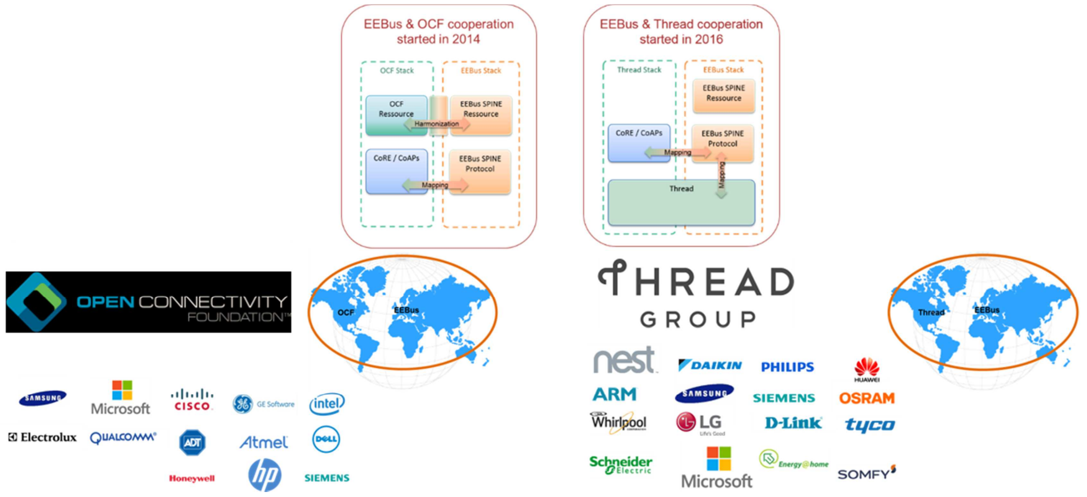

Figure 15: Liaison EEBUS Initiaitve with OCF and Thread

SPINE contributions to international standardization

As mentioned before, the main lever to ensure interoperability is to make SPINE available via all main solutions like OCF; Thread, ETSI / oneM2M, KNX and so forth.

For this, the EEBUS Initiative and Energy@home made EEBUS SPINE documentation available for free. All SPINE documents can be downloaded on www.eebus.org [12]

The first international standard, equipped with SPINE, is the CENELEC prEN50631-x, White Goods House Appliance network and grid connectivity. This standard is in the Final Voting phase process since beginning of 2017.

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

DRAFT
prEN 50631-1

February 2016

ICS

English Version

Household appliances network and grid connectivity - Part 1: General Requirements, Generic Data Modelling and Neutral Messages

To be completed

To be completed

This European Standard does not deal with safety requirements. Safety requirements have been set in IEC/EN 60335-x [17]. These requirements shall be applied to smart appliances using remote functionality.

prEN-50631 will provide interoperability on information exchange among various appliances in the home. The standard will be split into 4 parts:

prEN-50631-1: *Household appliances network and grid connectivity - General Requirements, Generic Data Modeling and Neutral Messages*

prEN-50631-2-x: *Household appliances network and grid connectivity - Product Specific Requirements and - Specifications*

prEN-50631-3: *Household appliances network and grid connectivity – General Test-Requirements & - Specifications*

prEN-50631-4-x: *Household appliances network and grid connectivity – Technology Specific Implementation and Test Requirements*

Figure 16: CENELEC prEN50631-x standard

A further contribution was made to enlarge the SAREF ontology (Smart Appliance Reference Framework) with SAREF4ENER.

The work on SAREF started in 2014 under the roof of DG-Connect (European Commission) and ETSI, describing a common ontology for Smart Appliances. SAREF4ENER contains SPINE and becomes part of SAREF. (see [14]).

Status

Today, SPINE is available in various solutions

- as native SPINE Resource and SPINE Protocol package, see [12]
- as part of the OCF Data Model
- mapped onto Thread
- mapped onto SHIP
- as SAREF ontology model for oneM2M

and is open to be included by further platforms.

A first demonstrator was presented at the Sustainable Energy Week in Brussels in June 2017. A Whirlpool washing machine, attached via a proprietary Whirlpool Cloud, a Miele washing machine, attached via a ZigBee Gateway and a Bosch dishwasher, attached via SHIP were connected to a Customer Energy Manager. All devices are speaking SPINE.

At the European Utility Week in Amsterdam on October, this demonstrator will be extended with a heat pump and later this year this showcase will be equipped with a EV charging station.

All devices are speaking SPINE and are fully interoperable even if devices are connected via different transport technologies.

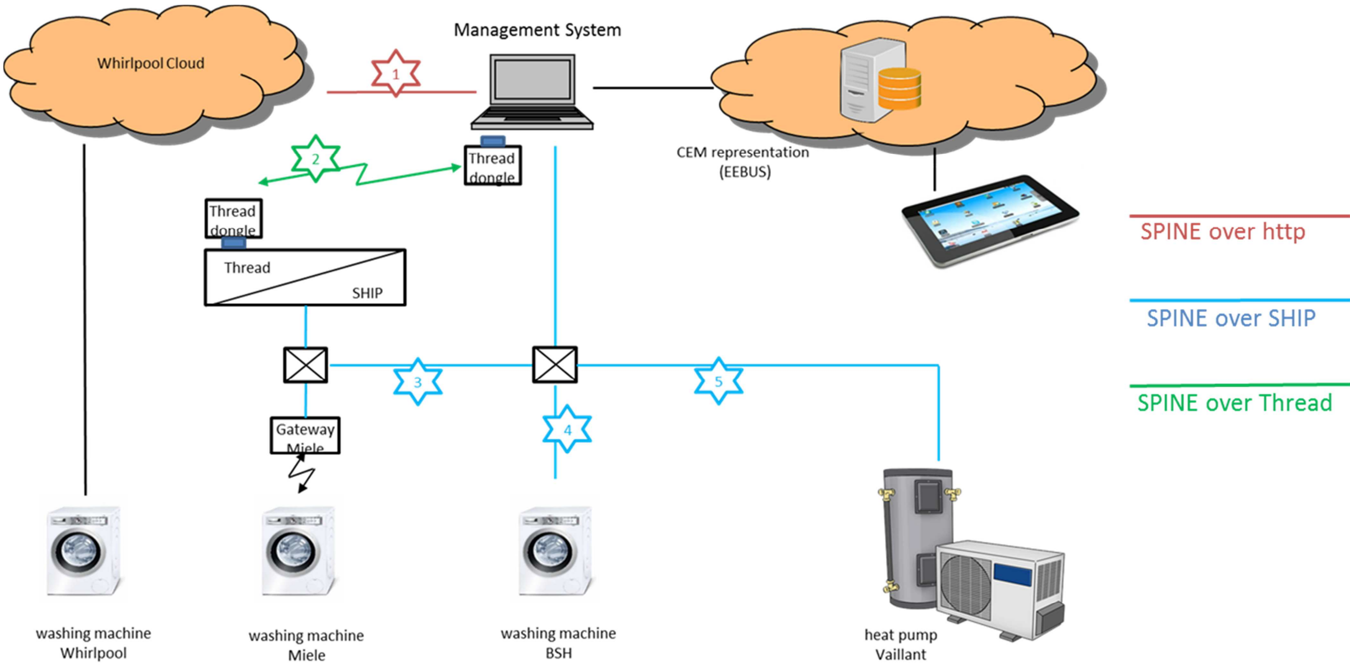

Figure 17: SPINE interoperability demonstration

Note:

CEM Customer Energy Management

Conclusion

As already denoted earlier, SPINE is covering all relevant energy related messages from the simple switch until complex functions like Demand Response and Demand Side Management.

SPINE is technology neutral.

SPINE can be transferred using various communication technologies, such as:

- SHIP (IP Ethernet & WiFi)
- Thread
- 6LoWPAN
- and so forth

SPINE can be mapped in various technologies. such as:

- OCF OneIoTa, CBOR, …
- oneM2M
- Echonet lite
- KNX
- Modbus
- and so forth

This could be a blueprint for further interoperable languages in other domains and a best practice to use SPINE in various Home Management Systems.

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Smart Grid Reference Architecture
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Extended Set of Standards support Smart Grids deployment
Overview Methodology
General Market Model Development
Smart Grid Architecture Model User Manual
Flexibility Management
Smart Grid Interoperability
Smart Grid Information Security

More information available at:
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ENERGY STAR: Energy Efficiency and the Smart Grid

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Abstract

An aging infrastructure and increased penetration of distributed energy resources drive the need for grid modernization toward a smarter, more robust, reliable, and resilient grid. One key to achieving a smarter grid is integrating a mechanism for bi-directional communication between the endpoints—utilities and consumers. Meanwhile, with the inception and growing popularity of the Internet of Things, devices that traditionally did not have network capabilities now do. When products such as electric vehicle supply equipment, thermostats, and other home devices communicate with the grid, they can play a key role in enhancing stability and reliability.

However, it is not always clear to consumers what benefits they get from purchasing such connected products. The United States Environmental Protection Agency (EPA) ENERGY STAR program has approached this challenge by defining and recognizing connected functionality in consumer products, such as pool pumps and connected thermostats, such that they offer both grid and consumer benefits. The connected functionality criteria fosters the use of open standard communications for smart grid integration, while protecting consumer interests.

ENERGY STAR has a track record of driving adoption of new efficiency technologies, for example achieving a 76% reduction in television energy use since 2008. This paper examines how energy efficiency specifications can incentivize connected functionality that promotes a more efficient smart grid and also delivers benefits to the consumer.

Introduction

The electricity delivery system in the United States and in many other countries was developed decades ago and has aged with minimal efforts to modernize it. In areas that have experienced population growth, the electricity grid can be over-used and less reliable. The strain on the current system is only expected to increase. Solely adding new power generation capacity will not increase the reliability of the aging infrastructure. While the primary focuses of upgrading the grid will be to deliver reliable electricity service, there is an opportunity to take into consideration energy efficiency and the need to better integrate renewable energy sources.

The goal of this paper is to examine the benefits of grid modernization and how EPA's ENERGY STAR program has taken on a role of promoting grid-interactive products that offer customer convenience, while also identifying potential energy efficiency opportunities that can be realized from connected products. The ENERGY STAR program framework provides a unique opportunity to help promulgate the savings potential that exists, while protecting consumer interests.

The Smart Grid

To address this widely understood problem, in 2009, the American Recovery and Reinvestment Act provided the Department of Energy (DOE) with $4.4 billion to modernize the electric grid and minimize the emissions and losses through a smart grid. A smart grid allows for bi-directional communication between the utility and its customers and includes sensors and controls that allow the electric grid to respond to changes in electricity demand[48].

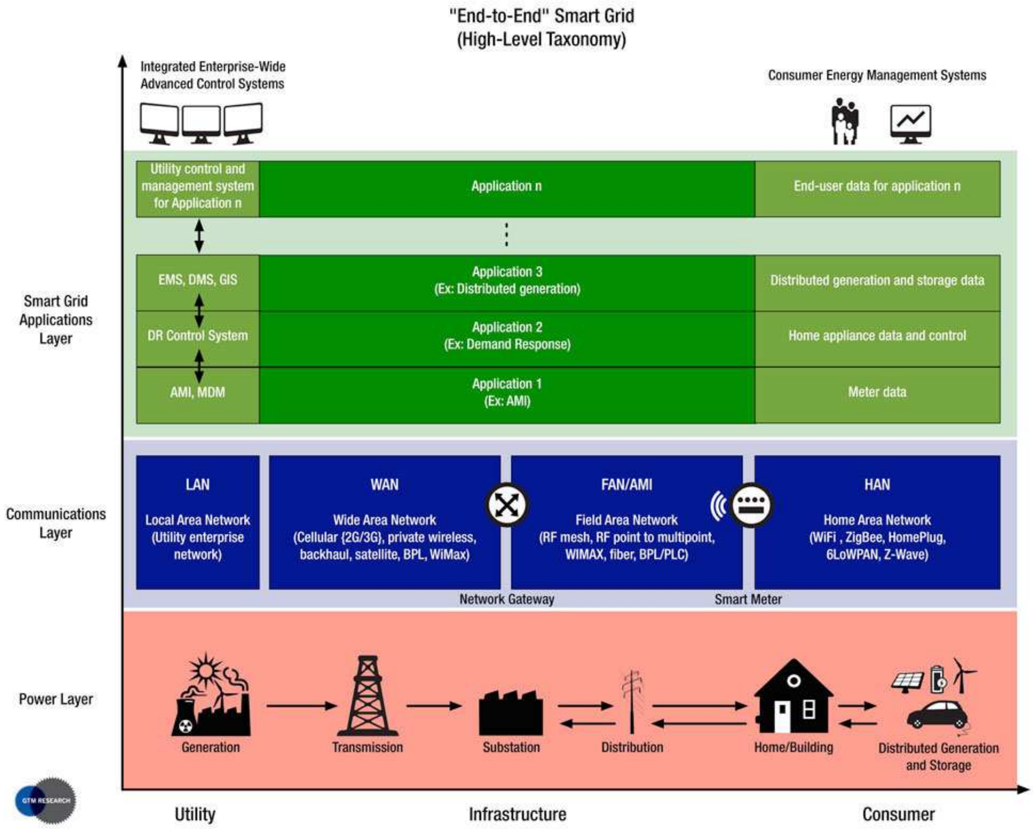

Figure 1: Layers and Connections in a Smart Grid[49]

Additionally, grid modernization has the potential to lead to additional energy saving and greenhouse gas (GHG) emission reduction. Since the U.S. transmission and distribution losses are estimated at about 5% or 190 TWH annually, each 1% reduction of those losses will save approximately 2 TWh per year[48]. As more utilities adopt Green Button, more households and businesses will have secure, electronic access to their energy use (meter) data, as well as potentially receiving actionable messages and tools to identify opportunities for additional energy savings. Finally, the smart grid can aid in evaluating, measuring, and verifying (EM&V) energy savings, further encouraging efficiency[50].

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[48] "What is the Smart Grid?", https://www.smartgrid.gov/the_smart_grid/smart_grid.html
[49] "Defining and End-to-End Smart Grid", Green Tech Media, http://www.greentechmedia.com/articles/read/defining-an-end-to-end-smart-grid
[50] GridWise Alliance, "Defining a Smart Grid Future", http://www.gridwise.org/smartgrid_whatis.asp

GridWise Alliance, an organization that furthers collaboration on building a smart grid, has identified the most important benefits that can be realized with the implementation of a smart grid, including:

- Integration of renewable technologies – utilization of clean renewable generation will be maximized by a grid that can adapt and respond to the intermittent nature of these energy sources;
- Enhanced reliability and resiliency as the smart grid will be able to distinguish between consumers that require seamless reliability and others that are less sensitive, to adjust cost of electricity appropriately;
- Monetary benefits for consumers in the form of enrolment and participation incentives as well as savings from load shifting for those consumers in Time of Use price programs;
- Identification of energy efficiency opportunities – educating consumers and businesses on their energy use patterns to pinpoint ways to save energy and money; and
- Demand Response (DR) – ability of the grid to manage power needs bi-directionally through the interconnection of interactive loads including appliances, electronics, and other products[50].

Demand Response: A Closer Look

Demand response in particular can provide an opportunity for consumers to interact with the grid and benefit from changing their electricity consumption. The U.S. Federal Energy Regulatory Commission (FERC) further defines Demand Response as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized[51]". More traditional DR implementations send signals that shut off appliances and other devices, such as water heaters and air conditioners (typically in a cycle), during peak periods. FERC's definition describes a more transactive grid where Time of Use, Real-Time, and other variable price programs encourage shifting of consumption away from capacity constrained peak periods.
To succeed in the long term, utility-implemented programs that incentivize user interaction with the grid to achieve a modification to normal consumption, or DR programs, must be cost-effective. Accordingly, utilities target widely used, highly consumptive product categories that contribute to peak load periods and for which the consumer impacts of DR are manageable. In the US, central air conditioners and electric resistance hot water heaters have been the most widely targeted products for residential DR programs. Utility interest is increasing for connected room air conditioners and pool pumps.

Efforts to Enhance Smart Grid Implementation

Implementation of the smart grid requires a change in utility business models, which will need to involve establishing incentives to include metering and communication capability in appliances and other significant residential loads[52]. A number of current efforts to facilitate this are summarized in Table 2, below.

Table 2: Programs Designed to Facilitate Smart Grid Design and Implementation

Effort/Program	Brief Description
EPRI Information and Communication Technology Program (previously IntelliGrid)[53]	A U.S. program that provides members of the power industry with information and analysis on

[51] Federal Energy Regulatory Commission (FERC), "Reports on Demand Response & Advanced Metering", http://www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp, 2015.
[52] IEEE Smart Grid, "Engineering Smart Retail Electricity Markets", http://smartgrid.ieee.org/newsletters/march-2012/engineering-smart-retail-electricity-markets
[53] Electric Power Research Institute, "Information and Communication Technology (ICT) Program", http://smartgrid.epri.com/IntelliGrid.aspx

	communications and interoperability standards, including industry best practices, to make recommendation for utility grid modernization planning
Connected Devices Alliance[54]	An informal international initiative of governments and industry under the G20 Energy Efficiency Action Plan to maximize network-enabled energy savings and minimize network and networked-device energy consumption.
GridWise Alliance[55]	A U.S. organization that created a forum for educating legislators on the need for modernization and to develop a comprehensive, industry-driven vision for the grid.
Smart Grid Interoperability Panel (SGIP)[56]	A U.S. industry consortium focused on promoting the interoperability of all grid components
Galvin Electricity Initiative[57]	A U.S. foundation whose goals include: 1. Promote regulatory reform, focused on customer needs 2. Support projects that improve quality, reliability, and security 3. Education of the advantages of small, modernized versions of the current grid
DOE Future of the Grid Initiative [58]	A U.S. effort to host regional workshops and develop an industry vision of how the grid must evolve
Institute of Electrical and Electronics Engineers (IEEE) Smart Grid[59]	An international effort of the IEEE to: 1. Encourage global collaboration 2. Provide education and research 3. Influence smart grid adoption through marketing

These initiatives have provided a foundation for moving forward the development of a smarter grid. While some of these programs focus on modernization efforts on the grid side of the meter, others address the consumer side. The ENERGY STAR program plays a role on the consumer side of smart grid development, specifically with products that communicate and react to grid conditions.

ENERGY STAR: Energy Efficiency Market Transformation

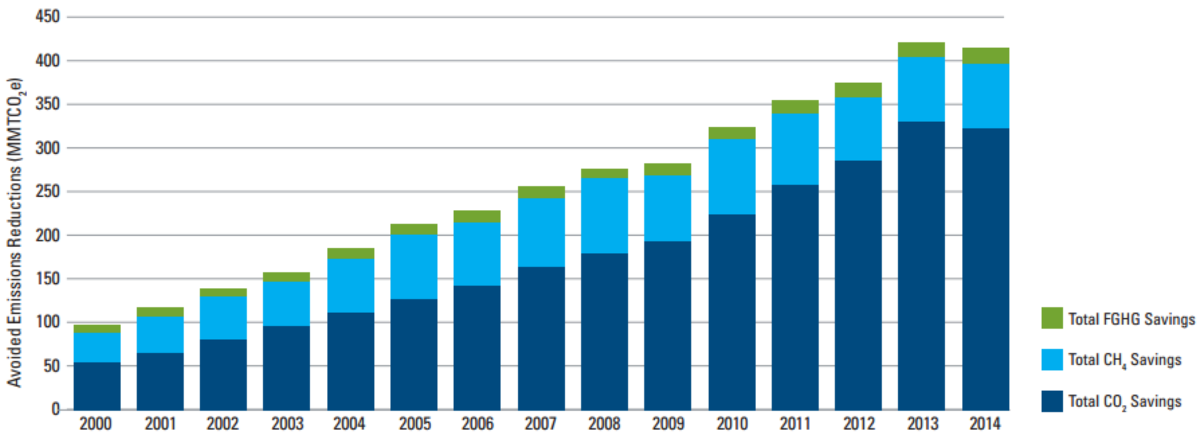
For over twenty years, the U.S. Environmental Protection Agency's voluntary ENERGY STAR program has identified the most energy efficient products, buildings, plants, and new homes, based on the latest government-backed standards and now on a rigorous third-party certification process. ENERGY STAR covers over 70 different product categories including residential heating and cooling equipment, residential appliances, home and office electronics, commercial kitchen equipment, and lighting. For each of these product categories, EPA develops a unique set of

[54] Connected Devices Alliance, "CDA Center of Excellence", http://cda.iea-4e.org/.
[55] GridWise Alliance, Inc., http://www.gridwise.org/gridwisealli_about.asp
[56] SGIP, http://sgip.org/
[57] Galvin Electricity Alliance, http://www.galvinpower.org/
[58] The U.S. Department of Energy Office of Electricity and Energy Reliability, https://www.smartgrid.gov/
[59] Institute of Electrical and Electronics Engineers (IEEE), http://smartgrid.ieee.org/about-ieee-smart-grid

efficiency and performance criteria a product must meet to earn the ENERGY STAR label. EPA's goal is to recognize the top performing products in a given market in order to encourage market transformation to more efficient products and technologies.

ENERGY STAR maintains a high market acceptance among consumers and institutional purchasers. In 2015, 88% of households recognized the ENERGY STAR label, 46% had knowingly purchased an ENERGY STAR-labeled product in the previous 12 months, and customer satisfaction with ENERGY STAR labeled products was rated a 4.2 out of 5[60]. The program continues to benefit consumers, government, and businesses across the US, with over 16,000 partners. Since the program began in 1992, it has cumulatively saved $362 billion in utility bills and avoided emissions of 2,480.8 MMTCO_2e.

Figure 3: Annual GHG Emissions Reductions from ENERGY STAR[60]



ENERGY STAR Connected Products: Advancing the Smart Grid on the Consumer Side of the Meter

EPA recognizes that numerous benefits from encouraging smart grid development will align with the guiding principles of the ENERGY STAR program, including the possibility of significant energy savings and enhanced product performance[61]. Consumer adoption has been identified as a key barrier to the spread of products that can interact with the smart grid. ENERGY STAR has a proven record of encouraging market transformation that achieves reduced GHG emissions and benefits consumers. As the majority of people interested in connected homes (70%) want to realize cost savings from energy efficiency[62], the program's efficiency message and prior success with transforming the market can be used to encourage efficiency of the grid itself, as well as to promote grid-interactive, energy efficient products to enable deeper energy savings and prevention of further GHG emissions.

The same product capabilities that offer support to a more efficient and reliable grid can also be used to offer a better product experience for consumers, and additional tools for energy savings. Whether a consumer is specifically seeking a product with these amenities, or one that can work with their utilities' demand response program(s), EPA has a role, through ENERGY STAR, in ensuring that the whole package is delivered together, along with energy efficiency. EPA has begun recognizing ENERGY STAR products that meet Connected Functionality (CF) criteria. These optional criteria are part of a number of relevant specifications, and include using open standards and open access communications to enable Demand Response and consumer focused energy saving features, all the while empowering the consumer to gain insight into their product's energy use. Although DR programs are focused on addressing utility constraints during

[60] EPA ENERGY STAR, "National Awareness of ENERGY STAR for 2015".
[61] EPA "ENERGY STAR® Products Program Strategic Vision and Guiding Principles", May 2012, https://www.energystar.gov/ia/partners/prod_development/downloads/ENERGY_STAR_Strategic_Vision_and_Guiding_Principles.pdf?1992-7400
[62] State of the Smart Home Report, Icontrol Networks, 2015.

peak periods and avoiding construction of new generating capacity (kW), it has been found that shifting loads to off-peak times also results in a roughly 3% reduction in energy use (kWh)[64].

ENERGY STAR product specifications with connected criteria that include DR readiness are shown in Table 2[63], including the recently released electric vehicle supply equipment (EVSE) and connected thermostat specifications. The criteria laid out in each of these unique product categories have the same general goal of offering consumers new convenience and energy savings features, while facilitating broader electric power system efficiency. Between 2014 and 2015, there has been a 45% increase in the recognition of ENERGY STAR connected functionality criteria by consumers[14].

Table 2: ENERGY STAR Product Specification (that are currently in effect) that contain Connected Functionality Criteria

ENERGY STAR Product Specification with Connected Functionality Criteria	Effective Date
Version 5.0 Refrigerators and Freezers	September 2014
Version 1.0 Clothes Dryers	January 2015
Version 4.0 Room Air Conditioners	February 2015
Version 1.1 Pool Pumps	March 2015
Version 7.1 Clothes Washers	March 2015
Version 6.0 Dishwashers	January 2016
Version 1.0 EVSE	December 2016
Version 1.0 Connected Thermostats	December 2016

ENERGY STAR connected criteria rely on three key requirements that can be found in some form in each of these specifications:

1. Grid communication to enable DR functionality
2. Open standards and open access to enable interconnection
3. Consumer option to override a product's response to a DR signal

The first requirement ensures that the product will be grid-interactive; having the capability to interconnect and interact with the smart grid. The second requirement, open standards and open access, encourages broad consumer and grid benefits through increased interoperability and integration with other devices and applications. Finally, by addressing consumer's ability to override, EPA helps consumers participate in grid stability without losing control of their products.

While traditional demand response (DR) programs have primarily focused on peak load reduction for system resiliency, future programs are expected to be broader. For instance, some of these end uses (pool pumps, for example) would be able to temporarily *increase* their load, which can help stabilize a grid that has a high proportion of intermittent generation. In addition, use of bi-directional communications between the utility and its customers to foster a highly transactive smart grid can enable consumers to save money and energy through effective management of their energy consumption. Lastly, products and systems that automatically adjust their energy use in response to energy prices may be useful in managing the interaction of onsite generation, storage and use of energy, whether or not a facility is grid connected. ENERGY STAR connected functionality requirements will evolve to support all of these use cases.

[63] EPA ENERGY STAR, "ENERGY STAR Connected Criteria Q&A", https://www.energystar.gov/sites/default/files/asset/document/ENERGY%20STAR%20Connected%20Criteria%20Q%26A_2.pdf

Energy Reporting and Alerts

In addition to allowing the consumer to participate in DR programs, most ENERGY STAR specifications require connected products to include energy reporting, as appropriate for the product type. Products that use energy in cycles (clothes washers and dryers, dishwashers), may report energy use for a cycle. Any product may report estimated energy use over an interval, which would make more sense for a product that uses energy continuously, like a refrigerator. Such data enables simple and actionable consumer engagement strategies to encourage energy savings. Unlike other aspects of a consumer's life, where an itemized breakdown of price is expected, electricity bills remain a black box. Customers typically have no insight into the energy consumption of any of the appliances, systems, or devices in their home or into what simple changes and strategies can save the most. Real time energy monitoring and feedback helps inform consumers to encourage adjustment of behaviours, usage patterns, and operating modes to save energy. The American Council for an Energy Efficient Economy (ACEEE) has documented annual energy savings of 9–12% from real-time feedback at the device level[64].

A similar ENERGY STAR requirement is to alert consumers to conditions that may be wasting energy, again specific to the product type. For many products, manufacturers retain significant flexibility in which energy-related alerts are implemented. A typical alert for refrigerators might be that the door of the refrigerator has been left open; for a room air conditioner, that a filter needs cleaning. Such alerts allow consumers to take prompt corrective action – in each of these cases the consumer would get improved product performance and longevity along with energy savings. With room air conditioners, consumers are able to remotely turn down their air conditioning or heat (e.g., from a smart phone) when away and turn it back on when on the way home[65].

Minimizing Impact: Standby Losses

While connected devices can provide some of these convenience and energy saving benefits to the consumer, in addition to realizing benefits of the smart grid, EPA is considering the energy impacts of the ever-increasing number of devices the remain network connected all the time. The number of connected devices will have to grow even further to enable a fully interactive grid. There are on average over 7 connected devices per U.S. household in use each day[66], a number that some expect to grow beyond 100 once not only electronics and appliances, but products such as lamps, windows, and doors, are connected[67].

To address the energy use of the connected devices we cover, EPA has included limits for network standby consumption in applicable ENERGY STAR specifications and has encouraged strategies to save energy in the whole system, such as network proxy[68] and Energy Efficient Ethernet (EEE)[69]. A network proxy allows a component within a product (or another external product) to be accessible to the network so that the rest of the product can enter lower power modes while maintaining network connection. This component is capable of waking up the product when required. EEE operates in active mode and uses less power to link the product to the network. These energy savings strategies can be found in product specifications like computers, telephony, and imaging equipment, where connectivity has long been taken for granted, but could be extended to the newer smart-grid connected products as well to decrease their energy impact.

Unique Opportunities for Connected Criteria in Certain Product Categories

Two specific ENERGY STAR product categories offer additional benefits to the smart grid. In the specification development for Connected Thermostats, ENERGY STAR has taken a unique

[64] Karen Ehrhardt-Martinez, Kat Donnelly, and Skip Laitner, Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities, ACEEE, June 2010.
[65] EPA ENERGY STAR, "ENERGY STAR Program Requirements for Room Air Conditioners", Version 4.0.
[66] Sandvine, "Global Internet Phenomena Report Spotlight", October 2016.
[67] Skip Ashton (Silicon Labs), Alex Gruzen (Witricity), Derek Peterson (Boingo), "Gazing into the Wireless Technology Future", CES, Las Vegas, January 6, 2016.
[68] ECMA International, "ECMA-393 ProxZzzy for Sleep hosts", June 2012, http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-393.pdf.
[69] IEEE, "IEEE Std 802.3az-2010 Media Access Control Parameters, Physical Layers, and Management Parameters for Energy Efficient Ethernet, September 30, 2010.

approach to promoting energy savings in the field through the use of a metric/methodology that may have broader applicability to connected devices over the coming years. In the future, EPA expects that EVSE will be able to both move charging off-peak and dispatch energy to the grid during critical peaks. These forthcoming grid-interactive features will bolster grid resiliency/reliability and can enable increased penetration of renewable energy sources.

Electric Vehicle Supply Equipment (EVSE)

Electric vehicles (EVs) have been identified as having the capability to both store and dispatch energy; providing a bi-directional flow of energy to and from the grid. Predictions indicate that EVs could account for 25% of vehicles sold in urban areas by 2030, an increase from under 1% in 2015[70]. As a result, EVs will have a large impact on the grid at certain times of the day[71]. Through the Version 1.0 EVSE Program Requirements, EPA hopes to standardize reporting of EVSE that are capable of connected functionality. In the future, EPA hopes to take this a step further by incentivizing those capable of enabling vehicle to grid (V2G) electricity flow as the EV industry develops. As such, EPA's test method for the accompanying EVSE specification development process outlines bi-directional energy flows[72].

Connected Thermostats (CTs)

By 2009, it was clear that ENERGY STAR programmable thermostats were often kept in long-term hold and thus did not achieve the desired energy savings from running a setback schedule. CTs, which became more prevalent in 2012, have several key benefits that increase realization of energy savings including:

- Sophisticated HVAC control and energy saving algorithms that update over time
- Ability to minimize energy use while accommodating 'learned' consumer comfort preferences and occupancy patterns
- Remote management that enables energy savings and enhances consumer convenience
- Analysis of CT data to demonstrate energy savings and to empower user interfaces that encourage more efficient settings

ENERGY STAR is taking a unique approach to this product category that:

- Considers a CT Device as a combination of software and hardware, recognizing the CT service providers as the partner
- Incorporates a metric and methodology to demonstrate CT field savings, regardless of how they accrue
- Allows the ENERGY STAR to be earned only after analysis of data indicates *a suitable level of annual energy savings* by deployed CTs

The requirements include the ability for consumers to set and modify a schedule and consumer access to information relevant to their energy consumption and choice of settings. ENERGY STAR CTs provide a minimum energy savings of around 8% annually, but individual products will save some consumers much more[73].

Recognizing the significant peak load contributions of residential HVAC, the ENERGY STAR CT specification includes broad DR capabilities that must be met for a CT to earn the ENERGY STAR label. More specifically, while DR is part of a set of optional connected criteria in a number of ENERY STAR products, it is mandatory for CTs. It is important to note that ENERGY STAR CT eligibility is based on annual savings estimates, and CTs are not evaluated quantitatively on demand reduction potential from the required DR sections, however the DR protocols must be implemented.

In the case of controls like CTs, where the savings come from the interaction of product characteristics and user behavior, connectivity offers the possibility of judging achieved energy

[70] Gohn, Carlos, Nissan Motor Company, CES 2017, Las Vegas.
[71] U.S. Energy Information Administration, "California leads the nation in the adoption of electric vehicles". http://www.eia.gov/todayinenergy/detail.cfm?id=19131
[72] EPA, ENERGY STAR, "ENERGY STAR EVSE Program Requirements, December 2016".
[73] EPA, "Cover Memo for ENERGY STAR Program Requirements for Connected Thermostats Version 1.0", December 2016, https://www.energystar.gov/sites/default/files/Cover%20Memo%20for%20ENERGY%20STAR%20Program%20Requirements%20for%20Connected%20Thermostats%20Version%201%200.pdf.

efficiency through analysis of field data, breaking the reliance on features that *enable* energy savings, but may not achieve it in practice.

Results of Key Smart-Grid Implementations

From 2012 to 2013, there was an almost 70% increase in the number of customers in the U.S. participating in a demand response program[74]. EIA estimated that in 2014, there were over 9.3 million customers enrolled in a program and on average customers saved about 100 kWh annually from participating. ENERGY STAR works with utilities during the development of product specifications to ensure that the connected functionality criteria reflect how DR programs are implemented. The following product categories highlight those that are of the greatest interest to utilities because they represent widely used, highly consumptive product categories that contribute to peak load periods.

Room Air Conditioners –The Version 4.0 specification incudes connected criteria under which RACs that qualify to the optional criteria may be additionally recognized as ‘connected’ on the ENERGY STAR website. In 2015, four U.S. utilities launched RAC DR programs, as follows:

- Con Edison – New York, New York
- ComEd – Chicago, Illinois
- CPS Energy – San Antonio, Texas
- National Grid – Amherst, Massachusetts and Buffalo, New York

These programs work with both traditional RACs, which require an add-on device, as well as with communicating, Wi-Fi-enabled RACs. For 2016, Con Edison will establish a retail presence to encourage consumers to apply for rebates when they purchase a connected RAC and sign up for the CoolNYC DR program. Con Edison has indicated that the rebate will completely offset the additional cost of a connected RAC.

Pool Pumps – Version 1.1 added optional criteria that enabled Pool Pumps with connected functionality to be recognized as ‘connected’ on the ENERGY STAR website. In homes that have a pool, the pool pump is commonly the most consumptive single product. Pool pumps are required in order to maintain the quality of the pool water. However, residential pools do not generally need to be pumped continuously and there is flexibility as to when pumping may occur. Connected pool pumps enable consumers to move consumption to off-peak periods and for those in a growing number of utilities, receive enrolment and participation incentives for DR programs.

Connected Thermostats – There is growing interest in both utility supplied Connected Thermostat programs and utility BYO (bring your own) connected thermostat DR programs. Some participating utilities and organizations include: Southern California Edison, ConEdison (New York City), Mass Save (Massachusetts), Efficiency Vermont, Energy Focus (Wisconsin), Energy Trust of Oregon, ComEd (Illinois), and Xcel Energy (Colorado). Many of these programs have a summer peak DR enrolment component to be eligible for the incentives/rebates, where the customer CT is configured to respond to summer peak load events. Residential central air conditioning is a primary contributor to peak loading in many US utilities, many of which have had central air conditioning DR programs for many years. Some of these programs offer an additional incentive when the customer is also a natural gas customer, anticipating a net reduction in customer use. Emphasis on anticipated net power and gas usage reduction versus anticipated DR benefits varies considerably by utility and region, and is seen in the program requirements (for DR connection) and incentive levels for a thermostat without DR incentive level, if allowed. Connected thermostats, however, provide expanded opportunities for both consumers and utilities to maximize energy savings and enable DR, while minimizing consumer comfort impacts, and reducing program implementation costs for utilities.

[74] FERC, “Demand Response & Advanced Metering”, https://www.ferc.gov/legal/staff-reports/2015/demand-response.pdf

Conclusion and Future Opportunities

Through continued development of ENERGY STAR product criteria that include connected and grid-interactive criteria, EPA seeks to deliver energy and cost savings for consumers and utilities to generate greater environmental and economic benefits. As the number of grid-connected devices increases, utilities will gain load balancing capabilities through expanded DR programs, while consumers can enjoy the resulting convenience and control over how much energy their devices consume, and when. Utility DR opportunities are expected to include signals-based load dispatch while adding price response and ancillary services. For example, in periods where capacity outstrips demand and energy prices are low, a utility signal might encourage products such as pool pumps, EV/EVSE and/or hot water heaters to temporarily increase their load, enabling decreased usage during high price peak periods. Such implementation of DR will empower consumers to more effectively manage their energy use and cost.

As broader adoption of time-of-use (TOU) electric rates increases consumer interest in connected and price-responsive products, increased consumer adoption of connected products may also accelerate utility programs' efforts to modernize the grid and more widely implement TOU, and DR programs. Within this environment, EPA is developing criteria within its product specifications to deliver grid and consumer benefits and plans to expand and adapt connected criteria to additional product categories in the future. As more products become connected, EPA's role in evaluating controls to deliver DR and energy efficiency will also grow. The ENERGY STAR Connected Thermostat specification offers a model for recognizing system controls intended to deliver energy savings.

Energy Reporting: Technology, Development, and Applications

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Abstract

Building owners and managers today rarely have good information about which devices are using how much energy, or when. In large buildings, they often don't even know what devices are present or where they are located within the building. This lack of knowledge impairs effective decision-making about changing device operating patterns, maintenance, and replacement. Instead, we could have a future where every end-use device can keep track of its own energy use and report this along with related information to the local network. We call this 'Energy Reporting'; a way for building managers to see where and how much energy is being used within the building. This ability to monitor energy usage of any device and at any resolution could help save energy through enhanced device operation, maintenance, and replacement. Energy Reporting data and mechanisms could also be used for device control.

Energy policy makers could use the data, anonymized for privacy, to observe actual device performance. This data could then be used to inform test procedures, energy standards, and ensure that software updates do not undermine device efficiency. Utilities could also use this data to base rebates on individual device operation rather than on assumed average savings thereby increasing the cost-effectiveness of such programs.

Creating this future requires an overall architecture, the implementation of such an ability in products, development of technology for communicating the data, a system to receive the data, and relevant policy guidance to support the creation and use of such a technology. This paper presents such an architecture and the status of the other needed components, with a particular emphasis on the required elements of data to be communicated, a review of potential policy drivers, and utility of Energy Reporting data in policy development.

Introduction

Reduction of energy use in buildings, and improvements in building operations, are hindered by a lack of detailed data about device energy use. Traditionally, such data have been expensive to acquire and usually required new hardware. However, advances in information technology offer opportunities to substantially remove this barrier for an ever-increasing portion of building energy use.

Today, building owners and operators usually rely only on whole-building utility billing data to understand energy use. Utility bills can be supplemented with information from a building inventory (e.g., from a maintenance schedule), manufacturer's device characteristics (e.g., rated power), and pre-defined operating schedules. However, these other sources are often unreliable, the information can be costly to obtain, and the data rarely have adequate granularity in time, product characteristics, or usage context to generate an accurate picture of energy use. Secondary sources of energy consumption data also fail to provide information about equipment that is not identified, that operates differently from the way that is intended, is malfunctioning, or is otherwise performing in a way that merits further investigation. Incorporating 'Energy Reporting' capabilities within devices can overcome these problems over time at no additional cost for devices that already have communication abilities.

We define "Energy Reporting" as the ability of a device to report information about its own energy use and related data to another device on the local network.

Products need energy to enable them to function and provide services for which they were purchased, with many requiring communication capabilities to do so. Some devices such as telephones, televisions, and network equipment are unable to function without communications while others, such as computers, can perform many useful standalone functions, but functionality expands greatly with communications. Therefore, in the current technology landscape, Energy

Reporting can be most readily added to communicating devices for free[75]—there should be no increase in manufacturing cost. While it is certainly possible to add communications to a device for the sole purpose of being able to report on energy use, this is unlikely due to the expense involved.

The following sections of the paper describe the existing technologies of Energy Reporting, how Energy Reporting works, technical details, applications for building owners, and uses for energy policy.

Existing technologies

Energy Reporting occurs today, but the number and range of devices is small—mostly a few IT devices and Power Distribution Units (i.e. sophisticated plug strips) in data centers. Also, reporting energy use information has no benefit unless a management system is available to collect the data. Our long-term goal is a future in which the great majority of energy consuming devices have Energy Reporting as a native capability, particularly in intensive energy-consuming devices, so that nearly all energy use can be tracked this way. Purchasers and building operators should come to expect Energy Reporting to be a standard feature in all products. Achieving this goal will require a number of steps, which can occur in parallel:

- Create communications standards for Energy Reporting
- Build manufacturer support for the incorporation of standards in products
- Develop management systems to acquire and interpret the data
- Deploy and use the products and management systems to analyze the data, reduce building energy use, and provide greater energy services.

Existing Data Models

If every technology relevant to Energy Reporting used the same underlying data model, then data in one format could be easily transformed into another. Unfortunately, there is a great deal of inconsistency about how different protocols and other systems encode Energy Reporting data. Table 1 shows how information as seemingly simple as the manufacturer and model number of a device is represented in a sample of a dozen plus systems [3]. These items of "general identification" are also often accompanied by others such as SKU, UPC code, retail number, description, Global Trade Item Number and version UPC (Universal Product Code), Part Number, and more. Aside from differences in terminology for the same piece of information, while most devices have two-part identities, some devices have three-part identities such as "HP LaserJet x3i". In model numbers spaces or capitalization or hyphens might be significant, or not.

[75] Any device that can communicate can compute, and so can keep track of events over time, and so can make estimates about its own operation, including energy use. This without any additional hardware.

Manufacturer	Model
vendor-identifier (a 2-byte numeric value) and vendor-name (BACnet) **Vendor** (FSGIM) **VendorName** (MODbus) **Vendor name** (VT) **deviceManufacturer and deviceVendor** (Haystack**)** **ENERGY STAR Manufacturing Partner and Brand Name** (ENERGY STAR) **Instrument/Manufacturer** (sMAP) **Manufacturer** (HPXML, XMPP, DMTF) **Manufacturer and Make** (BEDES) **Manufacturer and Brand** (NILM) **MakeModel** (CTA 2047)	**model-name** (BACnet, 70) **Model** (FSGIM, DMTF, VT, and NILM) **ModelName and ProductCode** (MODbus) **Device model number** (VT) **Instrument/Model** (sMAP) **Model Name and Model Number** (ENERGY STAR) **ModelNumber** (HPXML) **Brand and Product Line / Family Name** (TPEx) **Name** (XMPP)

Table 1. Diverse naming and structure of product metadata. (*Source*: [3])

This example is drawn from a report that evaluates about twenty different systems, covering ten major types of information as shown in Table 2. Each of these categories has one to several data items within it.

Existing end use devices

With rapidly changing technology capabilities, more and more end-use devices have the ability through one means or another to measure or estimate their own energy use. For example:

- In data centers, some computer server power supplies measure energy use and report that to the device's operating system, from where it can then be relayed outside the device. Large network equipment devices also often include such capability.
- A few commercially available lighting control systems in commercial buildings track and report energy use on individual light circuits or devices, and they are often coupled to cloud-based data systems.
- Internet connected thermostats report run-times of heating and cooling systems, also generally to cloud data systems. When combined with capacity information, a system's energy consumption can be estimated.
- Power strips are widely used to control power delivered to devices plugged into them. Advanced versions of these can monitor and report power levels and energy use of individual attached devices.
- Many Ethernet switches that deliver electricity to Power-over-Ethernet devices can monitor the power and energy delivered to each individual port.
- Energy data are particularly available for many mobile devices because maximizing battery life enhances usability. Some phones track energy use by application (albeit by %). For PCs, third-party applications are available to monitor device internal status. The example software in Figure 1 shows four voltages and six current levels from within an Apple PC, including for "DC in", from which power could be readily calculated and energy use accumulated.

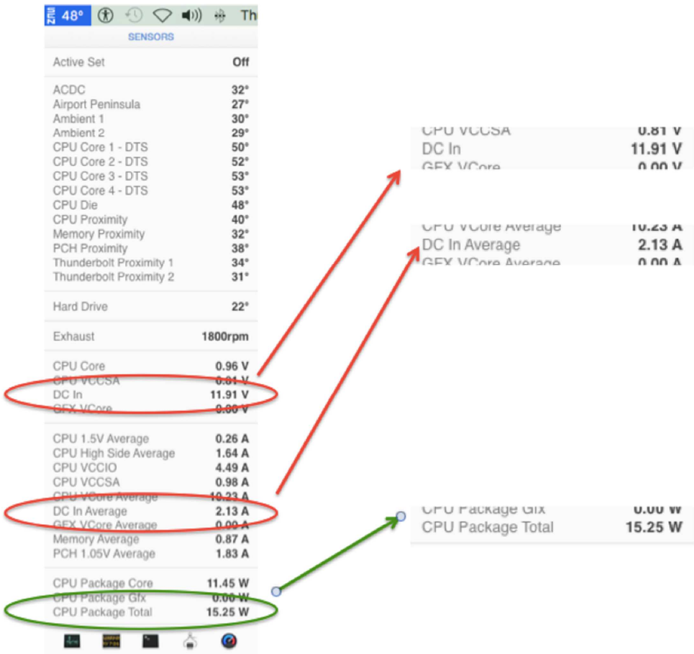

Figure 1. Example data from PC monitoring software showing power data [1]

Existing Management Systems

There are existing management systems that have the capability to collect energy use data from circuits but these are limited in their scope and not designed for use in the wide-ranging manner anticipated for Energy Reporting. Existing building management systems are complex and sophisticated by design and correspondingly expensive. Consequently, these do not appeal to building owners and managers who would rather have a system that is simple to use and inexpensive to install. Since the incentives for industry do not align with the needs of their customers in this regard, existing management systems for Energy Reporting have not been widely adopted.

Existing Policy Approaches

The most developed policy around Energy Reporting is the U.S. EPA ENERGY STAR program. Energy Star has referenced Energy Reporting as an idea for many years, beginning with enterprise servers, and more recently with other specifications including large network equipment, enterprise storage, and lamps. However, manufacturers have often resisted proposals to make such features mandatory within the specifications. In general, Energy Reporting is considered part of a larger set of "Connected" features. The program usually requires using "open" and non-proprietary standards, though in some cases allows a fully documented "manufacturer-specific method" to be used if it can accomplish the goal of access via "open" standards (these often include cloud connectivity). The requirements do not list specific protocols because the protocols have yet to be fully developed.

The ENERGY STAR specification for lamps [7] acknowledges 'Energy Consumption Reporting'. The Lamps specification notes that data on "Energy Consumption Reporting" is specified to be energy over intervals of time, and is recommended to be "reported in watt-hours for intervals of 15 minutes" but other units or time periods are allowed. In addition, other data may be reported so long as the manufacturer documents how to calculate energy data from this. ENERGY STAR acknowledges that the data are often an estimate rather than a formal measurement. The device must also be able to report "operational status (e.g., on/off)". Finally, the communication is also required to allow control of the lamp.

The specification for Enterprise Servers [8] has similar requirements but distinguishes between "measurement" and "reporting" wherein energy/power data must be measured, though processor utilization reported through the same mechanism is explicitly allowed to be an estimate. That said, the accuracy requirements are modest, and it does seem plausible that many systems could accomplish the specified accuracy with an estimate. A requirement for communications is that "Data must be made available in a published or user-accessible format that is readable by third-party, non-proprietary management software over a standard network". This addresses that the protocol must be open and essentially IP-based, but not necessarily an existing standard format.

Power measurements are just that, power levels, not accumulated energy measurements. The protocol for transferring data can be "push" (server autonomously sends out) or "pull" (external device initiates request). The device that receives the Energy Reporting data is responsible for determining the frequency at which the data are obtained, not the server. The other entity is "external management software".

Several ENERGY STAR specifications for appliances have content on Energy Reporting. In addition to content similar to that for lamps, they note that the product may also provide energy use feedback to the consumer on the product itself. On-product feedback can be in units and format chosen by the manufacturer (e.g., $/month).

System Architecture

Until recently, energy use could only be measured by dedicated meters for either an individual device or circuit. That is no longer always required as a result of recent developments:

- An increasing number of devices now have the internal ability to measure their energy consumption [2].
- Some devices can measure the electricity they provide to other devices.
- Many devices could readily estimate their own power and energy consumption.

As such data become more and more available, they have limited use if remaining internal to the device in question. They become much more useful if communicated, and so protocols are needed to convey the information across the local network. Figure 2 shows the basic architecture for Energy Reporting, where a central "management system" harvests data from many devices in a building. Energy Reporting data can be conveyed outside the building to a product manufacturer or third party, or for public policy purposes. These uses are not considered part of the basic idea of Energy Reporting (as we define it. Products can and will do such "external reporting", but it should not be considered essential or mandatory (or enabled by default), to assure consumers that the technology does not require undermining privacy.

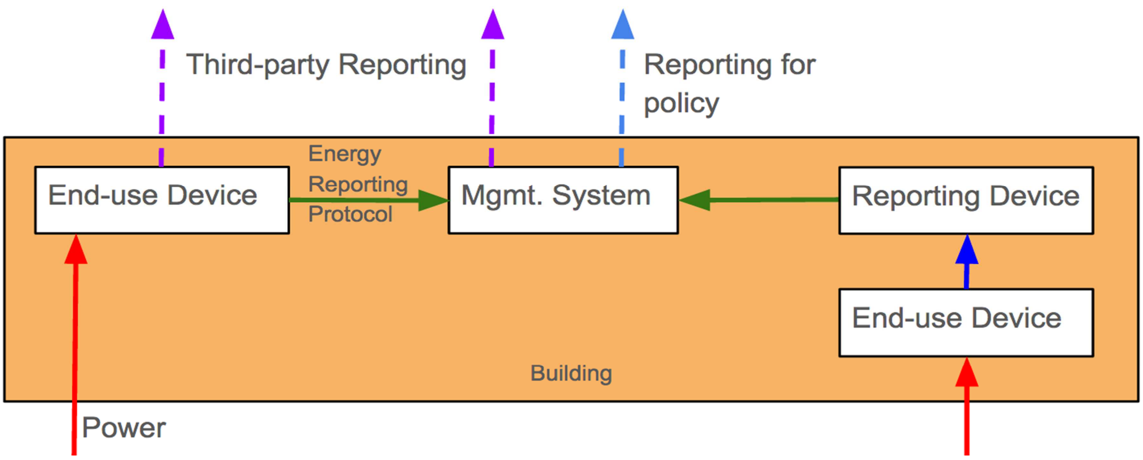

Figure 2. Energy Reporting basic architecture

The archetypal example of Energy Reporting is a device reporting on its own energy information to a single management system ("self-reporting"), using a standard Internet Protocol network. This case will likely cover most energy use and most devices.

However, in other cases a second "reporting" device has knowledge of the energy use of the end-use device consuming power which it then reports on behalf of that device ("other-reporting").

One such case is when the reporting device supplies power to the consuming device, and so can measure what is provided; examples include power strips and Ethernet switches. Another case is when a reporting device has proprietary communications to the end-use device, but is able to relay the information to the management system over a standard protocol. A third case is when the reporting device has operational information about the end-use device and so is able to provide a reliable estimate (e.g. a thermostat for an HVAC system or a lighting control system that reports on many lights).

Energy Reporting also includes the reporting of additional data such as the device type, brand, model, etc. (detailed in the next section). While such metadata are mostly static, there are exceptions; a product may change location within a building, or a device may have its hardware changed (e.g. a computer being outfitted with more memory).

The management system is a critical part of the Energy Reporting architecture with its ability to collect and analyze the reported data. To do this, it needs a discovery mechanism for identifying devices on the network. There are many standard discovery protocols that exist and can be utilized for this purpose. The management system is responsible for retrieving static data about each device and establishing a routine for querying each of them for energy and power data. Typically, the data will be collected on a fixed frequency for all devices, but can be customized to higher frequencies for ones where more granular data are useful. Similarly, the frequency of data collection can also be changed for particular periods of time of interest such as when at higher power levels, or during periods of high energy cost. Since the management system bears the entire burden of deciding the schedule for obtaining data, and for storing it, the complexity imposed on each end-use device is minimized. An alternative would be for each end-use device to accumulate its own time-series data for a time and then upload it to the management system infrequently, but this adds complexity.

While Energy Reporting often includes instantaneous data on power, voltage, and current, the most useful data point is accumulated energy use—essentially a meter reading similar to one provided by a utility meter or car odometer. With the timestamp, this provides an ongoing picture of energy use over time. If one or a few data points are missing, the total value of the remaining points is still valid.

Once the data are collected the management system can process and present them to the user numerically and graphically, aggregate them across devices, across time, or do various sorts of analyses. The details of this are beyond the scope of this paper.

Components of System Architecture

Data models

Any time that data are stored or transmitted, choices are made for how to name and represent individual pieces of information. Whether explicit or implicit, this structure is called a “data model” which is a mapping of the contents of an information model into a form that is specific to a particular type of data store or repository. A "data model" is basically the rendering of an information model according to a specific set of mechanisms for representing, organizing, storing and handling data. It has three parts:

- A collection of data structures such as lists, tables, relations, etc.
- A collection of operations that can be applied to the structures such as retrieval, update, summation, etc.
- A collection of integrity rules that define the legal states (set of values) or changes of state (operations on values) [9].

An information model which is what a data model draws upon for its content is an abstraction and representation of the entities in a managed environment, their attributes, operations, and the way that they relate to each other. It is independent of any specific repository, software usage, protocol, or platform.

Initial recommendations for the data item, name, format, and meaning are listed in Table 2 [3]. Beyond these nine core categories of data, earlier work [4] also identified seven additional ones, drawing on standards development work in the Internet Engineering Task Force [5]. These are: battery specifics, time-series data, proxy control, and more detailed data about device identification, power, energy, and reporting.

The data can be exported from this central entity to outside actors for policy purposes ("external Energy Reporting") or to a manufacturer or third party. This can be done with the same protocol as used to transfer data within the building ("local Energy Reporting"), or a variant of it. The key is to centralize policy decisions about data sharing with third parties to the building owner and operator.

End-use devices

Energy Reporting begins with individual devices assessing their own internal operation. Direct measurement can occur within an internal or external power supply [2] or in the device itself as shown in Figure 1. The most accurate data is obtained from sampling both voltage and current, but since voltages are usually within a modest range, even current data alone gives a good view of energy use.

Management system

The management system at a minimum discovers (or is instructed about) the devices it will monitor, obtains static data from each, periodically requests energy measurements, stores the data, and makes it available to a human or to another management system. Likely ordinary additional functions would be to aggregate data over time, location, and device type, and to provide summary statistics for easier user comprehension. Many additional analyses are also possible, including comparing with external data (e.g. test procedure results), and cross comparisons among devices.

Management systems that collect Energy Reporting data will rarely if ever be a stand-alone device; rather, they will be a feature of some device or system already present in the building (this to ensure it is not a source of notable additional energy use or hardware cost). In small buildings, a device like a network router that is always on (and has good network connectivity) is a good choice. In large buildings, a central management system (as for HVAC, lighting, or security) could incorporate Energy Reporting as an additional feature.

Item *Type* *Category*	**Data Type**	**Comment**
Sensors		
ItemType Units	Enumeration Text	one of: Sensor, Enumeration, Text, Float. UCUM or IEEE 1451
Identification, Unique		
UUID LocalIdentity	Uuid Text	128 bits (16 bytes) list of "keyword=value;"
Identification, General		
EntityManufacturer EntityBrand EntityModel EntityIdentityGeneral EntityURL	Text Text Text Text Text	name of Manufacturer, generally without suffix (e.g. Inc.) name of Brand if different from manufacturer, otherwise empty model number/name list of "keyword=value;"
Classification		
DeviceType	Enumeration (0..92)	Universal Device Classification [3]
Local Data		
LocalName LocalOtherInfo	Text Text	locally-determined name list of "keyword=value;"
Location		
LocationLocal	Text	list of "keyword=value;"
Power State		
PowerState	Enumeration (0..5)	
Timestamp		

TimeStamp	Float or text	unix time or RFC 3339 time
Energy Reporting		
PowerLevel CumulativeEnergy	Float Float	current electrical power in W accumulated energy use in Wh

Table 2. Summary of Data Model Needs [3]

It would be helpful to have open-source management system software freely available for a variety of platforms. This does not preclude companies from creating and selling systems with more features, just as the availability of the Linux operating system has not made alternatives such as Windows and MacOS obsolete. Free basic management systems would enable Energy Reporting to be added to any building at very low cost, with subsequent system upgrades if needed.

At LBNL we are creating a simple management system to use in demonstrations and enable anyone to be able to acquire the ability at no incremental cost, though as the technology becomes available in end-use devices we expect many free and purchased software systems to become available for managing the data.

Accuracy

Some policy purposes will require the establishment of minimum standards for accuracy, the types of data made available, and the mechanisms used to transfer the data. However, even having low accuracy data (±10%) is a good starting point for buildings with no existing information of device energy use. These factors will vary depending on the type of product, the application, and the state of technology development (how expensive or otherwise burdensome it is to attain a particular degree of accuracy), and will also evolve over time.

It is also important to distinguish between accuracy for each individual device, and the average accuracy for a brand/model based on data from a large number of devices. The data to be reported will likely include energy data as well as other data types such as general and unique device identification. Fortunately, verifying that the Energy Reporting data matches the actual energy consumed can be simple, involving only an electrical power test (in various device modes) and subsequent comparison to device-reported power, taking into account the reported accuracy levels.

Some discussions on Energy Reporting focus on whether the data are directly measured or estimated. We think this emphasis is misplaced, and that the focus should instead be on reporting the accuracy of the reported value. Measurements are commonly more accurate than estimates but either could be of low or high accuracy. The bottom line in both cases is the accuracy involved, which should be expressed as a percentage variation from the reported value that the actual value is guaranteed to be within. Many devices will have a static accuracy they can reflect for any value; others may need to maintain data to estimate the accuracy on a more dynamic basis.

Privacy and Security

Energy Reporting can potentially be used to undermine user privacy and security. Policy-makers must ensure that users fully understand the implications of decisions, and they should have to actively opt-in to sharing data with third parties if any risk could be involved. External reporting on an anonymous basis could be very useful for public policy development without undermining user autonomy or putting users at risk (a standard and trusted mechanism for this needs to be developed). While products may be sold that report data directly to an outside organization (e.g. manufacturer or service provider), such direct external reporting should not be part of any policy requirements on Energy Reporting; it should be made clear that policies only encourage or require local reporting, for the benefit of the building owner. External reporting should be optional, up to individual user's discretion.

For security, it would help to have only the reporting function enabled by default, with any device control mechanism require being actively enabled before functioning. This would also apply to any control signals from outside the building to the management system that might get passed through.

Benefits of Energy Reporting

The core utility of Energy Reporting is to provide information to building managers that they can use to save energy. Beyond the basic purpose of Energy Reporting, the data could be used for many other purposes, for the building owners and occupants, and for public purposes. Many useful IT technologies have been applied to usages not anticipated before their deployment, and/or unrelated to their original purpose. It is quite likely that Energy Reporting will follow this pattern. Each of these cases describes functionality or benefits that are not, or are not necessarily related to the primary function of a device. This makes Energy Reporting different from most network interactions, and applicable to any type of device.

Billing

A common problem in improving building energy efficiency is that the party that makes a decision determining future energy use is not the one that pays for the energy it requires. This is most common in rental contexts (residential or commercial) which have a mixture of devices bought by the owner and by the tenants. Building owners could use Energy Reporting data to bill their tenants for energy they use based on time of use, type of device, or both (and if the tenant pays the bill, the reverse could be done). Third parties that own and/or manage specific energy-using equipment, such as a vending machine or set-top box, could pay for the electricity their devices use to have the proper incentive to be efficient. Such financial arrangements would not be an electric utility relationship so that the accuracy requirements for revenue utility meters should not apply; the accuracy need only be agreeable to both parties.

Inventory

Energy Reporting systems will automatically inventory devices in a building. Today, conducting inventories is usually an expensive manual process, done periodically by companies and government agencies. With Energy Reporting, inventories can be done at very low cost as often as is useful. Obviously, devices that do not implement Energy Reporting (principally because they don’t communicate) will not appear in such inventories, but a partial list is better than none, and the device participation rate will expand over time. Energy Reporting protocols could be used to report the location of a device within a building (though how a device determines its location is outside the scope of Energy Reporting). Energy Reporting could also be used to identify unexpected usage during times when the location is unoccupied. It could also help in acquiring usage patterns to inform better equipment scheduling (e.g. based on occupancy data or equipment use) or aid in tracking equipment maintenance (e.g., filter and battery changes)

Operation and maintenance

Devices that implement Energy Reporting could self-identify potential or definite maintenance issues or failures, as could management systems that receive the data. For example, a refrigerator that suddenly requires more energy per day to maintain its normal setpoint may have a compressor or gasket malfunction. This could be identified by observation of a significant and ongoing change in consumption patterns, or by observing that the device is using significantly more than test procedure results indicate it should. The concern could be flagged to building operators, or (on an opt-in basis) to manufacturers and/or public policy organizations.

Embedded sensing

Other types of data could be relayed with Energy Reporting protocols that is unrelated to or abstracted from device functionality. For example, buildings may find it useful or important to know the ambient temperature around a device and this could be a free or inexpensive way to get additional sources for temperature data. Ambient light and sound levels could be similarly reported, as could the device’s assessment of occupancy of the surrounding space.

Policy Implications/Impacts

Energy Reporting technologies have not been developed and installed for public purposes but, once available, can provide valuable inputs to public policies. Policy applications include:

- Developing baseline energy use values — to understand how much energy that devices of a particularly type actually use in ordinary operation, including how this changes over time, to create a strong foundation for research and analysis, and inform policy decisions.
- Verification — to understand how the actual energy use of a particular brand/model compares to corresponding laboratory test procedure results. This information can also be used to improve the test procedures themselves.
- Program evaluation — to have more, better, and less expensive data than is currently available, enabling less expensive but higher quality evaluation of efficiency measures and programs.
- Rebate program design and operation — to inform utility rebate programs in amounts distributed to building owners, incentives paid to program operators, or amounts paid to manufacturers based on actual performance and tailoring incentives to individual users and products.
- Tracking performance over time — to inform policy and rebates. Products with mechanical components, and even those driven more by software, can reduce their service delivery over time, and/or increase energy use over time, from equipment degradation.
- Fixing principal-agent problems — shifting responsibility for energy costs to the technology provider. This approach—called "service provider pays"—makes the service provider responsible for the financial burden of powering equipment they place into the customer's site. "Service provider pays" ensures that these providers have the correct economic incentive to optimize the energy use of necessary technology standards (including Energy Reporting), hardware devices they deploy, and software installed on the devices.

Energy Reporting devices have additional policy benefits. Different regions may obtain greater benefits depending on their specific circumstances. We list below some of the most important benefits:

- Reducing uncertainty about analysis that informs or justifies policy actions, so that policy makers and others are more confident in them.
- Reducing data collection costs.
- Identifying or deterring manufacturers who deliberately cause products to appear to be more efficient than they actually are in standard test procedure measurements.

Public policy for energy efficiency can promote the development and use of Energy Reporting in a variety of ways such as:

- Work to guide technology development in this area
- Establish minimum standards for Energy Reporting device capabilities
- Incorporate Energy Reporting requirements into voluntary programs
- Set out a path to incorporating Energy Reporting requirements into mandatory standards
- Coordinate work with standards organizations on communication protocols
- Sponsor the development of the free, open source, management system software

Sharing Energy Reporting data with policy organizations should be encouraged but optional, and include making data anonymous and/or less granular in time, to address real privacy and security concerns. In addition to sharing with organizations with a policy interest, many companies would also like to have such data, to be able to sell services to the building or otherwise monetize the data. As with policy purposes, centralizing the buildings decision-making about such outside sharing of data and primarily keeping data within the building can help avoid unintended compromises of building and occupant privacy and security. While reporting directly from devices will occur, public policy need not encourage this.

Beyond Basic Energy Reporting

With additional data, Energy Reporting can support provide other applications capabilities. For example, many end-use devices have information about room temperature or insight into room occupancy, directly or indirectly. The Energy Reporting communications path, which can be universal to all devices, could be a mechanism by which the building as a whole could harvest such data to use for better managing the building for saving energy. There may be other such values as well that could be conveyed. The key is to bring this other data into the generic Energy Reporting data model.

Control

An Energy Management System in a building generally acquires data from end-use devices and sends out requests or commands to devices to change their functional behavior. While we define Energy Reporting to only cover passive acquisition of data, there is no reason that the technology has to be limited to that function. For most protocols that include the ability to report the power state of a device (e.g., on, off, or asleep), it is trivial to add the capability to set a state (though whether a particular device can support this feature is another matter).

That said, while there are occasional good uses for Energy Reporting protocols as a control mechanism, we expect that most control will be accomplished through other mechanisms, usually protocols specifically designed for device control.

Components, Batteries, and Aggregations

While the starting point for Energy Reporting is on entire individual devices, in some cases it can be valuable to obtain data on components, such as a fan, motor, memory unit, display, etc. At least one protocol (IETF/EMAN) provides a standard mechanism for defining structures of nested components and ways to report on their energy status. An internal battery is just another component, albeit one that can produce energy in addition to consuming it. Reporting for the product as a whole is for its connection to external electrical systems and would not be affected by power flows into or out of the battery. Devices or management systems which do not address components are not burdened by this additional complexity.

An aggregation is a summation of a collection of entities being reported on. These could be all devices in a building location, all devices on an electrical circuit, or all devices of a certain type. In addition, an aggregation could sum across components, e.g. all fans inside of products in a building. An aggregation just needs a list (of unique identifiers) of the entities it covers.

Future Work

Furthering Energy Reporting technology requires several steps as follows. These do not anticipate creating any new protocols but rather to define how to use existing ones in an interoperable way.

- Develop a reference data model for Energy Reporting data
- Define how to translate between each existing protocol and the reference data model
- Seek to harmonize new and existing protocols to the reference data model
- Build prototype devices that do Energy Reporting in line with the reference data model
- Create a free, basic management system that can receive data
- Demonstrate the complete system working to a variety of audiences
- Consider if and how Energy Reporting should be incorporated into energy codes and standards
- Consider how policy uses of the data should inform its deployment

Once the reference data model is defined, manufacturers that send out software updates to devices could "retrofit" devices already in the field with the capability, in addition to putting it into new devices. That no new hardware is required makes the technology especially easy to deploy.

Lawrence Berkeley National Laboratory is currently working on developing and prototyping a system that can do Energy Reporting. The system includes prototype hardware devices and a management system to collect the energy usage data from these devices. Simultaneously, a standard data model is also being developed that will then be proposed for adoption to standards committees.

Policy makers can promote the incorporation of Energy Reporting capabilities by mandating it as part of their procurement strategies as well as supporting research and development of the technology in collaboration with industry. LBNL expects to have content by mid-2018 that could be used to incorporate Energy Reporting into products, policies, and technology standards.

Power Distribution Topologies

A "power distribution topology" is the arrangement of connections among the source(s) of power (usually only through the utility meter), distribution points (e.g., circuit breaker panels), and end-use devices. Increasingly, this also includes local generation and local storage. Traditionally this is a tree structure of circuit breakers and panels between the meter and end-use device, but more complex arrangements are emerging. Energy Reporting can track flows through the distribution system, particularly if there are data at the circuit level to cross-check the sums of individual devices. Doing so requires having a map of what is wired to what in the building.

Most devices in buildings have a single source of power, and do not provide power to any other devices. That is, understanding their full power consumption context is no more complicated than assessing the single flow of power into the device. Other devices have more complicated relationships. Some devices obtain energy from more than one power source; this is most common in data centers where having multiple power sources increases reliability. Some devices provide power to other devices, most notably with Power Distribution Units as used in data centers, Power-over-Ethernet supplying devices (mostly phones and access points), and Uninterruptible Power Supplies (UPS).

To track power flows and account for total consumption by each electrical circuit, it can be helpful to understand how devices are electrically connected to each other. To address this need, the concept of "power interface" was developed in [6]; it derives inspiration from IT networking and was developed in that context. A Power Interface (PI) is an interface on a device through which power can flow into a device (an inlet) or out of it (an outlet). The flow of electricity within a building is determined by how power interfaces are connected to each other — the wiring topology. Thus, a key PI attribute is a list of the other interfaces to which the PI is connected. As local generation and storage are added to buildings, power distribution topologies will become more complex, particularly when the direction of flow of electricity can change on some power connections, as some technologies now provide for thereby requiring PI's to track power flows.

Conclusion

While limited examples of Energy Reporting occur today, several key barriers stand in the way of it becoming widely available and used. There is a need for a standard, reference data model, sample end-use devices that implement Energy Reporting (based on measurements or estimates), and freely available management system software. Once these are in place, we could see a rapid growth in Energy Reporting being used, and contributing to energy efficiency and other benefits.

While most end-use efficiency policies and technologies apply to the functionality of the device in question, Energy Reporting is rare in that the capability is unrelated to the primary function of any device. This is because no ordinary building device consumes energy as its primary function. Because of this, policy, technology, and usage of Energy Reporting can be horizontal across all energy use in buildings.

Energy Reporting can therefore become the basic mechanism for building owners to track and manage energy use in buildings. It could be seen as a basic function `of any device, that consumers will come to expect.

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15 TEST METHODS

Evaluation of performance tests of range hoods used for the European energy efficiency label

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Abstract

Several models of range hoods were tested by independent and accredited testing institutes. The results have been compared to the information declared by the manufacturer on the energy efficiency label and the product fiche. The measured electric power input of the lighting system and the measured grease absorption factor often differed significantly from the declared values. The reasons for these observations and the necessary steps to ensure accurate measurements and a meaningful EU energy efficiency label are elucidated. It is suggested that the ranges of the lighting efficiency classes are readjusted to fit the nowadays prevalent LED technology. Furthermore the tolerance in the regulation for the nominal electric power input of the lighting could be extended by a minimum absolute tolerance. The grease absorption test method may need a rework to achieve a satisfying accuracy.

Introduction

In the wake of climate change, a rethinking of our use of energy has to be evoked. In order to save energy through an increased efficiency of appliances, a number of international labeling programs were established. In the European Union the first energy efficiency label appeared on the public market in 1995 [1-3]. This energy efficiency label is mandatory for selected products and has the purpose to illustrate their quality of performance to the consumer. To determine all data relevant for declarations on the energy efficiency label the regulations refer to the European standards for performance measurements. The energy efficiency labels on the market must be controlled to guarantee correct declarations and thus maintain the consumer's trust. Moreover, the regulation and the test standard must be reviewed regularly to ensure accurate measurements and keep up with technological progress.

The regulation (EU) No 65/2014 [4] for range hoods refers to the European standard EN 61591. In this study several models of range hoods were tested by independent and accredited testing institutes according to EN 61591. The results were evaluated and analyzed. An overview of the current standard is given in the next section. The observed advantages and disadvantages were integrated in a review of the existing regulation and the test methods used for the energy efficiency label.

Current test standard

The standard EN 61591 comprises the test methods for: (i) volumetric airflow, (ii) effectiveness of the lighting system, (iii) grease absorption and (iv) odor extraction. The Energy Efficiency Index (EEI) for range hoods is defined in the regulation and is calculated on the basis of the volumetric airflow and the power consumption used for the ventilation and the lighting. The efficiency of the volumetric airflow is determined by the Fluid Dynamic Efficiency (FDE):

$$FDE = \frac{Q_{BEP} \cdot P_{BEP}}{W_{BEP}} \cdot 100 \qquad (1)$$

with Q_{BEP} as the flow rate of the domestic range hood at the best efficiency point, P_{BEP} as the static pressure difference of the domestic range hood at the best efficiency point and W_{BEP} as the electric power input of the domestic range hood at the best efficiency point.

The effectiveness of the lighting system is determined by measuring the average illumination E_{middle}. In addition, the regulation defined the Lighting Efficiency (LE), which is obtained by dividing E_{middle} through the nominal electric power input of the lighting system W_L:

$$LE = \frac{E_{middle}}{W_L}. \tag{2}$$

In the grease absorption test oil and water are dropped into a hot pot that has a temperature of 250 °C. The amount of dropped oil, w_d, is 44 g. As a consequence of the rapid water evaporation, nearby oil is dispersed in the air. After weighing all parts of the range hood and an additional absolute filter, the deposited oil in each part is known and the grease absorption factor g_f is calculated as follows:

$$g_f = \frac{w_g}{w_r + w_t + w_g} \cdot 100 \tag{3}$$

where w_g is the mass of oil in the grease filter, w_r is the mass of oil retained in the airways and w_t is the mass of oil retained in the absolute filter which is installed behind the exhaust opening especially for this measurement to filter all oil that has not been filtered before. The grease absorption test must be performed twice. The average of the two results is stated as the grease absorption factor of the range hood. In the regulation (EU) No 65/2014 the grease absorption factor is called "Grease Filtering Efficiency" and has the variable GFE_{hood}. The physical meaning of g_f of the standard and GFE_{hood} of the regulation is identical. In the following the Grease Filtering Efficiency will be referred to as grease absorption factor in order to achieve a consistent terminology.

The odor extraction is currently not considered on the energy efficiency label and therefore is not discussed in this study.

Performance tests

Performance tests were carried out by independent and accredited testing institutes. The measurements were performed according to the standard EN 61591. In addition, W_L was measured four times in four testing institutes for two selected range hoods in order to identify the repeatability and reproducibility of the test method. In contrast to the provisions in the legislation a value outside the allowed tolerance was not followed by a repeated test with three more samples. Therefore, there is no definitive result regarding actual legal compliance of the model. The objective of the project is rather to evaluate the method and the reasons for different results.

Results & discussion

49 different range hood models have been tested according to the standard EN 61591. The tested models are numbered consecutively "model 1" to "model 49". The results of the testing institutes were compared to the manufacturer information, when the information was available. The comparison of every measured parameter, that has a tolerance assigned in the regulation, is summarized in Table 1. In the "Comparison possible" column is the number of possible comparisons between the manufacturer information and the results of the test institute for each parameter. Sometimes a comparison was not possible, because the manufacturer information was not available, the parameter was not applicable for the particular range hood, or the range hood got broken during the test. When a comparison was possible and the result was not within the tolerance, it was listed in the "Not within tolerance" column. The last column shows the proportion of models not within the tolerance (*a* / *b*), with *a* being the number of models in "Not within tolerance" and *b* being the number of models in "Comparison possible".

Table 1. Comparison of the results obtained from the testing institutes with the manufacturer information for parameters that have an assigned tolerance in the regulation.

	Comparison possible	Not within tolerance	% not within tolerance
W_{BEP}	41	7	17
W_L	47	32	68
Q_{BEP}	41	13	32
P_{BEP}	41	12	29
Q_{max}	39	8	21
E_{middle}	46	12	26
g_f	48	23	48
P_o	18	0	0
P_s	12	6	50
L_{WA}	44	11	25

P_o is the electric power input in off-mode, P_S is the electric power input in standby mode and L_{WA} is the airborne acoustical A-weighted sound power emission.

In addition, in Table 2 the declared classes for FDE, EEI, LE and g_f have been compared to the classes obtained from the testing institute. When the institute determined a better class than the manufacturer had declared, the result was listed in the column “Better class”, when the determined class was the same, the result was listed in “Same class” and when the determined class was worse, the result was listed in “Worse class”. If no comparison was possible the result was listed in the “No comparison possible” column. The last column shows the proportion of models with a worse class (*x* / (49-*y*)), with *x* being the number of models in “Worse class” and *y* being the number of models in “No comparison possible”.

Table 2. Comparison of the declared class with the class obtained from the independent testing institute.

	Better class	Same class	Worse class	No comparison possible	% worse class
FDE	3	38	8	0	16
EEI	6	25	18	0	37
LE	9	33	7	0	14
g_f	6	16	26	1	54

In Table 3 the results of the parameters used for the calculation of LE and the LE class and the values given by the manufacturer are listed for two models.

Table 3. Comparison of W_L, E_{middle} and the class of the LE.

Model	$W_{L,manu}$ (W)	$W_{L,inst}$ (W)	$E_{middle,manu}$ (lux)	$E_{middle,inst}$ (lux)	LE_{manu}	LE_{inst}
42	6	**6,8**	683	780	A	A
45	3,3	**6,5**	320	319	A	A

The index “manu” means that the variable is declared by the manufacturer and the index “inst” means that the variable is determined by the institute. The results for $W_{L,inst}$ and $E_{middle,inst}$ that are not within the tolerance are printed bold.

In Table 1 it can be seen that W_L had the highest percentage of models not within the tolerance, while Table 2 showed that LE had the lowest percentage of models with a worse rated class. This surprising observation can be understood with a closer look at the LE class distribution among the models. Most of the models are either in the highest LE class “A” or the lowest LE class “G”, which can be explained in terms of the different technologies for lighting. The lighting is mostly achieved by either LEDs or halogen light sources. When LEDs are used the LE is in general rated far above the class threshold of class A and class B. Therefore, higher energy consumption or worse illumination does not lead to a change of the LE class. When halogen lamps are used the range hood is often already rated in the lowest LE class. This finding suggests that the ranges of the LE class, defined in the regulation, could be readjusted to better match the available technologies.

Moreover, it can be questioned if the tolerance for W_L is chosen inappropriately strict. The regulation (EU) No 65/2014 states that the determined value shall not exceed the declared value of W_L by more than 5 %. Model 42, which is shown in Table 3, exceeded this tolerance with the smallest difference between $W_{L,inst}$ and $W_{L,manu}$ of 0.8 W. Comparative tests showed that a total of 32 measurements of two range hoods at four different testing institutes had deviations of a maximum of 0.5 W. Hence, it can be concluded that all of the $W_{L,manu}$, which have a corresponding $W_{L,inst}$ not within the tolerance, could have been closer to $W_{L,inst}$ by proper measurement of the manufacturer. However, if the tolerance threshold is regarded, the demanded accuracy might surpass the achievable accuracy of the measurement. For instance Model 45, the other example shown in Table 3, has $W_{L,manu}$ = 3.3 W. Thus, a 5 % tolerance equals a total tolerance of 0.165 W, which is already below the observed deviation from the comparative tests. In the regulation the low-power modes P_o and P_s received a minimal absolute tolerance of 0.1 W in addition to the tolerance as a percentage. With the possibility of installing lighting that uses as little power as 3.3 W, it might be useful to add a minimum absolute tolerance of for instance 0.5 W to the parameter W_L as well. An additional problem is that the regulation is ambiguous in the definition of W_L. It is not clear whether W_L is the power input of the lamps alone, or whether it is the total power input of the range hood while only the lamps are turned on. Hence, some of the declared electric power inputs are probably the sum of the power inputs of all installed lamps, which does not take into account the power consumption of the electrical circuit, while the testing institutes measured the power input of the range hood while the lighting was turned on. The standard does not mention any measurement for the electric power input of the lighting system.

Table 1 shows that about half of all measured g_f are not within the tolerance. Another reason for addressing g_f is the fact that it had the highest number of models that were rated with a worse class than declared by the manufacturer, as it can be seen in Table 2.

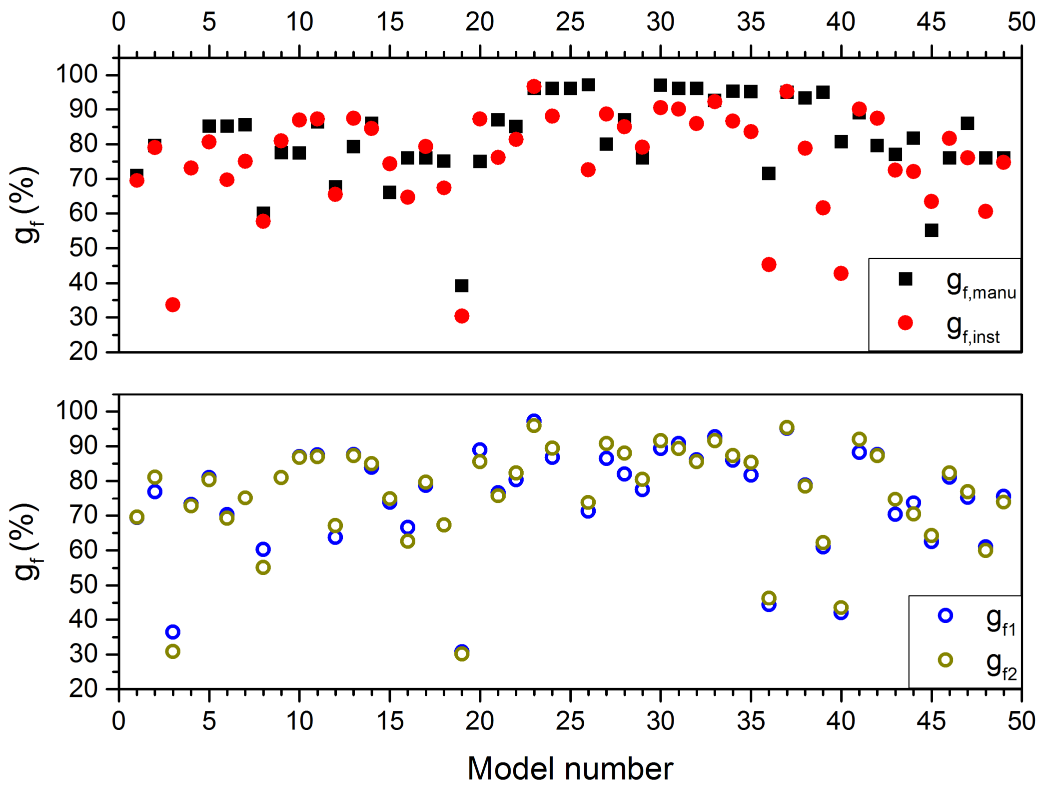

Figure 1. The top diagram shows the grease absorption factor declared by the manufacturer $g_{f,manu}$ and determined by the institute $g_{f,inst}$. The bottom diagram shows the grease absorption factor of the first measurement g_{f1} and of the second measurement g_{f2}.

Figure 1 contains two diagrams with results of the grease absorption measurements. The top diagram shows the grease absorption factor declared by the manufacturer, $g_{f,manu}$ and the grease absorption factor determined by the institute, $g_{f,inst}$. The bottom diagram shows the grease absorption factor of the first measurement g_{f1} and the grease absorption factor of the second measurement g_{f2} for each of the models. With these two variables $g_{f,inst}$ is calculated: $g_{f,inst} = (g_{f1} + g_{f2})/2$. For clarification it should be noted that in the following all statements with percentages are the unit of the grease absorption factor and not a ratio of two data points. The average deviation of $g_{f,manu}$ from $g_{f,inst}$ is 13.1 %, and the average deviation of g_{f1} from g_{f2} is 2.8 %.

The results between two measurements of g_f within one institute differ on average much less than $g_{f,manu}$ and $g_{f,inst}$. The fact that $g_{f,inst}$ is the average of two measurements and that $g_{f,manu}$ is usually the average of several measurements as well, promotes smaller differences than in the comparison of g_{f1} and g_{f2}, which are the result of only one measurement. However, g_{f1} and g_{f2} were determined in the same laboratory, while $g_{f,manu}$ and $g_{f,inst}$ were determined in different laboratories. Therefore, one explanation for the larger differences between $g_{f,manu}$ and $g_{f,inst}$ might be that the repeatability of the grease absorption test is significantly better than its reproducibility. Another explanation is that the manufacturers may tend to rate their range hoods deliberately higher than the outcomes of their own measurements. This would also explain why most of the measurements in the testing institute resulted in lower grease absorption factors than the declared ones, with on average being 5.8 % below the manufacturer information. However, it should be noted the institute has some results that are 12.1 %, 12.7 %, 15.1 % and 16.4 % higher than the respective $g_{f,manu}$. Consequently, the large differences between $g_{f,manu}$ and $g_{f,inst}$ are most likely the result of a mixture of both explanations.

When oil and water is dropped into the 250 °C hot pot during the grease absorption measurement, the water evaporates and creates oil mist as well as splashes of oil. The created oil mist is directed to the range hood by placing walls around the test rig. The oil mist deposits in the grease filter, in the interior of the range hood, its ducting or finally in an absolute filter. The total amount of deposited oil in these parts is $w_{total} = w_g + w_r + w_t$.

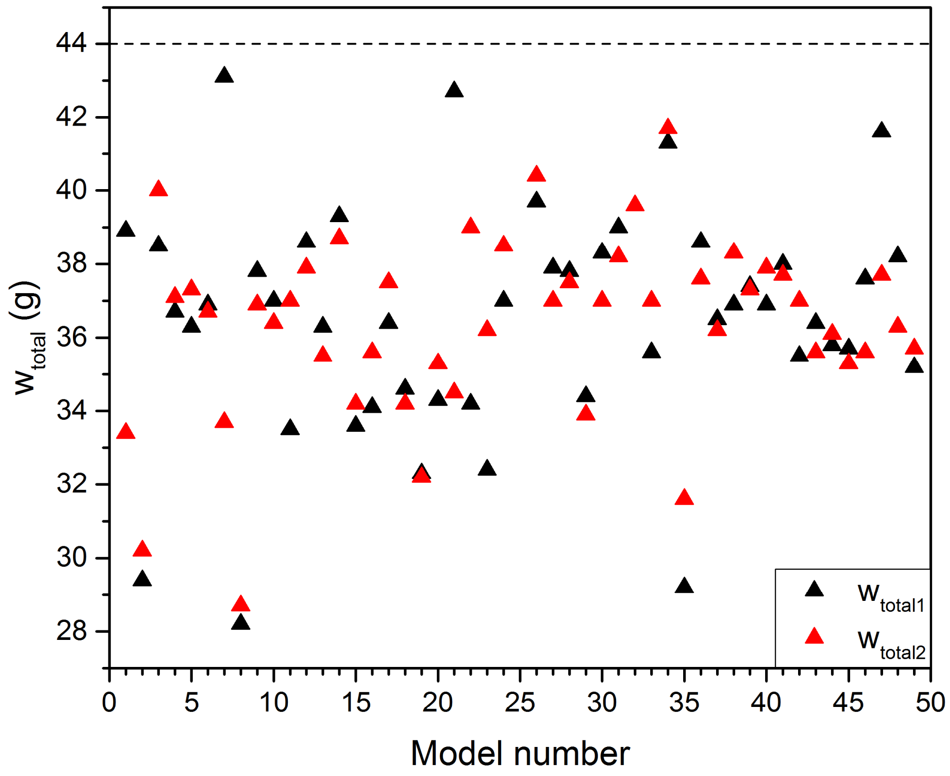

Figure 2. Total amount of weighed oil, $w_{total} = w_g + w_r + w_t$ of the first measurement (w_{total1}) and the second measurement (w_{total2}). The dashed line shows the amount of oil dropped into the pot w_d, which is 44 g.

Figure 2 is the evaluation of the same grease absorption measurements as evaluated in Figure 1. However, Figure 2 depicts the sum of the weighed oil masses of each grease absorption measurement $w_{total} = w_g + w_r + w_t$. The average difference between a w_{total1} and w_{total2} couple is 1.5 g. The average of all w_{total} is 36.5 g which is 83 % of w_d. Thus 7.5 g of the dropped oil, i.e. 17 %, could not be used for the measurement, because it was sprinkled into the surroundings, dropped out of the range hood or stayed in the pot as liquid or burnt oil. The standard deviation of all data points is 2.8 g, with deviations of up to 8.3 g being observed in single experiments, which is equal to 19 % of w_d. This is a large fluctuation, concerning that many grease filters get saturated during the test. Hence the amount of nebulized and evaporated oil has direct influence on the rating of g_f, which has a verification tolerance of 5 % according to regulation (EU) No 65/2014. A larger verification tolerance is no suitable action to deal with the large deviations since already at present more models were rated in a worse grease absorption class than models had g_f beyond the tolerance threshold. More accurate measurements of g_f might be the only efficient solution, which demands a rework of the grease absorption test method. A new grease absorption method could also include an evaluation of the range hood's ability to capture oil. So far the capture ability has no test standard and was only examined with other substances like CO_2 [5, 6].

Conclusion

The comparison of the information declared by the manufacturer with the results obtained by independent and accredited testing institutes revealed that the electric power input of the lighting system W_L and the grease absorption factor are often not within their tolerance. Although W_L was often not within the tolerance, most models were labeled with the same lighting efficiency class as determined by the testing institute. Therefore, it is suggested that the ranges of the lighting efficiency classes are readjusted to fit the nowadays prevalent LED technology. In addition, the tolerance in the regulation for W_L could be extended by a minimum absolute tolerance. Furthermore, the definition of W_L has to be clarified either in the regulation, or by adding a measurement instruction in the standard EN 61591. The grease absorption test method revealed large deviations in the results and may need a rework in order to achieve a satisfying accuracy.

References

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[2] Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products (Text with EEA relevance). ELI: http://data.europa.eu/eli/dir/2010/30/oj

[3] Commission Directive 94/2/EC of 21 January 1994 implementing Council Directive 92/75/EEC with regard to energy labelling of household electric refrigerators, freezers and their combinations. ELI: http://data.europa.eu/eli/dir/1994/2/oj

[4] Commission Delegated Regulation (EU) No 65/2014 of 1 October 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of domestic ovens and range hoods Text with EEA relevance. ELI: http://data.europa.eu/eli/reg_del/2014/65/oj

[5] https://eta.lbl.gov/sites/all/files/publications/16-pollutant-removal-efficiency-2011.pdf

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A methodology to assess consumer relevant aspects for product testing

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Abstract

Product testing is widely used to assess the characteristics, e.g. performance, energy consumption of a product. The procedures for executing the tests, including measurements and processing of measurement results, can be contained in standards. Standards should – amongst other – ensure that product tests are carried out in a uniform, standardized way so that the results accurately reflect product characteristics and differences between products in case several products are tested, and are not due to variations in conditions. Therefore, standards should produce results that are repeatable, reproducible and valid at a reasonable cost.

A number of stakeholders have questioned the validity of several standards: the results that these standards provide are different from what a consumer may experience in practice. In the end this can have negative consequences for the trust of consumers in the policy instruments (energy labels, minimum efficiency requirements) that use these standards and an energy savings deficit compared to what was expected by policy-makers. They call for standards that better reflect 'real-life' conditions, meaning those conditions that consumers experience at home. However, unlike the other criteria that standards should meet, there is no methodology to assess the correspondence to real life of a standard. An ad hoc group of CENELEC Technical Committee 59X, Performance of household and similar electrical appliances has developed such a methodology and presents the results for several household electrical appliances: washing machines, refrigerators and vacuum cleaners.

Introduction

Testing products to the requirements defined in standards is the usual way chosen by manufacturers and other economic operators when assessing characteristics such as performance and energy consumption. The results of such testing can then be used to determine if the product meets legal requirements, such as whether the energy label classification is correct, or to benchmark the product against other products." Standards should – amongst other things – ensure that tests are carried out in a uniform, standardized way so that results accurately reflect product characteristics and demonstrate in a fair way the differences between products in case several are tested.

Since such tests regularly take place within the context of European legislation, such as ecodesign and energy labelling, whereby the results are used to provide presumption of conformity and also inform consumers through e.g. product information and energy labels, this product testing should also be relevant to consumers.

Investigations by consumer and environmental organisations (Marketwatch, 2015; ComplianTV, 2015; Sivitos et al, 2015; Spiliotopoulos, 2014, Spiliotopoulos 2016) indicate that several standards describe test procedures that provide results which differ from what consumers may experience in practice. Member States are starting investigations as well (e.g. Bundesanstalt für Materialforschung und –Prüfung, 2016). Considering that the purpose of energy labelling is to influence end user's choice with the provision of accurate, relevant and comparable information on the specific energy consumption of products, information that is not relevant can misinform consumers, e.g. should the energy and financial savings materialised be far from what is expected. Although the notion that tests, especially those outlined in standards supporting legislation, should reflect typical usage conditions is not new (Toulouse, 2014), there is currently no methodology to assess the correspondence of a test method to real-life. This paper describes what consumer-relevant testing is and proposes a methodology for its evaluation within the context of standards that support ecodesign and energy labelling legislation.

Three examples are drawn from the household appliances sector, namely washing machines, refrigerators and vacuum cleaners, to demonstrate how the methodology can be applied. It is, however, the view of the authors that the methodology is relevant beyond household electrical appliances, e.g. other energy-related products. Finally, conclusions and recommendations for future study are provided, with the view to stimulate systematic discussion on the topic, and contribute to standards developed and revised being more consumer-relevant.

What is consumer relevant product testing?

Introduction: general requirements for product testing

Criteria to evaluate a test procedure/standard are (Siderius, 1991):

- Representativeness: the correspondence of the results from applying the test procedure to the results obtained in practice (at the end-users);
- Reproducibility: the consistency of results when the same product is retested under somewhat different conditions, e.g. in another laboratory, but using the same test procedure;
- Repeatability: the consistency of results, e.g. regarding energy consumption or performance when the same product is retested under the same conditions, e.g. in the same laboratory by the same staff;
- Costs: the costs for carrying out the test procedure.

The intention should be that a standard fulfils all the above objectives. Consumer relevant testing relates mainly to the first bullet. However, if it were possible to create a standard that was fully representative of results obtained in practice, but did not yield results that were repeatable, or reproducible, or could only be realised after very expensive testing, then that standard would not be fit for purpose.

An ideal test procedure should provide the same results when the product is retested in the same or in another laboratory (high repeatability and reproducibility), provide the same results found in practice and have low costs. Clearly, this combination is unlikely to be encountered in practice: a test procedure that is highly repeatable and reproducible will require, amongst others, a more detailed testing procedure, more expensive test equipment, more repetitions for statistical reasons and therefore a higher price tag. Furthermore, products can be used under different conditions, with different settings and in different modes; covering every single possible usage variation at the end-users would require multiple tests, which may in turn be associated with a higher cost.

Sometimes the phrase “real-life testing” is used, which is taken to mean measuring the product performance and/or energy consumption in practice at an end-user’s dwelling. If standards require testing to be made in one or more end-user´s dwellings, then the result will not be sufficiently repeatable and reproducible. Rather than performing “real-life testing” this document proposes instead to use “consumer relevant testing” as described in section Consumer relevant product testing.

Consumer relevant product testing

Consumer relevant product testing is product testing that provides results that correspond to results obtained when consumers use the product in practice. The general assumption is that, for a product with a given set of features, if the situational conditions, input conditions and user behaviour defined in the standard correspond to those found in practice, including also extreme conditions, as appropriate, by consumer usage then the measured performance and energy consumption can be said to be ‘consumer relevant’.

The key word in the definition is “correspond”. This section describes what is needed to assess the correspondence.

Products are operated by users and work under certain conditions (e.g. temperature, humidity), consume energy or water and other resources (e.g. detergent) to deliver a desired performance (cold space, clean laundry or dishes) within a certain time period. All these parameters influence each other. Conditions may depend on the placing of the product (e.g. kitchen, cellar, garage, attic) and may vary over the year. Relevant parameters are those that influence the performance and/or energy consumption or other inputs. This is illustrated in Figure 1.

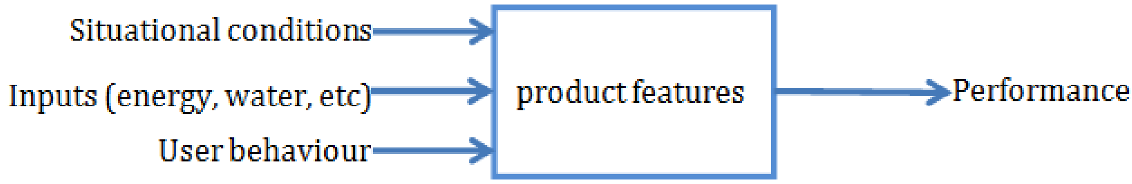

Figure 1. Demonstration of relationship and influences of parameters to performance in product testing

The following lists some of these parameters for household appliances:

Situational conditions: ambient temperature, humidity, ventilation (air circulation), lighting level, type of floor to be cleaned.

Input conditions: frequency, voltage and quality of the power supply, caloric value of gas, temperature and hardness and conductivity of water.

Product features: available programmes, attachments (e.g. nozzles) and capacity.

User behaviour: settings (installation/set-up, choice of programme), frequency of use, loading (amount and type), choice of detergent (composition and amount).

To demonstrate correspondence, it is important that: (1) the test procedure includes all parameters relevant for performance and energy consumption, (2) the variation in these parameter values reflect the variation of values at the consumers, and (3) the measured performance reflects the performance experienced by the consumer.

The methodology for assessing consumer relevant testing is based on these three aspects and is presented in the next section.

Methodology for assessing the consumer relevance of standards

The proposed methodology for checking consumer relevance of standards consists of the following steps.

1. a. List the parameters (product features, situational conditions, input conditions and user behaviour) that influence product performance or energy consumption; analyse the interactions and then select the (most) relevant parameters.

   b. Identify the main performance aspects expected by consumers and how these are experienced by consumers.

2. a. For the chosen parameters, indicate the variation found in practice and check whether it is considered in the standard being evaluated.

   b. Assess how the expected performance aspects are measured in the standard.

3. Evaluate the correspondence to practice (consumer relevant testing) of the standard according to:
   - Missing relevant parameters

- Variation in parameters taken into account
- Missing performance aspects
- Correspondence of the measurement of the performance with the experienced performance

These steps are illustrated in Figure 2.

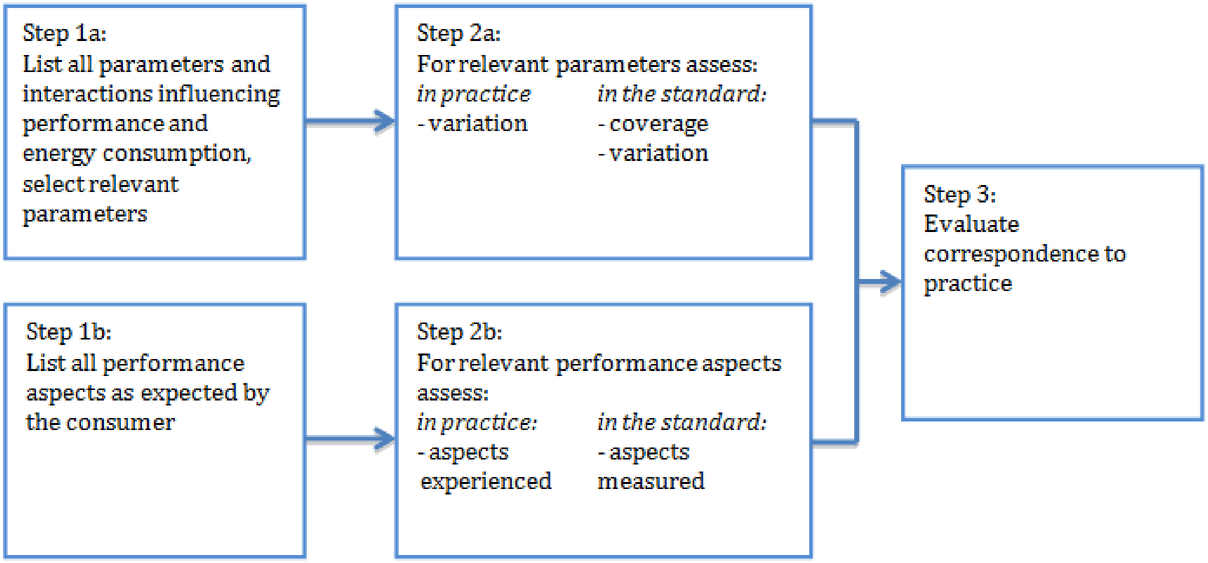

Figure 2. Steps of the methodology for assessing the consumer relevance of standards.

Step 1 involves consideration of available literature, knowledge of the principles of product operation and testing and experience with the product. The number of parameters can be very large, but the assessment focuses on the parameters considered relevant by the responsible working group. Therefore, the choice of the most relevant parameters can be guided by the influence of a parameter on performance or energy consumption. Caution is needed regarding interaction between parameters.

In Step 2, data on the product usage in practice and consumer expectations is collected. Existing literature, including preparatory studies for ecodesign and energy labelling measures, measured data from actual consumer use, consumer surveys, expert interviews can be sources of data. In Step 2a, it has to be noted that the variation of product usage in practice can be due to consumer segmentation (households with more persons use the dishwasher more often) but also geographical segmentation (households in northern Europe use clothes driers more often than households in southern Europe). Knowledge of the variation is important because average values cover the fact that the values for any individual consumer is normally below or above. Similarly in Step 2b, the challenge in identifying consumer expectation relates to the subjectivity of the observation process by the consumer. It also has to be noted that, in order to ensure that certain relevant performance levels are met in real life at all times, a value (far) above the average may need to be used in the standard, e.g. a washing machine is tested with cloths that are soiled with substances which cannot completely be removed. Also, testing declared performance claims may require a different level than the average. E.g. a washing machine is (also) tested at the declared maximum capacity and not only at the average load size at consumer´s homes. For those reasons, these values (e.g. maximum and minimum values) should be considered in the identification process.

Step 3 will be a qualitative evaluation, listing the areas that "cause" a reduction of the representativeness of the standard. This could be due to relevant parameters which are not evaluated, less variation captured by the standard, divergence between the values considered in the standard and those observed in practice or differences between actual product performance and consumer expectations on one hand, and between product performance in the lab and at home on the other. It has to be noted that on one hand, low representativeness can, in some cases, still be acceptable, whereas, in others, failing on one (important) parameter alone might be considered not acceptable. Evaluate the correspondence to practice (representativeness) of the standard according to:

- Missing relevant parameters
- Variation in parameters taken into account
- Missing performance aspects
- Correspondence of the measurement of the performance with the experienced performance

The use of three examples (see below) and evaluation of the corresponding standards is not the result of an official standardisation process or a consensus-building exercise amongst a wide pool of technical experts. Its purpose is to stimulate discussion on the methodology and provide the basis for further investigations, e.g. to identify potential shortcomings and/or the reasons for not including relevant parameters in a standard. Subsequently recommendations could be made to improve the consumer relevance of that standard if it is found that the validity is too low and/or should be improved. These recommendations need to take into account impacts on other criteria as mentioned above: repeatability, reproducibility and costs.

Application of the methodology to standards on household electrical appliances

In this section the specific aspects of applying the methodology to standards related to the performance of household electrical appliances are discussed. Household electrical appliances can be categorized in the following groups:

- Appliances that perform per cycle, e.g. washing machines and dish washers.
- Appliances that perform continuously, e.g. cold appliances.
- Appliances where continuous consumer interaction is necessary to deliver the performance, e.g. vacuum cleaners.

Each of these categories will put emphasis on a different type of parameter. Appliances that perform continuously are set-up once, probably using the default settings, and then are used by the consumer without much change. Appliances that perform per cycle will probably offer a (large) number of cycles, including settings of individual features, where the choice of the cycle has a large influence on the energy consumption.

Appliances where the consumer is active during the operation probably require extra attention how the consumer experiences the performance during operation since this will directly impact operation (and performance).

Consumer relevance evaluation of example standards

Introduction to the examples

This chapter presents the results of assessing the consumer relevance of three example standards:

- Washing machines (EN 60456)
- Household refrigerators (EN 62552:2013 with notes on future impact of IEC 62552 under development)
- Vacuum cleaners (EN 60312)

This section offers general observations, discusses specific issues on each example and then comments on the relation between the standard, the regulation and consumer relevance. The detailed assessment of each example is under preparation and will be published as a CENELEC document.

General observations regarding correspondence

The assessments show that, generally, variation of situational conditions in practice is not reflected in the standards. On the contrary, situational conditions and inputs mostly have a narrowly specified variation to achieve good test reproducibility. If the variation in practice is to be captured, this has to be done with multiple tests at various combinations of conditions and inputs, or by using a model approach. It has to be noted that using the average value of the range observed in practice does not mean that this is also the most probable value.

A second general observation is that assessment of performance in the standard is done through measurement instruments and not, as in practice, by human observations or senses. As such, this difference does not necessarily signify a correspondence problem of the standard, but that it is difficult to assess the correspondence of the standardized test with the use in practice. This would need separate, dedicated research, which in some cases (e.g. artificially soiled cloths) has been done in the past. The rationale for assessing performance aspects lies on the need to prevent product design that ensures low energy consumption, but not the fulfilment of the product's intended function.

Related to the above is that important parts of the user behaviour, especially regarding the type of load, are implemented as "artificial" in the standards, e.g. the washing machine standard prescribes artificially-soiled strips to reflect the soiling of cloths, while the vacuum cleaner one uses specially prepared dust. Whereas the artificial soiling for washing machines takes into account a number of soil types, the artificial dust for the vacuum cleaner test is less varied than the dust and soils found in practice on floors. Again, this does not necessarily signify a correspondence problem, but the difficulty of assessing correspondence. The reason for using artificial materials and measurement instruments is mainly reproducibility, repeatability and costs.

Specific observations regarding correspondence on example test standards

Washing machines

The washing machine standard can capture in principle a large number of washing programmes (type of cloths, temperatures). However, in practice, the performance delivered is not only determined by the appliance, but also by the detergent used. This combination varies with consumers and over time, since different consumers may use different detergents and the composition of commercial detergents varies over time. It is therefore apparent that similarly the correspondence to practice cannot be determined for the washing machine standard alone.

Refrigerators

The new IEC standard allows for the *calculation* of the energy consumption at any ambient temperature between the two ambient temperatures for which the consumption is measured. Furthermore, the new IEC standard allows for measuring the energy consumption of door openings and freezing and cooling capacity. The EN version will choose – as in the past – to emulate the effect by using a higher ambient temperature: 25 ^{0}C as opposed to 20 ^{0}C average kitchen temperature. Calculations (VHK (2015)) show that this difference in ambient temperature reflects a worse case situation. Although the correspondence to practice regarding door openings and the entry of food (that has a higher temperature) is considered to be sufficiently captured, revisions of the standard need to ensure that the assumptions are still valid and therefore the results of the emulation correspond to practice. Furthermore, the influence of ambient humidity and door openings on the energy consumption related to an automatic defrost cycle needs further investigation. There are several points where correspondence is considered low, e.g. regarding refrigerator volume and the load content. In these cases, a higher repeatability was prioritized over correspondence to practice.

Vacuum cleaners

In practice, there is direct feedback to consumers during vacuum cleaning: the experienced drag or force needed to move the head, visual inspection of dust pick-up. In the standard, this type of feedback is not implemented.

Relation between standard and legislation regarding correspondence

Although this paper concentrates on consumer relevance of the standards, this discussion cannot be seen outside the established legislative context, which uses the test results to provide information to consumers, and therefore plays important role. In the three standards assessed in this document, especially for washing machines, choices made in the regulation have impact on the correspondence to practice of the energy label. In this regard, two situations are identified and presented with examples.

First, a standard can in principle cover a (large) range of options (from those observed in practice) but the legislation needs to choose from these options in order to keep costs reasonable, or in order to provide confined information to the consumer. Of course, these choices should reflect practice and indeed are very important for the correspondence to practice of the information. In the washing machine standard example, a large range of washing programmes to be tested is allowed. However, the energy label for washing machines has a single efficiency indicator and the regulation needs to consider testing costs. Consequently, from the large number of programmes most washing machines have, two are chosen for the energy label: 60 ^{0}C and 40 ^{0}C cotton. Regarding the costs, the standard also influences the regulation. If the standard is revised in such a way that the cost per test decreases significantly, the regulation could choose to use more programmes without increasing the overall cost.

Second, the standard provides a result, but the evaluation of that result is done in the legislation. An example is how to deal with certain features, e.g. no-frost or climate class for refrigerators, in the energy labelling regulation. The standard specifies how a product with such a feature shall be measured, but it is the regulation that specifies whether the product will get a certain allowance (e.g. correction factor, bonus, …) on its energy consumption for this feature, how large this allowance will be and how it may be considered in the determination of the labelling class. If the allowance is larger than the impact during the test, then the label class may not reflect the efficiency in practice.

Conclusion and recommendations

This paper presents a methodology to assess the representativeness (defined as correspondence to practice) of a standard and applies it to three standards: washing machines, refrigerators and vacuum cleaners. Conclusions and recommendations regarding the methodology and the results of the examples are presented.

The methodology produces insight into the correspondence to practice of a standard, albeit at a qualitative level. It identifies and qualifies various sources that influence correspondence to practice. In general, the assessment of performance is the most difficult to evaluate because the type of assessment differs between practice and test. In the laboratory, the assessment of performance is preferably done through measurement instruments to arrive at objective results whereas, in practice, the assessment is in principle done by human observation. Without additional research, it is difficult to assess the correspondence of practice on performance aspects.

It has to be clarified that the assessments conducted here for three product standards are only examples, and are used as pilots to evaluate the methodology. Nevertheless, the following observations can be made:

- Generally, variation in situational conditions in practice is not reflected in the standards.
- As described above, the correspondence of performance in the standard versus real-life performance requirements on a product can only partially be fulfilled.
- In the washing machine standard, the artificial types of soil used show a variation that is intended to reflect variation of soil in practice. Furthermore, the detergent co-determines the correspondence to practice; however detergent composition is kept constant.
- In the refrigerator standard, no qualitative variation is applied to reflect the different load types and loading patters; only quantitative. Door openings and food load are emulated by a higher ambient test temperature. Other parameters (e.g. storage volume) are considered of low correspondence; in this case repeatability was prioritized over correspondence.
- In the vacuum cleaner standard, the variation of the dust particle size is smaller than in practice. Also, no feedback loop is implemented in the laboratory when measuring

performance, whereas in practice consumers react on the force they need to use for moving the head or dust that is not picked up.

- Finally, from the assessment is becomes clear that not only the standards but also the legislation determines the correspondence to practice related to product information.

The following recommendations are proposed:

- This new methodology assesses consumer relevance qualitatively. Quantitative assessment can be explored.
- A criterion which was not examined here but could be of future interest is that of ‘defeatability’ of a standard, in other words how easy it is for a standard to be circumvented.
- A future application of this methodology to other energy-related products and with different specificities would validate and enhance confidence in it.
- Improvements should be sought for aspects considered of low correspondence. Also, when it is decided to compensate low correspondence with other means, either in standards or regulations, assumptions and emulations should be re-evaluated during reviews, and see whether a more balanced prioritisation of criteria (e.g. repeatability over correspondence) is feasible or desirable.
- Systematic consideration of the criterion of consumer relevance for standards that used to support Ecodesign legislation. The methodology proposed in this paper could act as basis for such evaluations.
- Promote consumer behaviour studies to acquire better understanding of typical product usage at home.

Acknowledgements

The authors would like to thank all the members of CENELEC/TC 59X, especially Bernhard Scheuren, Richard Hughes and Mr Jeremy Owens for their contribution to the paper and provision of data.

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New Efficiency Metric for Fans Enables New Approaches for Efficiency Regulations and Incentives

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Abstract

Since June 2011, the American fan industry has been embarking on the odyssey of being regulated by the U.S. Department of Energy (DOE) for the first time. Nearly six years after the DOE published its intent to regulate fans, DOE has yet to publish a draft test and energy performance labeling procedure or a draft efficiency standard. It is impossible to state at the time of this paper's drafting, what the final rules will look like or when they will be issued.

There have, however, been developments in the rulemaking that provide strong indicators of what many of the key rule components may look like. A public negotiation among stakeholders under a rule-development process known as an ASRAC[76] reached agreement on how fan efficiency will be represented by metrics (FEI and an intermediary metric, Fan Electrical Power – FEP). As planned, an existing fan-test procedure will be the basis for the DOE test procedure [1]. These outcomes were reflected in the third Notice of Data Availability (NODA) published by DOE for the fan rulemaking, which gives Air Movement and Control Association (AMCA) International[77] confidence that the FEI metric has been accepted by DOE [2].

This paper explores and explains some of the innovative regulatory policy and technical recommendations which will maximize the energy savings for this product category, optimize air movement systems in buildings, maintain important customer required product utility, and do so at a reasonable cost and minimal burden to industry and customers.

Introduction

Over the past six years, the DOE fan initiative has initiated the development of relationships between AMCA and its member companies with advocacy organizations, regulators, and other associations. AMCA has worked with these organizations not only on the DOE regulation, but also on rebate programs and energy efficiency education and training.

Most importantly, the exercise has resulted in AMCA and its members developing the Fan Energy Index to replace a metric that will likely be rendered obsolete whether or not the DOE test procedure becomes final. The Fan Efficiency Grade (FEG) metric, which is an efficiency rating calculated in accordance with AMCA Standard 205 Energy Efficiency Classification for Fans [1], is used in model energy codes and standards that collectively have been adopted into at least 11 state energy codes. FEG also is used in fan-efficiency regulations in Taiwan, Thailand, Hong Kong and other Asian countries [3].

FEG has characteristics that may have caused DOE to not adopt an industry standard already so embedded in industry practice. For one thing, FEG is a fan-only metric, which treats only the aerodynamic qualities of the fan without considering the influences of motors and drives. Also, for the FEG to be effective, an application specification based on operating points must be amended to a FEG charging statement that could not be used by DOE for a product regulation. For example, "Fans must have a minimum FEG 67 rating and be sized and selected to operate within 15 percentage points of the fan's peak total efficiency. [4]" Finally, because FEG is based

[76] In 2015, DOE initiated Appliance Standards Rulemaking Federal Advisory Committee (ASRAC) to discuss negotiated energy conservation standards and test procedure for fans. For more information about ASRAC, visit http://tinyurl.com/l8cc4h5.

[77] AMCA International a not-for-profit manufacturers association based in Arlington Heights, Illinois. AMCA's member companies manufacture fans, dampers, louvers, air curtains, and other air-system products for residential, commercial, and industrial applications.

on Fan Total Pressure, it is not practical for un-ducted fans, which are sized/selected using Fan Static Pressure. This condition has forced exemptions for these fan types in existing codes and standards provisions [4].
The new metric, Fan Energy Index (FEI), is very different from FEG in many important ways, and by its nature, FEI stands to revolutionize how fans are regulated. Unlike FEG, FEI is a wire-to-air metric consistent with the regulatory approaches being taken for other motor-driven loads, such as pumps and air compressors. FEI also has the "sizing and selection" clause baked into the metric in a manner acceptable by DOE [5].

With these basic conditions in place, FEI stands to revolutionize how fans are sized, selected, and specified by practitioners. In fact, the rationale behind the development of FEI is consistent with "extended product" approach for regulating motor-driven equipment used in Europe Commission regulations for other DOE regulations. FEI takes this further by adding application-based parameters to the energy-savings opportunity, which possibly introduces new regulatory approaches to other equipment, as well.

This innovation has occurred because fans are unique from other appliances in that their operating efficiency varies significantly based on how they are applied and where they are selected within their operating performance curves. Fan application and selection is therefore far more influential than peak fan efficiency in determining the actual energy consumed by a fan. Unlike, for example, an incandescent light bulb, a fan that is least efficient in some applications may be the most efficient fan in other applications.

Instead of specifying a minimum peak efficiency level for the each of the various fan types, the FEI establishes a baseline efficiency and resulting baseline power that varies with both airflow and pressure, universally applied to all fan categories. This establishes a "range of compliant operations" rather than a single-point pass/fail efficiency threshold. Contrary to an aim to eliminate "inefficient models," the FEI metric seeks to eliminate "inefficient selections. [6]"

In the absence of a DOE test procedure, the FEI metric is currently being formalized in a rating standard by AMCA International, and concurrently being formalized in the ISO standard for fan efficiency. The harmonized AMCA and ISO FEI rating standards will prescribe how a FEI rating is calculated from data taken during performance-rating tests in accordance with AMCA and ISO standards. When finalized by DOE, FEI will eventually replace existing fan efficiency metrics in US model energy codes and standards. FEI already is being considered for utility incentive programs [6].

A Brief History of Fan Efficiency Metrics and Regulations

Although fans have existed for centuries, it wasn't until the 2007 timeframe that their energy efficiency entered the regulatory spotlight. The early thinking on fan efficiency regulations was to impose a minimum efficiency performance of 65% on fans. However, that would eliminate many fans on the market approximately 20-inches in diameter or smaller (Figure 1) [4]. This is because manufacturing constraints and the influence of bearings have a larger proportional impact on smaller fan sizes. After 20-inches, efficiencies tend to stabilize.

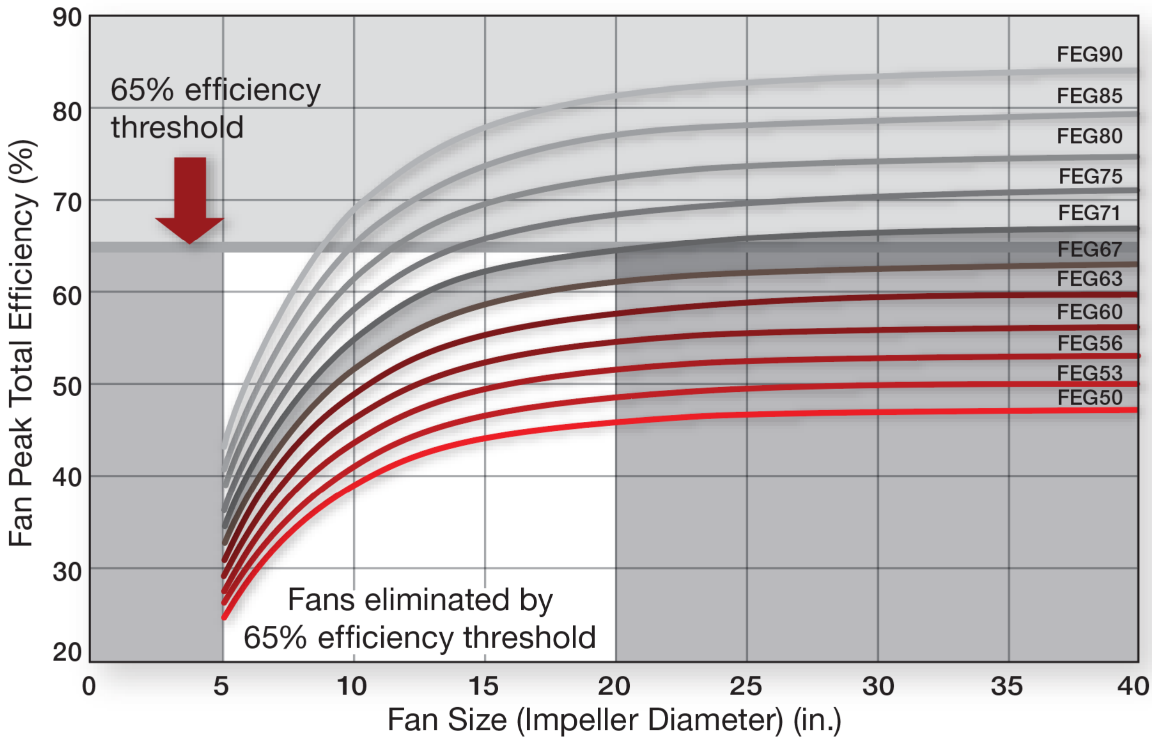

Figure 1: FEG ratings with sizing/selection window used to limit fan selections to larger sizes. FEG curves were developed from numerical analysis of fan data from manufacturers around the world. The 65% efficiency threshold was a starting point for energy standards but was removed because it eliminated fan selections below 20-in. diameter.

The FEG metric was designed around this characteristic of fans. Using numerical analysis on fan test data from a variety of manufacturers around the world and covering different fan types and sizes, FEG curves were developed to provide an index that remains constant over the fan sizes. These curves apply to fan types and sizes where a peak total efficiency can be calculated [7]. FEG curves, and associated mathematical equations embodied in AMCA 205 and ISO 12759 [8] can be used by fan manufacturers to calculate FEG ratings and by regulators to set minimum FEG requirements.

U.S. and European standards bodies worked jointly to develop the Fan Efficiency Grade metric, which was defined in rating standards published in 2010. ISO 12759 defines how to calculate FEG values from data taken during fan-rating tests. ISO 12759 also defines the Fan Motor Efficiency Grade (FMEG) metric. The difference between the two metrics is that FMEG includes the influences of motors and drives in the overall fan efficiency rating while FEG only covers the aerodynamic qualities of a “bare shaft” fan, i.e., without motors and drives. [9].

The differences in rating metrics presaged differences in regulatory approaches. ISO 12759 became the basis for the European Commission’s federal fan-efficiency regulation, EC 327, which took effect in January 2012 [10]. Beginning in 2012, AMCA 205 became the basis for fan-efficiency provisions appearing in all U.S.-based model energy codes and standards: International Green Construction Code (2012) [11], ASHRAE 90.1 (2013) [12], ASHRAE 189.1 (2014) [13], and the International Energy Conservation Code (IECC) (2015) [14].

The FEG provision remains in the subsequent editions of each of these publications, and is slowly making its way into state energy codes. To date, AMCA is aware of 11 states that have FEG-based fan-efficiency provisions by adopting model codes and standards[78]. FMEG remains in effect in Europe, with a revision underway that will not fundamentally change the metric being used [15].

[78] FEG uptake into state energy codes is coming through gradual adoption of the 2015 edition of International Energy Conservation Code and ASHRAE 90.1-2013. AMCA looked at the state-by-state adoption record of these editions at Building Codes Assistance Project (BCAP at http://bcapcodes.org/code-status/state/ and examined the published state codes to ensure the FEG provision carried through the adoption process.

DOE initiated the rulemaking for commercial and industrial blowers (CIFB) in June 2011 [16], well after the path had been set for FEG in model codes and standards. The fate of FEG being a short-term metric was effectively sealed in February 2013, when DOE published its Framework Document for the fan rulemaking [17]. The Framework Document signaled DOE's preference for a wire-to-air metric like FMEG, which was consistent with how DOE concurrently was working on a regulation for electric pumps, i.e., with a water-to-air metric.

A significant problem with FEG is that the metric alone is not sufficient to establish energy-saving regulations or code provisions. This is due to a characteristic about FEG – as mentioned earlier, by design, FEG ratings remain constant across different sizes of the same model even though fan efficiency varies with fan diameter for a given operating point (Figure 1). Hence, a manufacturer's hypothetical fan Model #123 with an FEG rating of 67 would have an FEG 67 across all its sizes. Thus, when an engineer is selecting a fan for a given application, the sizing/selection software would provide an array of sizes to select from - from, say, 18-inch (460 mm) diameter to 36-inch (920 mm) diameter (Table 1) [18].

As shown in Table 1, the fans of smaller diameter operate much less efficiently than fans of larger diameters to meet the airflow requirements at a given pressure. The airflow at a specific air pressure defines the fan's "duty point" for fan selection on a fan curve (Figure 2).

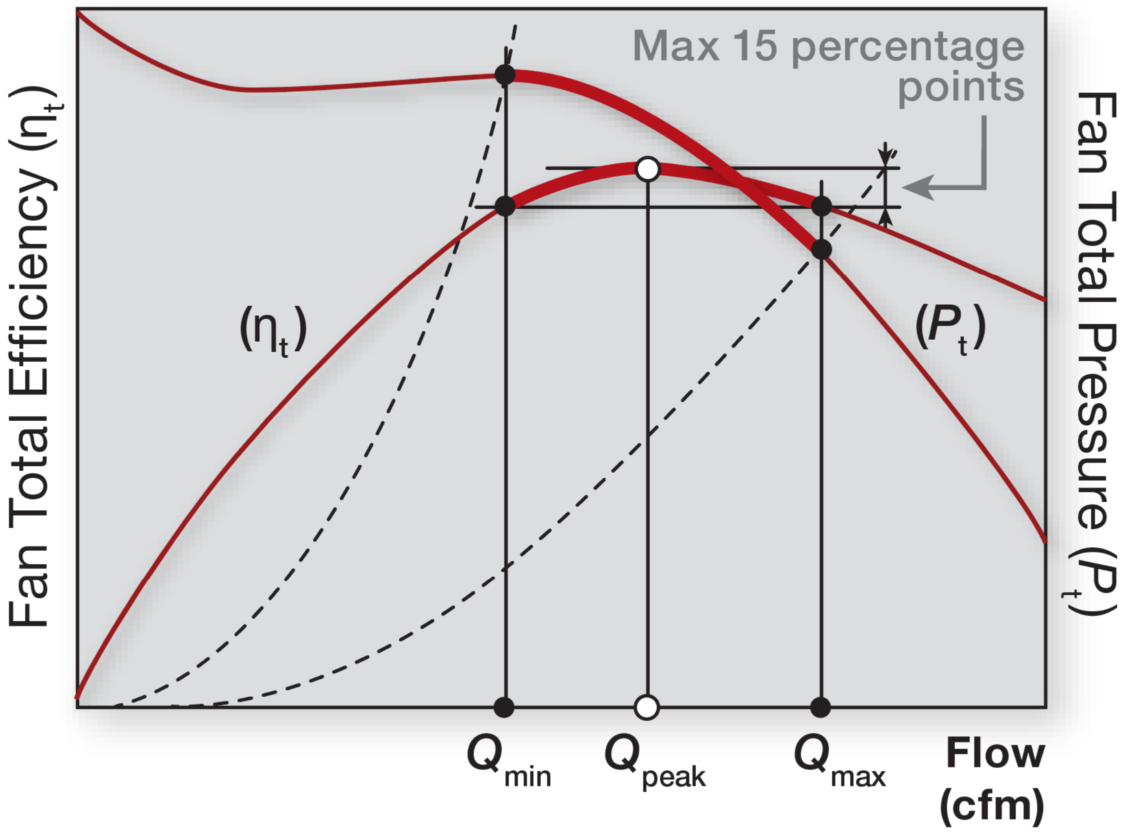

Figure 2. Typical fan curve showing total efficiency vs airflow vs total pressure. The sizing/selection window of 15 percentage points also is showing, which is applied during the design phase to lead toward higher-efficiency fan selections.

Thus, to nudge engineers toward selecting a larger fan, FEG-based code provisions must include a clause to limit fan operating points to be "within 15 percentage points of the fans peak total efficiency" (Figure 2) [19]. This clause makes FEG-based provisions more difficult to enforce because labels alone cannot be used for compliance. Code officials must go back to engineering submittals to verify the sizing/selection window is met. FEI, however, as will be shown later, has the operating point characteristics built into the calculation, so compliance officials for any program, code, or regulation need only check the FEI rating on the label [6].

Table 1: Example Impact of Fan Size on Annual Power Consumption and Operating Cost*

Diameter (in.) [mm]	FEG Rating	Total Efficiency (%)	Operating Power (hp) [kW]	Price ($)	Operating Cost Per Year ($)	Weight (lbs) [kg]
36 [920]	85	56	114 [85]	21,200	37,797	2,330 [1,056]
40 [1016]	85	62	90 [67]	16,100	29,939	2,850 [1,293]
44 [1118]	85	68	74 [55]	16,900	24,402	3,570 [1,619]
49 [1245]	85	77	60 [45]	17,600	19,926	4,170 [1,891]
54 [1372]	85	78	56 [42]	20,300	18,401	5,200 [2,359]
60 [1524]	85	81	51 [38]	23,800	16,976	6,310 [2,862]

*Data courtesy of Greenheck

Table 1 shows the output of a manufacturer's sizing/selection program for a double-width, double-inlet fan sized/selected for 80,000 cfm (37,755 l/s) at 3-in. (747 pa) static pressure. The operating costs are based on a run time of 16 hours per day, 250 days per year, and electricity cost of $0.10 per kWh. The $7,700 price differential for the larger fan is paid for in less than one year from reduced electrical costs of approximately $12,960 per year.

Table 2: Example Data Comparing FEG with FEI for Multiple Sizes of the Same Fan Model

Fan Size [in.] (mm)	Fan Speed (rpm)	Fan Power (bhp) [kW]	Actual Total Efficiency (%)	Baseline Power	FEG	FEI
18 (460)	3,238	11.8 [8.8]	40.1	7.96	85	0.67
20 (510)	2,561	9.6 [7.2]	49.5	7.96	85	0.83
22 (560)	1,983	8.0 [6.0]	59.0	7.96	85	0.99
24 (610)	1,579	6.8 [5.0]	69.1	7.96	85	1.16
27 (685)	1,289	6.2 [4.6]	75.8	7.96	85	1.28
30 (770)	1,033	5.7 [4.3]	82.5	7.96	85	1.39
36 (920)	778	6.0 [4.5]	78.7	7.96	85	1.32

Fan sizing/selection data for a FEI increases with fan size for a given baseline power requirement while FEG remains the same. Design point is 10,000 cfm (4,719 l/s) at 3.0-in. (747 pascal) total pressure.

Introducing FEI

From the ASRAC Term Sheet, FEI is calculated as the ratio of the actual fan efficiency to a baseline fan efficiency (Equation 1), both calculated at a given airflow and pressure point. Since these efficiencies are each calculated at the same airflow and pressure, FEI is also defined as the ratio of the baseline electrical power to the actual electrical power of a fan (Equation 2).

$$FEI = \frac{Fan\ Efficiency}{Baseline\ Fan\ Efficiency} \quad \text{Eq. 1}$$

$$FEI = \frac{Baseline\ Fan\ Electrical\ Input\ Power}{Electrical\ Input\ Power} \quad \text{Eq. 2}$$

Equation 2 is equivalent to Equation 1, but because the goal of mandatory and voluntary programs is to reduce wasted energy, Equation 2 is preferred because reducing electrical power consumption has more relevancy than simply increasing energy efficiency. Equation 2 also is easier to apply and has the added benefit of working along the entire fan curve.

Equation 2 suggests that there is an intermediary calculation leading to FEI which is the measurement or calculation of Fan Electrical Power (FEP). FEP is obtained either by directly measuring fan electrical input power during rating tests, or FEP is calculated by measuring fan shaft power and incorporating default values for motors and drives [1]. The default values are defined in AMCA Standard 207 Fan System Efficiency and Fan System Input Power Calculation [20], which currently is in press. Fan rating tests can be conducted using ANSI AMCA Standard 210 Laboratory Methods of Testing Fans for Aerodynamic Performance Rating [21], which the ASRAC fan working group agreed to being the basis of the DOE test standard per the ASRAC Term Sheet [1].

Once the FEP rating of a fan is known, it is compared against the baseline FEP, called FEP_{std} as shown in Equation 3. Note that FEP has engineering units of kW, which cancel out when FEI is calculated.

$$FEI = \frac{FEP_{std}}{FEP\ rating} \qquad \text{Eq. 3}$$

Table 3 shows how FEI can used for regulations and voluntary incentive programs [5].

Table 3: How FEI can be applied in regulatory and voluntary programs.

Fan Regulatory or Voluntary Program Body	Possible FEI Requirement
U.S. Department of Energy	FEI ≥ 1.0 at Design Point
ASHRAE 90.1 or International Energy Conservation Code	FEI ≥ 1.0 at Design Point
ASHRAE 189.1	FEI ≥ 1.1 at Design Point
Utility Incentive Programs	FEI ≥ 1.1 at Design Point

A useful characteristic of FEI is that for FEI ratings greater than one, the amount of energy savings over the baseline is FEI-1 on a percentage basis. So, a fan rated FEI = 1.1 uses 10% less energy than the baseline requirement. This makes FEI useful for comparing relative energy savings between any two fans, or between a fan and the FEI threshold in a fan code/standard/regulation provision.

Applying the FEI Metric

Instead of specifying a minimum peak efficiency level for the each of the various fan types, the FEI establishes a baseline efficiency and resulting baseline power that varies with both airflow and pressure, universally applied to all fan categories [5]. FEI defines a “compliant range of operation,” not a single compliant efficiency threshold. For a single speed fan curve, the compliant range is a subsection of the total fan curve (Figure 3) [22].

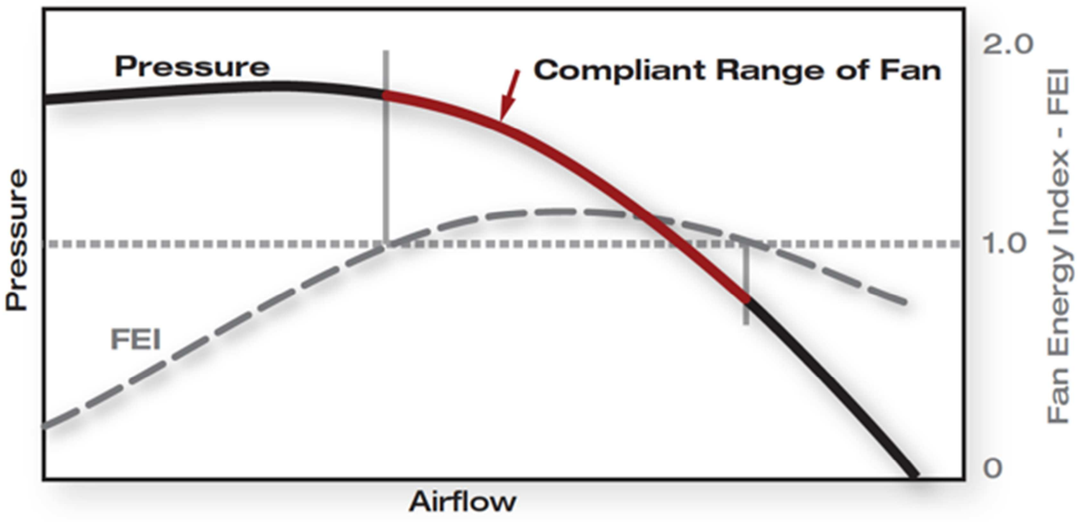

Figure 3. Compliant range of operation for a single-speed fan on a fan curve based on air pressure and airflow. The FEI curve's compliant range is FEI 1.0 and above.

On multiple speed fan curves, as would be used if a variable frequency drive (VFD) were being used, these compliant zones look like bubbles that are proportional to fan efficiency. Generally, the more efficient the fan, the larger the compliance bubble (Figure 4, Figure 5) [6]. In some cases, however, fans can be very efficient over a small operating range. The shaded regions in the figures indicate compliance FEI 1.0. Bubbles are defined within the compliance zone to indicate higher FEI levels, where applicable, and outside the compliance zone where FEI is less than zero. In Figure 5, a label for fan speed indicates the maximum speed the fan can be operated to achieve compliance. This gives operators and engineers an opportunity to set up variable speed drives and belts to restrict fan speed where needed.

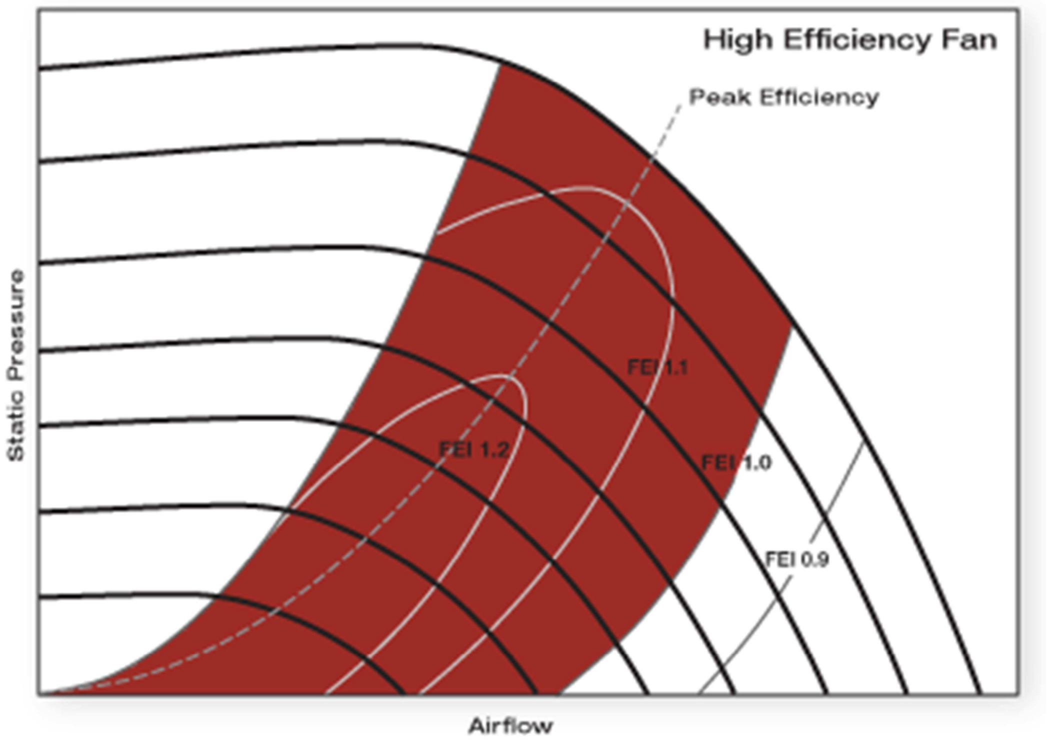

Figure 4. Compliance bubble for a high-efficiency fan operating at multiple speeds, such as those using a variable-speed drive. The colored region shows FEI 1.0 and higher with the larger FEI levels having smaller bubble regions. The high-efficiency fan has a larger FEI compliance bubble than lower-efficiency fans.

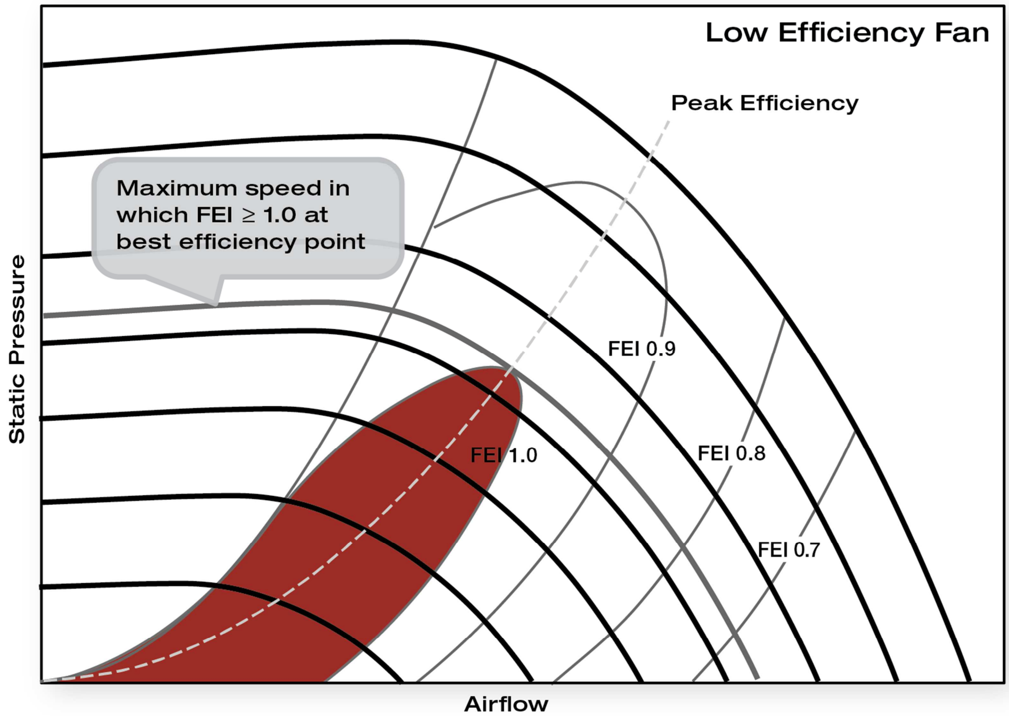

Figure 5. Compliance bubble for a low-efficiency fan operating at multiple speeds, such as with a variable speed drive. Note the smaller compliance region FEI = 1.0 compared to the higher efficiency fan in Figure 4.

Manufacturers' would include such diagrams or their tabular equivalents in product literature and sizing/selection software.

The ratio of fan power to this baseline power at design conditions is used to package the metric and make it easier to use for customers, owners, regulatory bodies and utility rebate programs to use relevant data. The baseline represents a reasonable efficiency level that is common to all fan types as they are normally applied.

The baseline value is an important component of a regulation, and needs to be selected to represent a reasonable benchmark efficiency. Regulations can be written around FEP_{std}, as documented in the ASRAC Term Sheet [1]. However, a regulation or program or written FEI of "1.0" could serve as an optimal FEI requirement, for example, for most types of fans. Exceptions where FEI is less than 1.0 could be allowable to include fans used for variable air volume (VAV) systems to encourage more use of VAV systems [6]. Fans used infrequently, such as emergency fans or fans used for material handling, could also have "less than 1.0" FEI requirements.

As shown in Table 3, high-performance-building standards (such as ASHRAE 189.1) or utility rebate programs would set FEI requirements to be greater than the baseline requirement. In the current fan efficiency provision in ASHRAE 189.1, additional stringency is added to the corresponding ASHRAE 90.1 provision by making the sizing/selection window smaller – from 15 percentage points to 10. This is because more energy is saved by further restricting fan selections to larger sizes rather than increasing the FEG rating from 67 to the next level up – FEG 71 [9, 13]. The approach taken by ASHRAE 189.1 further validates the utility of having sizing/selection criteria baked into FEI.

The FEI metric also supports the expected increased stringency in codes and regulations over time as fan technology improves. The baseline FEI can be moved, for example, from 1.0 to 1.1. This would nudge requirements higher while also preserving the integrity of fans labeled with FEI ratings set previously. A fan's label showing FEI 1.0 today showing compliance with a requirement of FEI 1.0 would be valid in the future if the requirement was raised to FEI 1.2. A building owner replacing the fan under the future regulation would replace the FEI 1.0 fan with a FEI 1.2 fan.

Absent a draft or final DOE labeling requirement, Figure 6 shows a label mocked up by Twin City Fans, for consideration in a rebate program being developed for motor-driven loads [5]. The Extended Motor Product Label Initiative (EMPLI) is a "collaborative effort involving over two dozen representatives from the motor-drive equipment manufacturing sector, trade organizations, utilities, energy efficiency program administrators, and energy efficiency nongovernmental organizations" [23]. Note in Figure 6 that both FEP and FEI are represented.

Under EMPLI, AMCA, Hydraulics Institute, and Compressed Air and Gas Institute (CAGI) represent fans, pumps, and air compressors, respectively by providing knowledge and experience in their given markets. Utilities program managers and their consultants bring program knowledge, including development, implementation, and measurement and verification [23].

For fans, EMPLI progress has been stalled due to the slow pace of DOE's fan rulemaking. However, when the AMCA FEI rating standard is complete, it should enable rebate program development and implementation.

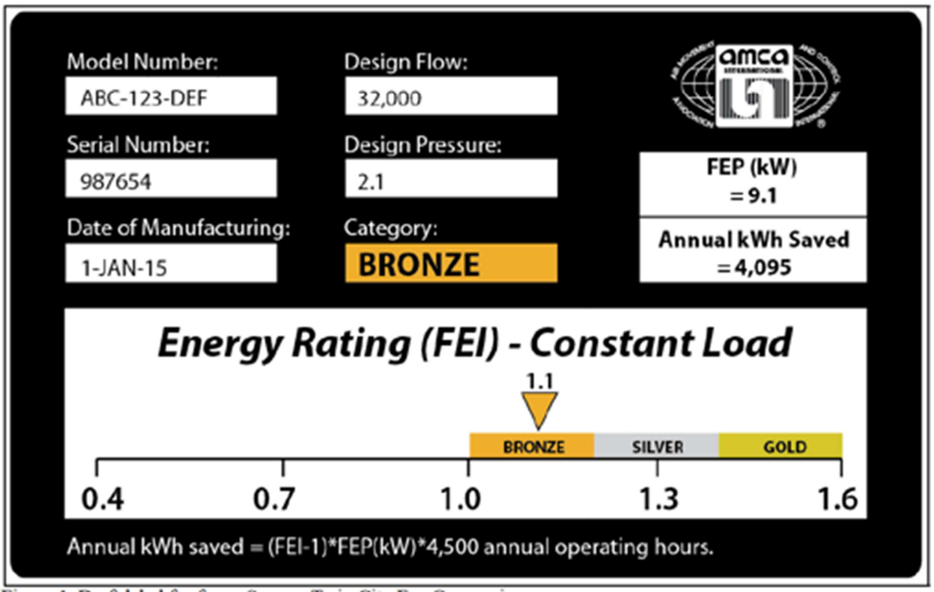

Figure 6. Draft of a possible label supporting fan rebate programs. Design flow and pressure are needed to provide context for the FEI rating. The designation of bronze/silver/gold are optional.

Fine Points about FEI

The fan energy index is calculated as a ratio of the baseline electrical power over the fan's actual electrical input power. The calculation method of AMCA Publication 207 [20] and the measurement method of ANSI/AMCA Standard 210 [21] are available to establish FEI as a wire-to-air metric. While code authorities and the DOE will establish minimum FEI (or maximum fan power) levels as they deem appropriate, fan suppliers and users have the freedom to meet these requirements in any manner they choose. A fan user can utilize any combination of fan, transmission, motor and speed control, if the combined FEI level meets the minimum requirement [1].

Even though the FEI was developed to focus on fan energy as applied, it can also be used as an application-independent metric when the design operating point is not known [5]. This would be true for fans sold off-the-shelf without a motor. In this case, the FEI is evaluated at the best efficiency point at the maximum published fan speed. If the fan on the shelf has a motor and drive, the distributor will provide the FEI bubble. By considering this single point, the metric establishes a restricted speed range while remaining consistent with its use at the design point of operation. As shown in Figure 5, the “restricted speed size” is the maximum speed the fan can be operated at to remain at FEI = 1.0 or greater.

While driving significant energy savings and technological improvements, the FEI will also help teach proper fan selection. Everywhere a consumer makes a fan selection decision, be it performance tables, fan curves or electronic selection software, the value of FEI for that selection will be shown. Consumers will know immediately how their fan selection compares to the maximum baseline fan electrical input power. They will also learn how the energy consumption of one product compares to another, regardless of product type, category, size or drive method [6].

Conclusion

FEI is a metric that allows many different types of fans to be compared on equal footing, and it does so by concentrating on the energy consumed by a fan as it is applied. It can be used by regulators and purchasers alike to make a price-sensitive market favor true energy efficiency. This can help consumers see how a fan can be affordable and efficient at the same time. Additionally, the FEI can provide manufacturers with concrete assurance they are creating energy-saving products that will appeal to their market. It is an all-encompassing, high level solution to a complex problem.

FEI was selected by DOE, AMCA and other industry stakeholders to be the metric around which a federal efficiency standard would be developed. FEI will replace FEG where used in existing energy codes and standards, and it can be applied in rebate programs for commercial and industrial fans. The long work that has gone into the development of this sophisticated and effective metric and supporting regulatory framework deserves to be brought to conclusion.

In the absence of DOE action, there are some nascent efforts to restart this process at the state level, but there are great risks to such a balkanized approach. It could result in confusion among regulators, manufacturers, distributors and customers; create a competitively un-level playing field across the country; and fail to strike the appropriate national balance of competing objectives. We hope that the commercial and industrial fan industry can finally complete its odyssey toward achieving unprecedented levels of cost-effective fan energy efficiency by application of the widely helpful metrics that have been developed.

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Why is knowledge on measurement uncertainty so important in setting policies on energy efficiency?

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Abstract

To encourage the efficient use of energy and other resources, governments all over the world have issued regulations, which mandate the provision of information to consumers or sets up essential requirements. This information is conveyed by labelling obligations or minimum requirements for placing certain products on the market. As soon as measureable values are part of those regulations, the measuring method needs to be considered. Methods for measuring resource consumption and performance characteristics should be clear and provide sufficient accuracy to project confidence to governments, consumers and manufacturers. The accuracy of a test method is expressed in terms of bias and precision. Precision, when evaluating test methods, is expressed in terms of two measurement concepts: repeatability and reproducibility. Therefore, appropriate procedures are required for determining the repeatability and the reproducibility of test methods. The repeatability of a test method should be such that different tests carried out by the same operator yield sufficiently accurate results. The reproducibility of a test method should be such that, when repeated with another measurement equipment at another location and by another operator, the results will be sufficiently similar and accurate. Both reproducibility and repeatability are measures of uncertainty, and should ideally be quantified numerically, before a measurement procedure is used for any regulation.

Reporting of uncertainty as part of the test results is essential to ensure that the measured data can be interpreted in a correct way. This is especially so when measurement data is to be compared between laboratories or when compliance with normative requirements is being determined as it is necessary to know the uncertainty associated with the measurement of a given parameter (and therefore the range within which the measured should, statistically, be found).

Introduction

To encourage the efficient use of energy and other resources, the European Commission, Parliament and Council have issued regulations which mandate the provision of information to consumers or which establish essential requirements. This information is conveyed by labelling obligations according to the Energy Labelling Directive (2010/30/EU) and ecodesign requirements under the Ecodesign Directive (2009/125/EC). According to these regulations, the information must be provided at the point of sale, in the user manuals or is required to be fulfilled for placing a product on the European market. Since compliance of the product with regulation and information provision are based on measurable limits, test methodologies are defined in approved test standards to rate the performance of applicable products. Standardisation Requests from the European Commission may be issued to Standardisation Organisations in order to develop the methodologies.

Methods for measuring resource consumption and performance characteristics should be clear and provide sufficiently accurate measurement and calculation methods to provide confidence to governments, consumers and manufacturers. The accuracy of a test method is expressed in terms of bias and precision. Precision, when evaluating test methods, is expressed in terms of two measurement concepts: repeatability and reproducibility. Therefore, appropriate procedures are required for determining the repeatability and the reproducibility of test methods developed by technical committee and its subcommittees. The repeatability of a test method should be such that different tests carried out by the same operator yield sufficiently accurate results. The reproducibility of a test method should be such that, when repeated with another measurement equipment at another location and by another operator, the results will be sufficiently similar and accurate. Both reproducibility and repeatability are measures of uncertainty, and should be quantified numerically.

Reporting of measurement uncertainty as part of the test results is essential to ensure that the measured data can be interpreted in a correct way. Measurement uncertainty is the parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measured value. This is especially relevant when measurement data is to be compared between laboratories or when compliance with normative requirements is being determined as it is necessary to know the uncertainty associated with the measurement of a given parameter (and therefore the range within which the measured should, statistically, be found). Every measurement is subject to some uncertainty. Measurement uncertainties can come from the measuring instrument, from the item being measured, from the environment, from the operator, and from other sources. This document does not address product variations or sample integrity. Sample integrity is whether the test sample was deliberately enhanced to attain higher performance during rating tests. Production variation and sample integrity are the responsibility of the manufacturer.

It is the task of each Technical Committee and Working Group of CEN and CENELEC dealing with specific performance measurement standards under the Ecodesign and Energy Labelling Directives to include information about the uncertainty of all the values measured and used for declaration of product performance. There are plenty of textbooks and existing standards on statistics and measurement uncertainty assessment, like ISO/IEC Guide 98-3:2008 [1], ISO/IEC 17025 [2], ISO 3534 [3] or ISO 5725 [4]. However, those documents often target statisticians and scientific experts and do not provide a concise document for practitioners on how uncertainties are to be assessed in the context of ecodesign.

Scope

This document provides guidance on how to assess and express the uncertainty of measurements for the determination of levels of repeatability (intra-laboratory variability) and reproducibility (inter-laboratory variability) for products under the Ecodesign or Energy Labelling Directives (2009/125/EC, 2010/30/EU). This includes round robin test (RRT), also sometimes called a ring test, as one of the tools to gather and analyse this data, especially with regard to mass production products.

This document does not cover the development of measurement methods, which are the sole responsibility of the Technical Committees developing the relevant standards. Instead it deals with gathering and evaluating the information needed by a manufacturer so that values can be stated after a product has been subjected to an agreed-upon test. The information on reproducibility of a measurement is also relevant for market surveillance authorities that must apply the verification tolerance in the context of a policy regulation under Ecodesign. This verification tolerance defines the permitted range of variation that the value of a parameter measured by market surveillance authorities during a product compliance verification procedure may have. This document does not deal with:

– the production variability of a product;

– how closely the measurement method reflects the normal use of the product.

General advice on proficiency testing of laboratories is given in EN ISO/IEC 17043 [5]. Further information on test laboratory practices can be found in EN ISO/IEC 17025 [2].

Assessment of repeatability and reproducibility

Repeatability is defined as the precision under repeatability conditions. This means conditions where independent test/measurement results are obtained with the same method on identical test/measurement items in the same test or measuring facility by the same operator using the same equipment within short intervals of time

Reproducibility is defined as the precision under reproducibility conditions. This means conditions where independent test/measurement results are obtained with the same method on identical test/measurement items in different test or measurement facilities with different operators using different equipment, but all in line with the measurement standard to be assessed.

To encourage the efficient use of energy and other resources, national governments and regional authorities have issued regulations which mandate the provision of information to consumers regarding the energy and/or water consumption of products and associated performance characteristics. This information is usually conveyed by labels attached to products at the point of sale and by brochures provided by manufacturers.

Methods for measuring values for energy and water consumption and performance characteristics should be of sufficient accuracy to provide confidence to governmental market surveillance authorities, consumers and manufacturers.

The accuracy of a test method is expressed in terms of *bias* and *precision*:

Bias is defined as the difference between the expectation of a test result or measurement result and a true value. In practice, bias, as the total systematic error, may not be specifiable. This is because the true value of a measurement cannot be known and is therefore it is substituted by the accepted reference value. This could be calculated as a mean value of a specified set of measurements, e.g. results from a round robin test.

Precision is defined as closeness of agreement between independent test/measurement results obtained under stipulated conditions. Precision, when evaluating test methods, is expressed in terms of two measurement concepts: *repeatability* and *reproducibility*. Therefore, standard procedures are required for determining the repeatability and the reproducibility of test methods developed. The *repeatability* of a test method should be sufficiently accurate for comparative testing. The *reproducibility* of a test method should be sufficiently accurate for the determination of values which are declared and for checking these declared values. Repeatability and reproducibility are determined by intra-laboratory and inter-laboratory testing procedures, called round robin test.

Values for repeatability and reproducibility are assessed to determine whether a method of measurement is suitable for comparative testing only, or if they are suitable for the measurement of declared values within a regulatory context.

For comparative testing, a minimum level of repeatability of the measurement method is required.

For the declared values, a minimum level of reproducibility of the measurement method is required.

The following requirements must be taken into account when assessing the reproducibility and/or repeatability of a test method:

a) repeatability and reproducibility of a test method has to be assessed by an intra-laboratory and inter-laboratory test respectively

b) standard deviations shall be significantly lower than the basic assessment ranges;

c) the necessary number of tests and laboratories participating in an inter-laboratory test depends on the type of product and shall be established by the responsible technical body. With respect to a statistical evaluation of the test results, at least five test results from each of at least five laboratories, excluding any outlier, should be available;

d) the test procedures must be specified completely and accurately, including the rounding of values from measurement results, the accuracy of the measuring instruments and the environmental conditions, as appropriate;

e) wherever possible, precise values of intermediate results (without rounding) should be recorded and used in subsequent calculations to ensure that the final result is as accurate as possible;

f) the test laboratories shall adhere to the test procedure specified in the standard or in the test programme;

g) only products with low production variability shall be used;

h) the reference product, if any, shall have the lowest variability.

Determination of standard deviations

The standard deviations of repeatability and reproducibility serve as a parameter for assessing:

– the suitability of a measurement method;

– the repeatability or reproducibility of a measurement method with respect to the product group concerned;

The repeatability standard deviation *sr* of a test method is calculated from the equations:

$$s_{L,i} = \sqrt{\frac{1}{n_i - 1}\sum_{k_i=1}^{n_i}\left(x_{k\,i} - \bar{x}_i\right)^2} \quad (1)$$

where

$s_{L,i}$ is the repeatability standard deviation within laboratory *i*;

n_i is the number of test results;

x_{ki} is the particular test result;

$\bar{x}_i$ is the arithmetic mean value of n_i test results x_k of laboratory *i*.

$$s_r = \sqrt{\frac{1}{p}\sum_{i=1}^{p} s_{L,i}^2} \quad (2)$$

where

p is the number of laboratories participating in the inter-laboratory test.

The reproducibility standard deviation s_R of a test method is calculated from the equations:

$$x_m = \frac{1}{p}\sum_{i=1}^{p}\bar{x}_i \quad (3)$$

$$n = \frac{1}{p}\sum_{i=1}^{p} n_i \quad (4)$$

$$s_R = \sqrt{\frac{1}{p-1} \sum_{i=1}^{p} \left(\bar{x}_i - x_m\right)^2 + \frac{n-1}{n} s_r^{\,2}} \qquad (5)$$

where x_m is the arithmetic mean value of the arithmetic mean values $\bar{x}_i$ of the participating laboratories and n is the number of tests in all laboratories. s_R is expected to be greater than s_r .

Determination of the expanded uncertainty

When a measurement has been performed, uncertainty provides a value of how close the result (i.e. the measurand) is expected to be to the true value.

In practice, there are many possible sources of uncertainty in a measurement:

a) incomplete definition of the measurand;

b) imperfect realisation of the definition of the measurand;

c) nonrepresentative sampling — the sample measured may not represent the defined measurand;

d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions;

e) personal bias in reading analogue instruments;

f) finite instrument resolution or discrimination threshold;

g) inexact values of measurement standards and reference materials;

h) inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm;

i) approximations and assumptions incorporated in the measurement method and procedure;

j) variations in repeated observations of the measurand under apparently identical conditions."

By means of an uncertainty amount an uncertainty interval $y \pm U$ may be calculated, where y is the measurement result and U the expanded uncertainty that is determined to give the confidence interval within which at a high coverage probability (often 95%) of the true value, Y, of the measurand lies. U is said to be the uncertainty associated with the result y.

The uncertainty interval of a measurement is therefore a basis for qualifying the measurement. The more narrow the desired confidence interval is , i.e., the smaller the value of the uncertainty U is pursued, the more careful the measurement method, the measuring equipment, the training of the operators and the number of repetitions of the same experiment have to be.

There are, in principle, two ways to estimate uncertainty: a bottom up method and a top down method. The two methods may often be used in parallel, or ideally, the bottom up preceding the top down to ensure a good repeatability before reproducibility is determined, in order to achieve a reliable uncertainty amount. The methods 'bottom up' and 'top down' depend on the validity of the model (for the bottom up method) or the data (for the top down method) used. It is the responsibility of experts within the responsible standardisation committee to conclude which methodology is the most appropriate way to define the reproducibility standard deviation for a certain product group. The decisions and the rational are to be recorded.

a) The bottom up method

In this method, the test result *y* is expressed as a function of input quantities. This function is often the formula used for the calculation of the result.

In the case of household appliances, the value of *y* may be one of the final test results - like water consumption, energy consumption, performance or program duration. The input quantities may be temperature, masses, times, power etc.

The magnitude of all the uncertainty contributions of each input quantity is estimated.

By combining the uncertainties of the input quantities according to the law of propagation of uncertainty the uncertainty of the result *y* can be calculated.

With this calculation, it can be seen how a specific uncertainty contribution from an input quantity influences the combined uncertainty of the final result and therefore how a reduction in an uncertainty contribution from an input quantity will influence the combined uncertainty of the final result.

Uncertainties can often be reduced at some cost by making more measurements, using other methods or other equipment. This means that different approaches can be followed to reduce the uncertainty of the final result in the most cost effective way.

This method is most suitable to assess the repeatability standard deviation within one laboratory.

b) The top down method

In this method, the reproducibility standard deviation is estimated from testing the same product (or very similar products from the same model) in different laboratories using the same measurement method. This testing is, in general, named a 'round robin test' or a 'ring test' [6]. The reason why the same product is preferred is to eliminate, as far as practicable, inherent variations due to the tested product , as determining these variations is not within the scope of what is being assessed. At least 5 laboratories shall take part in such a round robin test and shall deliver valid results, meaning not being identified as outliers [7]. Laboratories should be chosen which can meet the requirements of the relevant measurement method and the reproducibility conditions of testing.

The reproducibility standard deviation of the test results can then be seen as the inherent uncertainty of the measuring method. It may be influenced by remaining differences in the ambient test conditions and test equipment, the people and whatever else may be different between different measurements in different laboratories. In principle, it is only valid for the product investigated in each round robin test, but results from similar products of the same type can also be used.

Uncertainty propagation

When a value is derived from more than one measurement, each having individual standard deviations, then rules of propagation of uncertainty need to be applied to calculate the standard deviations of the combined value.

Example: If the first measurand *a* has a standard deviation of s_a and the second measurand *b* has a standard deviation of s_b, the standard deviation s_c of the combined value *c* is calculated as follows if there is a simple addition and multiplication:

Addition: $c = a + b$ then $s_c = \sqrt{s_a^2 + s_b^2}$ and

Multiplication: $c = a \cdot b$ then $s_c = c \cdot \sqrt{(\frac{s_a}{a})^2 + (\frac{s_b}{b})^2}$.

Note: This simple example is only applicable for linear combinations of non-correlated values with Gaussian distribution.

Expanded uncertainty calculation

The uncertainty of a measured result has two sources:

- the statistical uncertainty of what is measured, as expressed in the repeatability standard deviation, showing the accuracy of the measurements in the laboratory having done the measurements;
- the uncertainty of the measuring method itself. This is expressed as expanded uncertainty where it is common to set the borders at a 95% confidence interval, which give the minimum and maximum value where the average measured result may be found when the measurement is re-done at any other laboratory. <u>As basis for calculating the expanded uncertainty the reproducibility standard deviation shall be used.</u>

To be meaningful, the uncertainty statement should have an associated confidence level: i.e., it is necessary to state the coverage probability that the true value lies within the range given. The reasons for choosing a 95 % confidence level in this standard are as follows:

- it is established practice throughout much of Europe, North America and Asia [8];
- the Guide to Uncertainty in Measurement (GUM) assumes that the combined uncertainty has a distribution that is a close approximation to a normal distribution. A 95 % confidence level approximates to a range of 2 standard deviations. It is a widely held view that, for most measurement systems, the approximation to a normal distribution for the distribution of the combined uncertainty is reliable out to 2 standard deviations, but beyond that the approximation is less reliable. [1, 8]

If a normal distribution can be assumed, the 95% confidence interval is given by multiplying the reproducibility standard deviation by a factor of 2.

Whatever methodology is used to calculate reproducibility standard deviation, the results may be not just one value, but may differ due to different products being tested or different input data being used. Also, different round robin tests may deliver non-identical results. It is then the responsibility of experts organised in the responsible standardisation committee to conclude which reproducibility standard deviation is the most realistic expression of the uncertainty for a certain product group. Different values may be communicated for different product groups if necessary and justified. The decisions and the rationale are to be reported in the minutes of the meeting.

Reproducibility standard deviation can be a value of absolute or relative nature. Depending on the nature of the error, either one or the other shall be preferred. Absolute values of the reproducibility standard deviation shall be preferred when the measurement error is not likely to be influenced by the absolute value of the measurand. Relative values are preferred when the error will grow or diminish with the absolute magnitude of the measurand. It is also the duty of the responsible standardisation committee to conclude in which way the reproducibility standard deviation shall be expressed. If expressed in absolute values, the reproducibility standard deviation shall be given with the term ‘(abs)’, otherwise in ‘%’.

Reporting uncertainty

When reporting test results, all information should be given in the test report to allow a full judgement of the measurement: average measured value, repeatability standard deviation and expanded uncertainty. [9]

Example for relative reproducibility standard deviation for energy consumption = 5%:

– measurement of the energy consumption

Average measured: 1,44 kWh

Repeatability standard deviation of measurement: 0,05 kWh

Expanded uncertainty (10% of 1,44 kWh): 0,14 kWh

– reporting of the result

Average measured: 1,44 kWh

Range related to standard deviation: ± 0,05 kWh

Range related to expanded uncertainty: ± 0,14 kWh

meaning: while testing one product in one laboratory under repeatability conditions has been done with a standard deviation of ± 0,05 kWh, the same product in another laboratory following reproducibility conditions, the expected average value (at 95 % confidence) is between 1,30 kWh and 1,58 kWh.

Example for absolute reproducibility standard deviation for energy consumption = 0,075 kWh (abs):

– measurement of the energy consumption

Average measured: 1,44 kWh

Repeatability standard deviation of measurement: 0,05 kWh

Expanded uncertainty (0,15 kWh (abs)): 0,15 kWh

– reporting of the result

Average measured: 1,44 kWh

Range related to standard deviation: ± 0,05 kWh

Range related to expanded uncertainty: ± 0,15 kWh

meaning: testing the same product in another laboratory following reproducibility conditions, the expected average value (at 95 % confidence) is between 1,29 kWh and 1,59 kWh.

Example of uncertainty reporting

Uncertainty values for each measured parameter shall be reported, preferably as a part of the measurement standard itself. Where this is not possible, e.g. as the values are not available at the time the standard is in preparation, the uncertainties shall be reported in an amendment to the measurement standard.

A description shall be given with the model of the uncertainty (see GUM) and all uncertainty contributions as well as the origin of the data and reference to the applied standard, its version and reference to additional information, when appropriate. The specification of the product group for which the results are presumed to be valid shall be clearly expressed.

Example of expanded uncertainty reporting in a standard or technical report

EN50242/EN60436:2012 reports in Annex ZC: In 2009/2010, a round robin test was performed with 19 laboratories participating from all over Europe. One of the objectives was to check the robustness and precision of EN 50242:2008/EN 60436:2008. Five samples of two types of automatic dishwashers from different manufacturer were tested in two different cleaning cycles. These products under test were calibrated to be as identical to each other as possible and delivered to all participating laboratories.

Results were analysed by CLC/TC 59X/WG 02, and expanded uncertainties were calculated as shown in Table 1.

Table 1 – Relative expanded uncertainty [a] of dishwasher measured values of EN 50242:2008/EN 60436:2008

Measured parameter	Relative expanded uncertainty of measured value [b] (k = 2)
Cleaning performance index I_C	14 %
Drying performance index I_D	16 %
Total energy	5 %
Total water	4 %
Total programme time	2 %
Low power mode energy consumption	[c]
Noise (in re 1 pW)	[c]

[a] The expanded uncertainty only describes the uncertainty of the measuring method while the variance of the product is not included.

[b] These values are the average of measurement figures taken from a low and a high end machine.

[c] Not measured in this round robin test.

Conclusion

In the context of policy-making on the efficient use of energy and other resources, the provision of information to consumers or establishment of regulatory requirements is common practice in many regions of the world. Considering that measurable values are needed to check compliance with those regulations, a standardised measurement method needs to be considered. This paper described that, in order for these methods to be clear and accurate, the determination of the repeatability and the reproducibility of test methods is key. The paper also demonstrated how this determination process can take place, taking into account possible limitations in terms of time, resources and statistical knowledge.

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Telling the Truth - Validity of energy efficiency values of heat pumps determined under laboratory conditions

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Abstract

In this study, the test method EN 14825 for testing heat pumps is validated by verifying the sensitivity of the seasonal space heating energy efficiency η_s, (declared on the energy efficiency label) in relation to the nominal heating capacity P_{design}. Therefore, the two major parts of the test method, the measurement part and the calculation part, were investigated. The calculation part was subjected to a sensitivity analysis in order to identify the properties of a heat pump which have a strong influence on η_s. The analysis revealed that the energy consumption in special operating states, the duration in active-mode and seasonal performance values in active-mode ($SCOP_{on}$) significantly affect the sensitivity of η_s. Especially short operating times, in which the heat pump is in active-mode, lead to large changes in η_s with varying $P_{design.}$ In addition, the range of power of P_{design} turned out to have an increasing impact on η_s with decreasing P_{design}. For P_{design} values ≤10 kW, the sensitivity of η_s increases tremendously. Especially the determination of the η_s for devices with short operating times in active-mode (1400 h) and low values for P_{design} (≤10 kW) cannot be reproduced anymore.

Introduction

Significant energy conservations can be achieved in the residential sector especially when it comes to space heating. Space heating is responsible for the largest portion (about 70 percent) of the total energy consumption in the residential sector in Europe. [1] Currently, the most promising solution for the future heating sector in Europe are highly energy efficient heat pumps (HPs). [2] In the EU, HPs carry a mandatory energy label according to the energy efficiency labelling regulation since 2013 [3], [4] in order to inform the consumer in a comprehensive way about the efficiency of the product. To determine the classes on the EU energy efficiency label, this regulation refers to the European Standard for performance measurements of "air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling" EN 14825. [5] This standard includes a calculation method, applied by different stakeholders. On this account the calculation method has to be well developed. However, in the EN 14825, both the use of nominal heating capacity P_{design} given by the manufacturer and the measured value can be used during testing and for the calculation of the energy efficiency. Insufficient specifications of test standards can facilitate circumvention of test procedures, on the one hand, or might lead to deviating results of market surveillance authorities' activities by mistake, on the other hand.

In this study, the test method EN 14825 is analyzed focusing on its sensitivity on the declared P_{design}. In the section "Implementation of P_{design} and T_{design} in the EN 14825" the test method and the use of manufacturer declared values (P_{design} (T_{design})) is discussed more in detail. A subsequent section presents the sensitivity analysis and therefore the dependency of η_s on P_{design}. The influence of P_{design} particularly regarding the reproducibility of laboratory results and the potential opportunity for manufacturers to circumvent in the testing procedure will be discussed. As a conclusion, a revision of the EN 14825 is proposed.

Test method EN 14825

In contrast to EN 14511 [6], which includes only a reference methodology for the determination of the coefficient of performance (COP) and thus only represents the efficiency of the HP at a certain operating point, the EN 14825 determines the seasonal coefficient of performance (SCOP) and provides to calculate the seasonal energy consumption. The SCOP is calculated by using different COPs, measured at defined operating points, related climate zones and special operating states in non-active-mode (e.g. standby mode). To conclude for the primary energy consumption, the SCOP is used to calculate the η_s.

Implementation of P_{design} and T_{design} in the EN 14825

The test method EN 14825 is divided into two parts in order to determine the SCOP: (i) Testing Part and (ii) Calculation Part. Both parts are explained in the following with particular consideration of P_{design} and T_{design}.

Theoretical and measured heat load curve

Before testing an HP, the theoretical heat load curve has to be determined. Therefore, the nominal capacity performance P_{design} is used for calculating the part loads values $P(T)$.

$$P(T) = x \cdot P_{design} \quad (1)$$

The part load relation x is calculated by considering the temperature T at part load and the given value for $T_{design.}$

$$x = \frac{T-16}{T_{design}-16} \quad (2)$$

For P_{design} the value given by the manufacturer or the measured value can be used. Figure 1 shows the resulting heating curves of an exemplary brine/water HP based on calculated data as shown before and on the measurement procedure, which is given by the standard EN 14825. The calculated load curves decrease with rising temperature, but the measured load increases. The different progressions are due to the testing procedure. At first, the full load operating point (P_{design}, T_{design}) is approached. When a steady state is reached at a constant temperature complying with T_{design}, the heating capacity P_{design} and the volume flow in the heating circuit are determined. During the whole measurement in all operating points the volume flow is kept constant. As the brine temperature stays at a constant level, the part load conditions are simulated by varying the heat sink temperatures. For the testing of air/water HPs, the part load conditions are simulated by varying the heat source temperature. As a result, the measured load curve increases with rising temperatures.

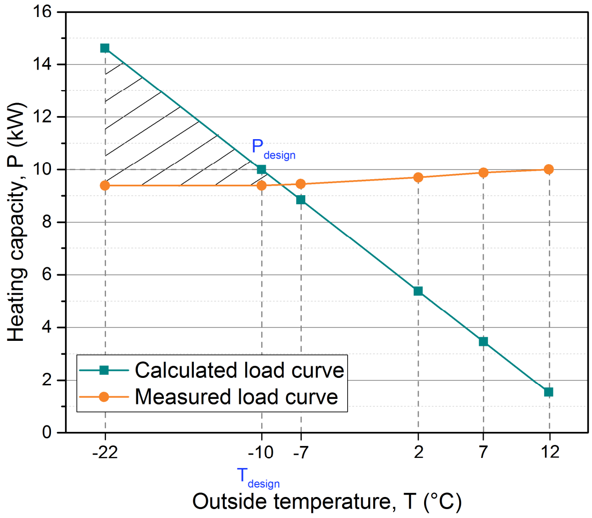


Figure 1: Heat load curve of an exemplary HP

Calculation of the $SCOP_{on}$, the SCOP and η_s

The seasonal performance of the HP in active-mode ($SCOP_{on}$) is calculated with the bin-method, which is part of the related standard and considers the climate conditions using reference conditions for warm, average and cold climates. The part load values of the two load curves are set into ratio. The result is the performance ratio (CR), which is used for the calculation of the COP values for each tested operating point (COP BIN). The COP BINs are assigned to temperature BINs, which represent a temperature with a certain occurrence probability. By interpolating the data for a temperature range, including the calculated part load $P(T_j)$ for each BIN, the occurrence probability of each BIN, the COP BINs and the heat demand for an additional heater, the $SCOP_{on}$, is calculated. $SCOP_{on}$ is the basis for the determination of the overall seasonal performance SCOP that includes also the power consumption for special operating states like standby-mode.

$$SCOP = \frac{P_{design} \cdot H_{HE}}{\frac{P_{design} \cdot H_{HE}}{SCOP_{on}} + \sum H_x P_x}, \qquad (3)$$

where H_{HE} is the duration of active-mode and $\sum H_x P_x$ is the overall consumption in the special operating states. In the EN 14825 it is not clearly specified which value is to use for P_{design}. Both the value given by the manufacturer and the value measured during testing can be used for the calculation of the SCOP.

To receive a seasonal performance value comparable with other heating systems the seasonal space heating energy efficiency η_s is calculated as follows:

$$\eta_s = \frac{SCOP}{CC} \cdot 100\% - \sum F(i), \qquad (4)$$

where CC is the conversion coefficient[79] and $\sum F(i)$ is the correction factor for an adjustment for further losses. $\sum F(i)$ is 8 % for brine- and water/water HPs and 3 % for air/water HPs. [5]

[79] 'conversion coefficient' (CC) means a coefficient reflecting the estimated 40 % average EU generation efficiency referred to in Directive 2012/27/EU of the European Parliament and of the Council (7); the value of the conversion coefficient is CC = 2,5

Sensitivity analysis of P_{design} on seasonal performance

For an entire analysis of the seasonal performance' dependency on P_{design} the measurement and calculation procedure have to be taken into account separately.

Influence of P_{design} on the test method procedure

P_{design} representing the initial value for the determination of the operating points for the measurement procedure. With P_{design} and T_{design} the part load values for the theoretical heat load curve is determined which builds the basis for further calculations for the identification of the COP-BINs. Due to the fact that laboratories are free to either use the value given by the manufacturer or the measured value the construction of the heat load curve and the calculation of the COP-BINs cannot be reproduced anymore. However, the influence of P_{design} on the results of the test method procedure is marginal. A decrease in P_{design} from 42,12 kW to 35 kW (-17%) results in a decrease of $SCOP_{on}$ of 0,5 % and a decrease from 10 kW to 8 kW (-20 %) results in a loss of $SCOP_{on}$ of 0,56 % respectively.

Influence of P_{design} on the calculation of the SCOP

According to equation (3) the SCOP is dependent on the following parameters: (i) Duration of HP being in active-mode H_{HE}, (ii) Declared or measured value for P_{design}, (iii) Energy consumption in special operating states $\sum H_x P_x$ and (iv) Seasonal performance in active-mode $SCOP_{on}$. In the following the results of the sensitivity analysis are discussed.

Variation of H_{HE}

According to equation 3 H_{HE} is assumed to have a significant influence on the energy efficiency calculation. Figure 2 confirms this assumption by showing η_s in dependency on P_{design} and for different durations for the active-mode H_{HE}. For different operation time in the active-mode,the trend of η_s is similar but with a different slope. With increasing operation time in the active mode, P_{design} has less influence on η_s. Using warm climate conditions (1400 h) small values of P_{design} (≤ 5 kW) affecting η_s is significantly (± 3 %) in case of varying the load (± 1 kW). For an air conditioner which is according to EN 14825 ,assumed to only stay 350 h in the active-mode, the seasonal performance decrease for cooling would be even more critical with about 6 % by a decrease of P_{design} of 1,5 kW.

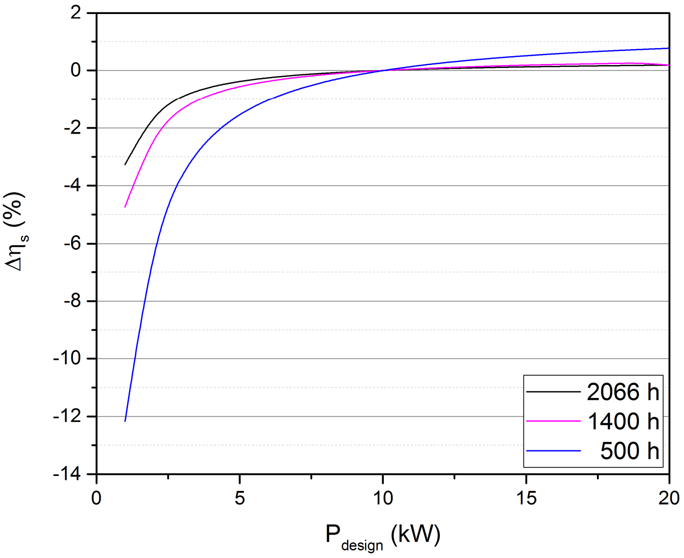


Figure 2: Dependency of η_s on P_{design} with variation of H_{HE}. Relative change of η_s as a function of P_{design} and H_{HE}.

Variation of $\sum H_x P_x$

Figure 3 shows the dependency of η_s on P_{design} for different values of additional consumption due to standby-mode, crankcase heating, OFF-mode and thermostat-OFF-mode. The behavior of η_s for each variation is very similar but with a different slope. Although the influence of the additional consumption is lower than the influence of the operation time in active-mode, the same characteristic behavior can be observed. HPs with a high amount of additional consumption indicate a higher sensitivity for P_{design}. For small P_{design} (≤ 5 kW) and high values for additional consumption (40 kWh) the change of η_s is ± 2 % in case of varying the load (± 1 kW).

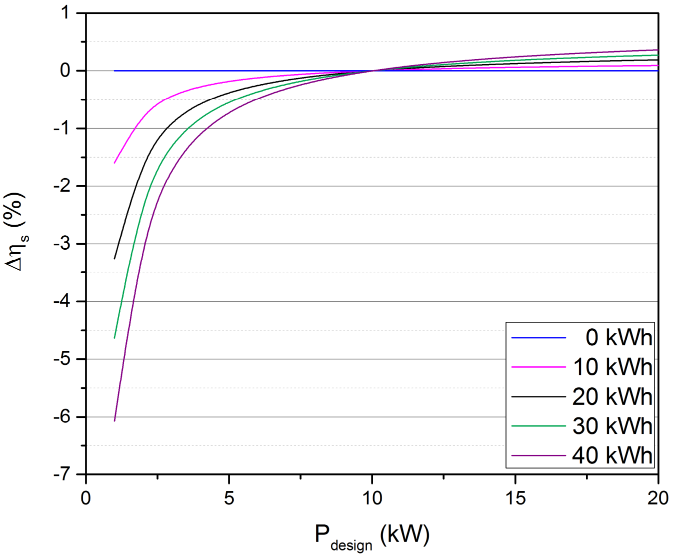
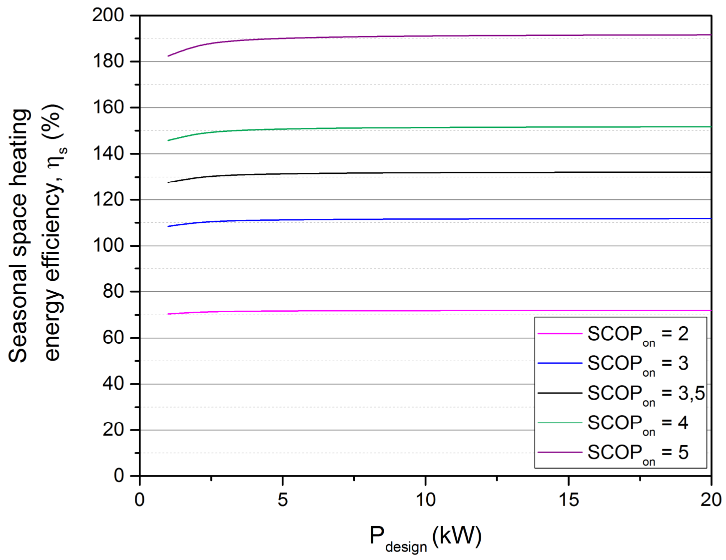


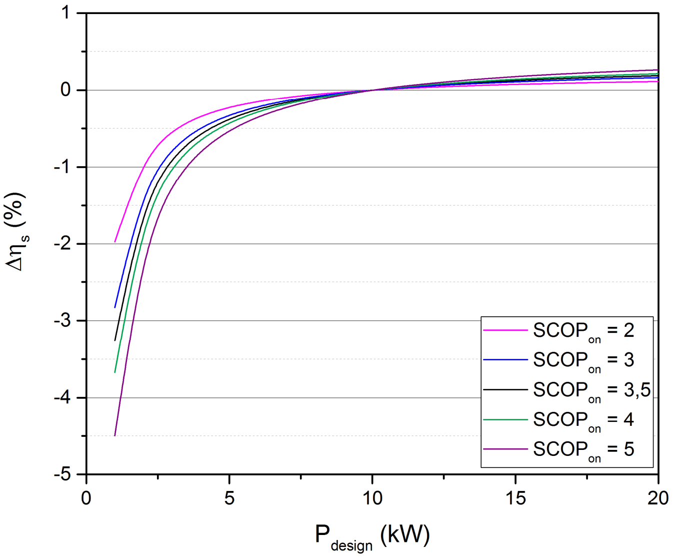
Figure 3: Dependency of η_s on P_{design} with variation of $\sum H_x P_x$. Relative change of η_s as a function of P_{design} and $\sum H_x P_x$

Variation of $SCOP_{on}$

Figure 4 a shows the dependency of η_s on P_{design}, for different values of the $SCOP_{on}$. According to equation 4 η_s increases with increasing values of the $SCOP_{on}$. Figure 4 b shows the relative change of η_s as a function of P_{design} and the $SCOP_{on}$. With increasing $SCOP_{on}$ the slope of the curve and thus the sensitivity of η_s on P_{design} increases. For small P_{design} (≤ 5 kW) and a $SCOP_{on}$ of 5 the change of η_s is ± 1,5 % in case of varying the load (± 1 kW).



a)



b)

Figure 4a: absolute change of η_s as a function of P_{design} and the $SCOP_{on}$. and 4b: relative change of η_s as a function of P_{design} and the $SCOP_{on}$.

Further examples

As the dependencies of η_s and their magnitude have been identified in the sections before, Figure 5 clarifies the range of influence that these parameters cause on η_s comparing two exemplary HPs. Therefore, the sensitivity of η_s to P_{design} is shown for two HPs where the first has parameter values that, based on the results of the analysis in the previous section, tend to cause large variations and the other has all requirements for a stabilized η_s. The values for the parameters are given in Table 1.

Table 1: Parameter values for heat pump 1 (HP1) and heat pump 2 (HP2)

Parameter	**Heat Pump 1**	**Heat Pump 2**
P_{design} [kW]	2	40
$\sum H_x P_x$ [kWh]	40	10
H_{HE} [h]	1400	2066
$SCOP_{on}$ [-]	6,5	3,2

Figure 5 shows the sensitivity of η_s regarding P_{design}. A similar curve for η_s is obtained for both HPs but with very different slopes. While HP1 records a high decrease in the low power range (≤50%), the seasonal space heating energy efficiency of HP2 remains nearly constant over the whole power range (abs. 6%, perc.5%). The different behaviors are clearly due to their properties in additional energy consumption, duration in active-mode and $SCOP_{on}$ values. This comparison shows very clear how different HPs and assumptions in the test method EN14825 have a large influence on the sensitivity of η_s. Especially the determination of η_s for HP1 tends to be subjected to fluctuations. In the case that laboratories do not verify the manufacturer value for $P_{designh}$ manufacturers may have the opportunity to influence the calculation of energy efficiency value of the product, which is finally declared on the energy efficiency label. On the other hand, the results show that it is of great importance to define which P_{design} have to be used (declared or measured). Thereby, the reproducibility of the method can at least be doubted for devices with low values of P_{design}.

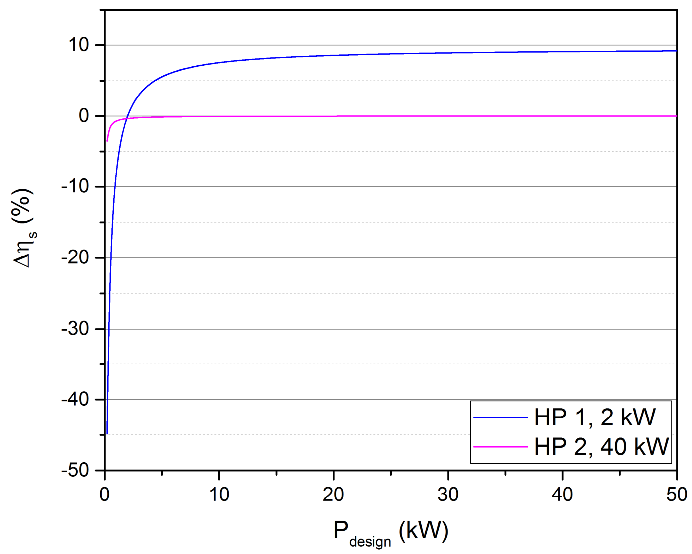


Figure 5: Comparison of the sensitivity of η_s to P_{design} by the way of example of two different brine/water heat pumps.

Conclusion

In this paper the standard test method EN 14825 is analyzed with respect to the sensitivity of η_s regarding P_{design}. Therefore, the determination of η_s was contemplated splitting the test method into the two main parts:

I) the preparation before carrying out the testing and

II) the calculation procedure based on the measured data/manufacturer data. It could be figured out that P_{design} has an impact on the calculated heat load curve which is the basis for the calculation of the $SCOP_{on}$.

Due to the fact that the EN 14825 does not define whether the measured value for P_{design} is to use or the value given by the manufacturer, the reproducibility of the test method is significantly decreasing. In some cases, the test results deviate about 20 % even by a slightly decrease of load of 1 kW. Moreover, a comprehensive analysis regarding the sensitivity of η_s regarding P_{design} is given.

The energy consumption in special operating states, the operation time in active-mode and the $SCOP_{on}$ values are are affecting thesensitivity of η_s.

Especially the short operation times in active-mode for warm climate conditions (1400 h) leads to a tremendous change of η_s in the low power ranges which is shown along two example for different HPs. Hence, the reproducibility of the test method for small values of P_{design} (≤10 kW) and low operation time in active-mode for warm climate conditions (1400h) is questionable. For air conditioners this effect could be even more significant compared to an operation time of for instance only 350 h.

To prevent the possibility of circumvention and the loss of reproducibility a significant definition of P_{design} is mandatory. The value declared by the manufacturer could be used for an orientation and for a determination of part load values. However, it is proposed that for the calculation procedure only the measured value should be used.

Acknowledgement

This project is financed as a part of the National Action Plan on Energy Efficiency (NAPE) of the Federal Ministry for Economic Affairs and Energy.

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Following the evidence – How quality of appliance components can hint at non-compliance with efficiency requirements

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Abstract

Improving the energy efficiency of products was identified as the most important short-term opportunity to decrease energy consumption and therefore CO_2-emission worldwide. More efficient products are created due to technical innovation. Restricting market access to efficient products only and making the most efficient products stand out by energy labelling are legislative approaches to encourage this development. Market surveillance authorities' checks are fundamental to protect the consumer from wrongly declared goods on the market and ensure fair competition between manufacturers. However, the activities of market surveillance authorities are limited by their financial resources. Testing all product efficiency parameters in an accredited laboratory is very time consuming and cost intensive. In this article, a theoretical concept is presented which can be used to develop screening tests enabling market surveillance authorities to perform product tests with less financial resources. The concept identifies components which lead to non-compliance or make a product less energy efficient with minimum effort. The principle is based on a combination of random product tests, disassembling specific products and comparing components. This represents a new approach in product testing procedures beyond the current market surveillance activities. The concept is being tested within a research project funded by the German government.

Introduction

During the last decade, two legislative developments are ongoing. They are based on different approaches with the same goal – to decrease the energy consumption and therefore CO_2-emmission worldwide. The first approach is aimed on the performance of energy consuming and energy related products. Market regulations were released in order to exclude non-compliant products from the market based on energy efficiency performance. The first approach uses regulations to limit consumer choices to household products and appliances that meet minimum energy performance characteristics, which helps to decrease per capita energy consumption over a time [1-3]. Another approach is aimed at labeling products which have access to the market as described above. The label is indicating information (among others) about the energy efficiency of the product. This helps to inform consumers about the specific energy efficiency of various products, which should help consumer during the decision-making process when buying new products or replacing existing products [4]. This approach increases competition between manufacturers, since more efficient products might be more attractive to consumers regarding energy consumption and the energy costs required to operate the products over the expected product lifetime.

The legislative tools described in the previous section only work when being enforced. In this way, Market Surveillance Authorities (MSA) are responsible to check whether a product is allowed to be brought on the market and/or put into service or whether its energy efficiency is declared as described in the concerning legislative text and is, therefore, compliant. During compliance tests, the MSA chooses products from the market randomly and tests the products in different steps, beginning with marking or presence of labels, through checking all of the technical documents, and ending with performance tests in accredited laboratories according to national and/or international standards. Especially the latter activities are relatively time consuming and therefore cost intensive. The extra time and costs are due to rigorous tests that can take days or even weeks to perform detailed analyses of all performance parameters.

In this study, an alternative concept is described, which could help the MSA to step back from both choosing the products randomly and testing all performance parameters. The concept determines whether or not a screening method can be developed and which parameters have to be screened. The concept may lead to more efficient product testing and enable the MSA to analyze a larger number of products with less time and cost.

Concept

Based on the common knowledge about the different technologies and energy performance of components used in energy related products, the concept presented in this study should help to identify components which influence the efficiency of a product and are responsible for non-compliance with a relatively high probability. Concerning these component types, screening approaches can be developed. The concept is described in the three different steps listed below and summarized in Figure 1:

Step 1: Compliance tests

Product tests of a single product group are performed in an accredited test laboratory. Products are chosen randomly and all performance parameters are tested. Based on test results a database is created listing products in two categories – products which were determined to be either compliant or non-compliant. In order to decrease the effort, especially the working time, the components of all non-compliant products but only some compliant products are listed as described in Step 2.

Step 2: Identification of significant components

In this step, during or after product testing, significant components, which define the product and are predominantly responsible for energy efficient performance, are identified. Identical and/or similar components should be characterized. The products (all non-compliant and some compliant ones) are dismantled and components are identified and listed. In many cases, removing the housing of the products and checking the name plate of components is sufficient. For the identification process, both groups, the non-compliant and the compliant products, are handled separately. The comparison between both groups is part of the next step.

Step 3: Separation of the “good” from the “bad”

In the third and final step, the type of identical and/or very similar components of the non-compliant products (“bad” components) is compared with the components built into products which are identified as compliant (“good” components). Again a new database is created to assign i) “good” components to compliant products and ii) “bad” components to non-compliant products. If components listed in i) **are not** different from ii), the reason for being identified as non-compliant could be found somewhere else, for instance in the field of the product design or software. If there **are** differences in used components in i) and ii), a possible reason for the non-compliance of the product could be most likely the choice of component itself. The information about the types of components inside a multi-component product are easily available for the MSA, e.g. by checking the technical file of the product and/or, prospectively the entries in product databases which will be implemented by legislators like the European Commission. Hence, it might be possible to screen the market for products with “bad” components.

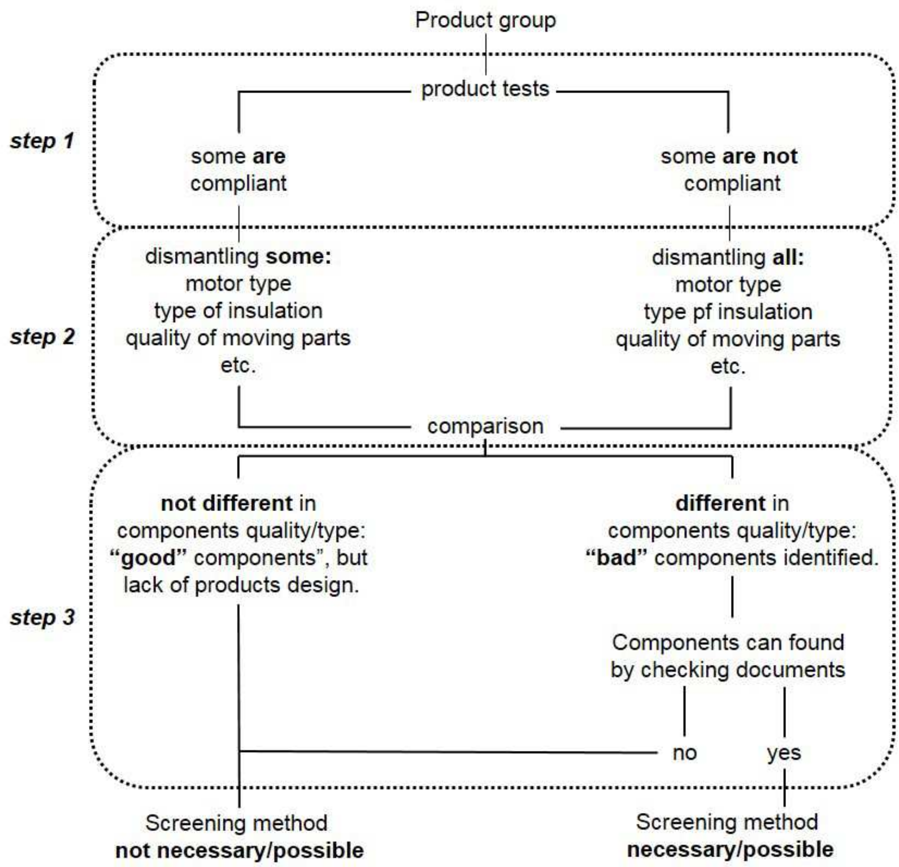

Figure 1: Scheme of the concept, which illustrates the three different steps (i) compliance tests, (ii) identification of significant components, (iii) separation of the "good" from the "bad".

Cost Consideration

The product tests are often commissioned by the MSA to accredited test laboratories, due to limitations of their own testing capacities and the large variety of products which have to be tested. The costs for a single product test, following all necessary steps given by the relevant national and/or international standards, strongly depend on the product group itself. For instance, testing the energy consumption of a kitchen hood (duration 1-2 d) is less time-consuming and cost-intensive than for a tumble dryer (duration up to 2 weeks). The cost for performing product tests at different test laboratories varies as well. Therefore, an overall cost consideration cannot be given, but in some cases reducing the number of test parameters will reduce the cost and time for a product test and helps the MSA to test a larger number of products.

Discussion

Values for an overall non-compliance rate are hardly found in the literature. There is a review study which is often cited and assumes a non-compliance rate between 10% and 25% [5-8]. These values are mostly related to the formal compliance concerning the use of the energy efficiency label or correct documentation and cannot be confirmed by the results of product test of German MSA. Despite the lack of information concerning the non-compliance rate, the concept in this study might be a promising tool to increase the identification rate of non-compliant products. The concept is not representing an alternative to the compliance tests performed these days by the MSA, it is rather one of useful additions which are identified as necessary due to the increasing number of regulated products [9]. The concept is also only working for products built up with more than one component which are significant for the product performance. Otherwise, identifying differences between the components between compliant and non-compliant products will not simplify the compliance test procedure. If a product consists of more than one component, which is significant for the product performance, it is necessary to determine whether all components are influencing the performance to the same extent. For instance, an efficient electric motor in a kitchen hood is influencing the grease separation less than the design of the grease filter. The other way round, a well-designed grease filter is influencing the energy consumption less significantly than the electric motor. However, identifying one of the two components as less efficient provides to focus the product test only on a single performance parameter (in this example: grease adsorption **or** fluid dynamic efficiency) and finally decreases the time and cost for a product test.

The theoretical concept for screening compliant versus non-compliant products based on random product tests of energy efficiency characteristics can provide a cost effective opportunity to identifying products based on laboratory testing alone. Even if only one less efficient component can be found, this knowledge can help to develop screening methods and strengthen the impact of the MSA activities. Instead of choosing products for compliance tests based on laboratory testing alone, energy efficiency characteristics can be cost effectively identified using a three step process where compliant and non-compliant products are compared. The identification rate can increase and more non-compliant products can be banned from the market. Finally, the concept could foster greater innovation and longer-term competiveness between manufacturers which will contribute to greater energy savings.

The concept is still tested within a research project with the scope to develop screening methods for the MSA. This project is financed as a part of the National Action Plan on Energy Efficiency (NAPE) of the German Federal Ministry for Economic Affairs and Energy.

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Laboratory and Field Tests of an Efficient Fan Controller® in Cooling and Heating Mode on Residential HVAC Systems

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Verified® Inc.

Abstract

Laboratory and field tests of a residential heating, ventilating, air conditioning (HVAC) Efficient Fan Controller® (EFC®) were performed at a third-party ISO-certified test laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with minimum Federal efficiency standards. The patented EFC® technology saves cooling or heating energy by extending fan operation after the thermostat call for cooling or heating has ended based on the duration of the thermostat call for cooling or heating. The variable cooling fan-off delay is based on the air conditioning compressor operating time which determines how much water vapor is condensed on the evaporator to provide evaporative cooling after the thermostat call for cooling has ended. The variable heating fan-off delay is based on the heating system operating time which determines how much heat is stored in the heat exchanger to provide additional heating after the thermostat call for heating has ended. For gas furnaces, the EFC® energizes the thermostat G terminal after a brief delay to increase fan speed and airflow to satisfy the thermostat sooner and save energy. Cooling energy savings vary from 3.9 to 38.3% with average savings of 15.2 ± 0.8% based on 46 laboratory tests and normalized cooling savings of 19.9% based on 22 field tests. Gas furnace heating energy savings vary from 4 to 21% with average savings of 15.9 ± 0.7% based on 24 laboratory tests and savings of 13.5% based on 10 field tests. Heat pump heating energy savings vary from 2 to 29% with average savings of 12.5 ± 1% based on 48 laboratory tests. Hydronic heating energy savings vary from 4 to 31% with average savings of 16.3 ± 1.7% based on 20 laboratory tests. The EFC® potential annual energy savings are 0.11 quadrillion Btu (quads) or 0.12 exajoules (EJ) in California or 4.65% of the total estimated annual energy use in California of 2.4 quads or 2.53 EJ.

Introduction

Residential and commercial heating, ventilating, and air conditioning (HVAC) consumption in the United States accounts for 30% of average summer peak-day electricity loads, 13% of total electricity use, and 44% of total natural gas use [1]. A 2002 study published by the Hewlett Foundation indicates that improving HVAC cooling and heating efficiency represents one of the largest economically achievable opportunities for energy efficiency and peak demand savings [2]. This paper provides lab and field test results of a patented Efficient Fan Controller® (EFC®) installed on residential split-systems and packaged HVAC systems with direct-expansion (DX) R22 refrigerant-based cooling and gas furnace, heat pump, or forced-air hydronic hot water heating [7].[80] The EFC® saves cooling or heating energy by extending fan operation after the thermostat call for cooling or heating has ended based on the duration of the thermostat call for cooling or heating. The variable cooling fan-off delay time is based on the air conditioning compressor operating time which determines how much water vapor is condensed on the evaporator to provide evaporative cooling after the thermostat call for cooling has ended. The variable heating fan-off delay is based on the heating system operating time which determines how much heat is stored in the heat exchanger to provide additional heating after the thermostat call for heating has ended. For gas furnaces, the EFC® energizes the thermostat G terminal after a brief delay to increase fan speed and airflow to satisfy the thermostat sooner and save energy. Laboratory tests were performed on four HVAC systems: 1) 3-ton (10.55 kW) split-system DX cooling and gas furnace, 2) 3-ton (10.55 kW) packaged DX cooling and gas furnace, 3) 1.5-ton (5.28 kW) spilt-system heat pump with DX heating and cooling, 4) 1.5-ton (5.28 kW) split-system DX cooling with forced-air hydronic hot water heating.[81] The equipment was set up in two

[80] US Patent 8763920, US Patent 9328933, US Patent 9500386. US Patent 9671125, US Trademark Efficient Fan Controller® Reg. No. 5,163,211 (First Use 03-01-2012), EFC® Reg. No. 5,198,335 (First Use 03-01-2012)

[81] One ton of cooling is defined as the heat energy removed from one short ton of water (2,000 pounds or 907.1847 kg) to produce one ton of ice at 32F (0 C) in 24 hours. The energy required for the phase change of liquid water at 32F (0C)

chambers to simulate indoor and outdoor conditions per AHRI 210/240 [3]. Test conditions differ from those used to rate cooling and heating systems to match typical installations in California.[82] Field tests were performed on a 3.5-ton (12.31 kW) split-system DX cooling and 120,000 Btu per hour (35.17 kW) gas furnace serving a single-family residence located in Reno, Nevada. Lab and field tests are provided for both cooling and heating.

Test Equipment Laboratory Setup

Tests were performed at Intertek®, an AHRI-certified laboratory, located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI equipment efficiency testing for the U.S. Department of Energy (DOE) compliance and enforcement program to meet energy conservation standards required by the Energy Policy and Conservation Act of 1975 (as amended) [8]. The test facility consists of climate-controlled indoor and outdoor chambers where ducts, evaporator, condenser, furnace or hydronic heating equipment and forced air units are located. The HVAC systems and standard test equipment were assembled and installed in the test chambers by laboratory technicians. The AHRI 210/240 cooling verification tests were performed according to ANSI/AHRI 2008 Standard for Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment Standard 210/240 and ANSI/ASHRAE Standard 37-2009 [2, 4]. Thermal Efficiency verification tests were performed according to ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006 [9]. The psychrometric room meets ASHRAE 41.2-1987 standard specifications [5]. Calibration for all equipment at the laboratory test this facility is conducted in accordance with ISO 17025 requirements by an ILAC accredited calibration provider. Gas furnace heating equipment performance and AFUE tests were performed per ANSI Z21.47 specifications.

The rated DX cooling capacity of the 3-ton split-system HVAC unit is 33,800 Btu per hour (Btuh or 9.67 kW) and the rated heating capacity is 54,000 Btuh (15.83 kW). The 3-ton split-system default cooling time delay is either 0 seconds or 90 seconds after the air conditioning compressor turns off, and the default heating time delay is 120 seconds after the furnace turns off. The rated cooling capacity of the 3-ton packaged HVAC unit is 35,800 Btuh (9.82 kW) and the rated heating capacity is 55,200 Btuh (16.18 kW). The 3-ton packaged unit default cooling time delay is either 0 seconds or 60 seconds after the air conditioning compressor turns off, and the heating time delay is 120 seconds after the furnace turns off. The EFC® fan-off time delay varies depending on system type, mode of operation, and length of time the cool source or heat source operate.

The 1.5-ton split-system Heat Pump (HP) rated total cooling capacity is 17,600 Btuh (Btuh) and the sensible cooling capacity is 13,900 Btuh (4.07 kW) at 95°F outdoor air temperature and 525 cfm evaporator airflow with 80°F indoor DB and 67°F indoor WB temperatures. The rated total cooling capacity is 17,000 Btuh (4.98 kW) and sensible cooling capacity is 13,600 Btuh (3.99 kW) at 95°F outdoor air temperature and 75°F indoor drybulb and 62F indoor wetbulb temperatures. The rated heating capacity is 18,000 Btuh (5.28 kW) at 47°F outdoor air temperatures. The heat pump rated cooling efficiency is 14-SEER and the heating coefficient of performance (COP) is 3.76 at 47°F outdoor air temperature. The heat pump cooling or heating fan-off time delays are fixed during setup at either 0 seconds or 65 seconds after the cool or heat source turns off.

into solid ice at 32F is referred to as the heat of fusion which is 144 Btu/lb multiplied by 2,000 lbs of water or 288,000 Btu of energy over a 24 hour period requires 12,000 Btu/hour to make one ton of ice in one day. The British thermal unit (Btu) is heat required to raise the temperature of one pound (0.454 kg) of water one degree Fahrenheit (°F or 0.556 C). The Btu is equivalent to 1055.06 joules or 251.997 calories.

[82] Cooling tests were performed at 95°F (35 C) drybulb (DB) outdoor and 75°F (23.9 C) DB and 62°F (16.7 C) wetbulb (WB) indoor temperatures. Gas heating tests were performed at 47°F (8.3 C) DB outdoor and 72°F (22.2 C) DB and 53°F (11.7 C) WB indoor temperatures. Heat pump tests were performed at 17°F (-8.3 C), 35°F (1.7 C), 47°F (8.3 C), and 62°F (16.7 C) outdoor temperatures and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. Hydronic heating tests were performed at 47°F (8.3 C) outdoor temperatures with 130F (54.4 C) and 140F (60 C) hot water temperature and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. The ARI 210/240 EER_A and EER_B indoor air dry-bulb temperature is 80°F (44.2C) and the wet-bulb is 67°F (37.2C). The EER_A outdoor air dry-bulb is 95°F (52.8C). The EER_B outdoor air dry-bulb is 82°F (45.6C). The SEER outdoor air dry-bulb is 82°F, indoor air dry-bulb is 80°F (44.2C), and indoor air wet-bulb is 57°F (31.7C).

The 1.5-ton hydronic (HYD) split-system rated total cooling capacity is 17,500 Btuh (5.13 kW) at 95°F OAT and 80°F indoor DB and 67°F indoor WB temperature, The hydronic system rated cooling efficiency is 13 SEER with the model MHH-19-410 condensing coil and 95°F OAT and 550 cfm evaporator airflow with 80F indoor drybulb and 67°F indoor wetbulb temperatures. The rated heating capacity is 18,000 Btuh (5.28 kW) with 550 cfm (235.98 liters per second, lps) airflow at 70°F entering air drybulb temperature and 3 gallons per minute (gpm or 0.189 lps) at 140F hot water supply temperature. The rated hot water heating efficiency is 78%. The hydronic heating coil is designed to receive 1 to 3 gpm of 120 to 180°F hot water circulated by a 1/25th hp (30W) pump where the water is heated by a storage water heater. The hydronic unit default cooling or heating time delay is fixed during setup at either 0 seconds or 60 seconds after the cool or heat source turns off.

The DX cooling tests were performed under non-steady state field conditions to measure sensible cooling capacity and efficiency with no time delay or fixed time delay of 60 seconds for the packaged unit or 90 seconds for the split-system after the air conditioning compressor turned off. Non-steady state cooling tests were performed with the EFC® product providing a variable time delay on the evaporator fan depending on length of time the compressor operated. The gas furnace heating tests were performed under non-steady state field conditions to measure the sensible heating capacity and efficiency with fixed time delay of 120 seconds after the gas furnace turned off. Non-steady state heating tests were performed with the EFC® product providing increased fan speed from low-to-high or medium-to-high speed after 4 minutes of furnace operation and variable time delay on the fan after the furnace turns off depending on length of time the furnace operated. The heat pump and hydronic tests were performed under non-steady state field conditions to measure sensible cooling or heating capacity and efficiency with no time delay or fixed time delay of 65 seconds for the split-system heat pump or 60 seconds for the split-system hydronic system after the cool or heat source turned off. Non-steady state cooling and heating tests were performed with the EFC® product providing a variable time delay on the fan depending on length of time the cool or heat source operated.

Cooling Test Data and Energy Savings Analysis

The laboratory performed 22 split- and packaged system cooling tests and 24 heat pump cooling tests with and without the EFC®. The tests were performed at 75F return air DB and 62F return air WB temperatures and 95F DB outdoor air temperature. The laboratory tests measured the additional sensible cooling capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the cooling equipment operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests measured sensible cooling capacity output (Btu or Joules) with and without the EFC® for compressor operational times varying from 5 to 50 minutes. The laboratory tests also measured total sensible cooling capacity for 60 minutes at the same conditions. The ratio of sensible cooling capacity for each test divided by the total sensible cooling capacity for 60 minute tests is defined as the cooling Part Load Ratio (PLR) as shown in **Equation 1**. The cooling PLR is used to normalize the cooling savings for each test or test scenario.[83]

Equation 1 $$PLR_C = \frac{Q_{c_o}}{Q_{c_r}}$$

Where, PLR_C = cooling part load ratio of delivered sensible cooling capacity for each test divided by the total sensible cooling capacity of the equipment (dimensionless),
Q_{c_o} = delivered sensible cooling capacity measured for each test (Btu or Joules), and
Q_{c_r} = total sensible capacity measured at same conditions for 60 minutes (Btu or Joules).

[83] Scenarios are defined as weighted average test results for test performed at approximately the same PLR where the baseline is either zero or a fixed fan-off time delay for the same class of DX or heat pump equipment independent of total capacity.

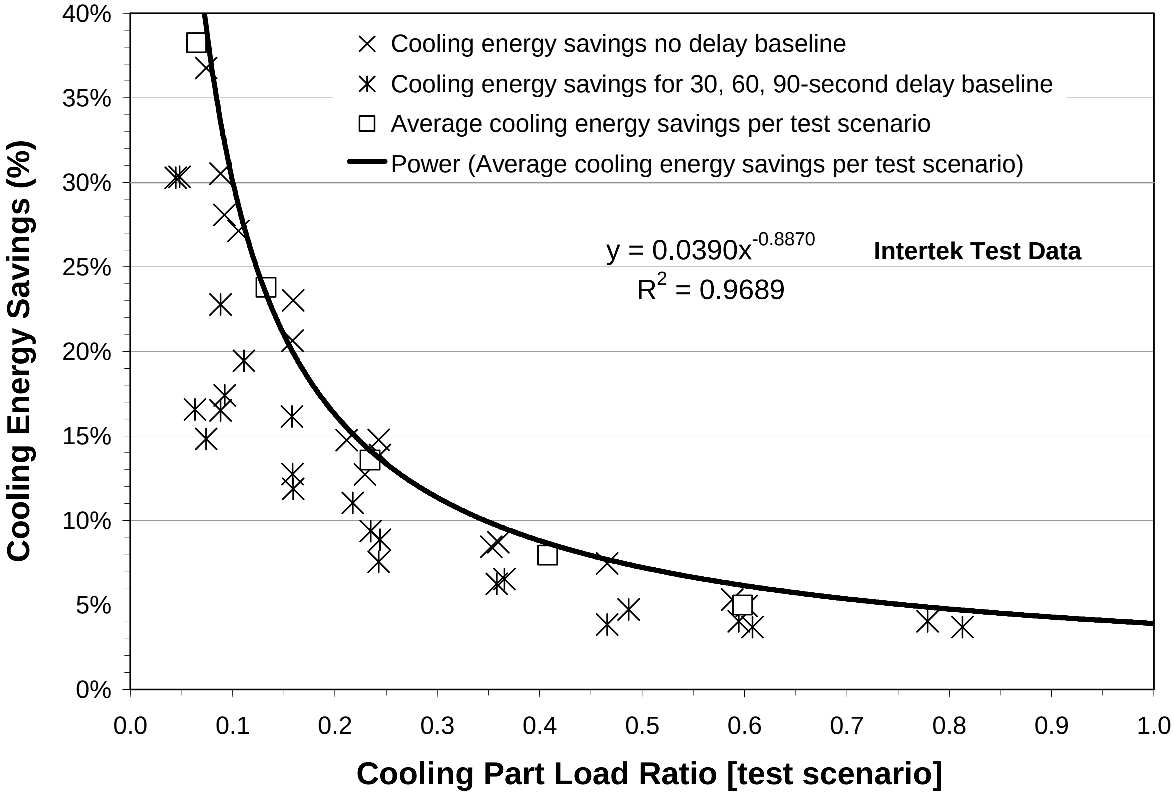
Laboratory test data of the cooling energy savings and the average cooling energy savings per test scenario are plotted in **Figure 1**. Cooling energy savings are calculated using the power function regression **Equation 2** based on the cooling part load ratio (PLR).[84]

Equation 2 $\Delta\eta_C = \left(0.0390\ (PLR_C)^{-0.8870}\right)100$

Where, $\Delta\eta_C$ = EFC® cooling savings compared to baseline based on lab tests (%).

Figure 1 shows the EFC® cooling energy savings varying from 3.9 to 38.3% compared to baseline fan-off delays of zero, 30, 60, 65, and 90-seconds and PLR values ranging from 0.044 to 0.813 based on 46 laboratory tests. Approximately 90% of air conditioners in California have a pre-existing fan-off time delay of zero based on field data from 61,545 units [7].

Figure 1: Cooling Energy Savings versus Part Load Ratio for EFC®



The eQuest building energy software (version 3.65) and the Database for Energy Efficiency Resources (DEER) eQuest residential single-family, multi-family, and mobile home building prototypes were used to evaluate the baseline HVAC energy use and peak demand for each building prototype and 16 California climate zones [11]. Based on the eQuest simulations, the average annual cooling PLR values range from 0.12 to 0.28 and the weighted average cooling PLR is 0.22 [7]. The average annual EFC® cooling energy savings are 15.2 ± 0.8% based on **Equation 2** and housing stock weights for each climate zone from US Census data [10].

Laboratory and field tests demonstrate that the EFC® improves thermal comfort by overshooting the thermostat setpoint and providing longer off-cycle times to reduce compressor on-cycle times. The EFC® can also prevent evaporator coil icing by continuing to operate the fan to evaporate cold-water condensate from the coil at the end of each cooling cycle. This prevents ice formation when the evaporator coil temperature is below freezing which can be caused by low airflow, dirty air filters, low refrigerant charge, low thermostat cooling setpoint, and refrigerant restrictions. Coil

[84] The power function regression equation is f(x)= a·x^n, where "a" is the coefficient or initial value of the function (y-intercept at x=1), "x" is the independent variable (PLR), "n" is the exponent, and "f(x)" is the dependent variable (output of the function).

icing can reduce evaporator airflow by 17 to 37% and reduce sensible efficiency by 4% to 12% [12].

Field test results for a 3.5-ton (12.31 kW) air conditioning split-system with 21% duct leakage and the same system with the EFC® are shown in **Figure 2**, **Figure 3**, and **Table 1**. **Figure 3** shows normalized cooling kWh savings of 19.9% based on EFC® usage of 20.7 kWh compared to normalized usage of 25.88 kWh for the base system (see **Table 1** row v). The base AC compressor operated for 306.5 minutes to satisfy the thermostat over the 429.5 minute test period, and the EFC® AC compressor operated for 264.2 minutes or 14% less than the base over the same test period. The EFC® provides 24.2% more compressor off time than the base AC system (165.3 versus 133 minutes). The difference is due to 52 minutes of EFC® fan-only evaporative cooling.

Figure 2: Field Measurements of Sensible EER* for the Base Air Conditioning System

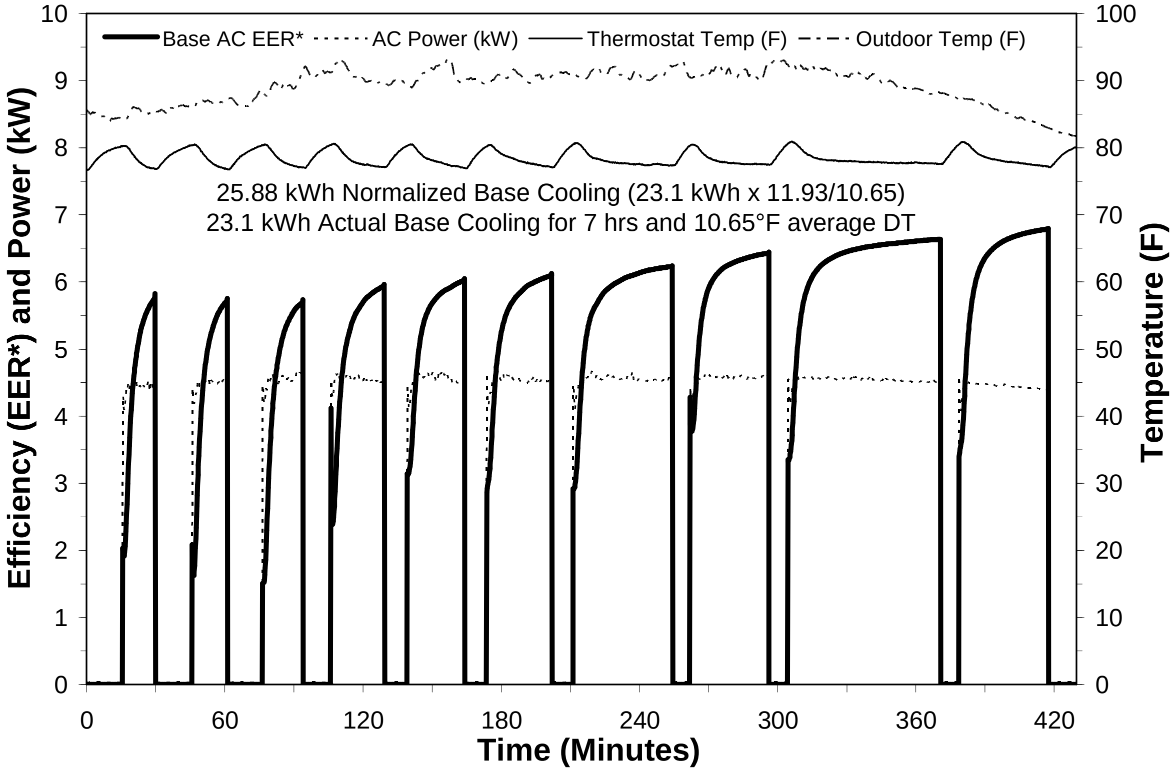
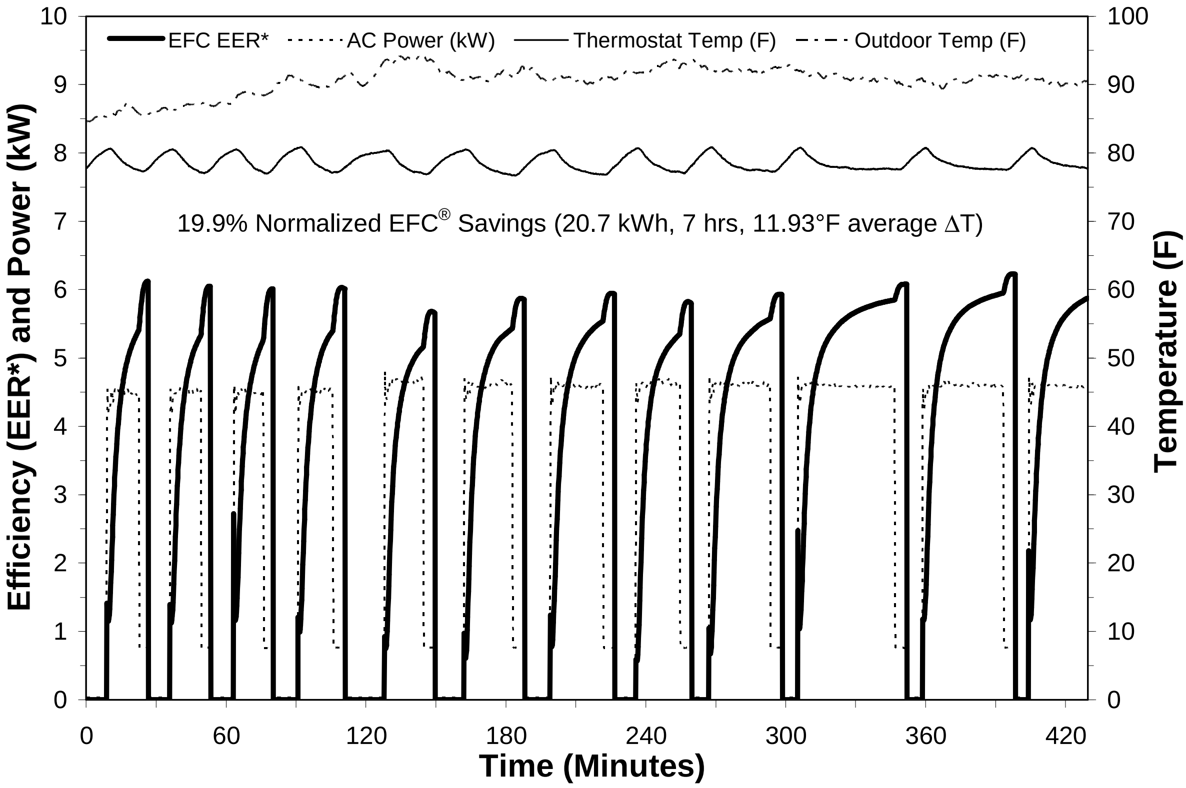


Figure 3: Field Measurements of Sensible EER* for the Air Conditioning System with the EFC®



The base AC operated with average outdoor air minus indoor air temperature difference (ΔT) of 10.65 +/- 0.1°F (Table 1, row m), outdoor temperature of 89.09 +/-0.09°F, and indoor air temperature of 78.44 +/-0.03°F. The EFC® operated with average ΔT of 11.93 +/- 0.08°F (p), outdoor air temperature of 90.51 +/-0.07°F and indoor air temperature of 78.58 +/-0.04°F. The EFC® used 20.68 kWh or 10.2% (s) less electricity than the base AC system which used 23.10 kWh. The EFC® average Part Load Ratio (PLR) is 0.32 and the EFC® cooling savings are 10.5% (u) based on Equation 6. The normalized EFC® cooling savings (v) are 19.9% based on normalized base AC energy of 25.88 kWh (d) equal to base AC energy of 23.1 kWh times 11.93 ΔT for EFC® (p) divided by 10.65 ΔT for base AC system (row m). Predicted savings (based on the PLR) do not include the increased off cycle time.

Table 1: Field Tests of the Base Air Conditioner with and without the EFC®

Description	Row	Total
Base AC Compressor On Time (minutes)	a	306.5
EFC® Compressor On Time (minutes)	b	264.2
Base AC Energy (kWh)	c	23.10
Normalized Base AC Cooling Energy based on ΔT (kWh)	d=c × [p/m]	25.88
EFC® AC Energy (kWh) includes 0.645 kWh for EFC® fan operation	e	20.73
Base AC Compressor Off Time (minutes)	f	133.0
EFC® Compressor Off Time (minutes) EFC® fan-only evaporative cooling is 52 minutes	g	165.3
Base AC Mechanical Sensible Cooling (Btu) [compressor plus fan]	h	145,102
EFC® Mechanical Sensible Cooling (Btu) [compressor plus fan]	i	112,491
EFC® Fan Only Sensible Cooling Energy (Btu)	j	11,129
Base AC Outdoor Air Temperature (°F)	k	89.09
Base AC Indoor Air Temperature (°F)	l	78.44
Base AC Average Outdoor minus Indoor Air Temperature (ΔT) (°F)	m	10.65
EFC® Average Outdoor Air Temperature (°F)	n	90.51
EFC® Average Indoor Air Temperature (°F)	o	78.58
EFC® AC Average Outdoor minus Indoor Air Temperature (ΔT) (°F)	p	11.93
Base AC Average Return RH (%)	q	33.46
EFC® Average Return RH (%)	r	33.87
EFC® Cooling Savings Non-normalized (%)	**s=1-[e/c]**	**10.2%**
EFC® Average PLR	t	0.32
EFC® Cooling Savings based on PLR and Eq. 1 $\Delta\eta_c = 0.0390(PLR_c)^{-0.8870}$ (%)	**u**	**10.5%**
EFC® Cooling Savings Normalized based on ΔT Base divided by ΔT EFC® (%)	**v=1-[e/d]**	**19.9%**

Figure 4 compares cooling energy savings based on laboratory and field tests. The relationship between energy savings and PLR with 21% duct leakage is provided in the power function regression **Equation 3**.

Equation 3 $$\Delta\eta_{c_d} = 0.0343 PLR_S^{-0.8393}$$

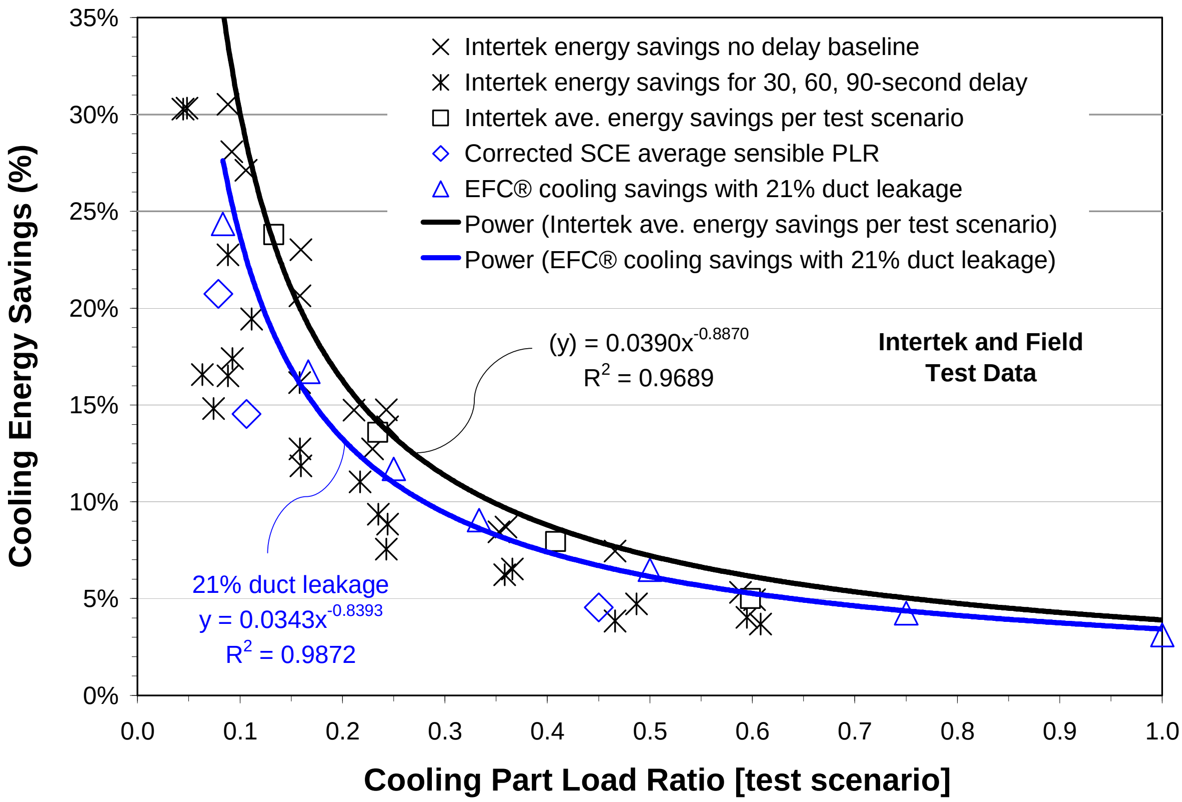
Where, $\Delta\eta_{c_d}$ = EFC® cooling savings with 21% duct leakage based on field tests.

Table 2 compares the difference between laboratory and field test cooling energy savings versus PLR. The field tests are within 1.3 +/- 0.4% of laboratory test results for PLR values from 0.17 to 1.0. Field tests are within 11% of laboratory tests for PLR of 0.08. These tests indicate duct leakage has a larger impact on cooling energy savings for short cycle PLR values. Otherwise, the field and lab tests provide comparable energy savings. Duct leakage has significantly less impact on cooling savings for compressor operating times of 10 minutes or greater (PLR ≥ 0.17).

Table 2: Field Test Results of Base and EFC® Sensible EER* with 21% Duct Leakage

Description	1	2	3	4	5	6	7
Compressor On Time (minutes)	5	10	15	20	30	45	60
Part Load Ratio (PLR)	0.08	0.17	0.25	0.33	0.50	0.75	1.00
Eq. 6 Laboratory test cooling energy savings [k]	35.3%	19.1%	13.3%	10.3%	7.2%	5.0%	3.9%
Field test cooling energy savings with duct leakage [l]	24.4%	16.7%	11.7%	9.1%	6.5%	4.2%	3.1%
Difference lab minus field test energy savings [m=k-l]	-11.0%	-2.4%	-1.6%	-1.3%	-0.7%	-0.8%	-0.8%

Figure 4: Cooling Energy Savings versus Part Load Ratio for EFC®



Gas Furnace Heating Test Data and Energy Savings Analysis

The laboratory performed 48 split- and packaged gas furnace heating tests (24 baseline tests and 24 measure tests). The tests were performed at 72°F (22.2 C) return air DB and 53°F (11.7 C) return air WB temperatures and 47°F (8.3 C) DB outdoor air temperature. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the heat-source operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests measured heating capacity output (Btu or Joules) with and without the EFC® for furnace operational times varying from 5 to 30 minutes. The laboratory tests also measured total heating capacity for 60 minutes at the same conditions. The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests is defined as the heating Part Load Ratio (PLR) as shown in **Equation 4**. The heating PLR is used to normalize the gas furnace heating energy savings each test and each test scenario.[85]

Equation 4 $$PLR_h = \frac{Q_{h_o}}{Q_{h_r}}$$

Where, PLR_h = heating part load ratio of delivered heating capacity for each test divided by the total heating capacity of the equipment (dimensionless),

Q_{h_o} = delivered heating capacity measured for each test (Btu or Joules), and

Q_{h_r} = total heating capacity measured at same conditions for 60 minutes (Btu or Joules).

[85] Scenarios are defined as weighted average test results for tests performed at approximately the same PLR where the baseline is the fixed fan-off time delay for the same class of gas furnace heating equipment independent of total capacity.

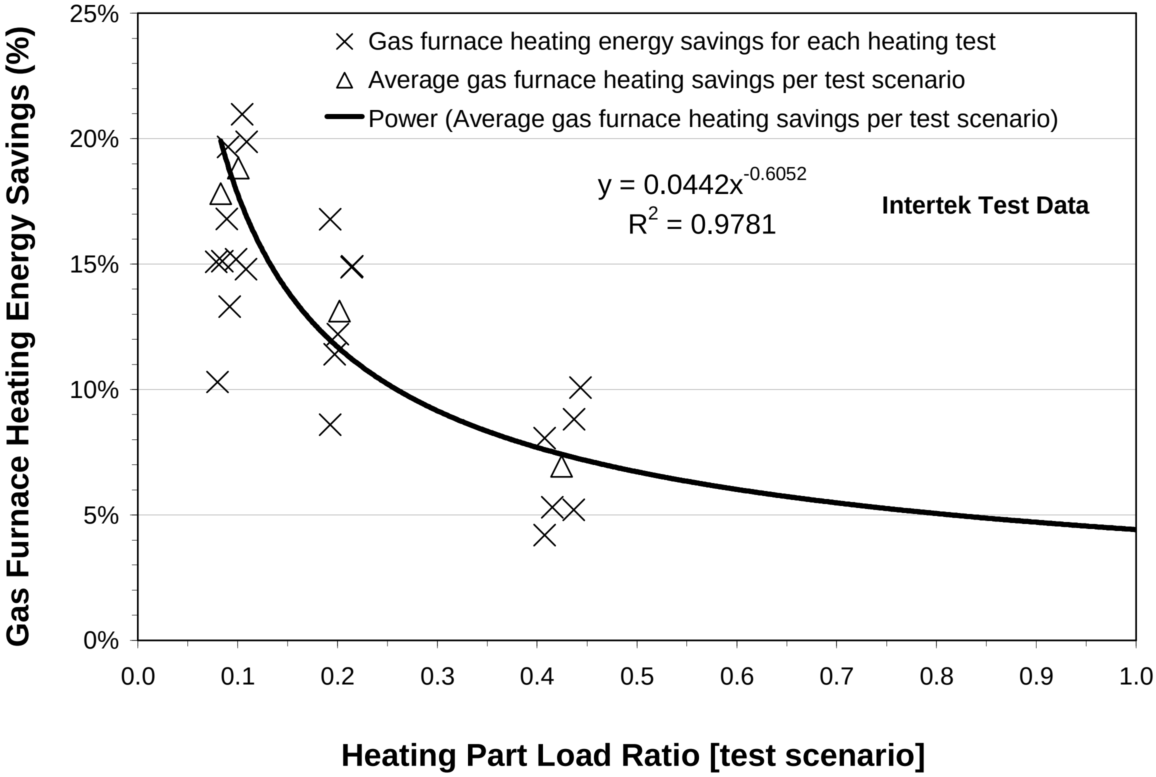
Laboratory test data of the heating energy savings and the average heating energy savings per test scenario are plotted in **Figure 5**. Gas furnace heating energy savings are calculated using regression **Equation 5** based on the PLR.

Equation 5 $$\Delta\eta_h = \left(0.0442\ (PLR_h)^{-0.6052}\right)100$$

Where, $\Delta\eta_h$ = EFC® gas furnace heating savings compared to baseline based on lab tests (%).

Figure 5 shows the EFC® heating energy savings varying from 4.2 to 21% with medium-speed or high-speed fan operation compared to baseline fan-off delays of 45 and 120 seconds with low-speed or medium-speed fan operation and PLR values ranging from 0.075 to 0.444 based on 24 laboratory tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.11 to 0.2 and the weighted average heating PLR 0.14 [7]. The average annual EFC® heating savings are 15.9 ± 0.7% based **Equation 5** and housing stock weights for each climate zone from US Census data [10].

Figure 5: Gas Furnace Heating Energy Savings versus Part Load Ratio for EFC®



Field test results of a 120,000 Btu per hour (35.17 kW) gas furnace heating system with 21% duct leakage and the same system with the EFC® are provided in **Table 3** and **Figure 6**. Test results provide furnace on time (minutes), energy use (Btu), sensible heating capacity (Btu), heating efficiency (%), efficiency improvement, and heating energy savings for the base unit without the EFC® installed and the same unit with the EFC® installed. Tests were performed with air sampling sensors located upstream and downstream of the forced air unit located in an unconditioned crawl space with ducts located in an unconditioned attic where the attic temperature is colder than the conditioned space.

Table 3: Field Tests of Base and EFC® Furnace Efficiency with 21% Duct Leakage

Description	8/9	10/11	12/13	14/15	16/17
Base Furnace On Time (minutes)	6	10	15	20	30
120-Second Delay Furnace Energy Input (Btu) [a]	10,574	18,382	28,142	37,903	57,423
120-Second Delay Heating Capacity (Btu) [b]	6,260	12,140	19,388	26,675	41,063
120-Second Time Delay Heating Efficiency [c=b/a]	59.2%	66.0%	68.9%	70.4%	71.5%
EFC® Furnace Energy Input (Btu) [d]	10,086	17,569	26,190	36,601	51,404
EFC® Delivered Heating Capacity (Btu) [e]	7,214	13,610	20,271	28,130	39,412
EFC® Heating Efficiency [f=e/d]	71.5%	77.5%	77.4%	76.9%	76.7%
EFC® Heating Efficiency Improvement [g=f/c-1]	20.8%	17.3%	12.3%	9.2%	7.2%
EFC® Extra Fan Energy (kWh)	0.022	0.024	0.033	0.014	0.012
120-Second Delay Furnace Input to Match EFC® [h=e/c]	12,186	20,608	29,424	39,970	55,114
EFC® Energy Savings (Btu) [i=h-d or i=(e-b)/c+a-d]	2,100	3,039	3,234	3,369	3,710
Part Load Ratio (PLR)	0.08	0.15	0.24	0.32	0.08
EFC® Heating Energy Savings [j=(1-c/f) or j=i/h]	**17.2%**	**14.7%**	**11.0%**	**8.4%**	**6.7%**

Figure 6 shows time series data for the heating efficiency, rated efficiency, and outdoor air temperature (°F).

Figure 6: Field Measured Gas Furnace Efficiency versus PLR with 21% Duct Leakage

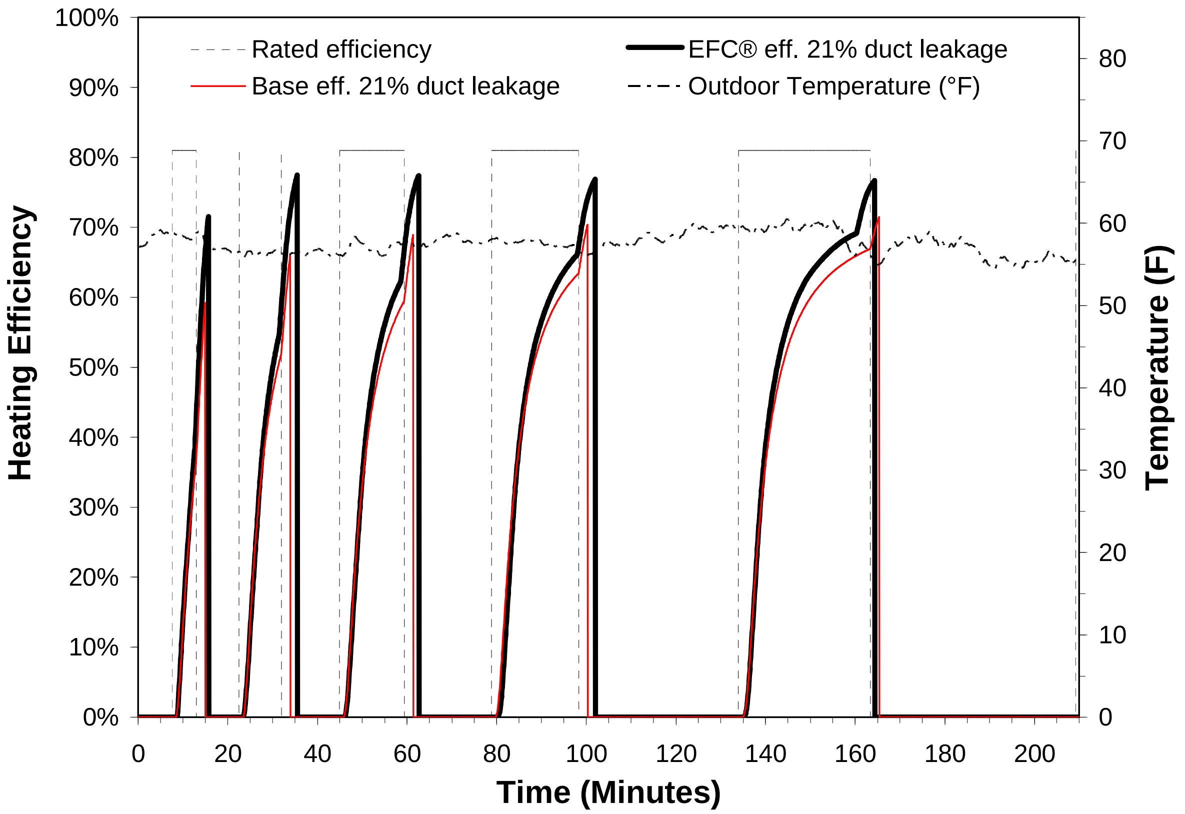


Figure 7 compares heating energy savings based on laboratory and field tests indicating similar results. Gas furnace heating energy savings based on field measurements with 21% duct leakage are calculated using regression **Equation 6** based on the PLR.

Equation 6 $$\Delta\eta_{h_d} = \left(0.0485\ (PLR_h)^{-0.5224}\right)100$$

Where, $\Delta\eta_{h_d}$ = EFC® gas furnace heating savings with 21% duct leakage based on field tests (%).

The average EFC® gas furnace heating savings are 14.5% based on 0.14 PLR and **Equation 6**.

Table 4 compares the difference between laboratory and field test heating energy savings versus PLR. The field tests are within 0.7 +/- 1.4% of laboratory test results for PLR values from 0.08 to 0.49. These tests indicate duct leakage has a larger impact on heating energy savings for short cycle PLR values. Otherwise, field and lab tests provide comparable energy savings. Duct leakage had less impact on heating savings for furnace operating times of 10 minutes or greater (PLR ≥ 0.15).

Figure 7: Gas Furnace Heating Energy Savings versus Part Load Ratio for EFC®

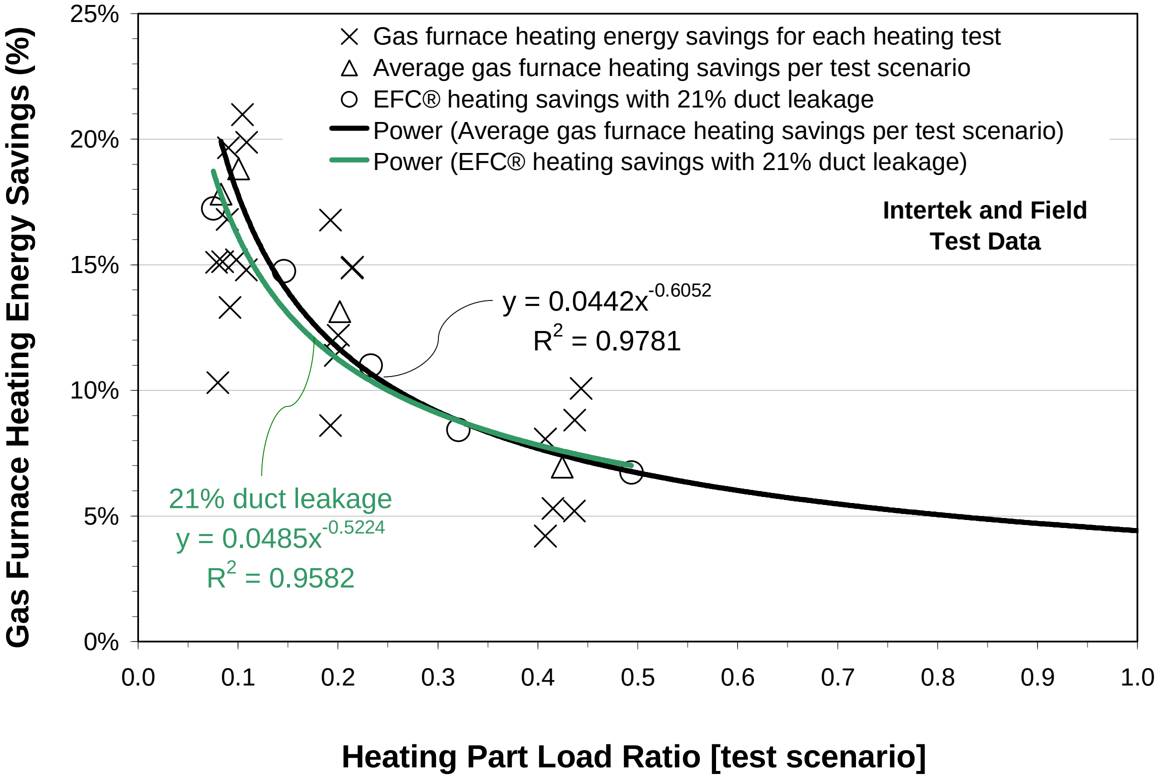


Table 4: Field Test Results of Base and EFC® Heating Efficiency with 21% Duct Leakage

Description	1	2	3	4	5
Furnace Operating Time (minutes)	5	10	15	20	30
Part Load Ratio (PLR)	0.08	0.15	0.23	0.32	0.49
Eq. 17 Laboratory test heating energy savings [k]	21.2%	14.2%	10.7%	8.8%	6.8%
Field test heating energy savings with duct leakage [l]	17.2%	14.7%	11.0%	8.4%	6.7%
Difference lab minus field test energy savings [m=k-l]	3.9%	-0.6%	-0.3%	0.4%	0.0%

Heat Pump Heating Test Data and Energy Savings Analysis

The laboratory performed 48 split-system heat pump heating tests (24 baseline tests and 24 measure tests). The tests were performed at 17°F (-8.3 C), 35°F (1.7 C), 47°F (8.3 C), and 62°F (16.7 C) outdoor temperatures and 70°F (21.1 C) DB and 55°F (12.8 C) WB indoor temperatures. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the heat-source operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests also measured total heat pump heating capacity for 60 minutes at the same conditions.[86]

[86] Heat pump input Btu values are based on measured kWh times 3412 Btu/h.

The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests at the same test conditions is defined as the Part Load Ratio (PLR) as shown in **Equation 6**. The PLR is used to normalize the heat pump heating energy savings each test and each test scenario. The heating PLR is used to normalize the heat pump heating energy savings each test and each test scenario.

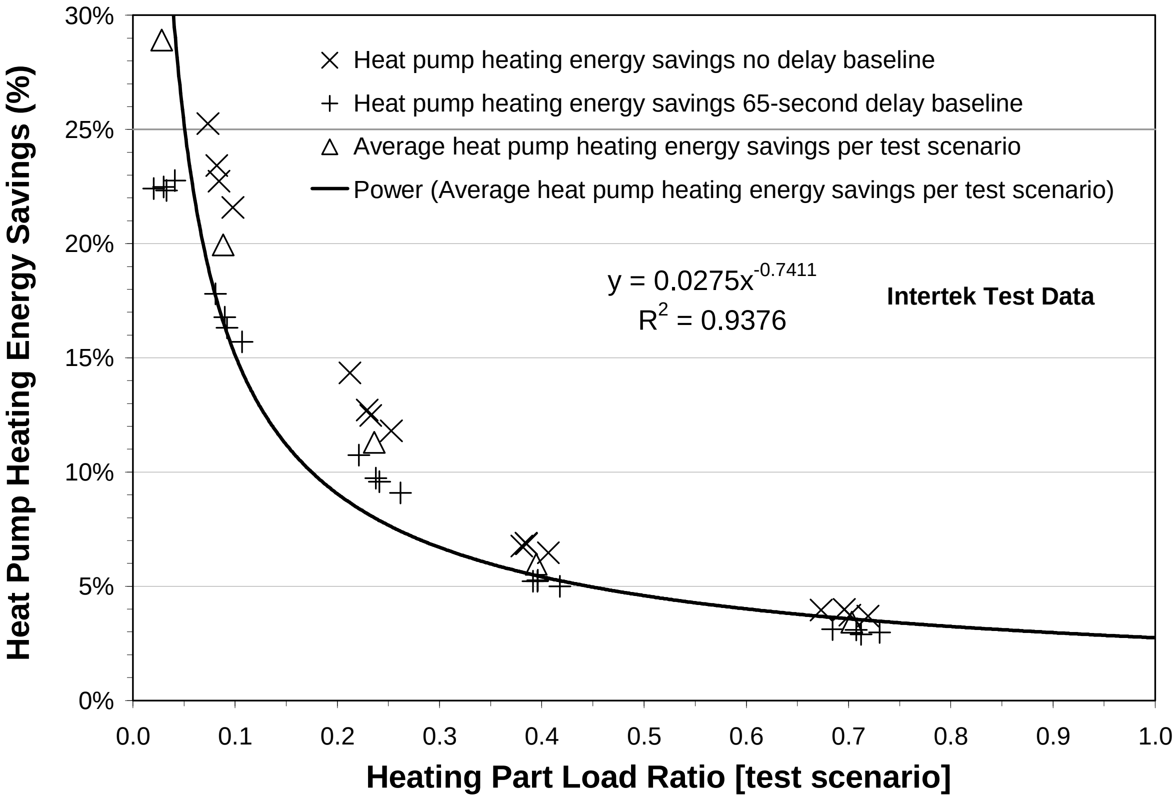
Laboratory test data of the heating energy savings and the average heat pump heating energy savings per test scenario are plotted in **Figure 8**. Heat pump heating energy savings are calculated using regression **Equation 7** based on the PLR.

Equation 7 $$\Delta\eta_h = \left(0.0275\left(PLR_h\right)^{-0.7411}\right)100$$

Where, $\Delta\eta_h$ = EFC® heat pump heating savings compared to baseline based on lab tests (%).

Figure 8 shows the EFC® heat pump heating energy savings varying from 2 to 28.9% compared to baseline fan-off delays of zero or 65 seconds and PLR values ranging from 0.02 to 0.72 based on 48 laboratory tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.09 to 0.27 and the weighted average heating PLR 0.13 [7]. The average annual EFC® heat pump heating energy savings are 12.5 ± 1% based on **Equation 7** and housing stock weights for each climate zone from US Census data.

Figure 8: Heat Pump Heating Energy Savings versus Part Load Ratio for EFC®



Hydronic Heating Test Data and Energy Savings Analysis

The laboratory performed 20 split-system hydronic hot water heating tests. The tests were performed at 47°F (8.3 C) outdoor temperatures with 130°F (54.4 C) and 140°F (60 C) hot water temperature and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the hydronic heating operating time compared to the baseline system with no time delay or a fixed 60-second time delay. The laboratory tests also measured total hydronic heating capacity for 60 minutes at the same conditions. The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests at the same test conditions is defined as the Part Load Ratio (PLR) as shown in **Equation 7**. The PLR is used to normalize the hydronic heating energy savings each test and each test scenario. The heating PLR is used to normalize the hydronic heating energy savings each test and each test scenario.

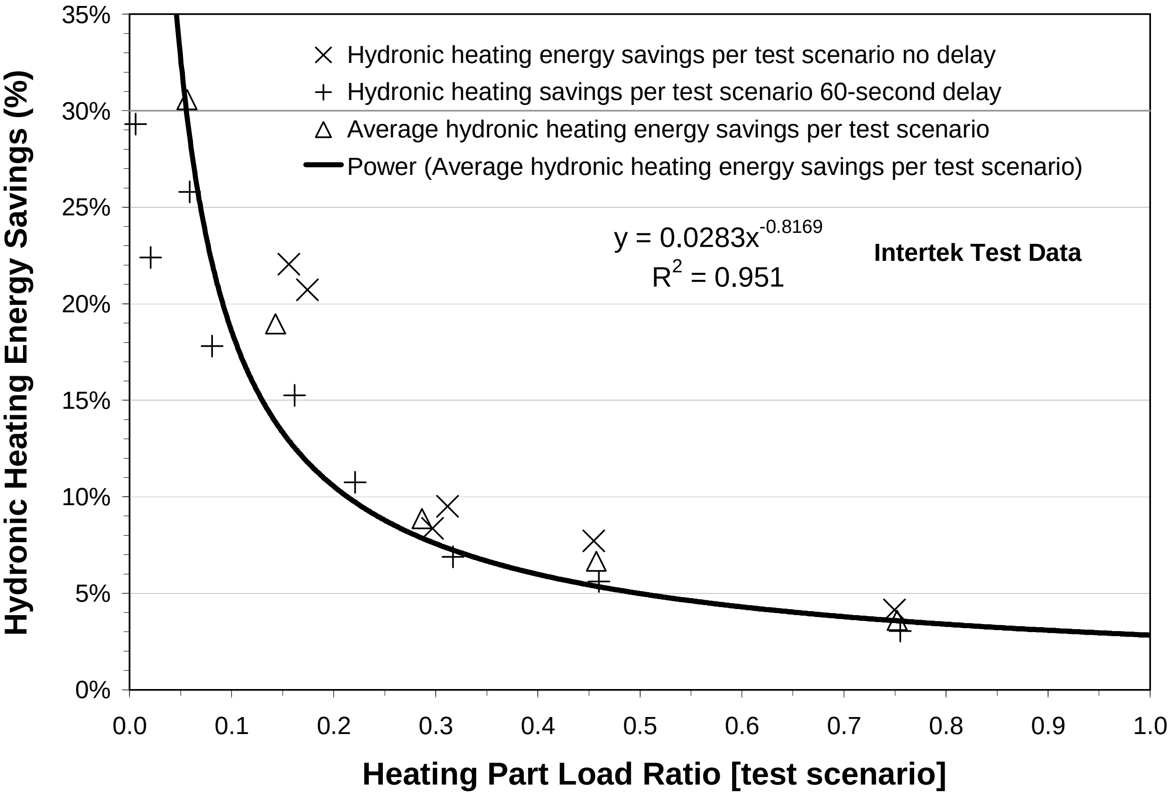
Twelve laboratory tests were performed with the water heater set at 130°F (54.4 C) and eight tests were performed with the water heater set at 140°F (60 C). Laboratory test data of the heating energy savings and the average hydronic heating energy savings per test scenario are plotted in **Figure 9**. Hydronic heating energy savings are calculated using regression **Equation 8** based on the PLR.

Equation 8 $$\Delta\eta_h = \left(0.0283(PLR_h)^{-0.6169}\right)100$$

Where, $\Delta\eta_h$ = EFC® hydronic heating savings compared to baseline based on lab tests (%).

Figure 9 shows the EFC® hydronic heating savings varying from 4.1 to 30.6% compared to baseline fan-off delays of zero or 60 seconds and PLR values ranging from 0.056 to 0.075 based on 20 lab tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.09 to 0.20 and the weighted average heating PLR 0.12 [7]. The average annual EFC® heating energy savings are 16.3 ± 1.7% based on **Equation 8** and housing stock weights for each climate zone from US Census data [10].

Figure 9: Hydronic Heating Energy Savings versus Part Load Ratio for EFC®



Discussion

The EFC® lengthens "off-cycle" times for subsequent cooling cycles by 3 to 36% by overshooting the cooling thermostat setpoint by 0.5 to 1.6F (0.3 to 0.9 C). The EFC® heating tests lengthen "off-cycle" times for subsequent heating cycles by 2 to 30% by overshooting the heating thermostat setpoint by 0.3 to 2.2F (0.2 to 1.2 C). Participant survey responses from occupants who had the EFC® installed in their cooling and heating system for 5 years indicate increased thermal comfort due to the EFC® overshooting the thermostat setpoint [7]. These tests results indicate that mild climates with frequent on-off cycles can realize greater savings than hot climates with longer cycles. Laboratory and field tests also demonstrate that the EFC® can prevent evaporator coil icing by continuing to operate the fan and evaporate cold-water condensate from the coil at the end of each cooling cycle which prevents ice formation when the evaporator coil temperature is below freezing. This helps maintain thermal comfort, efficiency and equipment life per the ACCA Standard 4 and Standard 5 HVAC Quality installation and maintenance standards [6].

The EFC® cooling energy savings vary from 3.9 to 38.3% with average savings of 15.2 ± 0.8% based on 46 laboratory tests. Field measurements of an air conditioning system with 21% duct leakage and the same system with the EFC® found normalized cooling energy savings of 19.9% based on 22 field tests. Gas furnace heating energy savings vary from 4 to 21% with average savings of 15.9 ± 0.7% based on 24 laboratory tests. Field measurements of a gas furnace heating system with 21% duct leakage and the same system with the EFC® found average normalized heating savings of 13.5% based on 10 field tests. Heat pump heating energy savings vary from 2 to 29% with average savings of 12.5 ± 1% based on 48 laboratory tests. Hydronic heating energy savings vary from 4 to 31% with average savings of 16.3 ± 1.7% based on 20 laboratory tests. According to the US EIA, California uses approximately 0.74 quadrillion Btu (quads) or 0.79 exajoules (EJ) per year for space cooling and heating [1]. Assuming the EFC® can save 15% on cooling and heating, the estimated potential annual energy savings are 0.11 quadrillion Btu (quads) or 0.12 exajoules (EJ) in California or 4.65% of US EIA total estimated annual energy use in California of 2.4 quads or 2.53 EJ.

Conclusions

Laboratory and field tests of the EFC® provide evidence to support the cooling and heating energy efficiency savings claims. Cooling tests demonstrate improved thermal comfort by overshooting the thermostat setpoint and providing longer “off-cycle” times from variable fan-off time delays based on cooling or heating operational time. Test results indicate that mild climates with frequent on-off cycles can realize greater savings than hot climates, but HVAC systems operating in either type of climate can realize increased efficiency and 10 to 20% energy savings. The laboratory and field tests also demonstrate that the EFC® can prevent evaporator coil icing by continuing to operate the fan and evaporate cold-water condensate from the coil at the end of each cooling cycle which prevents ice formation when the evaporator coil temperature is below freezing.

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Acknowledgements

Laboratory tests performed at Intertek in Plano, TX and field tests were performed in Reno NV, with funding from GreenFan® Inc.

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Durability testing procedure for washing machines – approach and first learnings [87]

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Abstract

Durable products allow to reduce the consumption of raw materials long-term and to contribute to waste minimization. Thus, durability plays a key role to enhance circular economy and resource conservation, for example in the category of electrical and electronic equipment. However, it was observed that the average lifetime of these products has decreased over recent years. We identified the washing machine product group as a relevant case study for the development of a durability test, and as a potential trigger to systematically address durability in the design of products. The main objective of this research was to develop a procedure to test minimum durability performance of washing machines, on which limitations and potentials for future improvements would be highlighted. The procedure was developed to potentially be used in policy.

The durability test was developed considering the whole product tested under overstressed conditions. A series of spinning cycles with fixed unbalanced loads was run on two washing machines, to observe failures and performance changes during the test. Even though no hard failures occurred, results clearly showed that not all of the washing machines are able to sustain such a test without abrasion, or performance deterioration. The proposed test allowed to have results in a relatively short amount of efforts and time, which makes it compatible with policy constraints.

However, the attempt to mimic the stress induced on a washing machine by doing a high number of pure spinning cycles with fixed loads did not allow equal testing conditions: The actions of the control procedure regarding unbalance loads differ from machine to machine. Therefore, future developments will need to replace the series of spinning cycles with various washing programmes, and the fixed unbalanced loads with real loads, paying attention to limit the time required by the test. The outcomes of this research can be used as a basis to develop standardized durability tests and to hence contribute to the development of future product's policy measures.

Introduction

Durability of products has the potential to play a key role to enhance circular economy and resource conservation. Product lifespan extension is indeed among the main product design strategies to address material efficiency (Allwood and Cullen, 2012; Ghisellini et al., 2015). However, a reduction of the service life of household appliances has been observed over the past years (Prakash et al., 2016a). For instance, the median lifespans of washing machines had changed over time, resulting in a decrease of the lifetime expectancy, from 12.1 years in 2000 to 11.7 years in 2005 (Bakker et al., 2014). Ardente and Mathieux (2014), and later Tecchio et al. (2016a) proved through a life-cycle based approach that environmental benefits may be gained by extending the lifespan of washing machines, even when this lifetime extension delays the purchasing of a more energy efficient product. Evaluations were done considering average products, lifetime extensions of 1-6 years and energy efficiency improvements of newer products up to 20%, compared to the old ones.

[87] This paper is a short version of a paper submitted to Journal "Resources, Conservation & Recycling" for publication

Similar conclusions were also drawn for other products groups: vacuum cleaners (Bobba et al., 2016), dishwashers (Tecchio et al., 2016b), refrigerators (Bakker et al., 2014; Ricardo-AEA, 2015), ovens (Ricardo-AEA, 2015), notebooks (Bakker et al., 2014; Prakash et al., 2012) and desktop computers (Prakash et al., 2016b). Durable products allow also to reduce the consumption of raw materials and to contribute to waste minimisation (European Commission, 2008; European Union, 2008).

Durability is however a material efficiency aspect not easy to evaluate upfront. Endurance tests in real life condition often last months (if not years) and are expensive. Some of the authors of this work already identified the need for a standardized methodology to address durability of washing machines (Tecchio et al., 2017). The product group was chosen because of its market penetration in the EU, because of the ongoing review of the Commission Regulation n. 1015/2010, implementing ecodesign requirements under the Ecodesign Directive, and because it is regarded by the authors as one of the most suitable product groups for the application of material efficiency and waste management methods. Therefore, we developed and tested an accelerated durability test aiming at establishing minimum durability requirements for the product group, and that can be potentially automated to reduce time and cost of testing. Such a test focuses on the spinning function, as spinning is the main source of mechanical stress during a washing programme.

Experiments were run with three main issues to address: 1) to verify if washing machines currently on the market are able to sustain a series of stress without any hard failure, 2) to define procedure parameters and to evaluate the degradation of a washing machine performance over time, and 3) to identify possible further developments, based on identified limitations and potentials. Starting from a literature review focused on life cycle perspectives, obsolescence and durability tests at the product level, a durability test is introduced in the methodological section. Two exemplary washing machines were used as case studies to test the developed procedure. Finally, outcomes were discussed in regards of the feasibility of the proposed durability test, highlighting final remarks, opportunities and drawbacks.

Scientific background

Life cycle perspective and obsolescence

Regarding the overall life cycle of a washing machine, the use phase can be considered the most important contributor to environmental impacts such as cumulative energy demand (80%) (Rüdenauer et al., 2005) and global warming potential (84%), while impact categories mainly dependent on resource depletion (i.e. abiotic depletion of elements) are largely affected by the production phase, which includes the impact of the extraction and refining of materials, manufacturing and packaging (Tecchio et al., 2016a). Moreover, the improvements of the efficiency of products during the use phase generally imply a relative shift of environmental impacts towards the production phase, for example due to the higher amount and complexity of electronic components (Rüdenauer et al., 2005). On average, the expected lifetime of a washing machine can be estimated in 12.5 years (JRC, 2016). However, it was found that products are more and more experiencing early failures. According to Prakash et al. (2016a), more than 10% of the washing machines disposed at municipal collection points or recycling centres in 2013 were just 5 years old or less.

Durability tests at the product level

In order to understand possible failure modes and the relevance of tests at the product level instead of the components level, a detailed analysis of washing machine failure modes was carried out by some of the authors, who analysed and categorizes thousands of repair services (Tecchio et al., 2016a). Most recurring failure modes involved the electronics (including control electronics, control panels, program selectors, relays, line filters, etc.), shock absorbers and bearings, doors (including seals, handles, hinges and locks) and motor carbon brushes. Another analysis, conducted through different sources of information (consumer reports, consumer organization test reports on life tests, service reports, manufacturer feedback) revealed that the spinning operation is a main source of stress for the whole machine and many failures are associated with the tub/drum system (Prakash et al., 2016a).

Engineers in the manufacturing industries have used accelerated life test (ALT) experiments for many years (Escobar and Meeker, 2007). ALTs with overstressed conditions try to simulate the actual user behaviour and can be an effective method of acceleration for washing machines. However, establishing a relationship between ALT experiments and the actual failure mechanism of a washing machine is usually extremely complicated (Escobar and Meeker, 2007).

Method

Spinning at a high speed is the most stressful part of a washing programme, for a horizontal axis washing machine (WM), therefore weak points on the mechanical design of such machines may be identified through a series of spinning cycles. The task of this research consisted of developing a durability procedure mainly based on spinning cycles, in order to reduce time and cost of testing, compared to conventional endurance tests. Even though the testing conditions do not reflect the real conditions WMs are working in real life, experiments were conducted to understand if such a concept can deliver useful information to assess the durability of washing machines.

Method development

The work conducted by Tucci et al. (2014) and De Carlo et al. (2013), and private communications with a WM manufacturer were used as a foundation of our durability test. As almost all washing machines offer programmes that either allow the spinning or a rinsing cycle combined with a final spinning cycle, the proposed test is based exclusively on the spinning programme. The “rinse & spin” program, which was used by the consumer organization Altroconsumo (2015) for an assessment of WM durability and reparability, could be adopted for future developments of the method. Aligned with relevant literature, the durability test includes the execution of 500 spinning cycles, run in series on the same machine. During each spinning cycle, an unbalanced load of maximum 500 g is fixed on the drum of the machine, in order to simulate an overstressed condition, and the machine is asked to reach the highest spin speed. After each spinning cycle, the washing machine is allowed to rest and cool down for at least 10 min. The duration of the spinning cycle is measured. During each spinning cycle, the spin speed is measured. Spinning duration, as in figures 3 and 4, is defined as the duration of spinning at maximum spin speed with a tolerance of 30 rpm.

The maximum unbalanced load considered in this procedure was initially fixed to 500 g. Differently from De Carlo et al. (2013), who adopted heavier unbalance loads, the present test does not bypass the machine control procedure for unbalance with external controls. The standard IEC 60335-2-7 (2012) requires slightly higher loads (200 g or 10 % of the rated capacity, whichever is greater), but for 4 cycles only; furthermore the endurance test is run for safety purpose.

Initial, intermediate and final inspections of the machines were included. These are conducted through visual inspection of the accessible components (especially for initial and final inspections), and by performing washing programmes according to EN 60456 standardized procedures (IEC 60456, 2010). Modifications of the EN 60456 procedure have been included for practical reasons: no soiled test strips and no detergent for washing performance measurements are used, as the only monitored parameters are water consumption, electricity consumption, time and spin speed profile. At the end of such a washing programme the weight of the spun load is recorded and the remaining moisture content (RMC) is calculated using the conditioned weight of the load (see EN 60456 for details). These washing programmes are done every 100 spinning cycles, for a total of 5 washing cycles during the spinning test, plus another washing programme conducted after the initial inspection. During the washing programmes, the unbalanced load is removed from the machine. Spin speed, energy consumption and water consumption are measured through appropriate sensors and recorded continuously. Any failure or deterioration of the WM has been monitored during the test.

Method testing phase

Two washing machines from different manufacturers were selected for the test, called WM A and WM B. Both machines are currently on the market, declared in Energy Efficiency class A+++ (EU

Regulation), declared highest spin speed at 1600 rpm and spinning performance class A (RMC < 45 %). Both are declared having a maximum washing capacity of 8 kg of cotton load.

During the spinning cycles, rubber plates have been used to mimic a constant imbalance. These plates were placed to the inner drum surface with a spring rod fixed to the opposite side of the drum.

At first, both machines were operated with different fixed unbalanced weights to see how the control procedure for unbalance works.

WM A delivered the same spinning profile for all unbalanced weights up to 500 g (Figure 1).

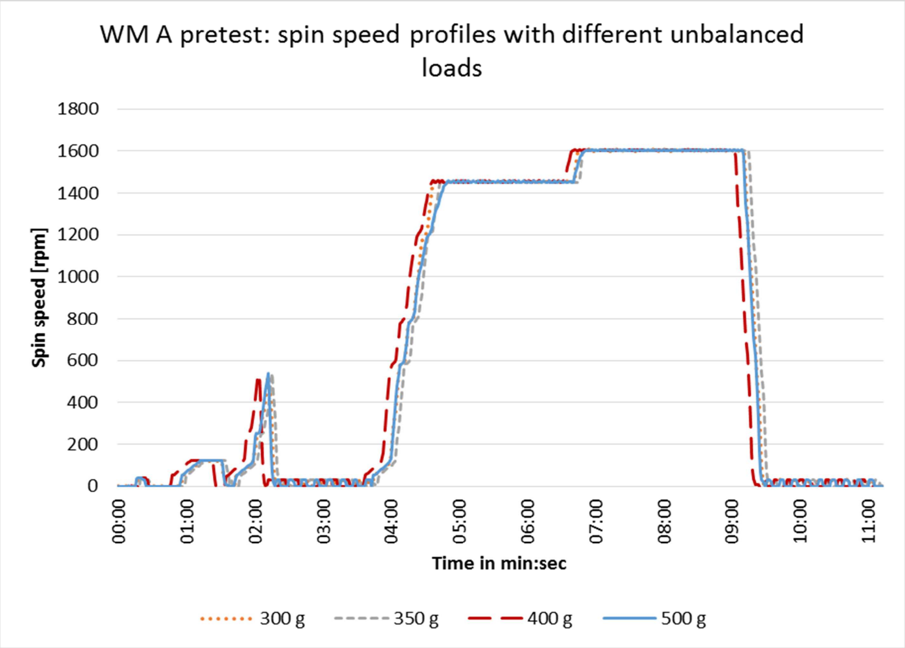

Figure 1 - Spin speed profiles of WM A, recorded during the extra spinning programme for various fixed unbalanced weights

WM B only showed an expected profile (up to 1600 rpm) for the lowest unbalanced weight of 200 g (Figure 2). For higher unbalanced weights, the machine repeatedly tried to distribute the load more equally on the drum surface and, when this failed, decided to spin at lower spin speeds.

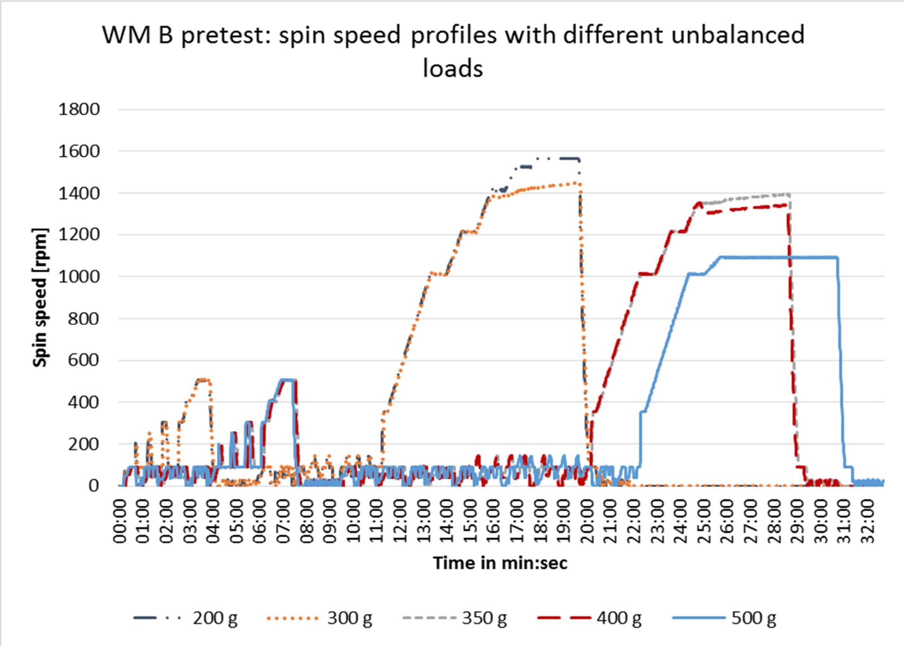

Figure 2 - Spin speed profiles of WM B, recorded during the extra spinning programme for various fixed unbalanced weights

Seeing both results, it was decided to start the spinning tests with an unbalanced load of 300 g for both machines.

Results

WM A: spinning cycles

Figure 3 shows the maximum spin speed and spinning duration for WM A from spinning cycle 1 to 500. Regular gaps between the data indicate the execution of the washing cycle after all 100 spinning cycles. It is also indicated the unbalanced weight used. The initial unbalance load of 300 g was chosen as for this mass, both machines showed in the initial test a straightforward spinning without redistribution phase. WM A performed at these conditions without any problems. Therefore, after 159 spinning cycles it was decided to increase the weight of the unbalance mass to 500 g, the maximum unbalanced load considered for this test, for the remaining spinning cycles. WM A showed a constant spinning rate at a spin speed of 1,605 – 1,610 rpm for about 145 sec most times. The increase of the unbalanced load at the 160th cycle caused a reduction of the spinning time to about 107 sec for about 50% of the cycles, then returning at the usual average duration of 145 sec. It was observed that WM A moved about 10 cm away from its original standing position in 20 cycles, although it was positioned well at the beginning of the test series. This movement always occurs in the first spinning tests of the day after the unbalanced weight was increased to 500 g. The machine was always placed back to the original position for the next cycle.

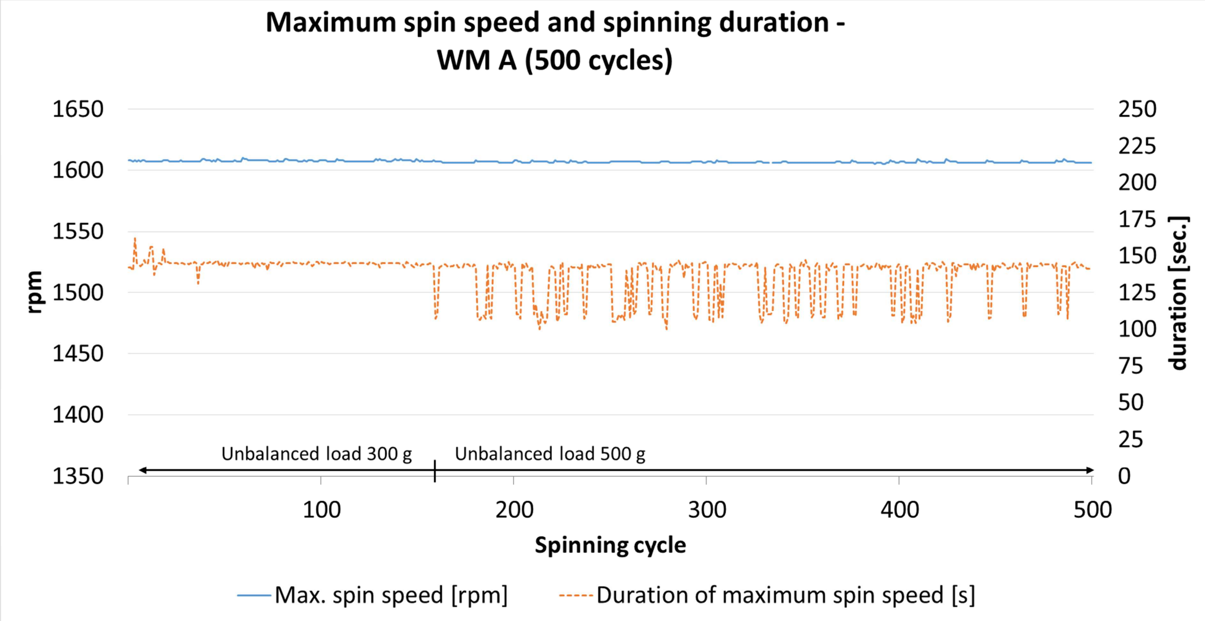

Figure 3 - Spinning profile parameters: maximum spin speed and spinning duration for WM A from cycle 1 to 500. Regular gaps between the data indicate the execution of the washing cycle after all 100 spinning cycles

WM B: spinning cycles

WM B (Figure 4) showed a more variable behaviour. At the beginning, the maximum spin speed reached was only 1,400 rpm, with an unbalanced load of 300 g. However, this speed increased cycle by cycle and, after about 20 cycles, it reached 1,540 rpm. The spinning time was about 150 to 175 sec. At the same time in the testing when on WM A the unbalance was increased to 500 g the unbalance of WM B was increased to 350 g (at the 108th cycle) to also induce a maximum stress on the structure of this machine. Then, the maximum spin speed dropped to below 1,500 rpm and the duration varied between 120 and 180 sec. From the 222th cycle onwards, the maximum spin speed dropped further to 1,468 rpm, which was kept constant for most of the cycles up to the end of the test. Spinning time varied between 140 and 230 sec. The total time of the spinning programmes extended by more than 10 minutes, due to continuous attempts of the control procedure to redistribute the load. This redistribution was however not possible due to the fixed unbalanced mass.

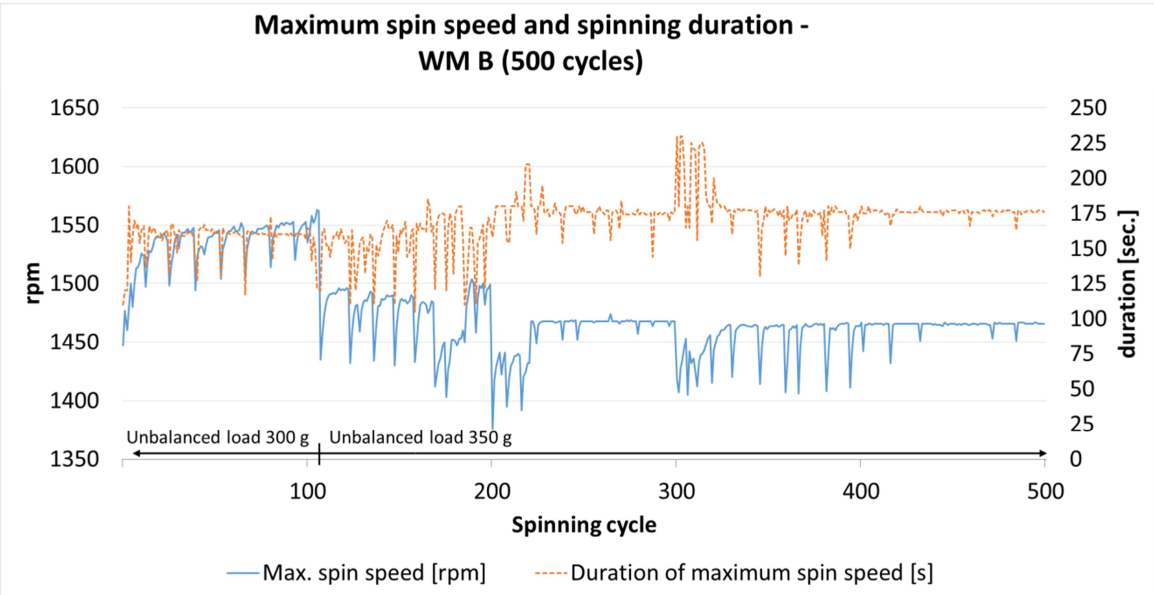

Figure 4 - Spinning profile parameters: maximum spin speed and spinning duration for WM B from cycle 1 to 500. Regular gaps between the data indicate the execution of the washing cycle after all 100 spinning cycles

Washing cycles

Complete washing programmes (Standard cotton 60 °C) were executed following the standard EN 60456:2012, as modified in the methodological section. Diagrams of all six washing cycles for water intake, energy consumption and spin speed over time are shown for WM A (Figure 5) and WM B (Figure 6). Water consumption for WM B was not correctly recorded the first two cycles, therefore it is only reported for cycles 3-6, in Figure 6. The profiles of WM A, especially the spinning profile, look very similar without any problems due to unbalance. Relevant differences are visible in the spinning profile, especially regarding the final spinning for WM B. It seemed that a full spinning occurred only in the first run, while the spinning in all other runs are somehow truncated due to problems of imbalance.

The instability of the spinning process does also show up in the RMC of the spun load (Table 1). While WM A shows almost constant RMC values for all washing programmes, RMC results for WM B were affected by higher variation. For WM B only the RMC value of the first washing cycle is aligned with the declared class A of spinning performance.

Table 1 - Remaining moisture content (RMC) of the six washing cycles

Remaining moisture content (RMC)	**WM A**	**WM B**
Washing cycle 1 (before spinning cycles)	44%	42%
Washing cycle 2 (after 100 spinning cycles)	43%	56%
Washing cycle 3 (after 200 spinning cycles)	44%	52%
Washing cycle 4 (after 300 spinning cycles)	46%	50%
Washing cycle 5 (after 400 spinning cycles)	44%	50%
Washing cycle 6 (after 500 spinning cycles)	44%	51%

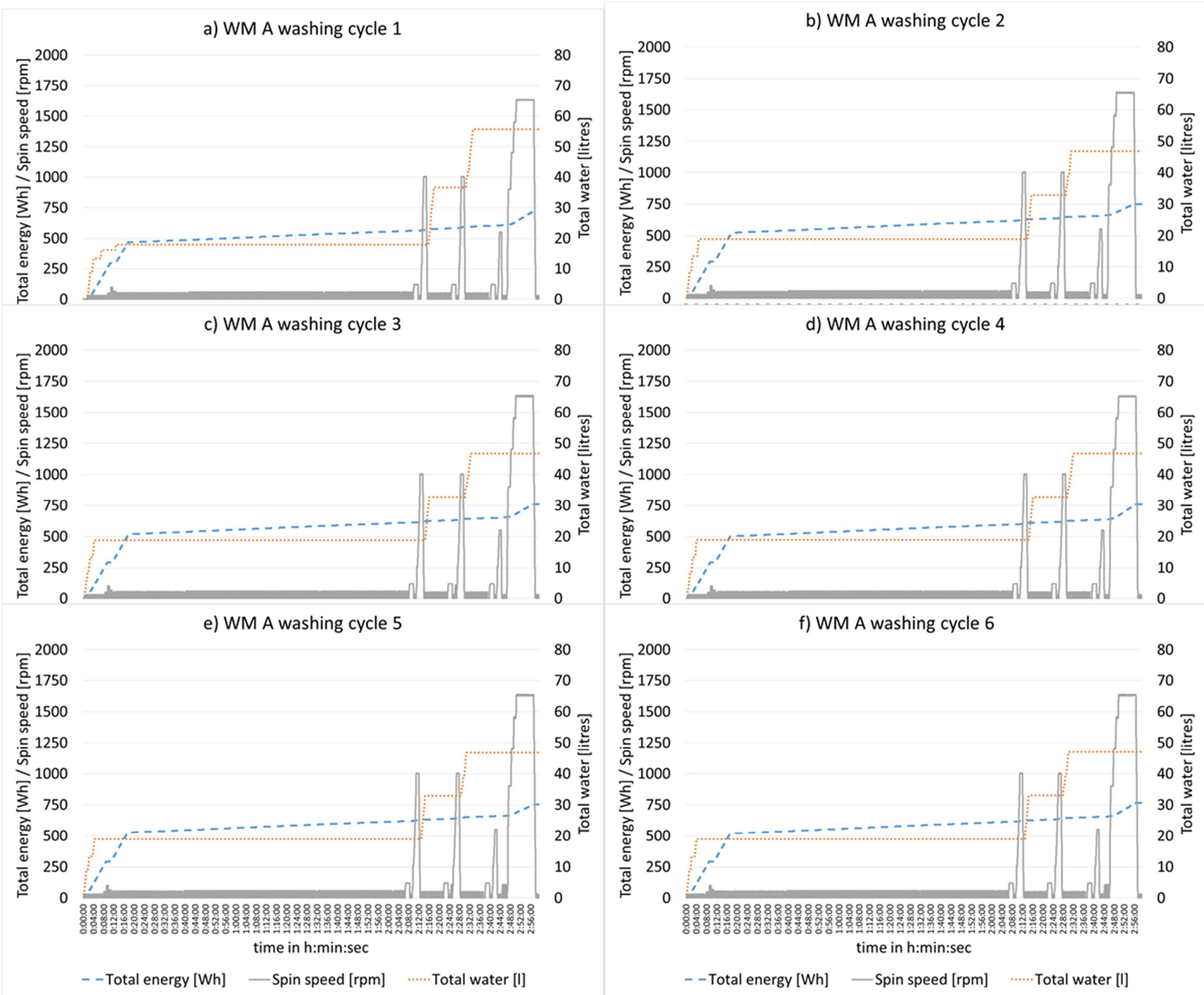

Figure 5 - Profiles of water intake, energy used and spin speed for the six washing cycles for WM A

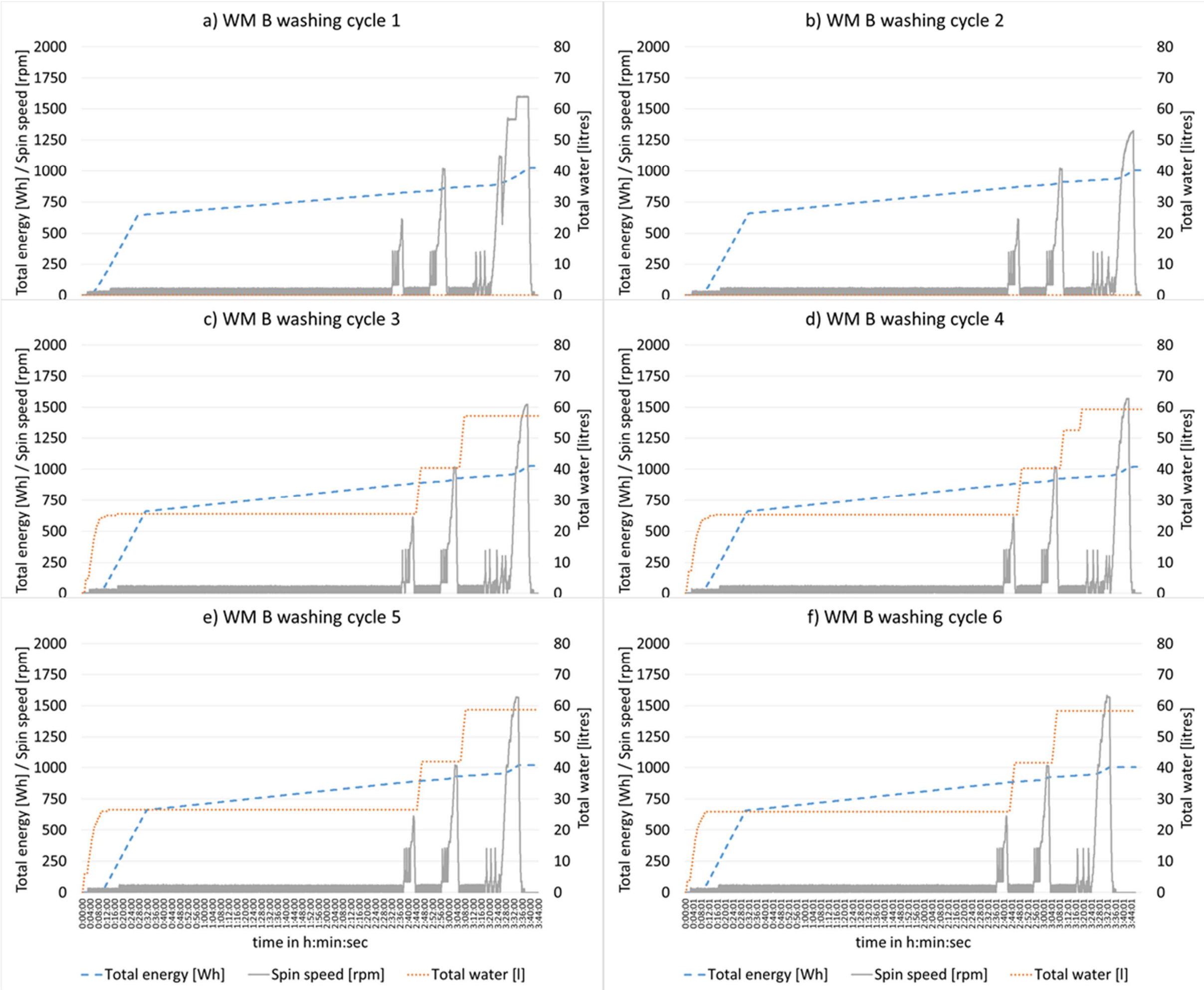

Figure 6 - Profiles of water intake, energy used and spin speed for the six washing cycles for WM B

Visual inspection

A visual inspection was performed before and after the testing. To do so, the backside cover sheet and the top plate were removed. Pictures were taken for parts that may be subject to deterioration or damages during the testing. None of those parts exhibited any sign of abrasion, stress or leakage. Rubber debris was found in WM B during the spinning cycles and at the final inspection, due to the contact of the door gasket to the rotating drum. Indeed, the stainless steel front side of the drum in WM B came in contact with the rubber door gasket under the stresses test conditions, causing abrasion of the rubber.

Some spots of debris were also found on WM A, but much smaller in size and of a dark colour. However, it was not possible to identify the origin of the debris.

Discussion

Results of the spinning cycles clearly show the behaviour of the control procedure when detecting an unbalanced situation, and its effectiveness in mitigating the stress induced by this unbalance load to the structure and components of the washing machine. This ensures a reduced stress on the WM structure as the control procedure tries to avoid the excessive wearing of key components and preventing early failures. However, the consumer may have to wait longer for the execution of the washing programme, as the repeated attempts to distribute the load equally takes time and, if the maximum spin speed and duration is limited, it also reduces the spinning efficiency, meaning that the load is wetter than it could or should be.

Looking specifically at the performance of the two washing machines, the overall durability test showed that the execution of washing and spinning programmes is not carried out uniformly throughout the five hundred spinning and the six washing cycles. The spinning tests showed variations in maximum spin speeds and respective durations. WM A showed uniform trends (Figure 3), with a spinning duration at the maximum spin speed ranging from 100 to 145 s, when the unbalance load was 500 g. On the other hand, WM B results were very variable (Figure 4) and stable trends can be observed in cycles 401-500, when the unbalance load was 350 g. In this range, the maximum spin speed was about 1460 rpm, kept for 170 s, in average. It was additionally noticed that the programme running time of the spinning programme in WM B did prolong by about 10 min from the first to the 500th spinning cycles.

Regarding washing cycles, results for WM A show comparable behaviour regarding spinning in all of the six washing cycles (Figure 5). For WM B, instead, the declared highest spin speed is reached in just one of the six washing trials (run #1 in Figure 6). In the other trials, the highest spin speed is not reached or is only reached for a very short time. If these results were to be confirmed in a test carried out fully according to EN 60456:2010, the declared spin speed (1,600 rpm) and spinning performance (class A) of this machine may be challenged.

In WM B, the presence of rubber debris at the end of the spinning cycles reveals to the phenomenon of deterioration of the machine itself. Under no stress conditions, there is normally a gap of about 1 to 3 mm between the (rotating) drum and the door gasket. Under stress conditions, however, the drum is deformed during spinning and the gap may be reduced to 0 mm and, consequently, abrasion starts. In the long run, leakages in the rubber door gasket may result. Regarding WM A, it was recorded an unexpected movement of the machine in the first spinning tests of the day, in the first spinning cycles right after the increase of the unbalanced load to 500 g. A higher friction of cold dampers might explain this. During conventional washing cycles, dampers are typically already warm when starting the spinning function.

The approach adopted in this durability test lies between the strategies used by Altroconsumo (2015) and by De Carlo et al. (2013). Altroconsumo observed hard failures in four of the twenty-four washing machines analysed, but through a conventional test of 2500 rinse & spin cycles, with partial load (60% of the rated capacity, of which 85% cotton textile and 15% sponge material), which can be very lengthy. De Carlo et al., instead, used 500 spinning cycles with different unbalance loads, but in their experiments, the control procedure was by-passed through external controls, making the test no longer relevant for a washing machine of the market. Our approach, on the other hand, aimed to be relatively fast (500 spinning cycles and 6 washing cycles) and applicable to different washing machines, without deactivating the control procedure for unbalance detection. The idea of having a common procedure to be used to guarantee minimum durability requirements of WMs is still an interesting task, but the definition of realistic loads (and therefore mechanical stress) remains the most challenging issue.

Conclusions and recommendations

The first objectives of this research were to develop a procedure to test minimum durability performance of WMs, and to verify if washing machines currently on the market are able to sustain a series of stress conditions without any hard failure. The application of the durability test did not show any significant failure of any part of the two exemplary washing machines used in this first experiment. However, the attempt to mimic the stress induced on a washing machine by doing a high number of pure spinning cycles with fixed loads did not allow equal testing conditions: the actions of the control procedure regarding unbalance loads differ from machine to machine. In detail, actions regard the procedures and precision in detecting the unbalanced load, the procedures to uniformly distribute the textile load at the start of spinning cycle, and the reactions in adapting the spinning profile to a certain level of stress.

With these conditions, it appears that the attempt to induce certain stress on a washing machine by doing a high number of pure spinning cycles with a fixed unbalanced load does not allow having equal testing conditions. Such kind of testing protocol could be counter-productive if used to assess and compare durability performance of WMs, as it pretends to replicate durability, while real performance (e.g. RMC, washing time) is deteriorated already after some cycles. The outcomes of this experiment suggest addressing durability of washing machines with tests where real life stress conditions are applied and real performance are measured. Stress tests on individual components may be useful for certain aspects, like safety requirements, but need to be considered in the context of the product and the way they are used in this specific product.

This exercise has also shown what parameters of a washing machine (unbalance treatment procedure, actual spinning profile, remaining moisture content, and maximum spin speed) are relevant to assess durability of a washing machine. Future developments could then replace spinning cycles (with fixed unbalance loads) with a series of washing cycles, with real load and various programmes. The selection of washing programmes should include all temperature levels and could consist mainly of short programmes. The number of washing cycles, for instance, should represent two or more years of washing practice in an average European household (500 cycles seems to be the minimum number of cycles for reliable tests). In this way, the overall duration of such a test would not be much longer than the stress test applied in this work. Moreover, it would have the advantage to mimic actual stress conditions, as the stress is coming from real scenarios. A related durability test could hence require that, when three machines of the same model are tested in parallel, at least two withstand the test (double 3 method according to IEC 60410) without any failure and without deterioration of the values declared on the energy label. This can be verified by performing a full test following EN 60456, where all parameters as required by Energy Labelling and Ecodesign are measured, at the beginning and after all cycles. Ecodesign and Energy Labelling regulations should then be amended to include the requirement that the declared and required values are to be maintained also after at least two years of operation, as simulated by a pre-set sequence of washing cycles.

This work also aimed at further stimulating the discussions between industry and policy makers about industrial practices that will enable a circular economy, focusing in particular on product lifetime extension. Minimum durability requirements at the whole product level proved to be needed and could be enforced via product policies and standardization. However, they will be only successful if they are verified by responsible market surveillance authorities based on affordable and reproducible test procedures. The example of WMs has the potential to trigger activities to develop horizontal standards on durability of household appliances and similar electrical appliances.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

Acknowledgements

This work is a shortened version of a paper submitted for publication to the Journal Resources, Conservation and Recycling.

Results of the research have been financed by the European Commission, by the Directorate General Joint Research Centre (within the expert contract CCR.IES.C392572.XO) and by Directorate General Environment within the project “Environmental Footprint and Material Efficiency Support for product Policy” Administrative Arrangement 070307/2012/ENV.C.1/635340).

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16 LIGHTING

Sustainable residential lighting practices and light pollution

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Abstract

LED lighting is widely considered as a promising solution to improve the energy efficiency of residential lighting due to its higher luminous efficacy compared to conventional residential lighting and the potential for having an even higher efficacy in the future. High luminous efficacy reduces the electrical energy required for lighting service but the lighting products of high luminous efficacy may pose other environmental concerns as a trade-off for energy savings. In residential lighting, this kind of trade-off was seen in (compact) fluorescent lamps containing mercury, which is a toxic heavy metal. Recently, a potential environmental concern has been identified: light pollution caused by artificial lighting.

Light pollution is defined as the sum of all adverse impacts of artificial light. It may mean the wasted energy, the potential negative impacts of light on human health or ecosystems, light trespass, or the sky glow hampering the astronomical observations. Light pollution is associated with several health issues from retinal damage to cancer and obesity. This paper aims to review the scientific evidence of the potential negative impacts of artificial light on human health, including indoor and outdoor lighting, also in residential areas. Other forms of light pollution, such as impacts on fauna and flora and the astronomical light pollution are excluded from the scope of the current study.

Introduction

Artificial light is a necessity in modern societies. It provides illumination when sufficient amount of natural light is not available, thus enabling a multitude of activities also after dark. In residential lighting, artificial light is intended to improve the visual performance and it may also serve as a source for relaxation, aesthetics, improved alertness and productivity. The intention is to *benefit* from artificial light but it is not free from adverse impacts on the environment, including humans.

Light emitting diode (LED) technology has potential to provide high quality lighting and energy savings to benefit both the human and the environment. However, it may cause, as any other artificial lighting, harmful impacts on human health. The main concerns with LED and human health are especially due to radiation approximately between 440 nm and 470 nm and high brightness. It is noted that despite this general concern, LED technology can be designed to avoid this spectrum range and using low intensity and/or dimming lighting. Blue and blue-enriched white light has been linked to the disturbance of human circadian rhythms and the suppression of melatonin secretion, potentially causing health problems. In residential lighting, LED lamps are increasingly replacing conventional lamps, such as incandescent, halogen and compact fluorescent lamps.

Analyzing the environmental impacts of artificial light has traditionally focused on the energy consumption of the lighting systems and respective environmental concerns, such as climate change. The potential environmental impacts may be evaluated by life cycle assessment (LCA), taking into account all material and energy flows of the system during its life cycle from raw material acquisition to end-of-life. In practice, light, despite it is a form of energy, has never been taken into account in the LCA case studies, as it is currently not possible to evaluate the environmental impacts of light. This paper serves as a first step in developing a calculation method for evaluating the light pollution impact, focusing on human health.

The aim of this paper is to present the preliminary literature survey on the adverse impacts of artificial light on human health. Given the expected rapid penetration of LED products in the lighting sector and its potential health concerns most notably caused by the blue-enriched white light, it is imperative to review the current understanding of the relation between human health and artificial light. The literature survey is planned to serve the development of an environmental impact category of light pollution on human health in LCA methodology.

Literature research methods

A preliminary literature survey has been conducted on the impacts of artificial light on the environment. Originally, the search included literature on light pollution affecting humans, animals, plants and ecosystems, but due to the large number of hits in the first search, it was necessary to divide the survey. Current survey focuses only on humans.

Adapted from [1], the literature review was designed to contain four steps: 1) defining the scope of the review, 2) defining the concepts of the topic, 3) conducting the literature search, and 4) analyzing and synthesizing found literature.

Scope

Regarding the scope of the literature survey, the focus was in the research outcomes, i.e., the results of the previously reported research. The goal was to summarize the findings from the scientific literature regarding the impact of artificial light on human health. The literature search was conducted using conceptual organization, i.e., the search was divided into concepts (instead of historical or methodological organization). The audience of the survey is estimated to be scholars in general, and the literature search aims at an exhaustive coverage of the literature. Only peer-reviewed, scientific journals were included in the search, excluding conference papers, books and theses.

Concepts

The first set of key terms was developed based on author's assumptions on the field. As the primary aim of the literature survey was to collect all scientific literature on the impacts of artificial light on environment (including humans, animal and plant species, and ecosystems), the search was designed to include all these environmental aspects. In addition, the literature on all kinds of light pollution affecting any part of the environment was deemed relevant in the development of an environmental category for light pollution. Used search terms were related to light, environment and light pollution: (Light* OR "Electromagnetic radiation" OR "Electro-magnetic radiation" OR "EM radiation" OR EMR OR "Visible radiation" OR Illuminat*) AND ("Environmental impact*" OR "Environmental aspect*" OR "Environmental burden*" OR "Environmental hazard*" OR "Impact on human" OR "Impact on animal*" OR "Impact on fauna" OR "Impact on flora" OR "Ecological impact*" OR "Biological impact*") AND ("Light pollution" OR "Light trespass" OR "Obtrusive light").

Originally, the literature search was aimed at identifying *all* impacts artificial light potentially has on the environment, including humans, animals, plants, and ecosystems. This comprehensive search was targeted to get a wide, overall conception of impacts. For a more in-depth analysis, the impacts on humans are separated from the rest; review on the impacts on animals, plants and ecosystems shall be studied separately. The search process is here described as it was, starting from the original wide search and limiting it to the research on human health.

Search

The literature search was conducted in March 2016 using three reference databases: Web of Science [2], Scopus [3] and ProQuest [4]. Databases were chosen due to their multidisciplinarity and because they cover thousands of peer-reviewed academic journals, ensuring wide and comprehensive approach, as environmental impacts of artificial light may fall into several disciplines.

The combined search (including studies on humans, animals, plants and ecosystems) resulted to 8881 references, of which 102 were related to human health according to sorting the papers based on their titles. Based on the abstracts, 42 papers were deemed relevant in terms of artificial lighting affecting human health in the preliminary search ans subjected to further analysis. The analysis includes both review papers and papers presenting original research.

The current study excludes backward and forward searches, i.e., the search for previous literature cited in found papers, and search for papers citing the found papers. The backward and forward searches are expected to be included later in the research work, as this study is a preliminary literature research.

Analysis of literature research

The scientific papers found in the literature survey were linked to several health concerns, as summarized in subchapters. Most papers were linked to circadian disruption (22 papers) and/or cancer (17 papers). Other diseases, conditions and health aspects included obesity and metabolic disorders, mood and mental disorders, sleep disorders, Parkinson's disease, migraine and retinal damage.

Circadian rhythm disruption

Circadian rhythm is the physiological, biochemical and behavioral rhythm following approximately 24-hour cycle. Circadian rhythm is entrained by several cues, such as feeding times, physical exercise, sleep and social contacts [5], but human circadian rhythm is primarily entrained by light (e.g., [5]-[9]). In humans, light is detected by retina, where rods and cones project visual information to visual system, and where ipRGCs project the information to circadian system and limbic brain regions [6]. Light detected by ipRGCs activates melanopsin, a photopigment most sensitive to blue light (approximately 480 nm) [10]. Stimulation of melanopsin affects the responses to light, including melatonin secretion. Normal melatonin secretion requires darkness but not sleep [8], [11], whereas bright daytime light exposure entrains and re-sets the circadian rhythm [11].

The circadian rhythm mechanisms are hypothesized to include ALAN-induced nocturnal melatonin suppression, circadian disruption, disruption of sleep-wake cycle with sleep deprivation, and a combination of some or all of these [15] [32]. Melatonin suppression in human due to nocturnal light exposure is well documented [12]-[14]. Studies have demonstrated that retinal exposure to ≤1 lx monochromatic blue (440-460 nm) light, or approximately 100 lx broad-spectrum white light can suppress nocturnal melatonin [14] [15], and phase shift the circadian rhythm [15]. However, it must be noted that presenting the intensity of the light exposure in illuminance, i.e., in luxes (lx), distorts the amount of radiation: illuminance expresses the amount of visible radiation (W) on a surface (m^2) weighted by the spectral sensitivity distribution (lm/W), which emphasizes green and yellow wavelength areas but minimizes the blue part of the spectrum. Thus, illuminance is a limited quantity to express the non-visual impacts of light.

Cool white and daylight fluorescent lamps have been detected to suppress melatonin when using lighting 1 h prior to bedtime [18]. The impact is related to age, as ALAN induces melatonin suppression greater in children than in adults [15].

The master clock located in the suprachiasmatic nucleus (SCN) in the hypothalamus controls circadian rhythms, influencing several physiological processes and functions, such as body temperature, sleep-wake cycle, hormone release (most notably melatonin and cortisol) and metabolism. Master clock controls the secretion of melatonin, a hormone that makes human sleepy (high levels approximately at 0:00-5:00 h, low 9:00-20:00), and of cortisol, a stress hormone (high 6:00-12:00 h, low 18:00-24:00 h) [20].

Artificial light at night (ALAN) exposure can disrupt circadian rhythm. The impact depends on the spectral power distribution (SPD) of light entering the eye (e.g., [12] [15] [21]-[24]), intensity at the eye level (e.g., [6] [15] [25]), timing and duration of the exposure (e.g., [6] [15] [21] [24]), the preceding light exposure of human [21], and chronotype [26]. Flickering may also contribute to health impacts, such as migraine and epileptic seizures [27] [28].

Based on experimental studies on animals and epidemiological studies on humans, circadian rhythm desynchronization has been linked to development and/or enhancement of several health problems: cancer [29], obesity [7] [12] [26] [29] [30], type 2 diabetes [7] [31], metabolic syndrome [29] [30], hypertriglyceridemia, low high-density lipoprotein [7], cardiovascular disease [7] [29], mental activity, immunity, autonomic dysfunction, and endocrine abnormalities [29], and depression [6] [29].

Cancer

Epidemiological studies have associated circadian disruption to cancer incidence. International Agency for Research on Cancer (IARC) has classified shift work containing circadian disruption as probably carcinogenic to humans (group 2A) [33]. Particularly night shift work and rotating shift work, such as flight attendants, have been linked with cancer [13] [34]: Based on epidemiological studies, circadian disruption due to night or rotating shift work and jetlag increase the risk of breast [6] [11] [13], prostate, endometrial, and colorectal cancers [11] [13], compared to humans whose occupation does not involve such conditions. Epidemiological studies also indicate that outdoor ALAN level is a risk factor for breast cancer and indoor ALAN exposure were associated with cancer risk [21] [35] [78]. Increased ALAN exposure is suspected to increase the risk of cancers, especially breast and prostate cancers [15] [21] [78]. Laboratory animal experiments confirm the association of ALAN exposure and breast and prostate cancer risk [32] [15]. The link between shift work with circadian disruption and cancer risk is based on animal studies showing faster tumor growth as result of nocturnal melatonin suppression and/or circadian disruption [15] [33] [34].

The mechanism is not fully understood how shift work and circadian disruption affect cancer incidence. Different mechanisms have been suggested: **circadian pathway** where ALAN causes circadian disruption [11] [33]; **melatonin pathway** where ALAN suppresses melatonin secretion [12] [13] [33]; and **sleep pathway**, as shift work and other circadian rhythm disruption may involve disturbance of sleep-wake cycle [15] [33]. It may also be *several* mechanisms contributing to cancer risk. However, prior light exposure during daytime has been found to affect the melatonin suppression by nighttime light exposure: Bright daytime light exposure was shown to increase melatonin suppression the following night [36] [37], and too dim daytime light exposure may suppress nocturnal melatonin [35] [38].

Breast cancer and ALAN exposure are claimed to be associated based on epidemiological studies on cancer incidence and ALAN exposure characterized by imagery from US Air Force Defence Meteorological Satellite Program Operation Linescan System (DMSP OLS) (several studies, see [21]. However, it must be noted that the impact on melatonin secretion can be analysed based on the image data only in a limited manner, as the images by DMSP OLS provide data on light between approximately 500 nm and 900 nm [39], excluding wavelength area around 450 nm having the greatest impact on melatonin secretion. In addition, some epidemiological studies have characterized ALAN exposure also by self-reported evaluations by the subjects [21]. Nighttime lighting environment may be related to cancer risk, as elevated breast cancer risk was found in women who turned lights on more frequently during the night [40]. However, neither self-reported nor satellite-based ALAN exposure are accurate characterizations of actual light exposures indoors, but subject-specific measurement techniques exist [9].

It has been suggested that cancer is linked to vision. Smolensky et al. [15] concludes that breast cancer incidence is associated with the extent of visual impairment, and blind women have lowest breast cancer incidence compared to visually impaired or normally sighted women (e.g., [40] [41]). However, visual impairment cannot unanimously be linked to lower cancer risk, as conflicting evidence exists [42] [43]. Conflicting evidence exists also on the cancer incidence and ALAN: breast cancer risk was not elevated because of turining on lights during night [44] and ALAN exposure and breast cancer risk were not significantly associated in another study [45].

Scientific evidence support the role of pineal gland in cancer development. Animal experiments show that light deprivation inhibits carcinogenesis, and epidemiological studies on humans show that breast, prostate, and colon cancer risks are high but it has been claimed that breast cancer risk is lower in blind or visually impaired women [13]. This suggest that light exposure is linked to cancer development but the exact impact mechanism is not understood yet. Melatonin is suggested to be used to prevent cancer in humans exposed to light pollution [13], but such suggestions should be made with cautiousness as impact mechanism is not fully understood and part of the evidence is based on epidemiologic studies that are unable to determine cause-effect relationships but only the coexistence of light exposure and cancer rate. Other factors in modern lifestyle are likely to contribute to cancer risk.

Obesity and metabolic disorders

The circadian disruption and ALAN exposure have been linked with metabolism and obesity (e.g., [6] [7] [11] [21] [26] [30] [46]). Increasing obesity rates have been linked with sleep-wake cycle [24] [46], and, in contrast, reduced obesity rates were found in a group having low light level in bedrooms at night [47]. Circadian disruption due to shift work, lifestyle or sleep disorders has been associated with insulin resistance and development of type 2 diabetes mellitus (T2DM) [11] [31]. Sleep loss has been linked to increased food intake and preference for high-energy food, increasing the risk of obesity, insulin resistance and thus, T2DM [31]. Obesity may cause further health concerns, including cardiovascular disease, hypertension, dyslipidemia, endothelial dysfunction, T2DM, and impaired glucose tolerance, most of which are associated also with circadian disruption [11] [24].

Epidemiolocigal studies on humans support the hypothesis that circadian disruption and ALAN exposure would induce metabolic dysfunction and obesity. Obesity, other metabolic disorders, and exposure to artificial light have all increased over last 100 years, but so does the amount of shift work [7] [48]. Shift workers have had an elevated risk for metabolic syndrome and obesity [24] [47], and shift work has been identified as a significant risk factor for obesity, independent of age, BMI, drinking, smoking or exercise [7] [30]. Human lifestyle may include confounding factors, as Old Order Amish have lower rates of obesity compared to general population [48]. Interestingly, obesity rates have increased not only in humans exposed to artificial light but also in domestic animals, such as dogs, cats, and horses [30], but it is not only light exposure but other environmental, dietary and behavioural factors that are likely to have an influence.

Experimental studies to support the hypothetical link between circadian disruption and obesity are conducted mainly on animals, typically nocturnal rodents [48] but some studies have been conducted on humans [21]. Causal relationship between circadian disruption and obesity is claimed to be proven by animal studies [46], but it is not possible to state a causal relationship in *humans*. Satellite images and maps of obesity rates were compared in epidemiological studies, indicating a geographical correlation between obesity and ALAN exposure. However, the satellite images from DMSP OLS have their limitations (light below 500 nm cut off).

Exact mechanism how circadian disruption induces obesity or other metabolic disorders are not known. Several pathways have been suggested, including circadian disruption in general, melatonin suppression per se, and disruption of sleep-wake cycle. Changes in melatonin secretion and circadian disruption can affect the metabolic rate and obesity [21] [30] [48]. It has also been found that prolonged daily light exposure increases fat mass by reducing brown adipose tissue (BAT) activity, supporting the hypothesis that impaired BAT activity mediates the link between circadian disruption and adiposity in humans [46]. Garaulet et al. [7] suggested also a pineal-hypothalamic-adipocyte pathway, autonomic nervous system pathway, and changes in food intake, that would make the circadian disruption to induce obesity.

It is noted that bright light exposure has been suggested to be used in obesity treatment as well as in conditions related to obesity, such as bulimia, anorexia, insomnia and depression [7]. This suggests that obesity may be not only a result of ALAN exposure but also a result of too little light exposure during day.

Mood and mental health

Circadian disruption and light have been associated with mental problems and mood disorders, such as seasonal affective disorder (SAD) and depression [7]. SAD is affected by the natural variations in daylight availability. Melatonin suppression was suggested as a mechanism, yet controversial [27], for SAD. IpRGCs conveys light to the mood-regulating brain regions [6].

Reduced daylight exposure and excessive ALAN exposure may contribute to mental health [49]. The depressed group of elders had significantly higher ALAN exposure compared to the non-depressed elders [21]. Light, whether natural or artificial, can affect mood, e.g., by contributing to comfortable visual environment. Pleasant lighting conditions have been linked to positivity, feeling of satisfaction and productivity [23].

The link between mental health and the exposure to artificial light has been studied in epidemiological and experimental studies. Epidemiological studies show that the rate of major depression has increased over the past few decades in parallel with an increasing exposure to ALAN [6]. Epidemiological studies also report that shift workers have increased depression rates, whereas the Old Order Amish have low rates of depression and other psychiatric disorders, but other variables are expected to contribute [6]. Experimental studies are conducted on rodents suggesting that ALAN contributes to depressed mood. Even low light levels (1 lx) suppressed melatonin in hamsters [50], but human melatonin was suppressed at less than 20 lx [51].

Light exposure or a lack of light exposure may affect mental health. It is suggested that the daily light exposure contributes to mood. Light exposure 4 h prior to bedtime did not significantly relate to depressed mood but the total amount of illumination during a 24 h period was linked to less depressed mood [63]. Light exposure may have also indirect effect on mental health and mood, as ALAN-induced sleep disturbance may affect mood disorders [21] and circadian disruption has been associated with depression [11].

In addition to duration, the spectrum of light exposure affects mood. SPD of light is suggested to influence the performance of schoolchildren: Full-spectrum fluorescent lamp with ultra-violet (UV) supplements (plastic diffusers removed from the luminaire to obtain radiation at the UV range from the lamp) resulted to better attendance, achievement and development outcomes in fourth grade students [79], further suggesting that the light environment plays a role in student learning, behavior, and thus, academic performance. Fluorescent lamps, having SPD more equally distributed for the whole visible range and not emphasizing the long wavelengths as incandescent lamps do, were claimed to improve morale and mood [27].

Drawing conclusions from various studies is difficult in the potential link between light and mental health, as the test methods and conditions vary study by study, and confounding factors are not or it is difficult to take them into account [23] [52]. Evidence is not clear how much light exposure explains the depression and other mental problems, as other variables are likely to contribute to it.

Bright light can be used as a treatment for many mental diseases, such as SAD and non-seasonal depression, sleep disorders, and obesity [7] [23]. 3000-5000 lx hours per day are currently suggested to treat SAD but the effect of the treatment is spectral-dependent: 45 minutes of light exposure of 2500 lx was found to reduce depression ratings, when the light was blue-enriched or white-appearing with high photon density at the blue wavelength range (424-532 nm) [53]. The use of bright light as a treatment for various mental disorders suggests that it may be the too little light exposure during the day that potentially affects the development of such conditions in addition to the ALAN exposure.

Sleep disorders

Normal sleep-wake cycle can be distorted and sleep disorders developed due to changes in light environment. Light environment during the day and night has dramatically changed in last 130 years. The change may have contributed to reduction of sleeping time: Human nighttime sleep is approximately 7 h/d in today's society, whereas other primates sleep approximately 10 h/d [26]. Exposure to ALAN is linked with disruption of sleep-wake cycle and sleep loss, which further contribute to circadian disruption (e.g., [15] [21] [25]). Darkness during nighttime is needed for normal melatonin synthesis, which is essential for sleep.

Light exposure during sleep could suppress melatonin and induce subjective sleepiness depending on the duration of light exposure [54] [55]. Subjective insomnia was increased in a group exposed to more intense ALAN [56]. However, the evidence is not clear: A clear pattern of ALAN affecting the sleeping of hospitalized elderly was not found, as only a weak correlation was found between sleep and ambient light [57]. Cycled light, i.e., more light during day and less during night, affected infant sleep-wake cycle and increase infant activity but no effect was found on growth [58] [59].

Sleep impairment has been found to be involved with ALAN exposure but also with low light levels during daytime [5]. Sleep affects cognition, but the link between cognition and melatonin suppression is not clear, as the role of retinal photosensitive cells is not clear regarding cognitive impacts [22]. Cognitive performance was significantly changed in sighted humans after only 30 min of illumination [60]-[62], but also brain activity changed after only 55 s of exposure [22], suggesting that even short-term light exposure may affect cognition.

The disturbance of sleep-wake cycle and sleep loss have been linked to other human health concerns, including obesity [21] [24] [46], cognitive impairment [5] [15] [60]-[62], mood disorders, diabetes, heart disease [21], aging and metabolic processes [21]. The experiments on rodents have linked sleep impairment with circadian disruption, delirium and sepsis but it is not possible to verify a connection in humans based on animal studies, and causality is probably multifactorial [5].

The impact of light exposure on sleep quality (less deep, periodic arousal) depends on several factors. The characteristics of the light esposure matters, such as spectrum (wavelength), intensity, timing, duration [63]-[65], and correlated colour temperature (CCT) [66]. However, as CCT is a limited metric for lighting design, a detailed SPD shall be used to characterize the colour of light instead of CCT. In addition, the impact of light on sleep depends on the characteristics of the subject, such as chronotype and prior light history [63].

Sleep quality was deteriorated in individuals exposed to 40 lx ALAN with the source at 1m away from the eyes during sleep [67]. Sleepiness was reduced by exposure of 5000 lx but was not by 100 lx [68] [69], and reduced by exposure of >2500 lx compared to <150 lx [70]. It is noted that high illuminance levels (above 500 lx) do not usually occur in residential lighting environments. Blue light exposure decreased both melatonin concentration and sleepiness [21]. Even low intensity, blue-enriched light can influence electro-encephalographic (EEG) activity during sleep [66]. Retinal exposure to low light level (<= 1 lx) of monochromatic blue light (440-460 nm) or approximately 100 lx broad spectrum white-light can suppress nocturnal melatonin [14] [15] and disrupt sleep [14] [62]. Contradictory results exist, as blue-enriched light was found *not* to affect nighttime performance and sleepiness, but it did affect melatonin levels [71]. The results are not clear and further studies are needed to understand the mechanism by which light exposure affects sleep.

Other diseases and conditions

Parkinson's disease

The prevalence of Parkinson's disease (PD) has been found to correlate with ALAN exposure characterized by satellite observed images, even when accounted for population density, age and race [72]. It is noted that the satellite-based imagery data has a limited spectrum, approximately 500 – 900 nm. Experimental studies have been conducted on animals to find a link between PD and exposure to artificial light. A study provided *preliminary indications* and more future research is necessary to determine the mechanism how light may induce PD [72].

Willis et al. [73] claims that it is not justifiable to suggest that light pollution causes PD, based on the review of recent studies on experimental studies on animals, epidemiological studies on humans and studies suggesting that pigment neuromelamin was toxic and increased light exposure increased toxic pigmentation. However, retinal damage, caused by long-term exposure to light, occupational chemical exposure and cerebral trauma, may be involved in development and enhancement of PD [73]. Many PD patients are living in nursing homes, which tend to lack sufficient ambient light [73]. The mechanisms between retinal damage and PD as a brain disease are suggested to be anatomical, neurochemical or neuroendocrinological, but further research is necessary to determine the mechanisms.

Migraine

Migraine has been reported to be triggered by bright and flickering lights, i.e., factors related to light and visual environment [28]. In addition to light level, SPD is suspected to affect, as migraineurs find red light especially uncomfortable [27] [28]. Migraineurs tolerate less light, discomfort glare, flicker, colors and busy visual patterns (such as sine grating distortion) compared to general population [28]. Due to their low tolerance to light, it has been suggested that migraineurs may have defective adaptation to light [28].

Retinal damage

Sufficiently high light exposure may damage retina [25] [74]. Light penetration in the tissue is the weaker the lower the energy of the radiation is, and thus, longer wavelength has poor penetration. Infra-red radiation damages the eye due to the high temperature that damages the cells, whereas ultra-violet radiation damages the eye as it is short wavelength that can penetrate further in the tissue [74].

Retinal damage caused by light exposure depends on the type of radiation, irradiance, wavelength, intensity, duration, area of exposure, and absorption of tissue [12] [73]-[75]. The photochemical sensitivity of the retina peaks at approximately 440 nm, and exposure to light of 380-520 nm may cause photochemical injury in approximately 10 s to 2 h [76]. Luminance under 10 000 cd/m^2 is not likely to damage the retina [77].

Discussion and conclusions

Human health is affected by the light environment but the detailed mechanisms are largely unknown. The potential negative impacts on human health caused by artificial light include circadian disruption, melatonin suppression and disruption of sleep-wake cycle, and numerous resulting impacts have been linked to light exposure, such as obesity and metabolic disorders, mood and mental problems, and cancer. Retinal damage by light exposure is linked with Parkinson's disease, and especially bright, red and flickering light act as triggers for migraine.

The most robust evidence is found in melatonin suppression and circadian disruption by ALAN. Many factors of light exposure and the subject in question affect the impact of light: spectrum, intensity, timing, duration, and frequency (flicker) of light; and prior light exposure (light history), chronotype, age and sex of the subject; in addition to potential confounding factors, such as dietary habits, smoking, alcohol consumption, and chemical exposure. It has also been suggested that it may not only be the exposure to ALAN but also the too little and wrong kind of light exposure during the day that may adversely affect human health.

Except for the studies on melatonin suppression and circadian disruption, the scientific evidence of artificial light affecting human health is not very robust: most evidence is based on either epidemiological studies on humans or experimental studies on animals. It is problematic to use the results of animal studies, typically on nocturnal rodents, to extrapolate the results to humans, as nocturnal rodents are more sensitive to light. Furthermore, epidemiological studies show a *co-existence* of increasing use of artificial light and health concerns, but they do not provide evidence of any *causal* relationship between the conditions. There is also a concern of usability of satellite imagery in characterizing the ALAN exposure, as DMSP data excludes visible radiation below 500 nm. However, other satellite data sources exist with a possibility to cover radiation starting from approximately 400 nm [39]. In addition, conflicting evidence exists, and thus, findings are not unanimous.

The mechanisms how artificial light causes negative health impacts are not known. Several pathways have been suggested: melatonin suppression, phase shift of circadian rhythm, and disruption of sleep-wake cycle with sleep loss.

Further studies are necessary to determine the causal relationship, if any, between light or ALAN exposure and impacts on human health. Further studies shall clearly define the characteristics of light such as SPD or wavelength, timing, duration, frequency and subjects prior light exposure and chronotype. The lack of such factors in previous studies may partially explain the conflicting findings.

Based on a preliminary literature survey, the evidence on potential hazards of artificial lighting were found to be mixed: the evidence was rather solid in some health impacts, such as for circadian disruption and retinal damage, whereas the evidence of other impacts, including cancer and mood was less robust, disputable and mixed.

As this paper presents the preliminary literature survey, the literature review work continues by elaborating the list of found scientific papers by backward and forward searches. Special attention shall be paid to causal relationship in comprehensive literature survey, as the preliminary survey lacks clarity in defining *causal* relationship of light exposure and health impacts. A preliminary model for human-health related light pollution impacts will be developed on the basis of the comprehensive literature review. Causal relationships need to be determined in order to effectively evaluate the health impacts of light in LCA. In a later stage, literature on light pollution affecting animals and ecosystems can be reviewed and an impact category for ecosystem light pollution could be developed if scientific evidence is sufficiently robust.

Recommendations for residential lighting

Several methods exist to reduce the potential negative impacts of artificial light on human health in general and in residential lighting. First, the intensity of the light must be on a sufficient level for the task or function but overillumination needs to be avoided. Second, the spectrum of the light needs to be chosen to minimize the negative impacts. Third, light must be oriented and targetted to areas where it is needed, not outside the intended area. Fourth, timing and duration of the light shall be limited. Light late in the evening or at night shall be avoided, and if light is necessary at night, it shall be of low intensity and the spectrum shall avoid radiation around 450 nm. These four means minimize the impacts by limiting the intensity, spectrum, location and temporal characteristics of the light exposure.

LED products, as a lighting technology increasingly used in residential lighting, may contribute to the negative health impacts of lighting, but it may also be a solution for tackling light pollution. LED lamps can be effectively dimmed until very low light level, reducing the dose of the light exposure. In addition, there are LEDs of various colours and thus spectral power distributions available on the market. The selection of colours and phosphor materials enable the production of various tunes of white light and coloured light not only for decoration but also for circadian synchronization, avoiding light around 450 nm during nighttime. As LED packages are small in size, it is possible to effectively direct the light produced by it to a certain direction, limiting light spill optically. Together with preset timing and presence and light sensors, LED lighting can reduce the amount, type and duration of *unnecessary* light exposurewhen designed well. In addition to lighting-specific means to reduce the impacts of light pollution, light exposure in residential buildings can be limited by using curtains.

Acknowledgements

Author would like to thank the support by Academy of Finland grant (#285443).

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Some Insights to the Lighting Electricity Consumption of Turkish Households

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Abstract

The residential sector accounts for almost one fourth of the national electricity consumption in Turkey. Due to an increase in household income levels, newer homes are built with increased floor areas which consequently increases lighting electricity consumption in Turkish homes. Studies on residential lighting electricity consumption conducted in many other countries show that lighting electricity consumption accounts for about 10 to 25% of the total household electricity consumption. However, no study has yet been conducted in Turkey to determine the amount and fraction of lighting electricity consumption and lamp type preferences of Turkish homes. In this study, the amount and share of the lighting end-use electricity are determined, and the socio-economic factors affecting the lamp type preferences and lighting electricity consumption are investigated. A detailed survey is conducted to 260 homes in Ankara to obtain data on the types, wattages, and operating hours of all the lamps at the homes, as well data on the properties of the all appliances, economics and demographics of the occupants, and billing data are gathered. Data on a total of 2299 appliances and 3423 lamps are collected during the surveys. Using the survey data, the average household lighting electricity consumption and share are estimated as 209 kWh/yr and 8%, respectively for an average home. The analyses conducted to determine the effects of socioeconomic factors on lamp type preferences and lighting energy consumption showed that household income and home floor area are the major factors for the households.

Introduction

Lighting electricity consumption has a significant share in global and residential electricity consumption of most countries. Lighting electricity consumption accounts for 15% of global power consumption and 5% of worldwide CO_2 emissions [1]. Lighting accounted for 19% of total residential electricity consumption globally [2]; the share of lighting is about 9% in US homes [3], 25% in Chinese homes [4], 17% in 15 EU member states [5], and about 13% in EU-28 countries [6]. Electricity savings in lighting electricity consumption can be achieved by replacing inefficient incandescent (INCD) lamps with compact fluorescent lamps (CFL) or light-emitting diode (LED) lamps. In a recent Energy Efficiency Status report [7], even though electricity consumption in the residential sector of many EU Member States is reported as increasing, the lighting electricity consumption is reported as decreasing, mainly due to the large share of the use of mainly CFLs in these countries.

There are many studies in the open literature on determining the electricity savings that can be obtained by replacing INCD lamps with efficient lamps [8, 9, 10, 11, 12, 13, 14, 15, 16). These studies presented significant decreases in residential electricity consumption and emissions associated with power generation. The results of a lighting retrofit in Brazil comparing LEDs, CFLs, and fluorescent tubulars lamps demonstrated CFLs is the type of lamps with the highest cost and toxic waste disposal and fluorescent tubular lamp is the most economical alternative. However, it was also stated that if LED prices would drop or their efficacies would increase, LED lamps would become the most sustainable and economically attractive lighting alternative [11]. As stated by Hong et al. retrofit of old lamps with energy efficient ones also has some minor disadvantages by increasing the space heating energy consumption by reducing internal heat gain from the lighting (4.5%) [12].

The total electricity consumption of Turkey was 207 GWh in 2014, 22% of which was residential [17]. There are very limited number of studies in Turkey on residential lighting. In one of these studies, the share of lighting electricity consumption was investigated. The results of the simulations showed that the share of the electricity consumption for lighting varied between 24% and 18% based on the geographical location [16]. In addition, according to another study conducted in Turkey, 28% of total electricity consumption was due to lighting electricity consumption in a single-family detached house [18]. In another study, it was found that it would be possible to achieve a substantial energy savings should all households of Turkey replace one of their 100 W INCD lamps with 23 W CFL [19].

The results of these studies conducted in Turkey are based on surveys conducted on very limited numbers of homes or surveys conducted for only determining lamp characteristics of the households. Thus, in this study lamp type preferences, lighting electricity consumption, and fraction of this end-use of the total residential electricity consumption for Turkish households are determined by a using whole-house measurements approach. These analyses are conducted using very detailed survey data obtained from 260 homes in Ankara which included recording the power and hourly operating time of each lamp in these households.

The next section of this paper explains the methodology used to determine household lighting power and electricity consumption and fraction of lighting electricity consumption of the total household electricity consumption in detail. The lighting and household power and consumption statistics are given in the following section. The discussion and conclusions are presented at the end of the paper.

Methodology

Energy consumption studies are conducted using either a whole-house measurements approach or a bottom-up estimates approach. In this study a whole-house measurements approach is used. The whole-house measurements approach mostly involves visiting a number of sample houses, conducting a detailed survey about appliances and occupant electricity consumption behavior, and measuring active and standby power of the appliances in the household. In this study, the volunteer households for the whole-house measurements are identified mainly based on their household income levels, since it is desired that the sample of this study would be a representative of the Turkish urban household stock. The other criterion is that these households do not use electricity for space heating. A survey with 45 questions is prepared. The survey questions are prepared to get detailed information of the dwelling, occupants, appliances, appliance usage, billing data, and lighting (lamp power and usage).

During house visits, data on characteristics and usage of the lighting and appliances of the household is documented. Total household electricity consumption is calculated by using the survey and billing data of the households. The lighting power determined from the survey data on lamps is multiplied by the number of hours the lamps are used which is also determined by survey questions. Then the fraction of lighting in the total household electricity consumption is determined.

In order to determine the total household electricity consumption, average electricity consumption of major household appliances are gathered from open literature based on their size, model, brand, age, etc. The active appliance electricity consumption is first calculated by summing the electricity consumption of all appliances in the household when they are performing their primary functions. The lighting electricity consumption of each household is then determined by multiplying the power of each lamp with its operating time (number of hours per day). Similar to the household lighting electricity consumption, standby electricity consumption is determined by multiplying the standby power of the appliances by the number of hours it is left at standby mode. The total annual household electricity is then calculated by adding the lighting, active, and standby appliance electricity consumptions. This estimated total annual electricity consumption determined using the survey and appliance consumption data is then compared with the billing data, where available. If the difference is higher than 20%, the survey data is checked again and homeowners are contacted should an anomaly is determined. After determining the total household electricity consumption the share of lighting in the total household electricity consumption is determined. In the next step of the study, the effects of socio economic variables on lighting electricity consumption and lamp type preferences are investigated using the survey data.

Results

The results of the study are presented in two sections; namely lamp type distribution analyses and lighting consumption statistical analyses. In this study, a total of 260 homes located in Ankara are surveyed. The majority of the surveyed homes are apartments (92%), owner occupied (77%) with occupancy varying from one to seven person, on average 3.2 person per household, and average floor area of 110 m^2. These statistics are found to be similar to those presented by various demographic studies of the Turkish Statistical Institute [20]. A total of 3423 lamps are identified in the surveyed 260 households which yields on average 13.2 lamps per household.

Lamp Type Distribution

The operating time, type, and wattage of lamps were collected from the survey data of 260 households. Among the homes surveyed, six types of lamps are identified, namely compact fluorescent (CFL), incandescent (INCD), spotlight (SPOT), fluorescent (FLUO), light-emitting diode (LED), and halogen (HAL) lamps. The number of lamps for each type and the percent distribution of the types of lamps are tabulated in Table 3. As it can be seen in this table, almost half of the lamps are CFL, which is followed by inefficient INCD lamps. SPOT, FLUO, LED, and HAL lamps constitute only about 13% of the lamps. The main reason behind the high percentage of CFL distribution is the energy efficiency campaigns conducted by The Ministry of Energy since 2008 towards replacing INCD lamps with CFLs [21].

Table 3 Number of lamps for each type

Type of Lamp	Count	Distribution
Compact fluorescent lamps (CFL)	1666	49%
Incandescent lamps (INCD)	1331	39%
Spotlight lamps (SPOT)	133	4%
Fluorescent lamps (FLUO)	154	4%
Light-emitting diode lamps (LED)	121	4%
Halogen lamps (HAL)	18	1%
Total	3423	

The occupants’ preferences on the type of lamps depend on a number of factors, such as household income, house floor area (m^2), and number of occupants. Income level is thought to have an important impact on the number and type of lamp usage. In this study, the monthly household income levels are categorized into five levels. The distributions of the types of lamp preferences in each lamp category based on five monthly income levels are presented in Figure 11.

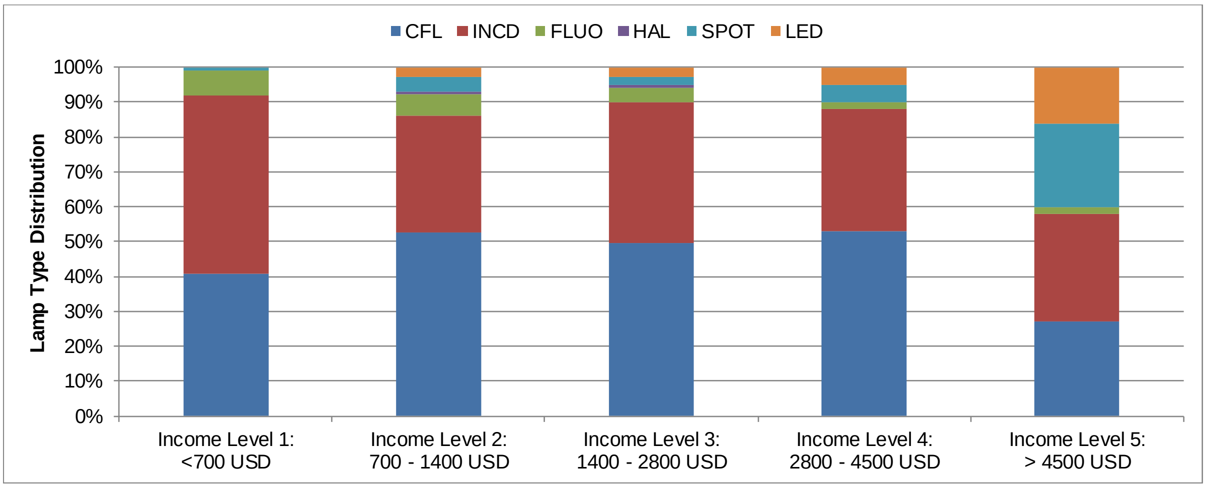

Figure 11 Lamp types distributions based on monthly household income levels

As it is seen from Figure 11, approximately 50% of lamps in income levels 2, 3, and 4 are CFL whereas lowest monthly income level homes preferred mostly incandescent (INCD) lamps. The distributions of CFL, INCD, and SPOT lamp types are close to each other in these income levels. The LED share is the highest in monthly income level 5 category homes and INCD share is the highest in monthly income 1 category homes. These results are expected since LED lamps have the highest and INCD lamps have the lowest purchasing prices among these lamp types.

In addition to income level, the effect of floor area of the dwellings is also examined in the preference of the lamp types. Lamp type distribution based on home floor area (FA) category is presented Figure 2.

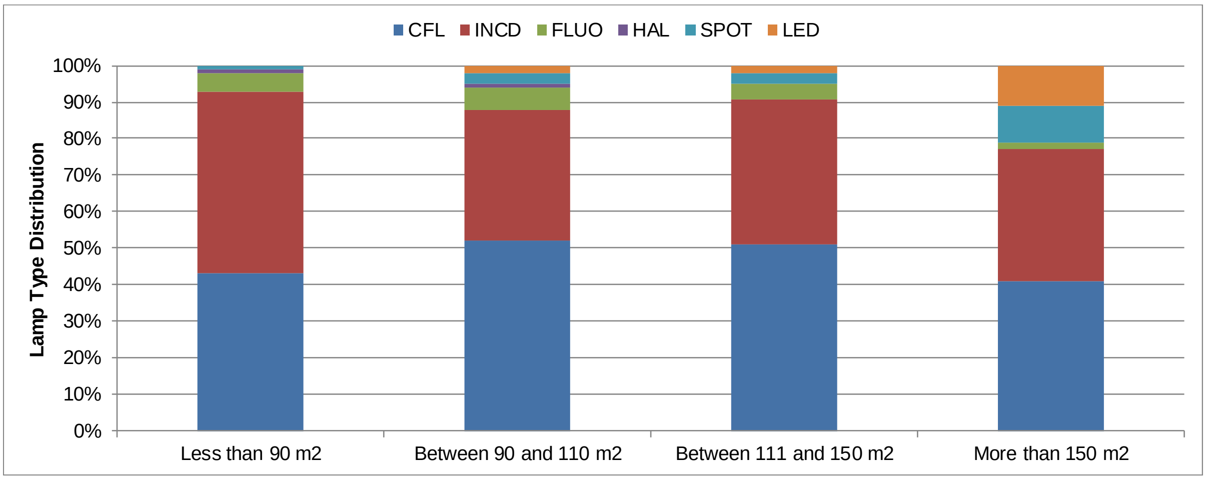

Figure 12 Lamp types distributions based on floor area category

The lamp type distributions based on floor area showed that even though 17% of the surveyed houses have floor areas less than 90 m^2, only 11% of lamps are owned by these houses. When the homes with FA larger 150 m^2 analyzed, while these home constitute 11% of the surveyed homes, 17% of lamps are owned by these houses. This shows clearly that as the FA of the homes increases the number of lamps in the homes also increases, as expected. The lamp type distributions based on lamp type present similar trend as seen in **Figure 11** for income levels, *i.e.* INCD lamp share is the lowest in smaller homes and LED share is the highest in larger homes. This result is also expected since there is a very strong relationship between FA and income level, such that as income level increases FA of the homes increases.

Another factor whose effect on lamp type preference examined is the number of occupants in the homes. As stated before the number of occupants per home ranged between one and seven in the surveyed 260 homes. The average number of occupants was determined as 3.2 per household. In Figure 3 the distributions of lamp types based on one-, two-, three-, four-, and more than four-occupant homes are presented.

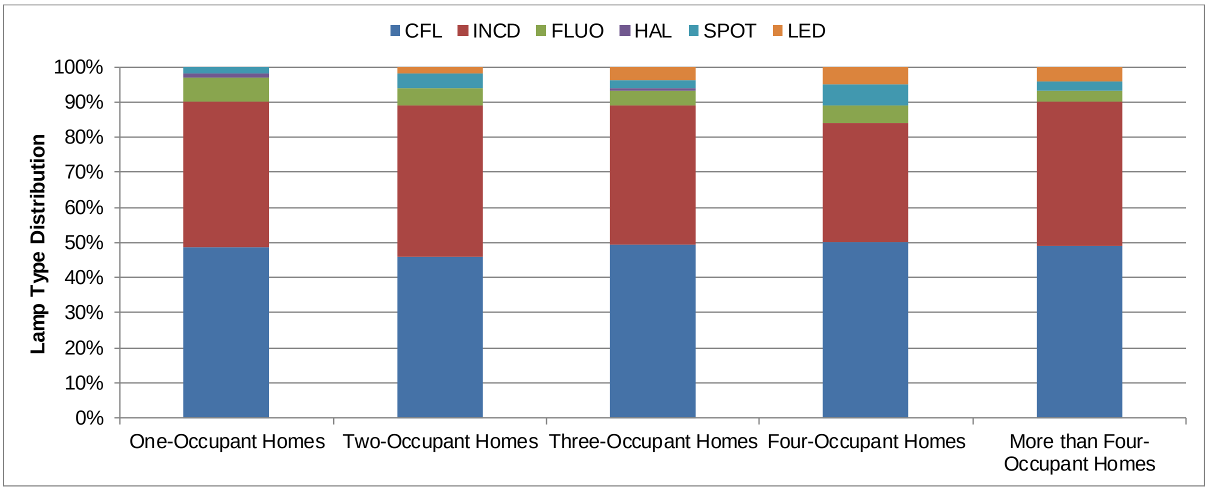

Figure 13 Lamp types distributions based on number of occupants

As it is seen from **Figure 13**, the distributions of the lamp types based on number of occupants do not present a well-defined trend. The distributions of the lamp type for each occupant count are very close and almost half of the lamps are CFL for each category. Except for the four-occupant homes, almost 90% of the lamps are CFL and INCD lamps, and the remaining 10% are FLUO, HAL, SPOT, and LED. The share of INCD lamps in four-occupant homes is the lowest (35%), whereas the remaining 15% not served by INCD or CFL is equally divided among LED, SPOT, and FLUO type of lamps.

Lighting Electricity Consumption Statistics

The lighting electricity consumption (LEC) of the surveyed homes is determined by summing the electricity consumption of each lamp, which was determined by multiplying the lamp power with the number of hours of usage of the lamp. The annual LEC of the homes ranges between 28 kWh/yr and 1021 kWh/yr. In order to determine the average annual LEC of the surveyed homes, these distributions of the annual household LEC of the homes are examined based on log-normal, normal, uniform, and Weibull distributions as seen in **Figure 14**. As seen in this figure, the distribution of LEC fits more into log-normal distribution.

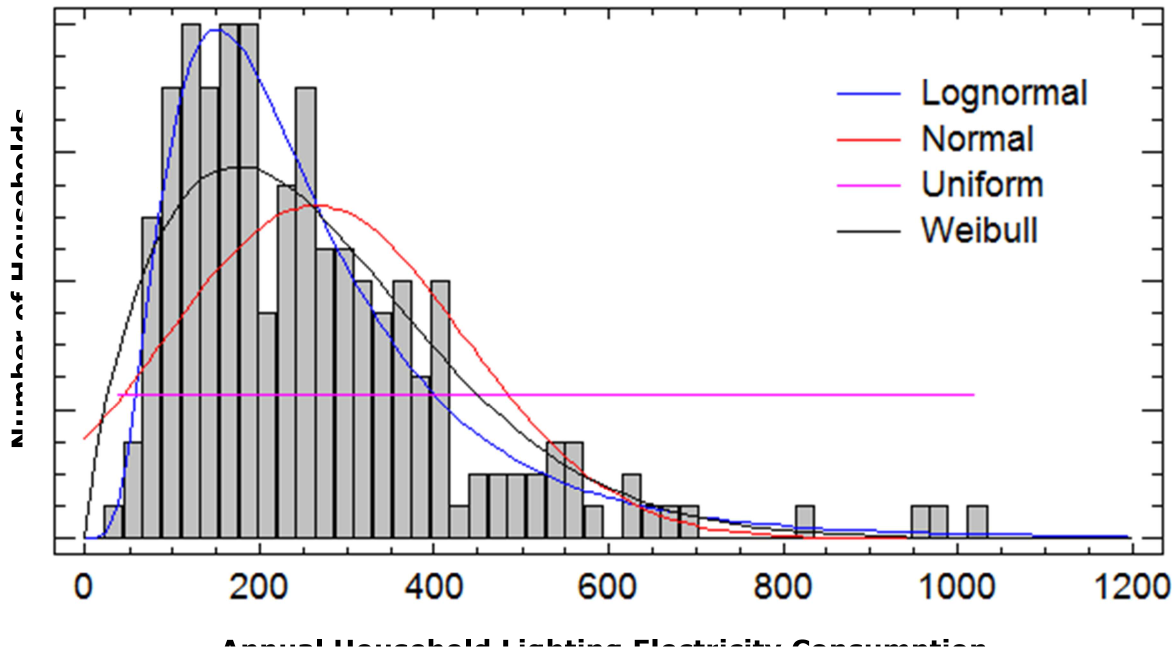

Figure 14 Distribution of annual household lighting electricity consumption

After determining that the LEC of the households follows a log-normal distribution, the average LEC is then determined by calculating the geometric average of this end-use consumption of the households, which is 209 kWh/year per household. To determine the fraction of LEC in the total household electricity consumption, the standby and active appliance end-use electricity consumptions are calculated for each household and summed with the lighting electricity consumption. The average annual household electricity consumption is determined as 2448 kW h/yr. This presents that the average household LEC is about 8.5% of the total household electricity consumption for the surveyed 260 households. The share of LEC in these Turkish homes is lower than those of US homes (9%, [3]), EU homes (12-23% [5, 6]), and Canadian homes (12% [22]), probably due to high share of appliance electricity consumption of Turkish homes.

The number of lamps; minimum, average, and maximum power; operating time, and electricity consumption values for each lamp type category are tabulated in Table 4. As can be seen in this table, HAL lamps have the highest power and electricity consumption among six lamp categories. These types of lamps are usually used for special illumination of rooms in the high income households. The INCD lamps present the second highest consumption due to their high power values. As also presented in **Figure 11**, these types of lamps are preferred by mostly low income homes due to their low costs.

Table 4 Lamp power, usage, and electricity consumption

Lamp Type	#	Lamp Power (W)			Lamp Usage Hours (hour/day)			LEC (kWh/year)		
		Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
CFL	1666	5	22	40	0	2	15	0	16	110
INCD	1331	5	54	120	0	1	12	0	25	263
SPOT	133	2	18	100	0	1	5	0	6	43
FLUO	154	8	31	60	0	2	12	0	25	109
LED	121	3	10	20	0	1	10	0	8	110

HAL	18	100	293	500	0	3	8	2	208	708

The effects of monthly household income, number of occupants, age of children, education level, and floor area on the household LEC are analyzed by conducting one-way ANOVA tests based on household LEC for each socioeconomic factor. As presented in **Table 5**, the p-values of the household income, education level, and floor area factors are less than 0.005, which indicate that the data represented in each category of these factors are independent from each other. It can also be seen that as the household income level, education level, and floor area increase, the average household LEC also increases, except for the households with floor area between 90 m^2 and 110 m^2. This is as expected since as people with higher educational level have higher income levels and as income levels of the households increase they tend to choose bigger homes.

A significant trend was not found between the age category of the children in the homes and household LEC. However, there is a significant difference in LEC of homes with and without children. This is probably due to the fact that couples tend to move bigger homes when they have children which would eventually increase the LEC. However, similar correlation is observed between LEC in terms of kWh/m^2 per home and homes with or without kids. Thus, it can be concluded that the kids have significant effect on increasing the LEC of the homes. Another interesting outcome of these analyses is that LEC of homes does not show an increase when the number of occupants is higher than four. The LEC increases as the number of occupants increases from one person to four people probably due to the fact that most homes with high number of occupants live at homes with large floor areas.

Table 5 Average household lighting electricity consumption (LEC) based on various socioeconomic factors

Factor	Category	Avg. LEC, kWh/yr	p- Value
Monthly Household Income	< 700 USD	198	0.0000
	700 – 1 400 USD	218	
	1 400 – 2 800 USD	267	
	2 800 - 4 500 USD	353	
	> 4 500 USD	451	
Number of Occupants	1 person	166	0.0727
	2 people	233	
	3 people	242	
	4 people	280	
	≥ 5 people	274	
Children Age Category	No children	237	0.6838
	Children ages 0-9	269	
	Children ages 10-18	262	
	Children ages 18-25	251	
Education Level	Elementary School	153	0.0028
	High School	198	
	University - Undergraduate	247	
	University – M. Sc.	268	
	University – Ph. D.	336	
Floor Area	< 90 m^2	224	0.0000
	90 – 110 m^2	214	
	111 – 150 m^2	272	
	> 150 m^2	363	

Conclusion

There is a rapidly growing demand for electricity especially in the residential sector for Turkey, which is mainly due to increase in household income levels and population. Various energy efficiency campaigns had been conducted and are already underway by the Turkish government to reduce the electricity demand in the residential sector. Lighting is one of the major electricity end-uses in the total household electricity consumption in which energy efficiency measures in this end-use would result in a significant decrease in the total household electricity consumption. In this study, to the authors' knowledge, for the first time, based on an extensive survey data of 260 homes, the lighting electricity consumption and lamp preferences are determined. By using the survey data on appliances, the total household electricity consumption of the homes are determined to calculate the fraction of LEC in the total household electricity consumption. Six types of lamps are found to be used at the surveyed homes. The effects of various socioeconomic factors on the lamp type selection and LEC are also examined statistically. The surveyed homes are selected mainly based on their household income levels, since it is aimed to obtain a representative sample of the Turkish urban household stock. However, choosing household income as the only representation criteria and the sample size of the study can be the listed as the limitations of the study.

A total of 3423 lamps in six categories are identified in 260 homes. Among the lamps identified almost half of the lamps were CFL, 40% were INCD and the remaining 10% were SPOT, FLUO, LED, and HAL. It was found that INCD lamps are mostly preferred by low income homes and the LED share is the highest for the high income homes. It is also observed that as the home FA increases, the number of lamps owned increases. Similar to the income trend, INCD lamps are predominant in smaller homes and LED has the highest share for the large homes. The distributions of lamp types based on number of occupants do not exhibit a well-defined trend.

The distribution of LEC of the surveyed homes exhibits a log-normal distribution, with the geometric average of the sample determined as 209 kWh/year per household. The LEC is then determined as 8.5% of the total annual household electricity consumption, which is found to be lower than those of some countries. The effects of monthly household income, number of occupants, children age category, education level, and home FA on household LEC are analyzed statistically. It was found that income, education level and home FA have strong direct proportionality with LEC, however number of occupants and children age category have weak direct proportionality with LEC.

Nomenclature

CFL	compact fluorescent lamps
FLUO	fluorescent
HAL	halogen
INCD	incandescent
LEC	lighting electricity consumption
LED	light-emitting diode
FA	floor area
SPOT	spotlight

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A Language for Light: A User Interface Standard for Lighting Control

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Abstract

For over a century, the only form of control for most lights was just on or off, controlled from one location using the simplest user interface, usually a push-button or toggle switch. From physical appearance, and placement on a building wall, it was clear that it was a lighting control. Today, we can easily control dimming and color of light, and make lights responsive to occupancy, daylight, scheduling, and more. As complexity rises, control dimensions multiply. As each manufacturer determines its own conventions for how to communicate concepts to users, the frequency of users correctly understanding the controls is certain to drop. A solution to this problem used in other domains, such as vehicle dashboards, is a global language of symbols, supplemented with words, colors, metaphors, and physical mappings.

Previous work has identified that no such language for lighting exists. This paper presents results from a survey of current lighting control products, and initial proposals for parts of a lighting user element standard, focusing on elements for several areas: Lighting in General, Switching, Dimming/Brightness, and Dynamic Control. The results include recommendations for a standard; other topics merit consideration for future development, such as lighting scenes, color control, and scheduling.

While the intent is to place such content with a recognized Standards Development Organization, manufacturers can begin to use this material in product designs immediately. Ultimately the language embodied in these symbols and other elements should be part of the future ordinary life.

Background

Almost all uses of energy in buildings actively deliver services to people and have mechanisms to configure or control that process. From a temperature setpoint to appliance operation to lighting levels, humans need to occasionally or frequently understand a device's operational state, the potential ways that state could be changed, and how to make that change using controls efficiently and correctly through a user interface.

Probably the most complicated energy-related control system that most people interact with is that of vehicles and dashboard symbols and indicators are globally standardized [10]. While not all of the controls in a vehicle have energy impact, the most important ones do. That the controls also have severe safety implications is likely an important reason for their standardization. Vehicles are shipped globally and when people travel, they often drive, so international consistency is critical. Even when the steering wheel is flipped to the opposite side of the car, the order of the gas and brake pedals does not.

Some generic user interface principles have been used in lighting (e.g. that more is "up"—at least in many countries—and "clockwise"), and some basic symbols such as on "|" and off "◯" are used in some lighting controls (though mostly outside the U.S [3][5] However, the lighting industry for a variety of reasons has lacked any basic structure or set of elements for constructing user interfaces. This situation and the implications it has for lighting were reviewed in a report from 2010 [7][8]. A key point is that user interface standardization does <u>not</u> require all controls to be the same (e.g. vehicle dashboards vary widely). Rather, they just need to be constructed out of the same vocabulary of individual elements, in the same way that written text is constructed out of the same set of words (for a given language) but writers still have wide latitude to be creative and compelling. Basic elements in user interfaces are words, symbols, colors, metaphors, dynamic behavior, actuation methods, and audio and tactile interactions; standards can address all of these.

Due to the lack of a standard for lighting user interfaces, manufacturers who desire to make their products more understandable to users cannot; users have difficulty in obtaining the right quantity, quality, and timing of light that they want; and energy is wasted to the degree that people end up asking for more light than they want by being unable to make the needed precise request. Companies cannot reduce manufacturing costs or sell more units because controls are inconsistent. Ultimately, there are no winners from the status quo, only losers. While energy savings is the motivating factor for exploring this topic, it has benefits well beyond just reducing energy use.

Previous work by one of the authors addressed the topic of power control of electronics—turning devices on and off, and most importantly, making it easier for them to be asleep most of the time [4][6]. That process involved surveying the standards landscape, assessing the user interface elements in a wide variety of products, understanding implications for and of internal system technology, reviewing some cultural aspects of the elements, and ultimately proposing content for an international standard.

This paper is organized as follows. We begin with a summary of findings from past research, and a sketch of the research plan. The next section reviews core results from the survey. The paper finishes with a summary of next steps and conclusions, including outlines for potential content for a standard.

Past Research and Research Plan

In earlier work [7][8] we reviewed relevant standards and literature, assessed the nature of existing lighting control user interfaces, and organized our findings into a taxonomy of the types of information present in the interfaces. We confirmed that there is no existing standard that covers this topic area specifically, and with an extensive review of related standards, found relevant content covering graphical symbols, associations for color and movement, use of indicators, and terminology. In reviewing relevant literature we found nothing directly on our topic, but did find articles that addressed closely related issues. The focus in the literature is most commonly on the overall structure of an interface, how users accomplish tasks, and how to develop and design interfaces.

In the previous work, we reviewed many existing products, from simple switches, to those with many buttons, to those using graphic display technology. From this we developed a classification scheme for the entire ‘form’ of the control, to organize data and conclusions about interfaces. We forecasted a continuing increase in the use of complex control interfaces, as the controls themselves gain increasing capability. Another aspect of the research was identifying the use of specific “elements” in the interfaces, most prominently, the terms and symbols in use, but also colors and actuation methods. Finally, we extracted topics (“concepts”) that embody meaning and are represented in collections of interface elements (example concepts include basic switching, dimming/brightness, dynamic controls, and scheduling).

For our current work[88] we focused on devices intended for sale in the U.S. This was due to resource constraints, as well as because our initial target for standardization is limited to the U.S. We also address only controls that ordinary people may experience in their work and home life—not interfaces only used in a professional context such as systems for large building control or specialty applications such as theater lighting[89]. We extracted individual elements (mostly symbols, but some indicators, words, and actuation mechanisms); in some cases, their physical arrangement and pairing is important, though in most cases it is not.

In the survey, we sorted elements into the topic areas identified in prior work, though combined the topics of dynamic behavior and scheduling due to their intimate connection and paucity of content we found for scheduling. Below are presented summaries of the most important of these topics. The full results can be found in [9]. We relied primarily on information about products from

[88] This project was sponsored by the California Energy Commission’s Electric Program Investment Charge (CEC/EPIC) Program. The CEC also sponsored the earlier background research. http://nordman.lbl.gov/lightui.html

[89] However, it would be helpful if professional controls drew on a foundation from ordinary controls, much as truck controls do by starting from the standard automobile symbols but adding many that are only found in specialized trucks.

manufacturer web sites; this provides a good record of visual elements such as words and symbols, but indicator light color and behavior and dynamic actuation or behavior are sometimes ambiguous or missing.

We began by surveying manufacturers that are members of the National Electrical Manufacturers Association (NEMA) or in the Lighting Controls Association which collectively cover the vast majority of lighting controls solid in the U.S.

General Observations

Lighting controls are traditionally in prominent locations in a room for convenience, and are generally designed to be visually simple ("quiet") and attractive. Thus, they tend to be opaque in terms of exposing details of their capabilities or operation (Figure 1). The number of types of common control modalities is modest and includes toggle/rocker switches, linear sliders as well as rotary controls. Many controls indicate status by their mechanical position, while others use indicator lights.

Recent controls have added more capabilities, but to avoid expense and visual clutter have often packed more actuation methods into the same hardware. Some switches behave differently if pressed, then held down, or tapped two or three times in close succession. Some devices no longer have a mechanical switch at all, but only a tactile pad that can be tapped or pressed in. These mechanisms are rarely made clear upon visual inspection.

Figure 1. A typical "opaque" lighting control with no symbols or text.

In recent years, the number of products that include displays is rising, as hardware costs drop, network connections (that can take advantage of more control modalities) increase, and the number of control abilities present in light sources moves past what is reasonable to include in a compact mechanical control. User interface elements do not need to be displayed continuously when on a display rather than in hardware, and for that and other reasons many elements are much more often included on display-based controls (fixed or mobile).

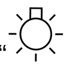
In our survey (products intended for sale in the U.S.) manufacturers generally rely on the normal international conventions for physical mappings of more and less: more is up, to the right, and clockwise [1][90]. Thus, labeling of which direction is more (or "on" in the case of a binary control) is not needed, as long as it is clear that on/off or more/less is involved in the control (it is of course important that a user is able to first readily identify that the device is a lighting control). It is key that the user understand that state is indicated by the mechanical position of the control.

Some controls have "locator lights" to make it easier to find them in the dark. We did not find any controls that labeled such lights, and they were found in various colors (e.g. white, amber, green). Locator lights were found on the switch itself, and on an entire group of brightness level indicator lights. In most applications a locator light need not be on when the light is on; some controls turn them off when the light is on, but whether all do is not known.

Most actuators have a single action—a switch is thrown, a button pushed, or a dial rotated. In some cases, a second action has a different meaning—we call this "secondary actuation." Examples include holding a pressed button for a few seconds rather than immediately releasing it, a quick double-press, or pushing in a rotary dial. In most cases, there is no indication on the control that the secondary action exists. A rare example where a secondary actuation (in this case actually two) is communicated in the user interface is shown in Figure 2; normal operation changes the brightness level while pushing the control in turns on/off, and pushing then turning changes the color. However, even in this case there are unstated modalities, such as holding it in during a push also has a meaning, as does a double-push (and pushing it is also involved in linking the control wirelessly to a light source, but this is not an ordinary user interaction).

Figure 2. A control with multiple secondary actuation mechanisms.

Lighting in General — The overall concept of lighting

The most common symbol for lighting in general is a bulb shape with emanating rays. Most of the examples we found had seven rays, though a few had five, six, or nine (Figure 3). In addition, the symbol was found with the base up in some cases and down in others. The international standard symbol for lighting "" has the base at the top and seven rays. The versions using color were all used on displays, and the color did not seem to have any specific meaning. The variation with a "w" symbol in the middle of the lamp symbol (probably to represent the filament) was found in products from several manufacturers, all apparently targeted for the China market.

[90] However, in many other countries, the reverse convention is used, at least for vertical controls, so that "up" means "off".

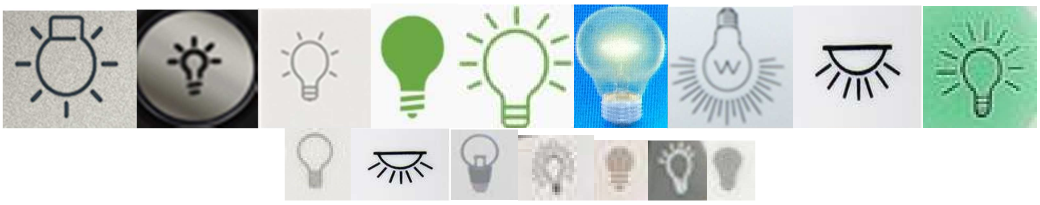


Figure 3. Basic light symbol with diverse use of rays and orientation.

Most controls did not include a generic symbol for lighting, and presumably manufacturers assume that users will recognize a lighting control because of its appearance and location; usually the bulb symbol is only present on controls that also include non-lighting functions.

For potential standard content, the existing standard symbol " " deserves deference and is largely compatible with what is found on products, so there is no clear reason to diverge from that. Some may observe that this lamp shape is derivative of incandescent lamps, and so becoming obsolete with the advent of LEDs. However, the key for such symbols is not that people intuit their meaning each time they encounter it, but rather, they are learned once and then recognized. The power symbol "⏻" does not by itself convey power in any intuitive sense, but can be readily recognized through repeatedly seeing it on power controls. Today's flat and rectangular smart phones commonly use the international symbol for telephone, which is a handset shape from several decades ago.

Switching (Static) — Basic turning on and off of a light source

We encountered both vertical and horizontal switches, and a few rotary dials for brightness that included an off position for switching. Several controls had a pad for tapping to toggle between power states; some pads involved no physical contact to actuate and instead responded to proximity and/or gestures.

Most on/off switches were unlabeled. A few had text for "On" and "Off" (Figure 4). The international symbols for on "I" and off "O" are more commonly used outside of the U.S. One product was shown with the symbols on a manufacturer's site international site, but a U.S. retailer showed the same product with the words "ON" and "OFF" (right two images in Figure 4). We also found the power symbol "⏻" on a small but increasing number of products.

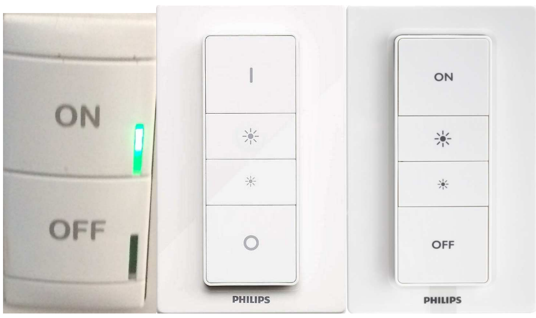


Figure 4. Example basic switch with text; Two versions of same switch model.

Several devices used a typical bulb symbol with emanating rays to indicate on, and a corresponding bulb symbol with no rays to indicate off (Figure 5). These are examples of symbols that only convey the correct meaning when used as a pair.

Figure 5. Lamp-based “On” and “off” symbols on a single lighting control.

All controls we found used the convention that pushing a control up, or a higher control, was associated with either “on”, or “more” (as with brightness control). Some countries have the reverse convention (up = off or less), particularly the UK and former British colonies, but also others. In some countries, both conventions are widely used. The U.S. convention is consistent with the relevant ISO/IEC standard on actuators [1][2].

Some lights use a “soft on” or “fade off” to ramp the light level between off and on—a feature that first became common in automobiles. We found this referenced in instructions or documentation, including on how to enable or configure this feature, but we did not find it in any product user interfaces.

Traditional switches, from antique push-button models to the more familiar toggle or paddle switches of the last 50 years, show by their mechanical position whether they are on or off. More recently controls have increasingly used momentary contact switches that lack a distinct mechanical position. In these cases, to give feedback to the user on the state, some controls include indicator lights.

Standard content for basic switching should include basic mechanical associations (e.g. up = on), the on and off symbols, and standard translations of ‘on’ and ‘off’ to each language. In addition, the power symbol “⏻” should be used for on/off controls that have only one actuator (e.g. push-on, push-off).

Dimming / Brightness (Static) — Adjusting light level

Changing the light level was one of the first advances beyond basic on/off control. The terms “dimming” or “brightness” are both widely used as the underlying term/metaphor in current controls. One product’s specification sheet noted a feature that “Dimmers offer control of brightness level.” Dimming is the *action* (a verb) and brightness the *result* (a noun).

Most dimming controls were not explicitly labeled, but rather relied on dimming being the only traditional linear control found on lighting controls. Most controls separate the dimming function from the on/off function, though on a few they are combined. We found some controls with the dimming function much smaller than the on/off function, and others with the reverse size relationship.

We found vertical, horizontal, and rotary dimming controls. These took the forms of continuous sliders, a series of individual level actuators, as well as pairs of up/down controls[91]. Up/down were sometimes arranged vertically, sometimes horizontally, and sometimes as a diagonal. In the diagonal case, up (more light) is in the top/left triangle, and down (less light) is toward the bottom/right (Figure 6: this control actually for shade controls but a similar light control is available). Figure 6 also shows a dimming control with separate buttons for each of four levels of on, plus an off button (with no indicator).

91 On controls with up/down buttons and indicator lights, sometimes it takes several presses of a button to advance the control between indicator settings, so that for example a 7-indicator control might have about 20 actual brightness levels.

Figure 6. Up and Down controls arranged diagonally; 4-level dimming.

In the horizontal arrangement of up/down pairs, we found examples with the left button actuating more light, as well as others with left button actuating less light (the general actuation standard suggests that the control for more light should be to the right). One product specification sheet had a photographic image of the product with left being down, and two line drawing versions of the same control with left being up. In general, up and down are indicated by triangles pointing in the relevant direction (left part of Figure 7), though some controls use a "+" and "-" . One product used a large and a small version of the brightness symbol to increase or decrease the level. Several other products used the brightness symbol emanating small and large rays to indicate the minimum and maximum light levels (right part of Figure 7).

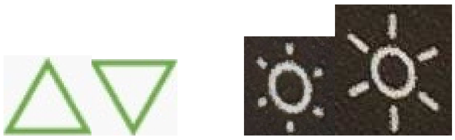


Figure 7. Examples of typical Up and Down symbols; also Minimum and maximum light

Dimming levels are sometimes indicated with a set of LEDs, and usually the level can be adjusted by a pair of up/down buttons, with the LEDs changing to match. This is also helpful when the dimming level can be set from more than one location (two conventional wall-mounted controls, or a second one being a dedicated remote control or software application). We found several examples with seven lights; another had seven lights that could be touched/pressed to actuate (combining the dimming level actuation and indication into a single vertical bar), plus an eighth position at the bottom for selecting Off. Another had four LEDs, with a fifth indicating off. We found indicator colors of white and green, though the color is often not clear from photographs[92].

On one product in which rotating a dial changes brightness, pushing the dial in and holding it increased light output to maximum brightness. One wall switch had buttons labeled "Raise" and "Lower." This switch operated by "ramping" the light while a button is held in, but if pressed in only briefly (less than half a second), the lights turned full on or full off.

A final issue for brightness that is the meaning for the user of the scale; for example, should the middle (e.g. 50%) level reference electricity use, the control signal level, absolute light output, or human-perceived light output[93]. We found examples of the last three of these, though as the final result depends on the pairing of the control with the source, studying the control only can be inadequate.

For potential standard content, the first question is whether the overall concept is "dimming" or

[92] Also, in no cases did we identify any significance to what color was chosen for the locator light.

[93] The user-perceived light level is commonly cited as having a mathematical square relationship to the physical brightness level. For example, a 25% actual light level will be perceived as 50%, and 1% as 10%.

"brightness". We think the latter is more on target, which can then utilize the existing international symbol, "☼" (though it may be that the rays are too short for use at small scale, so a redraw of the figure may be helpful, along the lines of the first and third symbols in Figure 10). The normal physical associations of more and less should be applied. Any symbol pair which clearly conveys more or less seems acceptable. The brightness scale should be keyed to human-perceived light output.

Dynamic Control — Automatic changes in response to sensor or other information

Occupancy sensors have long been deployed in residential and commercial buildings. When the sensor detects a human in the space, the lights turn on; similarly the lights are shut off when no person is present. We found no occupancy sensors that have any text or symbols on them to indicate their purpose. The sensors by themselves require no ongoing interaction, but users will commonly want to know that a sensor is involved in controlling light, and understand what sensors are present; sensor location can be important. Most common today are sensors that combine both passive infrared (PIR) and ultrasonic sensing (though other technologies are emerging). Such sensors have a relatively similar physical appearance, with a grill for the ultrasonic technology and a plastic lens for the PIR sensor. Manufacturers may be relying on this similar appearance for user identification.

Occupancy sensors often have indicators, typically one red and one green LED. At least some products use the convention that the Ultrasonic sensor is green and the Infrared one is red (an obvious association with red and infrared). Whether all such devices use this convention we do not know. The indicators flash when motion is detected so that people in the space can understand when detection is occurring (to know what motions cause detection), and to know if the lack of a light coming on is due to lack of detection or some other reason. In most cases, one LED indicates the status of one of the sensing mechanisms, and the other LED represents the other mechanism. However, for the product on the right of Figure 8 the green LED indicates network status, not sensing status.

Figure 8. Two occupancy sensors with red and green indicators; meaning of green is different.

A vacancy sensor is the same as an occupancy sensor for its sensing function, but results in different control actions. A human manually turns on a light when entering a space. When the vacancy sensor subsequently detects that no humans are present, the lights shut off. We found no controls that made clear on the exterior which type the control is.

Figure 9 shows several marketing symbols for an occupancy sensor (the first from a display interface; the rest from marketing materials), with the first conveying an electromagnetic beacon, that passive infrared (PIR) is the specific mechanism, that people are being detected, and that the light is being turned on and off. The symbols from other manufacturers that similarly show people when referencing occupancy sensing. One advantage of showing people moving in these symbols is that it clearly distinguishes them from standard restroom logos in which a person is standing still.

Figure 9. Occupancy sensing symbols from marketing materials

Some symbols for occupancy sensing indicate the sensing technology. For example, we found one symbol that clearly conveyed a dual-sensor device. One potential issue with this approach to referencing a sensing function is that the concentric arcs look very similar to the common Wi-Fi symbol, and so could connote communication rather than sensing. Further complicating this is that occupancy sensors do needs to be communicated as well.

A key way to save energy in lighting is dimming (or turning off entirely) artificial light when natural light is available. This requires sensing and actuation, with the term “daylight sensor” often used (also sometimes “ambient light sensor”). Similar to occupancy sensors, few if any daylight sensors have a symbol or text on them—they are designed to be minimal and recede into the background. They do not need to call attention to themselves, and do not require user interaction. However, we did find some marketing materials with symbols that reference daylight sensing (Figure 10). Several of the images are evocative of the sun, but also are similar to the brightness symbol often used in lighting controls.

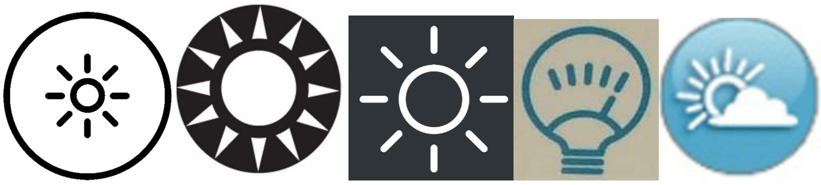


Figure 10. Light/Daylight sensing symbols from marketing materials.

A few controls include elements for time-based scheduling, using clock or calendar symbols. More common are controls to turn a light (or fan) off after a time interval. Often these just list times with the fact that they are a turn-off timer implicit. One product calls this a “sleep timer” though only in documentation, not on the product itself (TVs often have this feature); note this is for the person going to sleep, not the light going to sleep. Some controls have the ability to turn lights on and off at “random” intervals to simulate someone being home when they are not.

For standard content, a symbol to reference each of occupancy sensing and daylight sensing is needed, to label sensors, indicators, and in controls to show their presence or status. For indicating sensing, the communication aspect of a sensor is indispensable and as the symbols in Figure 9 show, that is conventionally done with the radiating arcs. For occupancy, having part of the symbol convey a person moving seems to be the common theme and so some variant of the symbols shown would be appropriate. For light sensing, building off the brightness symbol seems like a promising direction, though light sensing would need to be clearly different and also convey the communication aspect.

Other topics

Our survey covered additional topics within lighting control. An increasing number of controls enable selection of on/off or brightness levels for a collection of light sources at once, commonly called a “scene”. These are commonly labeled with a site-specific term that derives from the time of day or activity the scene is designed for. No early standardization seems likely other than a symbol for the general concept of a scene.

An increasing number of light sources can change the color of light, and others can change the color temperature of white light. As one can see on many computer-based interfaces, color selection is a complicated topic, and relatively new to light, so that early standardization is unlikely. For color temperature however, the problem is much simpler—where along a scale to emit light, with one end being “warm” and the other “cool”. Warm and cool are already common concepts in user interfaces (e.g. in vehicle climate controls). However, color is measured with color temperature, but increasing color temperature means a cooler color—the opposite of how people experience regular temperature. This makes it problematic to have up/down or left/right associations for color control as the “correct” one is counter to what most people will expect. A potential solution is to use warm/cold elements (terms, symbols, and colors), but use some other organizing idea that doesn’t reference “temperature”, and then have warmer colors associated with “more”. As an example, color variations could be associated with time of day with cooler colors identified with the morning and warmer with the late afternoon or evening.

It is important to ensure that the widest range of people can use lighting controls. One dimension of this is to make any accommodations that can be made for people with disabilities, such as blindness, or other limitations, as from being particularly elderly or particularly young. We found very little content for these topics. Another issue is making lighting controls work across countries, in the way that vehicle controls do. This suggests avoiding words when at all possible, and when they are used, to have standard translations for words that are used, including a standard word meaning for each symbol.

Other topics relevant to lighting control are window shading, ventilation, networking, international products, configuration, energy saving or consumption tracking, and emerging user interface modalities (e.g. speech or gestures). At this time speech seems a particular priority to address.

Potential Standard Content

While the content for a proposed initial standard area is still in flux, the following is likely to show up at least in some form.

- A symbol for ‘lighting in general’, based on the current IEC symbol.
- Principles on meanings of motions for various types of information, based on long-standing ISO principles of man-machine interaction.
- Terminology and symbols around basic switching, drawing on standard IEC symbols and assumed meaning of mechanical associations.
- Terminology and symbols around changing light levels, with brightness the underlying metaphor.
- Interpretation of light level quantities, with human perception of light the core scale to use.
- Terminology and symbols around light color temperature, but likely avoiding “temperature” as a reference or metaphor.
- Symbols and indicators for occupancy sensing and daylight sensing, newly created, but drawing on an abstract person walking and a sun symbol.

Topics that might be covered if a clear solution emerges include:

- Symbols, terms, and indicators for timers, based on existing IEC symbols.
- Terminology and symbols around shading, with ‘open’ and ‘closed’ the key metaphor.
- Symbols, terms, and indicators for ventilation, based on existing IEC symbols.
- Accessibility to people with disabilities.
-

Summary and Next Steps

We found a variety of circumstances for lighting control user interface standardization in the products we surveyed. These include:

- Content for which there is already broad consistency and standardization directions are clear.
- Content in which there is not consistency but a good approach is clear.
- Areas in which content is absent but is needed.
- Areas that are not ready for standardization at this time.

The last item raises the issue that this project is not trying to cover all aspects of lighting controls. That would be too great a leap to accomplish in one step, even within a single country, let alone trying to achieve international agreement. Some areas, such as color selection, need more time for experimentation to see what approaches seem to work best. Others, such as scene naming, may never be suitable for broad standardization. Picking a modest set of content that covers several important areas can best balance benefit and feasibility.

Our intent is to present this content to the lighting control industry in general for review and consideration, revise the content, and then make it available to the Lighting Systems Committee (C137) of the National Electrical Manufacturers Association. This body is most suited to considering what might be in a standard on this topic. The most important outcome of this is manufacturers using the standard (or a draft of it) in their design of new products. Voluntary or mandatory energy standards could consider referencing the standard in their requirements, though whether this is necessary or desirable is a point that needs careful consideration. Most successful user interface standards do not have legal requirements behind them, but rather do so based on having achieved a critical mass of market penetration and thus consumer 'mind share'.

The primary ultimate goal of this project is to affect the design of all ordinary lighting controls on the planet, and save energy at no incremental cost. In addition, this can serve as an example of other domains of energy-relevant controls that could benefit from similar standardization such as climate control, electricity prices, and generic scheduling and occupancy.

Acknowledgments

The authors would like to thank Adel Suleiman and the rest of the EPIC team at the California Energy Commission for their interest and support, and the CEC for funding the project. For review, comment, and insight we thank Aditya Khandekar, Erik Page, and Marco Pritoni.

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Reducing carbon dioxide emissions by global transition to LED lighting in residential buildings

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Abstract

The global potential for reducing carbon dioxide (CO2) emissions was estimated by the means of energy-efficient LED lighting in residential buildings. LED lamps typically have greater luminous efficacy compared to conventional lamps used in residential lighting, which suggests potential for energy savings and reducing CO2 emissions. In addition to evaluating the CO2 emission reduction, the study included a cost analysis and evaluated indirect (life cycle) CO2 emissions of the transition to residential LED lighting. The life cycle costs were estimated based on purchase prices and operating costs (energy).

Results indicated that approximately 6.6 Gt of CO2 emissions could be reduced with high (90 %) adoption of LED lamps in residential buildings over the 30-year period (2015-2045). The transition to LED lighting was estimated to start from 3 % adoption in lumen-hours in general lighting applications in 2014 and to result to 90 % of lumen-hours in 2045. Changing from conventional residential lighting to LED solutions is clearly an important means for CO2 mitigation. In order to realize this great potential for CO2 emission reduction, good quality LED lamps need to be available at a reasonable purchase price and their luminous efficacy must continue to be improved.

Introduction

Lighting accounted for approximately 19 % of global electricity consumption in 2005 including all stationary lighting [1], and approximately 16 % of electricity consumption in residential buildings [2]. Residential lighting, as a notable energy consumer, was responsible for approximately 34 Mt of carbon dioxide (CO2) emissions in 2013 globally [2]. In illuminating engineering, there are several possibilities to reduce the energy consumption and respective CO2 emissions. This study focuses on the CO2 emission reduction potential of residential lighting when replacing conventional lamps with LED-based products.

Global warming is an increasingly important environmental concern. The consequences of human actions are accelerating the rate of global warming. The scientific community is strongly expressing their concern and the aim is to limit the man-induced global warming to 2 degrees compared to global temperature of pre-industrial level. This 2 degrees level is estimated to be such a level that climate change processes can be *reversed*, but exceeding the 2-degree increase in global temperature is considered irreversible.

Numerous methods and means exist to limit the CO2 emission of human actions. Several existing solutions are being evaluated in Project Drawdown [3], a project listing approximately a hundred technological, social and ecological solutions for CO2 mitigation. The solutions range from the use of renewable energy sources and energy efficient technologies to educating girls, walkable cities, tree intercropping and recycling. The aim is to evaluate the impact of climate solutions that already exist and that can be deployed in a large scale. Project Drawdown consists of a group of scientists who use a systematic, common calculation method to evaluate the CO2 emission reduction of the solutions and their respective costs. Residential LED lighting is one of the energy efficient solutions in Project Drawdown.

The aim of the study is to evaluate the CO2 emission reduction potential of LED lighting in residential lighting applications. Only the general lighting is included, focusing on general lighting service. Decorative and special lighting are excluded from the study. The study considers only the lamps, not luminaires.

Materials and methods

Residential LED lighting is one of the technological solutions to reduce CO2 emissions. The key terms, main characteristics, respective data sources and assumptions are presented. The study was conducted using version 0.6.6 of the model and the period under study ranges from 2015-2045, year 2014 being a base year for the analysis. Data collection includes, where available and relevant, global data, regional data and country-specific data. The global study comprises of five regions: OECD90, Eastern Europe, Asia (sans Japan), Middle East and Africa, and Latin America. Country-specific data were collected for three countries: China, India, and US, as well as for EU.

There are two main scenarios in the study: reference case and optimistically plausible (OPT) scenario. The reference case is based on current use of LED technology in residential lighting. The rate of growth in reference case is based on population and GDP per capita estimates made in AMPERE project (AMPERE WP2+3 MESSAGE model [4]). In addition, the reference case considers the grid emission factors (kg CO2 per kWh) to remain at year 2015 level until 2045. In contrast, the OPT scenario describes the case in which the LED lamps are adopted in residential lighting at a vigorous, yet realistic rate, in addition to estimated economic and population growth. The grid emission factors in OPT scenario are based on AMPERE/MESSAGE model [4], without significant technological changes. Thus, the calculations address primarily the effect of the transition to energy efficient lighting, excluding the transition to low-emission energy production from renewables.

The functional unit of the residential LED lighting is petalumenhour (Plmh). This functional unit refers to the amount of lighting service needed in terms of luminous flux (lm) and operating time (h). The lighting demand is expressed in Plmh's.

Lighting demand

Total addressable market (TAM) represents the total potential market of residential lighting demand. The TAM of residential lighting includes the lighting demand provided by all technologies typically used in the application, i.e., incandescent, halogen, compact fluorescent (CFL), linear fluorescent (LFL) and LED lamps. The growth of TAM data is based on the growth rates of gross domestic product (GDP) per capita [4], floor surface area in residential buildings [5-7], number of households [8], and residential lighting electricity consumption [2].

The TAM data, illustrated in Figure 1, were collected from several sources. Due to the scarcity in residential lighting demand data expressed directly in lumenhours, conversions had to be made to be able to collect as many data points as possible to get representative data. The lumenhour data, provided by IEA [1], was used for year 2005 TAM estimate, and global and regional growth rates based on growth of GDP per capita were assumed to estimate TAM growth in (2005-)2014-2045.

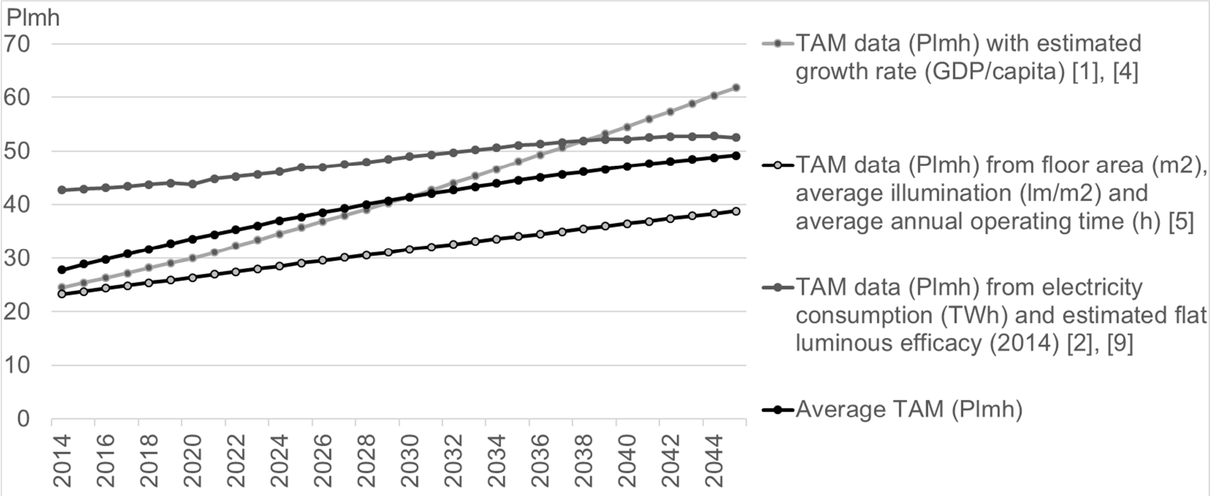

Figure 1. Total addressable market of residential lighting demand in base year (2014) and in analysis period (2015-2045) in Petalumenhours (Plmh)

Regarding data not expressed directly in lumenhours, data were retrieved by conversions. First, TAM data were calculated from residential average floor area (m^2) [5-7] using estimates for average illuminance levels (lx; lm/m^2) and annual operating time (assumed constant 1000 h/a). The second conversion method converted the average electricity consumption [2] in residential buildings (TWh) to Plmh's using estimates for global luminous efficacy (lm/W). The ETP2016 data [2] for 6-degree scenario were used together with constant, 2014 level, average luminous efficacy of installed residential lighting (43 lm/W). Average luminous efficacy of residential lighting was estimated based on the development of luminous efficacies of individual lamp types and their shares in producing lumen hours [9] in residential lighting. Fourth, the number of households and respective lighting demand (klmh) per households were used to calculate TAM in EU [8].

The available data is interpolated for years in between the data points, when the difference between data points does not exceed 10 years. Extrapolation was avoided, as it results to less certain data. Extrapolation was only used for TAM data that was available for at least 5 consecutive years, and the TAM data was extrapolated only for three years. The TAM data were collected globally, regionally and per country, and the average TAM data were calculated for each year by adjusting the data by the most suitable trend line (linear, 2nd order polynomial, 3rd order polynomial, exponential) for the growth.

Lamp data

Several lamp characteristics were needed in the analysis. Table 1 lists the luminous efficacies of lamps averaged based on data collection from multiple sources [1], [8], [10]-[15]. The share of the technology in residential lighting service (% of total Plmh's) is based on McKinsey [12] data for the conventional lamp types, and on US DOE [16], UNEP [9] and Bergesen et al. [17] for LED adoption. US DOE [16] provided an estimate of 3 % of LED adoption in residential lighting. The United Nations Environment programme provided global and country-specific LED adoption data as % of Plmh's [9]. Bergesen et al. [17] provided estimates for LED adoption for years 2010, 2030 and 2050 in their calculations, of which the 2010 data were used together with the estimated growth rate for LED sales 2010-2014 by McKinsey [12] to retrieve data point for LED adoption for 2014.

Table 1. Lamp characteristics and share of lumenhour production in residential lighting in base year (2014).

Lamp type	Luminous efficacy (lm/W)	Lamp life (h)	Share of installed lighting service in 2014
Incandescent lamp	14	1000	19 %
Halogen lamp	22	2000	32 %

Compact fluorescent lamp	61	10000	32 %
Fluorescent lamp	80	20000	14 %
LED lamp	73	50000	3 %

For the LED adoption in 2045, an estimate of 90 % of TAM was used globally and regionally. The LED adoption was estimated to grow linearly, as accurate LED adoption data was not found for the lighting consumption. Several LED *sales* forecasts were available but as they were expressed in monetary terms, they were not used in estimating the residential lighting service provided by lamps in use.

Assumptions

Several assumptions had to be made to accomplish the CO2 emission reduction calculations. First, luminous and electrical qualities of the lamps used in residential lighting were based on mostly global, US and EU data. Limited amount of data was found for other regions and countries. Second, the average luminous efficacy of residential lighting (43 lm/W) (not of any individual lamp type) was estimated based on lamp luminous efficacies and respective Plmh shares developing from the base year to 2045. Third, TAM data calculated from IEA data [1] for Plmh lighting consumption in 2005 was assumed to grow at the same rate as GDP per capita. This approach was chosen as the Plmh development in residential lighting does not only correlate with the increase of population or floor area but also with the economic growth of the area: more developed areas tend to have more lighting. Fourth assumption estimated the annual operating time to remain constant over the 30-year period (1000 h/a). This results approximately to 2.7 hours per day. It must be noted that this is an *average* for all general lighting service lamps in residential buildings. Regional differences are expected, and the annual operating time may change in 2015-2045.

Energy savings

Energy savings are calculated per functional unit (Plmh). LED residential lighting was calculated to consume approximately 14 TWh per Plmh, whereas the aggregated conventional technologies consumed 29 TWh per Plmh.

Financial analysis

The financial analysis included both first cost, i.e., the purchase price, and operating cost. The purchase prices of conventional and LED lamps were collected from several data sources in all regions for the base year converted to USD per Plm (e.g., [8], [10], [12], [18], [19], and online shops [20]-[30]). First cost data were collected from various sources to cover global and regional scope. Purchase prices were converted to USD2014/Plm. In case the luminous flux was not given in the lamp data sheet, default luminous flux was used in conversion from price per piece to price per Plm. LED lamp price development is estimated based on [8], [10], [12], [19].

Operating costs (C_o) were calculated according to equation:

$$C_o = P \times c_{el} \times t$$

where P is the lamp power (kW), c_{el} is the electricity price (USD/kWh), and t the annual operating time (h). Electricity price was estimated to be 0.14 USD/kWh globally [31].

Indirect CO_2 emissions

Indirect CO2 emissions, i.e., the CO2 emissions of raw material acquisition and manufacturing of the lamps, were estimated based on recent (2009-2016) life cycle assessment (LCA) case studies of lighting products. The amount of CO2 equivalents for incandescent lamp, halogen lamp, CFL, LFL and LED lamp were collected from eight LCAs published since 2009 [32]-[39]. The average indirect CO2 emissions of residential lamps are collected to Table 2, expressed in Mt of CO2 per Plmh (luminous flux and life of lamp). Long lives of FLs and LED lamps explain their relatively low indirect CO2 emissions.

Table 2. Indirect CO2 emissions of lamps used typically in residential lighting. Various LCA case studies resulted to a great range of CO2 emissions.

Lamp	**Average CO2 emission of life cycle stages prior to operation (Mt CO2/Plmh)**
Incandescent lamp	360
Halogen lamp	580
Compact fluorescent lamp	1 300
Florescent lamp	43
LED lamp	590

Results

The total emission reduction from LED residential lighting, given the high global adoption rate in 2045 (90 %), was approximately 6.6 Gt of CO2 in 2015-2045 globally. The total emissions reduction of each region and country are listed in Table 3. The regional emission reductions do not add up to global reduction due to differences in global and regional data.

Table 3. Total CO2 emission reduction in 2015-2045 globally and in regions and countries.

Region/Country	**CO2 emission reduction 2015-2045 (Gt CO2)**
World	6.6
OECD90	1.8
Eastern Europe	0.70
Asia (sans Japan)	2.8
Middle East & Africa	0.33
Latin America	0.50

Annual CO2 emission reductions are illustrated in Figure 2. Global maximum annual CO2 emission reduction, approximately 320 Mt CO2, occurs in 2045. Greatest regional emission reduction potential is found in Asia (sans Japan), accounting for 43 % of global emission reduction.

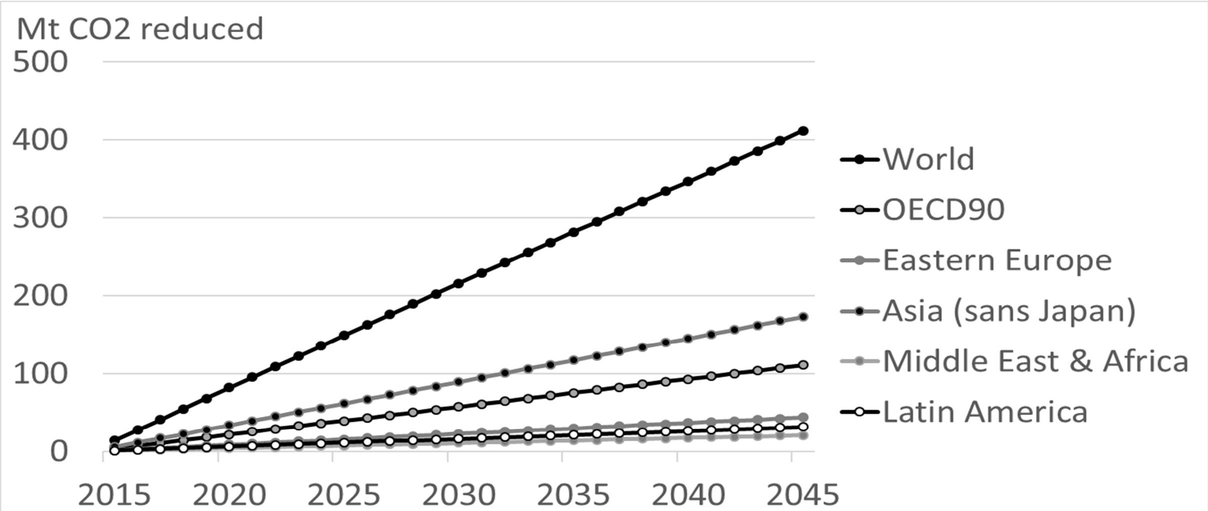

Figure 2. Annual CO2 emission reduction of residential LED lighting in 2015-2045 in million metric tonnes (Mt CO2) globally and regionally

Financially, LED residential lighting saves approximately 4.9 trillion (4.9 x 10^12) USD globally compared to conventional technologies, which converts to 1 130 billion USD considering the time value of the money (net present value; discount rate 4 %). In terms of energy saving during operation, LED solution consumes less electricity compared to conventional lamps: In a global scale, LED residential lighting was estimated to consume approximately 14 TWh per Plmh, whereas conventional technologies (all technologies aggregated) consumed 29 TWh per Plmh, resulting to savings of 53 % of electricity in operation.

Discussion and conclusions

CO2 emissions can significantly be reduced by changing conventional, in-efficient lighting to LED solutions in residential buildings. Globally, the emission reduction was estimated at 6.6 Gt of CO2 in 2015-2045 assuming 90 % LED adoption rate in 2045. Energy savings from conventional lighting technologies to LED solution was estimated at 53 %, from 29 TWh/Plmh lighting service to 14 TWh/Plmh.

IEA estimated that energy efficient lighting might reduce 449 million metric tonnes (Mt) of CO2 in 2030, including all lighting sectors [1]. However, this estimate does not fully consider the dramatic change in lighting sector and the improved energy efficiency of LED technology, as LED lighting products had not yet proved their great energy saving potential at that time. It has also been estimated that a global overnight transition to efficient LED lamps would result to a reduction of 801 Mt of CO2 emissions [40], but this estimate includes all lighting sectors and an adoption rate of 100 %. UNEP En.lighten Initiative [41] estimates that the replacement of inefficient on-grid lighting globally would reduce the *annual* CO2 emissions by over 530 Mt. In comparison, this paper estimated the emission reduction to approximately 6.6 Gt (6 600 Mt) of CO2 in 2045. It must be noted that it is impossible to compare emission reduction estimates accurately due to differences in LED adoption and scope (all lighting sectors vs. residential sector).

The reliability of the findings can be further improved by future research. First, assumptions in data conversions can be fortified. Second, as luminaires and other parts of the lighting system, such as lighting controls, were excluded from the current study, future studies could address the actual, effective lighting in households by taking the efficiency and functionality of luminaires and lighting controls into account. Considering the entire lighting system could result to even greater CO2 reductions, as the energy consumption would be minimized by optimal luminaire design and lighting control systems. Future studies may also address the lighting quality, such as color rendering. Third, regional data should be collected, as the current study frequently uses global data. In addition, fluctuation in parameters could be analyzed in more detail, e.g., regarding electricity price, lifetimes of lamps, and annual operating time. Fourth, rebound effect could be taken into account. Finally, in order for the CO2 reduction to be realized, the LED technology needs to penetrate the lighting market globally. A set of measures can be taken to do that: promotion campaigns, energy efficiency programs, and informing the consumers about the benefits in life cycle costs, added functionalities and energy savings.

Acknowledgments

Authors would like to thank Project Drawdown Fellows Ryan Allard and Kevin Bayuk for their help.

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Relative drift towards blue spectral region of white LEDs during ageing

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Abstract

In this work, to understand an observed relative increase of blue light proportion in the spectrum of LED lamps along their lifetime, we analysed the spectral characteristics drift of LED lamps during their ageing. This analysis is based upon several laboratory-controlled ageing experiments of LED components and lamps samples submitted matured, for some of them, up to 20 000 hours. Performed experiments confirm a relative increase of blue light proportion testified by both correlated colour temperature increase and colour point drift towards blue region. We show that this drift may be either "catastrophic" (it occurs in less than 2000 h of operation) or "parametric" (it occurs slowly and becomes observable after at least 5000 h of operation). Catastrophic type failure is due mainly to thermal effects that causes phosphor blackening at LED component level (or even remote-phosphor melting in extreme situations). The parametric (gradual) degradation is mainly due to deterioration of polymer/epoxy matrix/encapsulant used for phosphor coating at LED component level, or, any plastic part, like remote-phosphor substrates, of the lamp.

Introduction

Solid State Lighting (SSL) is currently revolutionizing the field of lighting and its applications. In the long term, inorganic and organic light emitting diodes (LEDs) will become the most widely used light sources. White LEDs have shown a steady growth of their luminous efficacy for more than fifteen years; promising to make significant energy savings as they replace older lighting technologies. Phosphor-converted white LEDs (pcW-LED) are now widely used in general lighting. This popular technique for converting blue emission from a LED die is using phosphor based down-conversion mechanisms. The phosphor converts a part of the blue light coming from the die into green-yellow and orange-red light. This combination of blue from the chip (die) and yellow from the phosphor produces a white light sensation interpreted as such by the human brain. If Φ_0 is the flux emitted by the bare LED chip, τ_b the phosphor transmittance in blue region and S_{by} the phosphor's transfer function (Stokes shift tensor) from blue to yellow, we can then calculate the flux in the yellow region, Φ_y, and the blue leakage flux, $\Phi_{b;leak}$ as indicated in Figure 1. Following this principle, it is impossible to avoid a relative increase of the blue light transmitted through the phosphor from the LED component.

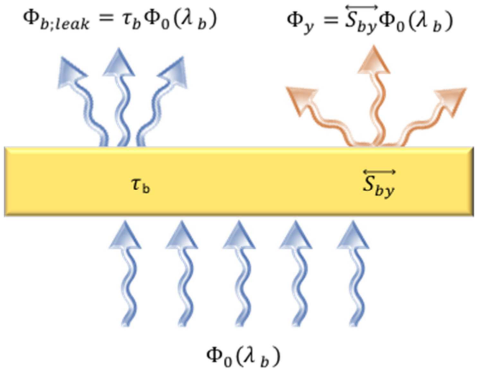


Figure 1: Transfer function diagram of blue source and the emitted light due to the Stokes shift in the phosphor layer.

However, as any new or emerging technology, LED products should be proven to be at least as safe as the products they intend to replace. The potential risks posed by LEDs to the human health are mainly linked to the emitted optical radiation [1]. Phosphor-converted white LEDs currently used in SSL have the advantage of emitting a negligible amount of ultraviolet and infrared radiation. Due to the specific spectral characteristics of pcw-LEDs, and especially the blue light component, have raised some concerns regarding photo-biological safety [2]. Indeed, radiation in the blue wing of the spectrum is recognized as being harmful to the retina because it induces a cellular oxidative stress. This light-induced retinal degeneration is known to involve complex series of events such as apoptosis (cellular death), inflammatory response, and free radicals, but the full understanding of the phenomenon is still an active research field in ophthalmology. Furthermore, it has been demonstrated that artificial light-at-night (ALAN), particularly of short wavelength is a highly effective inhibitor of N-acetyltransferase, the rate-limiting enzyme in melatonin in synthesis, thus resulting in markedly lower melatonin levels and increased human health risk [3]. More recently, Zubidat and Haim published an excellent review on ALAN exposure to short wave lengths showing clearly that there are still some health issues, other than retinal damages, to be taken into account [4].

All these findings concern blue light component of the spectrum. Indeed, most LED products tended to have higher colour temperatures but this is not an intrinsic characteristic of the technology [5]. In principle, lamps based on pcw-LEDs do not produce more blue light than other types of lamps of the same colour temperature [6]. In theory, phosphors attenuate photo-biological risks by absorbing partially blue light. Furthermore, LED manufacturers answer the problem by proposing more efficient and less expensive warm white LED components that lighting manufacturers can integrate to their systems, this solves to a satisfactory manner the most of the problems [7]. Today, good quality SSL products in the marked and accessible by consumers are blue-light risk free. However, the emission spectrum of the lamp may be affected by various ageing processes that may change to a significant way the relative balance of yellow-blue radiations. Even if, due to flux depreciation with ageing, the absolute value of blue light is inescapably reduced (this is a guarantee that the product remains blue-light risk free for the retina) the change of the blue-yellow ratio can induce some Correlated Colour Temperature (CCT) and colour drifts that could induce ALAN effects. The objective of the present paper is to investigate the relative changes on white light quality emitted by LEDs at both component and lamp levels.

Evidences of drifts towards higher wavelength regions with LED ageing

Very recently, some research done within the framework of the European PremiumLight sponsored by EACI [8] and of French national project LEDAge [9] supported by ADEME projects shown some systematic and significant radiation shift towards blue spectral regions during LED ageing. This blue shift could be explained by phosphor degradation due either to thermal quenching or radiative solarisation processes. Similar effects have been reported earlier by the U.S. Department of Energy's (DOE) in the frame of GATEWAY program [10][11]. More especially the study based on Laboratory data collected by DOE's CALiPER program between 2008 and 2010 reveals that many early LED products shifted beyond acceptable tolerances in as little as a few thousand hours, even if good quality products seems to have an excellent colour stability [10].

The most common factor that causes the deterioration in the phosphor layer is the temperature. Blue light is converted in the yellow band by Stokes shift. In this process, heat will be generated by light absorption from the LED chip [12][13]. Polymer/epoxy material is often used a matrix to incorporate the phosphors over the die, as well as to protect the die and the wire bonding. Heat can deteriorate both polymer encapsulant and phosphor. Due to this deterioration, the shifting characteristic of the phosphor layer can be translated in terms of wavelength and irradiance change of the emitted photons [14][15]. Many studies have related the thermal ageing of the phosphor coating layer to its type and configuration [16][17].

Catastrophic failure accompanied by blue light increase

In some extreme cases, the phosphor layer deposited on plastic substrates may be irreversibly damaged as shown in Figure 2. As can be seen, in this extreme case, the phosphor coating has been pulverized under excessive heat exposure of the plastic substrate; the blue LEDs are now unprotected and blue light escape is obvious. However, during LED ageing, less “violent” phenomena can appear progressively and lead to a significant increase of blue light escaping from the lamp/luminaire.

Figure 2: LED modules with remote-phosphor layer damaged. The blue LED chips are directly visible (Photo credits A. Barroso, LAPLACE Lab. 2016)

However, beyond extreme situations as shown above, phosphor gradual degradation due to thermal stress and/or impurities, may lead very rapidly to an observable colour point drift towards the blue region. Figure 3a shows this colour point drift in the CIE1931 colour triangle during the first 2000 h of LED continuous operation. Associated phosphor blackening can clearly be seen in Figure 3b on a 3000K-95CRI LED component at nominal current operation (350 mA) and 45°C stabilized pad temperature. It should be noted here that for a LED with such colorimetric characteristics lot of blue light is converted by green and red phosphors, contributing to significant thermal stress inside phosphor. This is a rather surprising effect because if we rely to manufacturer’s data based on LM-80 tests we can’t expect such degradations or colour drifts. However, this effect has been observed on 4 on 16 LED chips exposed at the same conditions with the 2000 h operating period.

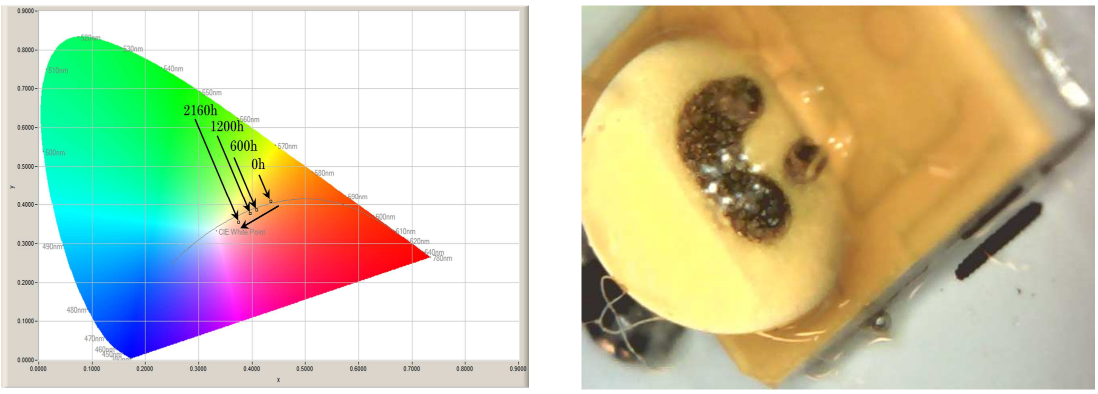


Figure 3: (a) Observed colour point shift within the first 2000h of operation [18] (b) associated phosphor blackening. (Photo credits G. Zissis, LAPLACE Lab. 2016)

Spectral measurements performed on the same LED chip shows a decrease of the yellow-red wing and an increase of the blue wing radiation, Figure 4. We can here consider that the yellow-red radiation decrease is due to the phosphor damage. However, the relative increase of the blue wing can’t be explained by any logic reason because the blue emission is linked to the semiconductor itself and within 2000h the ageing of the semiconductor is not a justification. This behaviour indicates that when phosphor degrades due to blackening, it converts less blue light into yellow and then, of course, blue radiation escape increases.

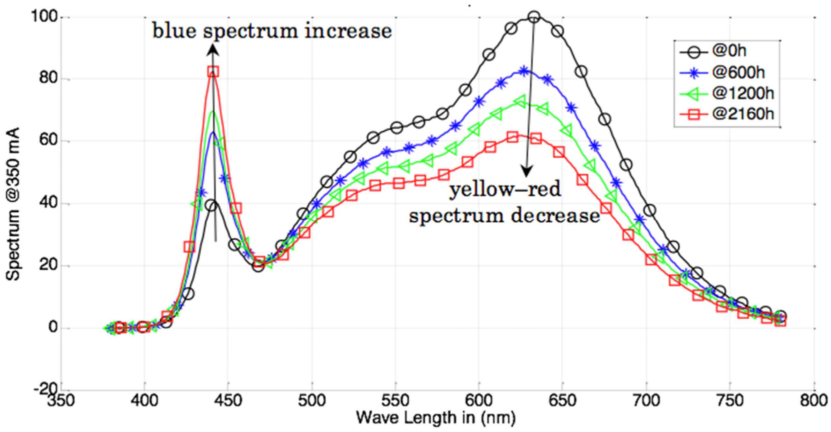


Figure 4: Measured 16 chip average spectral variation during the first 2 000h of continuous operation of a warm-white LED under constant pad temperature and constant current Measurements done in 2016 [18].

Gradual degradations accompanied by blue/yellow balance increase

These observations confirm that at the LED component level, blue leakage increase is not only observable, but it can be rapid. The main question is how this component-level degradation will impact the global light quality emitted by a LED lamp. The following part of the paper is dedicated to this issue.

Figure 5 shows evidence obtained in the European Union (EU) PremiumLight project [8], indicating that the loss of the blue–yellow balance of emitted radiation is probably an inherent characteristic of an ageing pcW-LED. More than 330 lamps of 95 types were tested in the project. Among these lamps, 7 brands of LED and 3 brands of CFLs have been submitted to a controlled ageing process in order to observe, among other parameters, any systematic Correlated Colour Temperature drifts. All these lamps were initially belonging to 0 blue-light risk group (RG0).

The lamps have been placed in vertical racks and supplied by constant current power supplies that feeds the lamps with a fixed power. Even if there is not a specific standard for LED-lamp ageing environmental conditions, in our experiment as for classic lamp ageing we opted for the following: all racks have been placed in a room with controlled temperature fixed at 25±1°C and with low air flux around the racks. The lamps have been removed from the racks every 1000 hours and tested using an Ulbricht's integrating sphere equipped with a calibrated spectro-radiometer. The sphere has been calibrated using a standard lamp where the absolute value of the luminous flux is known (measured by the National Bureau of Standards). Furthermore, as the spectral reflectance of the painting used in the integrating sphere, the collected data sets have been corrected in order to balance any spectral distortion due to the multiple reflexions in the inner surface of the sphere.

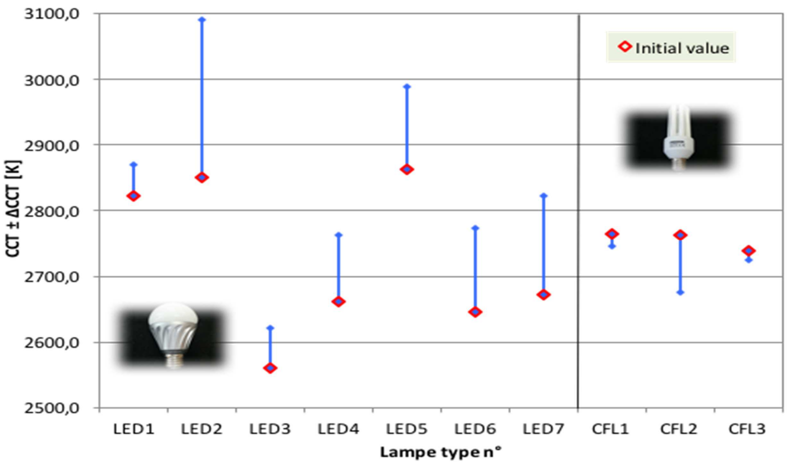


Figure 5: Average CCT shift measured after 6 000 hours of operation for seven pcW-LED lamps and three CFL brands (for each brand, 7 sample lamps have been measured in 2014 and 2015). After 6000 h, all pcW-LEDs emitted more bluish light, whereas all CFLs emitted more yellowish light with higher stability.

As shown in Figure 5, after 6000 h of operation (11h ON - 1h OFF cycle), the LED lamps exhibited a systematic drift towards a higher CCT, while the compact fluorescent lamps (CFLs) were rather stable or were drifting toward a lower CCT. Each point shown in Figure 5 corresponds to the average value obtaining from the measurement on 7 samples from each brand. Each measurement is repeated for 3 times to reduce the statistical errors. The standard deviations for the measured values was in all cases less than ±20 K and the relative measurement incertitude less than ±1%. This means that the observed different CCT drifts are reliable and robust.

Blue-yellow balance drift during ageing

The observed systematic CCT drift behaviour indicates that the ratio between the blue light and yellow light in the LED spectrum was increasing. To confirm this blue-yellow balance change a second experiment was carried out supported by the ADEME LEDAge project. In this experiment, systematic spectral measurements were carried-out in 2016 on 17 LED lamp brands aged under their nominal operating conditions for a duration of 20 000 h [19]. All lamps had similar ratings (14W power under mains 240 V operating voltage). In this experiment, the same integrating sphere was used to evaluate the light emission from each lamp. These lamps were measured according to IES LM-79-08 at LAPLACE laboratory. The light irradiance spectrum was processed using CIE standards to obtain numerical values of the lamp's colour properties; Figure 6 shows schematically the calculation procedure.

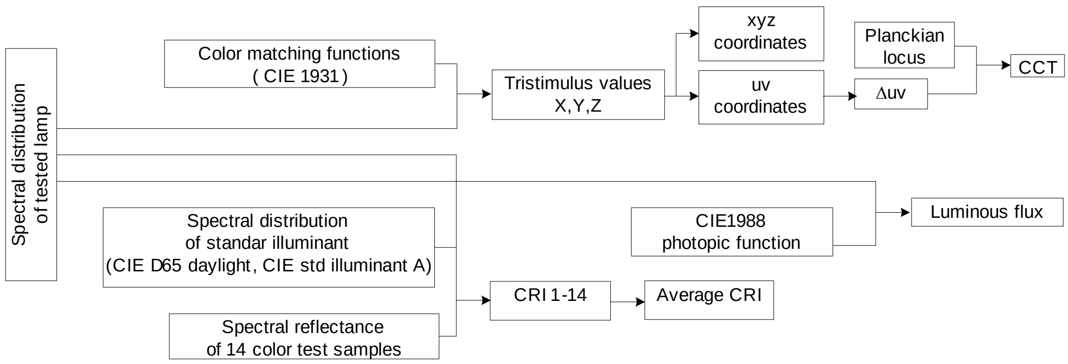


Figure 6: Calculation procedure for obtaining photo-colorimetric characteristics of a lamp

During this experiment, the spectral distribution was measured with 500 h interval period till 20 000h of operation. Figure 7 shows how the spectral distribution from the lamp changes gradually over the ageing process up to 20 000h. The observed spectra are typical for LED lamps, with one peak in the blue region and another one around the yellow-green region. The analysis was performed by automatically finding the maximum irradiance value and position of the two local extrema. To increase the accuracy, the noise in the spectral data was reduced by using quadratic polynomial interpolation.

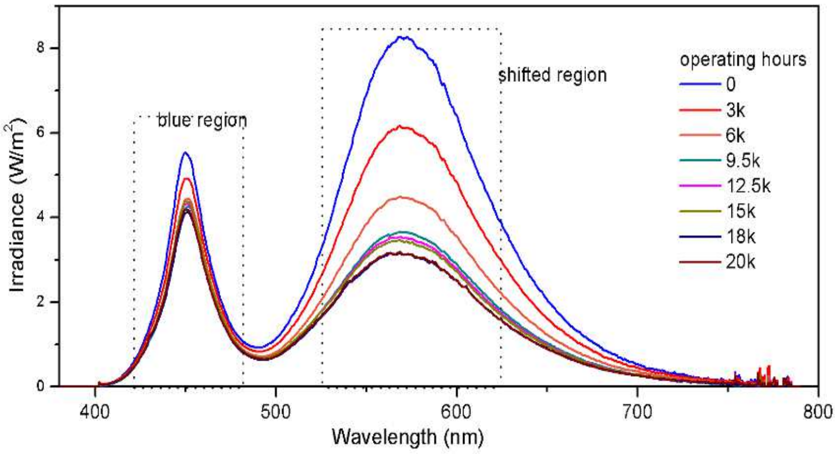


Figure 7: Observed spectral variation during 20 000h of LED lamp operation under nominal operating conditions (measurements carried out between 2014 and 2016) [19]

To better illustrate the change in the dominant colour of the LED lamp, Figure 8 shows the colour point drift in the CIE1931 diagram. This drift is slow but it is going toward higher CCTs.

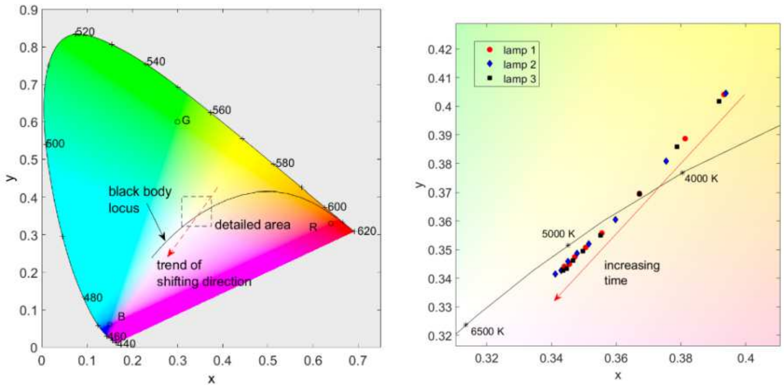


Figure 8: (left hand side) Colour shift trend of the lamp appearance in the CIE1931 chromaticity diagram illustrated by the arrow. (right hand side) Detailed area shows the colour evolution of for three LED lamps

Furthermore, the maximum irradiance corresponding to the two wavelength peaks (blue and yellow) for each set of data can be compared as shown in Figure 9 for 3 of the 17 lamps from our laboratory test set. Figure 10 shows the ratio of maximum yellow-wing (shifted by the phosphor) irradiance upon the maximum blue irradiance linked to the chip emission. The observed decrease is obvious and suggest that the phosphor ageing is predominant. It can be observed that after 5000-6000 hours of operation the relative yellow-blue balance is inverted and the correlated colour temperature is drifting toward higher values. However, as the global radiant flux is depreciated with LED ageing, the global amount of blue light escaping from the lamp is lower than that escaping from the same lamp at the beginning of its operation. In fact, the evaluated blue-light risk group doesn't change with ageing (it was found in all cases to be RG0).

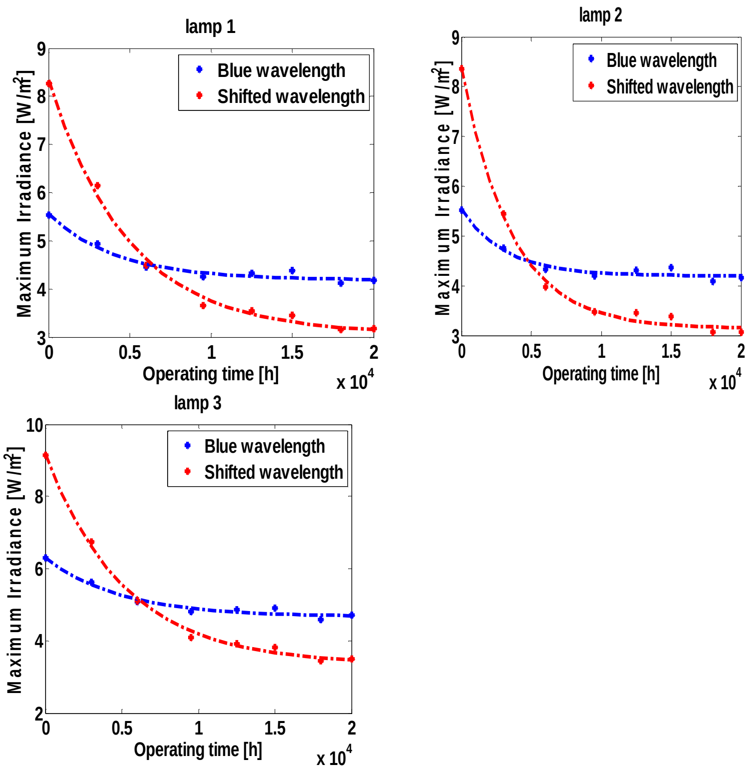


Figure 9: Drift of the maximum irradiance for blue and yellow wings for 3 different LED lamps during 20 000h of operation

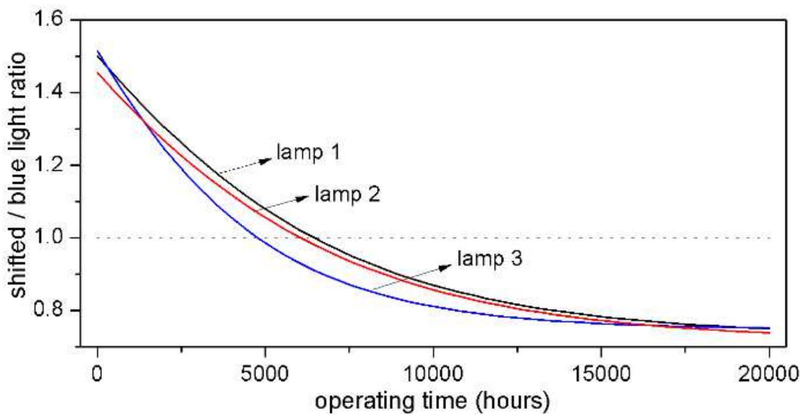


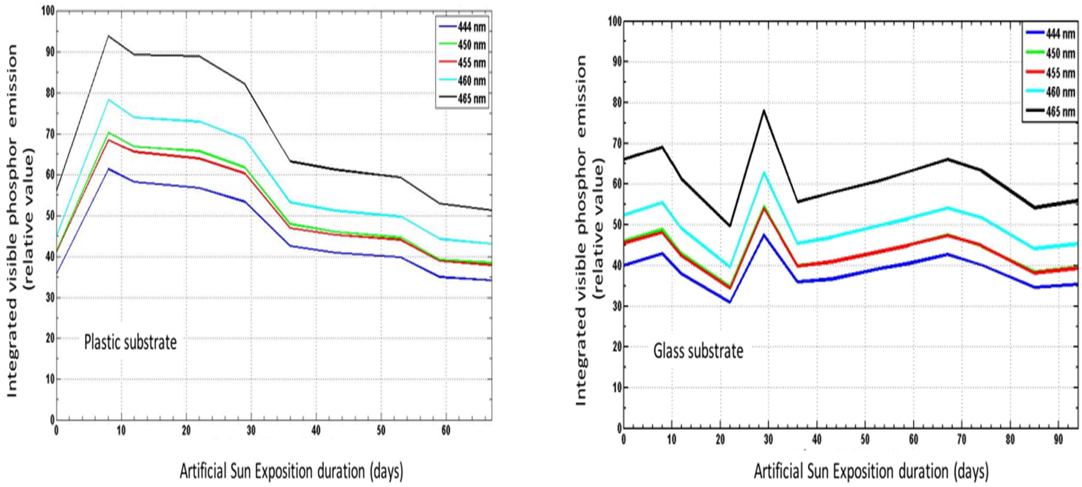
Figure 10: Degradation of phosphor conversion properties are shown by the decrease of the ration of yellow/blue maximal spectral irradiance

Phosphor degradation

From the spectrum shown in Figure 7, it can be observed that irradiance both in the blue and yellow wings tends to decrease over the extent of operating hours. In the blue region, the decrease of the irradiance is caused by the degradation of the LED chip. In the yellow region, the spectral irradiance decrease much more rapidly than in the blue wing. In a first glance this behaviour seems to be opposite of the case of catastrophic degradation observed in figure 4 which has been associated to a phosphor blackening effect. This is most likely resulting from the gradual deterioration of the phosphor coating which is a slower process than blackening and it is due either, to phosphor's conversion efficacy decrease, or, to a global coating "fatigue" linked to intense light exposure. In general, polymer materials can be degraded by depolymerization, random chain scission, and oxidation due to environmental stress factors such as heat, chemicals, sunlight, or torsion. The fatigue due to the cumulative exposure on intense light is known as "solarisation effect"; it consists in a continuous degradation of spectral transmissivity/reflectivity of a given transparent/translucent material when exposed to intense light for long periods.

The most sensitive parts to this effect are plastic components used in LED lamp technology: external bulbs used to shape the lamp, substrates supporting remote phosphor coatings, or even at component level, epoxies/polymers used as matrix and encapsulants for phosphor coatings on the chip. Looking at the time scale of the drift observed by our experiments, we assume that plastic part solarisation is the main responsible of the degradation.

To check this hypothesis, in an independent experiment were performed based on ISO 11341:2004 standard: during 2000h we exposed several thin phosphor layers especially coated on plastic and glass substrates ($1cm^2$, 20 samples for each substrate type) to the illumination of an artificial sun simulator. To this end we used a KHS SOLAR CONSTANT 575 (CLASS AAB) solar simulator that is following ASTM E927 Standard recommendations (illuminance at sample's position 120 klx; total luminous flux 49 klm) and which often is used for materials ageing studies. Then, using a spectro-reflectometer, we measured the spectral reflectance of all samples each week (roughly every 170h) excited by selected wavelengths. Figures 11a and 11b show our results concerning the spectral reflectance when the samples are excited by blue spectral region wavelengths (440 to 460nm).



(a) (b)

Figure 11: Phosphor's response to blue region excitation wavelengths (from 444nm to 465nm) after exposition to an artificial sun (a) coated on plastic substrate; (b) coated on glass substrate.

Figures 11a shows a constant degradation already after 10 days for phosphor on plastic substrate of exposure shows. On the opposite, phosphor coated on glass substrate (Figure 11b) shown only a marginal variation after 90 days of exposure (more than 2000 h). This can be seen as an indirect proof that exposure to intense light induces a solarisation effect on plastic materials than a phosphor's conversion efficacy degradation. This allows us to conclude that at a time scale in the order of 2-5000 h, the observed drift towards higher CCTs is mainly due to the solarisation of polymer matrix and epoxy encapsulants used for phosphor coatings or, more generally, any other lamp plastic parts.

Conclusions

In this paper, we have shown using independent experiments (performed under the same stress conditions), at both LED-component and LED-lamp levels, that the relative blue-light balance in pcW-LEDs emission spectrum, almost systematically, tends to increase during ageing. This observation is supported by both increase of CCT and colour locus drifts towards blue region. It should be stressed here that, as global luminous flux is depreciated during the ageing, the absolute value of blue spectral component is always decreasing.

During our investigations, we have seen that this behaviour may be either “catastrophic” (it occurs in less than 2000 h of operation) or “parametric” (it occurs slowly and becomes observable after at least 5000 h of operation). Catastrophic type failure, rather seldom, is mainly due to thermal effects that causes phosphor blackening at LED-component level and it should be considered as “extreme” situation. The parametric degradation is gradual and it mainly due to polymer encapsulant or any plastic part deterioration due to solarisation effect that becomes observable as earl as 5000 h of operation.

On the one hand, our experiment shows almost a systematic deterioration of white light quality during ageing and of course this is not desirable for some applications. On the other hand, as absolute value of blue light is always decreasing, the photobiological risk for the retina of commercial products based pcw-LEDs with such behaviour, is always reducing with product ageing. However, the relative variation of the short/long wavelength regions in the emission spectrum may still representing some health issues, other than retinal damage, in the case of longue ALAN exposures. This last part has to be investigated in more details in the future.

Acknowledgments

Authors acknowledge the partial funding of this work by ADEME LEDAge and European Commission EACI PremiumLight projects. Furthermore, authors acknowledge the experimental works performed in the frame of PhD project of Dr S. Leng and internship of Mr. Z.O. Silalahi.

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LED Lighting Efficiency: a systems approach

Ron Bonné

Lumileds

Abstract

In the past decade, much research and development efforts have gone into improving the efficiency of LEDs. Efficacy for a 4,000K, 70 CRI, high power LED (typical for outdoor use) has improved from 45 lm/W in 2007 to over 160 lm/W in 2017. Though improvements are still possible, we should consider other approaches as well. The industry, therefore, needs to transition from addressing the energy efficiency improvements from largely focused on the LED itself, to a broader luminaire and lighting system level approach.

In this paper we will at first address the potential areas of efficacy improvements in the LED package itself, followed by a look at areas of improvement in the ecosystem surrounding the LED. This ecosystem consists of the board material the LEDs are mounted on, secondary optics, drive electronics, sensors and controls. Further improvements can be made by an interconnect collapse, integrating as many of these functions as practically possible in a single light engine.

Finally, we will make the case that an increased adoption rate of LED lighting is the largest single advancement in macro-level efficiency of lighting. Adoption rate of solid state lighting in North America is about 6%, despite the large gains in LED efficacy. We will suggest certain improvements in the quality of light and the usability of LED-based lamps and luminaires that will help improve the adoption rate.

1. Introduction

LED manufacturers have made great improvements in LED efficacy over the past 20 years. The rate at which gains in efficacy are achieved is slowing down due to fundamental limitations and diminishing returns of high R&D investments. At the same time the cost of LEDs has come down to a point where it is not the main component anymore in the cost breakdown of a luminaire. This is forcing a shift to look into the broader lighting ecosystem to improve efficiency. Some of these advancements can be made on a luminaire level, but significant consideration has to be given to how those luminaires are used, and at a more macro level, at the adoption rate of solid state lighting. This paper will address these aspects and highlight some trends and suggestions for future developments. We will consider four areas:

§2: The light source itself: we will present some of the efficacy improvements that can still be achieved in the LED.

§3: The light engine: there are still incremental improvements that can be made in the optical and electrical ecosystem supporting the LED, as well as reliability and lifetime.

§4: The lighting system: improvements can be made in how such a system is used by employing sensors and controls to adapt the lighting in real time to the needs of the occupants. This will contribute to lower energy use and better space utilization

§5: Adoption of Solid State Lighting: in this paragraph we will consider improvements that can be made to the lighting system that may not directly impact the efficacy, but may improve the adoption rate of energy efficiency lighting.

2. Light Source Efficacy

Practical limits to the efficacy of phosphor-converted white LEDs, which ranges from 225 to 250 lm/W depending on the CCT of the light (Figure 1), at a drive current density of 35 A/cm^2. Today's LEDs have efficacies around 150 lm/W under such conditions and may achieve in excess of 200 lm/W. Due to omnipresent system inefficiencies, practical limits to luminaire efficiencies are 180 to 225 lm/W, dependent on the application.

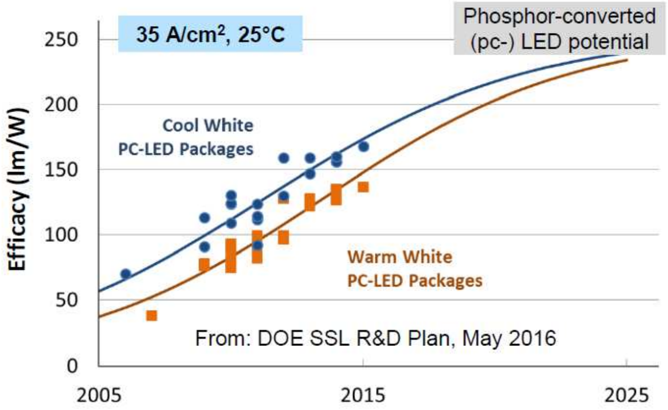

Figure 1: Practical Limits to LED efficacy (source: U.S. Department of Energy)

2.1 Components of LED efficacy

LED efficacy can be expressed as

$$\eta_{LED} = WPE * CE\ [\frac{lm}{W}]$$

where WPE is the wall plug efficiency of the die in $W_{optical}/W_{electrical}$ and CE is the conversion efficacy of the phosphor and package in $lm/W_{optical}$.

The wall plug efficiency WPE consists of three components:

- Electrical efficiency (ELE): this represents the energy loss of electrons before they reach the active region. Manifested in the forward voltage of the LED.

- Internal Quantum efficiency (IQE): the ability of an electron to recombine with a hole and generate a photon

- Extraction efficiency (EXE): the percentage of generated photons actually extracted from the semiconductor die

The conversion efficacy CE consists of four components:

- Quantum efficiency of down conversion (QED): accounts for photons that are absorbed in the phosphor converter

- Quantum Deficit (QD): accounts for the energy loss when converting blue photons into yellow or red/green photons

- Package efficiency (PE): accounts for down converted photons that get trapped in the LED package.

- Luminous Efficacy of Radiation (LER): accounts for the V(λ) human eye sensitivity curve and thus photons generated that do not contribute to perception.

2.2 Wall Plug Efficiency

Currently, wall plug efficiencies for $In_xGa_{1-x}N$ based LEDs are around 65% and are considered to have a practical maximum of 80%. This improvement is most likely equally split between advances in IQE and EXE. Electrical efficiency ELE has no further room for improvement. (All WPE numbers based on 35 A/cm^2 current density and 85°C T_j)

The improvements possible in internal quantum efficiencies for today's LED die will come mostly from droop reduction and substrate material development leading to less lattice defects. Droop is the effect of high current density causing loss in efficiency of photon generation and is an active area of research. Lower droop will allow for higher drive currents without efficacy penalty and those higher drive currents can be used for either high luminance or lower LED count (figure 2).

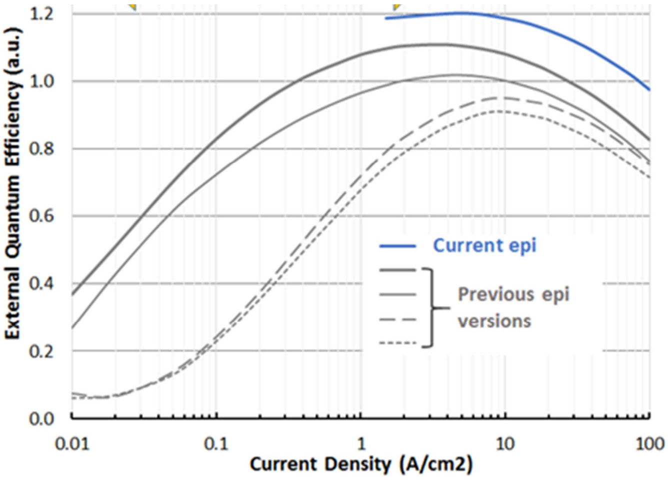

Figure 2: Droop improvement (source: Lumileds)

Some improvements in the extraction efficiency are possible by improving the metallurgy of the p-contact, improved current distribution layers and adding layers to the top of the die to increase the critical angle to aid in photon extraction.

2.3 Conversion Efficacy

The most significant improvements in LED efficacy can be made by generating less photons that fall outside the human eye sensitivity curve. Today's LEDs generate quite a few photons well above 700 nm, where the human eye sensitivity drops rapidly. By employing novel red phosphor materials with a narrow red emission band, some of these "useless" photons can be eliminated and the LER can be improved (Figure 3). Such materials already exist, but simultaneously fulfilling all requirements (high quantum efficiency, low photo thermal quenching and desired emission peak and bandwidth) is very challenging.

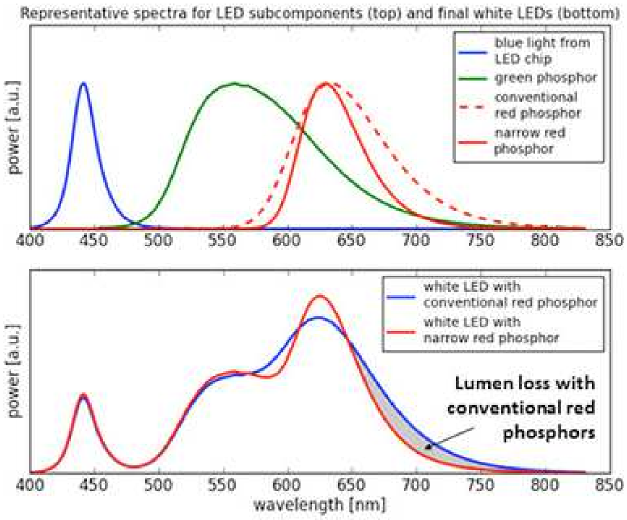

Figure 3- Narrow Band Phosphors (Source: Lumileds)

3. The light engine

3.1 Drive Electronics

The majority of the circuits used today to provide a constant current to LEDs are fairly conventional in nature. Efficiencies for such circuits range from ~50% for a brute-force linear regulator to ~90% for non-isolated buck or boost drivers. The majority of LED drivers are isolated flyback or resonant regulators with efficiencies in the 82...88% range.

Very often, the LED driver is a standard “off-the-shelf” product which is rarely optimized for the LEDs it is supposed to drive. Improved systems can be achieved by designing the driver and LED array to match each other to create a single-board light engine. In most systems, the increased cost due to loss of economies of scale is more than made up by the reduced cost of interconnects, housings, hardware, manufacturing efficiencies and improved system efficiency.

A longer term approach to driving LED light engines involves splitting the power architecture into a high power AC/DC converter that supplies a local DC “µgrid” at 24 or 48V and DC/DC constant current drivers built in with the LEDs and optimized for the array they are driving. Though at first this may seem to be less efficient, the reality is that this allows for different topologies, the aggregate of which is equal to or better than the existing system. High power AC/DC converters can use very efficient topologies such as bridgeless converters and full bridge forward that are too complicated and expensive in the low power versions typically used for individual luminaires. The DC/DC converters can benefit from the great advances in this technology field made for the mobile and telecom industries. Specifically, highly integrated and miniaturized devices are available, as well as converters with HD-PWM inputs (High Definition Pulse Width Modulation), allowing for very accurate and deep dimming levels.

Low voltage LED drivers inside the luminaire also make the entire system design more efficient, as the safety isolation is far upstream and away from the luminaire, making housing designs simpler and allowing for the use of optics with lower flammability ratings but higher transmissivity (figure 4). This will allow for faster time to market, easier integration of low-voltage add-ons (WiFi, security cameras, sensors etc.), lower installation cost and simplified re-configurability.

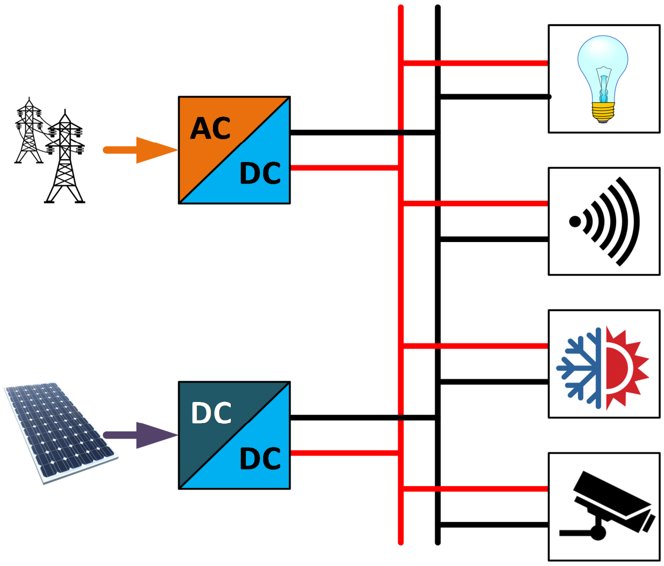

Figure 4: DC Microgrids

3.2 Secondary Optics

The majority of LED light engines today use reflective or refractive optics. There are minor improvements that can be made by optimizing the radiation pattern of LEDs to eliminate light below 90° and even shaping the emission to narrower angles or batwing-type distributions.

More advances are to be expected in the area of light guide plates (LGPs). LGPs are aesthetically pleasing and offer a lot of design freedom, but with today's systems, the light in-coupling is very inefficient, as are the losses in the plate; optical efficiencies of 60...75% are common place. Improvements can be made by matching the LED's radiation pattern to the LGP's entrance pupil, using novel ways of employing bezel reflectors, improve diffuser and polarizing films, extraction methods and plate edge shaping. We believe it is possible to attain efficiencies upward of 80% in the next few years.

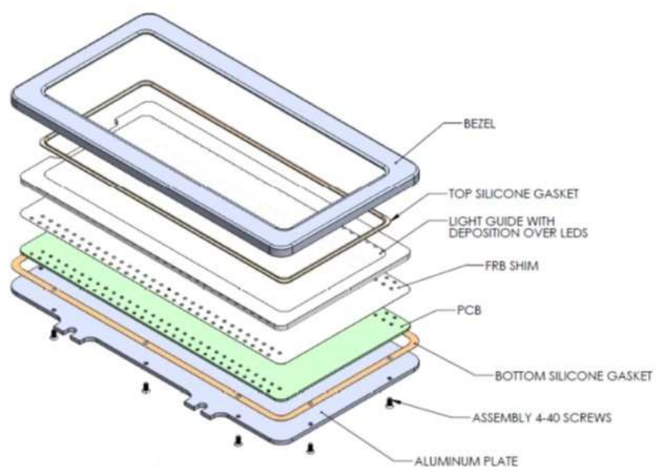

Figure 5: Light Guide Plate layering

3.3 Reliability and Lifetime

Lifetime of a light engine is typically measured as a function of lumen maintenance of the LEDs themselves. The most common industry metric determines the lifetime as that point in time where

50% of the population of LEDs has a light output of 70% or less when compared to the 0-hour flux, with a 90% confidence interval (figure 6). The main problem with this metric is that it does not account for component failures. Though the MTBF of modern day high power LEDs is in the millions of hours, there is still a failure rate associated with solder joints, wire bonds etc.

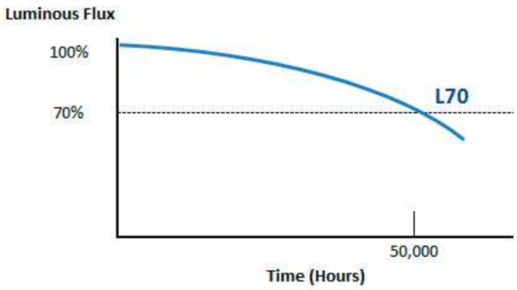

Figure 6: Definition of LED lifetime

This metric also ignores the failure rate of the driver. The weakest link when it comes to the failure rate of drivers are the electrolytic capacitors used for ripple reduction. For this reason, drivers are often still separate components in the lighting system, to allow for easy service and replacement. However, using different driver topologies can reduce the need of capacitive storage to the point where film or ceramic capacitors can be used, which have significantly lower failure rates at elevated temperature and stress conditions. This will eliminate the need for separate drivers and permit the use of integrated systems as proposed in §3.1. (figure 7). Using these technologies, the lifetime and reliability of the drive electronics can meet or exceed those of LEDs (>50,000 hours B50L70)

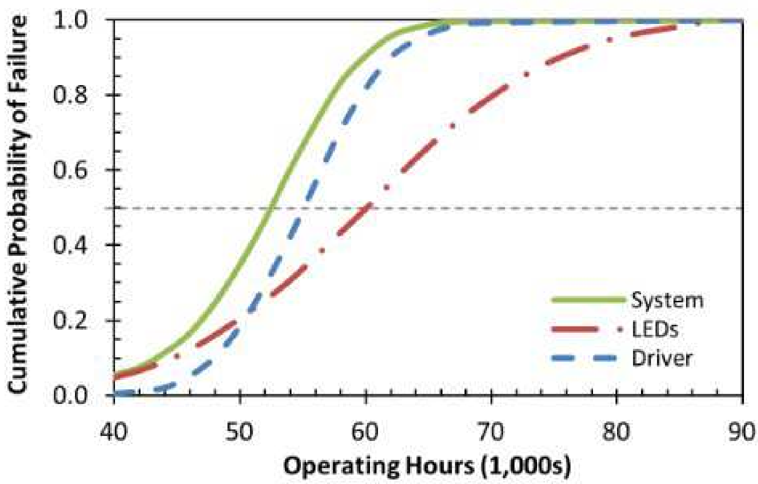

Figure 7: Comparison of driver and LED reliability (Source: US Department of Energy)**.**

3.4 Lifecycle Management

Today's LED fixtures are almost exclusively designed to be non-serviceable. There is an opportunity to design for replaceable light engines, enabling easy disassembly for recycling. This can be done using a modular approach to the light engine design and also allows for a less expensive upgrade path. Doing so may remove a barrier to adoption of solid state lighting. For example, it should be possible to replace a light engine without changing the housing, optics or interconnects of a luminaire.

4. Lighting System Implementation

Using efficient luminaires is only the first step to efficient lighting systems. How those luminaires are installed, commissioned and used is the next step in achieving a functional and efficient illumination solution

4.1 Useable Light

The first aspect of optimal lighting system design is the concept of useable light. The optical system needs to be designed such that the light is only delivered where it is needed, avoiding spill light. In indoor situations this is usually less of a problem as the spill light will reflect off the room's surfaces, contributing to the general ambient lighting. However in outdoor situations such spill light is generally unacceptable. Close cooperation between lighting designer, luminaire designer and light engine provider can lead to optimized lighting design in such cases. Also, aforementioned droop reduction in LEDs enables efficient use of high luminance light sources, which can lead to optimized system design for eténdue limited applications.

4.2 Optimization and Intelligence

The most common way to optimize the use of a lighting system is to detect occupancy and turn on or off the lighting accordingly. By embedding sensors and intelligence in the light engine, such as space usage data, "habit watchers" and low resolution IR image sensors, the lighting system can adapt better to the space occupants.

Inside the light engine, temperature, voltages and usage characteristics can be used to signal replacement or maintenance needs, potentially reducing the replacement cycle for luminaires. Further improvements can be made by allowing for "user in the loop" control of CCT and light output.

Integrating these sensors and intelligence in the light engine eliminates multiple power supplies, reduces interconnects (wires, connectors) and mechanical overhead (housings, fasteners).

4.3 Commissioning

Proper commissioning of a lighting system becomes even more important with intelligent or connected systems. Proper interaction needs to be set up and verified with other parts of lighting system, as well as proper alignment, setting of flux, color, integration with building controls etc. Use of wireless interfaces with the light engine and/or VLC (visual light communication) greatly simplifies and shortens the time needed for commissioning.

5. Adoption of Solid State Lighting

Probably the biggest single impact on reducing energy consumption and carbon emissions is to accelerate the adoption of solid state lighting. Currently, only 6% of the installed lighting in the US is solid state. See figure 8.

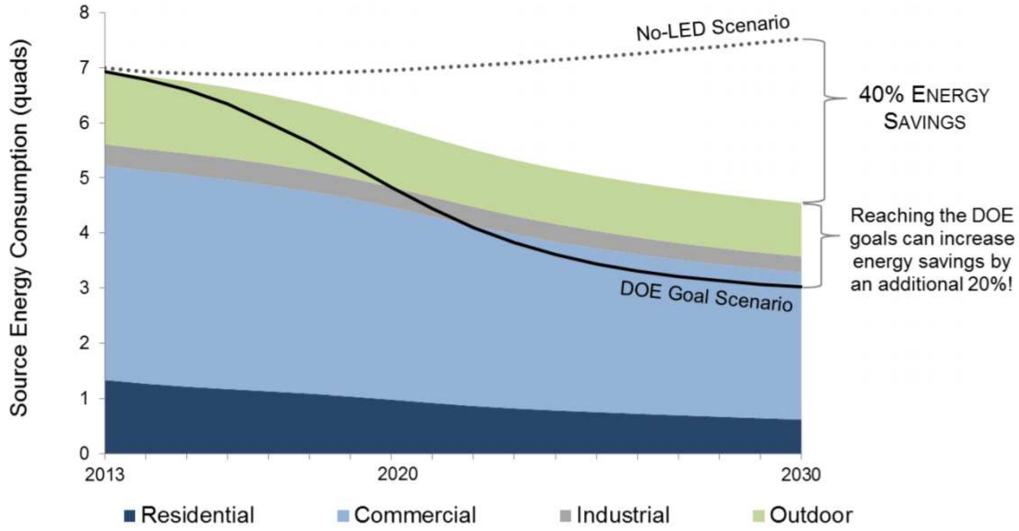

Figure 8: Energy impact of adoption of Solid State Lighting (Source US Department of Energy)

5.1 Quality of Light

Often aesthetics or optical performance characteristics such as glare, flicker, color uniformity and illuminance uniformity are sacrificed for the sake of efficacy. By de-compartmentalizing the lighting system design, it is possible to improve on such characteristics.

Very low or no-flicker lighting systems require driver topologies with higher complexity or bigger energy storage components. These are typically more expensive, less reliable and more bulky. There are a lot of studies done around the effect of flicker and stroboscopic effects on humans and there is a tendency in the industry to gravitate towards the lowest common denominator. For reasons mentioned above, it is best to choose a flicker rating commensurate with the application, low enough not to cause physical discomfort, but as high as possible to achieve the benefits of optimal driver design.

Given the increases in lighting efficiency are slowly tapering off, there should be an increased focus on quality of light, such as low glare, optimal flicker, illumination that is visually pleasing (uniform where needed, spotty to add visual interest as desired). Add to this the need for better color rendering, color control and dim-to-warm. For example, in outdoor applications, there is a shift to lower CCT's to address visual comfort and potential circadian rhythm impact, with some sacrifices to luminaire efficacy.

5.2 Building Codes

Building codes often encourage replacement with "tubes and bulbs" to avoid meeting much higher efficacy standards, rather than optimized, state-of-the-art intelligent connected luminaires. We believe building codes should be written to strike a better balance between adoption rate and efficiency targets.

Quite a few performance and safety standards relating to illumination were written with fluorescent and incandescent lighting in mind. Rewriting and updating these standards at a higher pace may lower the bar for architects and lighting designers to adopt solid state lighting.

5.3 Financing

Consideration should be given to the way lighting retrofits are financed. There are more companies entering the market of financing lighting retrofits by taking a portion of the initial energy savings to pay back for the investment. This is especially useful in public projects, where considerations for payback of an investment in a lighting system are often driven by the terms elected officials serve.

6. Conclusion

Though the efficacy of LED devices and the efficiency of drivers and optics can still be improved, we suggest the industry shifts towards a more intense focus on quality of light and human centricity in an effort to improve adoption rates of solid state lighting. Energy use for lighting can be reduced at increased rate by emphasizing adoption rates over incremental technology improvements.

We propose that a more holistic approach to illumination system design, considering optimal matching of LEDs to the optical and electrical system, including intelligence, connectivity and predictive analytics. Implementing this close to the light source, will accelerate the adoption rate and improve the efficient usage of solid state lighting systems, meeting or possibly exceeding the DOE goal scenario of fig.8.

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17 DEMAND RESPONSE

Recent Developments in Access to Consumer Consumption and Billing Data for Use in Distributed Energy Resource (DER) Programs

Bonnie Datta and Chris King

Siemens Digital Grid

Abstract

Easy access to essential consumption and billing data, in spite of widespread penetration of smart meters, remains a significant barrier to developing, implementing, and optimizing successful distributed energy resource (DER) programs. These include energy efficiency, demand response, distributed generation, electric vehicle charging, and microgrids. Data are essential for marketing to and recruiting customers, providing ongoing feedback to program participants to enhance performance, measuring and verifying the results, and other uses. With the deployment of tens of millions of smart meters, including over 60 million in the U.S., much data is now being collected. California policymakers and utilities are at the forefront of defining data access rules and business processes, as well as data exchange standards, with the goal of making data access seamless, automated, inexpensive, and convenient for energy consumers and their chosen service providers. This paper discusses the market developments in California.

Introduction

Easy access to essential consumption and billing data, in spite of smart meter data becoming more widely available, remains a significant barrier to developing, implementing, and optimizing successful distributed energy resource (DER) programs. DER includes energy efficiency, demand response, distributed generation, electric vehicle charging, and microgrids. Data are essential for marketing to and recruiting customers, providing ongoing feedback to program participants to enhance performance, measuring and verifying the results, and other uses.

With the deployment of tens of millions of smart meters, including over 60 million in the U.S., much data is now being collected. California policymakers and utilities are at the forefront of defining data access rules and business processes, as well as data exchange standards, with the goal of making data access seamless, automated, inexpensive, and convenient for energy consumers and their chosen service providers. For example, the California Public Utilities Commission issued its comprehensive data access and consumer privacy decision in 2011, containing policies and regulations that are more comprehensive and in more detail than we have observed in any other jurisdiction through 2017.

Key developments in this area are related to 1) further specification of the Green Button and Green Button Connect data exchange standards, 2) harmonization[94] of implementation of the Green Button standards, and 3) development and implementation of click-through processes and technical standards. The first includes adding pricing and billing data to the original data set focused only on consumption data, thereby enhancing the ability of energy service providers to deliver better products and services to their customers. An example would be to use consumption and pricing data to determine how much it would cost a consumer to operate a new electric vehicle at their home and based on the specific consumption of their home. The second is a lacking, yet essential, feature of data access implementation so that service providers can build an interface once and use it many times, at different utilities, in different states, and even in multiple countries (e.g. Canada as well as the U.S.). The third, customer authorization, is the gateway that stands at the beginning of every customer interaction or relationship with an existing or potential energy service provider.

[94] - “Harmonization” means ensuring that implementation of the standards is done consistently by different utilities so that a service provider can develop a single product with the knowledge that the product will work with multiple utilities without customization for each different utility.

California Policy Context

California has a comprehensive regulatory approach to consumer energy data access and privacy; the only state within the US and even internationally to do so. The subject of access to customer energy data in California goes back to 2008, when the CPUC issued an Order Instituting Rulemaking (OIR) (R.08-12-009) in December of that year dealing with customer data access and privacy. In December 2009, the CPUC issued its Decision addressing Energy Independence and Security Act (EISA) requirements and identified customer access issues for the next phase of the OIR (D.09-12-046). In that Decision, the CPUC declined to adopt PURPA standards as suggested by EISA. The Decision also set a schedule for providing customers with retail and wholesale price information by the end of 2010, access to usage data (including through an agreement with a third party) by the end of 2010, and access to usage information on a near real-time basis for customers with advanced metering by the end of 2011.

The final Decision adopting privacy rules and policies on customer access to data (D.11-07-056) was issued on July 29, 2011. All three of California's investor owned utilities (IOUs) were required to make information available to customers in a consistent manner, specifically providing customers with approximate electricity price, actual usage and estimated final monthly bill, updated daily. In addition, the utilities were directed to provide bill-to-date, bill forecast data, projected month-end tiered rate and notifications of crossing tiers. The Decision also directed utilities to develop a process to allow customers to utilize a Home Area Network (HAN) to access meter data.

The final decision also adopted a framework for protecting customer privacy and delineated "primary purposes" needs that did not require customer consent from "secondary purposes" that do. It directed utilities to allow customers to share usage information with third parties with such consent and use a standardized method for third party access, as well as the use of a standardized customer access format. A similar Decision applicable to natural gas companies was issued in August 2012.

By the end of 2012, all three IOUs had completed advanced metering infrastructure (AMI) installations. A total of over 11 million advanced electric meters and associated two-way communications infrastructure were installed at a cost of over $7 billion.

With regard to common data format, all three IOUs agreed to implement Green Button Download My Data, which was ready for implementation in January 2012. This provides a standardized format for customers to digitally download usage data once downloaded, the data can be analyzed or shared with a third party. By October of the same year, PG&E and SDG&E announced that Green Button Connect My Data was ready to go live. This provides an easy way for end users to grant authorization to a third party to retrieve customer data directly from the utility's website, thus avoiding the need for customers to download and then share their data.

It should also be noted that the CPUC adopted Customer Privacy measures based on Fair Information Practice Principles; these are applicable to utilities, utility contractors and third parties that obtain data from the utilities.

All of these efforts in California mean that the necessary rules and regulations to govern and allow for customers to access their own energy usage data have been in place for several years.

It

Figure 1: Overview of Green Button collaborative initiative

The Challenge

Given the supportive ecosystem created in California, and more importantly, interest in the subject matter, expectation of an active data access/exchange market would not be misplaced. In reality, however, there has been limited activity by third parties in the marketplace. There has not been a surge in end-customer targeted products and services by third-party providers – nor has there been a customer push for the same. This is especially true of the residential customer segment where third party activity has been led by solar rooftop providers accessing usage data, in addition to some customer engagement companies, such as WattzOn and Ohmconnect. In the commercial sector, activity is primarily related to the provision of energy efficiency and management services. In discussions with one IOU, we understand that while approximately 25 third parties have requested and been authorized to access data on the IOU's site via Green Button, a much smaller number is actively using the service.

Several factors contribute to the current lack of robust activity, including, though not limited to, the following:

- Lack of awareness among industry participants and end customers
- Disparity in technical understanding/capability among third-party providers
- Inter-IOU disparities in data exchange platforms based on interpretation of the Green Button and Green Button Connect standards
- Lack of a standard state-wide third-party authorization process
- Availability of information, i.e., data fields, because the initial Green Button implementations provided only usage data but no billing information

Recent Developments

Raising customer awareness and understanding of access to energy data and its potential to benefit end user energy usage and costs is possibly one of the most important steps that the CPUC could undertake to animate the market for energy services that utilizes customer usage data to create new products and services as well as ancillary products that could be bid into the wholesale market (.e.g, aggregated DR or storage). This could be made part of the statewide *Energy Upgrade California* initiative that the CPUC already funds at a level of many millions of dollars via the IOUs.[95] It could also be part of the education and outreach being planned as part of the transition of residential customers to default time-of-use pricing, especially given the synergies between access to granular energy use data enabled by AMI and TOU pricing, which helps customers to tailor their usage in response to on time-varying pricing.

Progress is already being made on consistent implementation of the Green Button standards. The Green Button Alliance has commenced a testing and certification process to make it easier for an energy provider to ensure its Green Button implementation complies with the Green Button standard, while also assuring developers they can write a single application that can work across many utilities. We believe this will go a long away toward ensuring that third-party providers are engaging with the utilities from a level playing field that will streamline the current process. Green Button Progress is shown in the sidebar.

Another area in which the CPUC could potentially make an impact is to mandate that the IOUs have a standardized process for customers to authorize third parties to have data access, irrespective of territories of operation. An online process that companies such as UtilityAPI[96] utilize is an example that could be duplicated. This commonality should also be mandated by the CPUC in the manner that the data standard is implemented by the IOUs – consistency in interpretation of standards and deployment has a direct impact on the development and operating costs that third-party providers incur in their business processes.

While there has been limited availability of billing data thus far, PG&E – which launched its first publicly accessible API in 2015 – now allows information such as billing data and gas usage to be added to the existing features of electrical usage; this will include customer account information and service locations in addition to a streamlined authorization process. This offering, called *Share My Data*, is the next generation of PG&E's Green Button *Connect My Data* and went live in December 2015. With it, PG&E customers no longer have to log in to download and share their energy usage files. Instead, the customer can authorize access through a third party's website, and, once the service is set up and the customer authorizes access, the API does the work for them automatically. This service packages PG&E customer data, informs the authorized third-party businesses when the data is ready and securely sends it out.

SCE launched its Green Button Connect My Data program in 2015. In the next generation of their Green Button Connect My Data program targeted to be available end of Q1'2016, customers will have the capability to share billing, meter, program, and customer account information. SDG&E initiated soft launch of Connect My Data program in the summer of 2012, targets to offer access to billing data and gas usage by Q2' 2016 as well as add one step authorization process for third parties (so long they are registered with the IOU, a process common to all the IOUs).

Such enhancements are essential to make the data access process simple, engaging for customers, and cost effective.

[95] The Energy Upgrade Initiative is a "state initiative to help Californians take action to save energy and conserve natural resources, help reduce demand on the electricity grid, and make informed energy management choices…"

[96] UtilityAPI is an enterprise software company that provides DER and energy management professionals with standardized access to energy usage data.

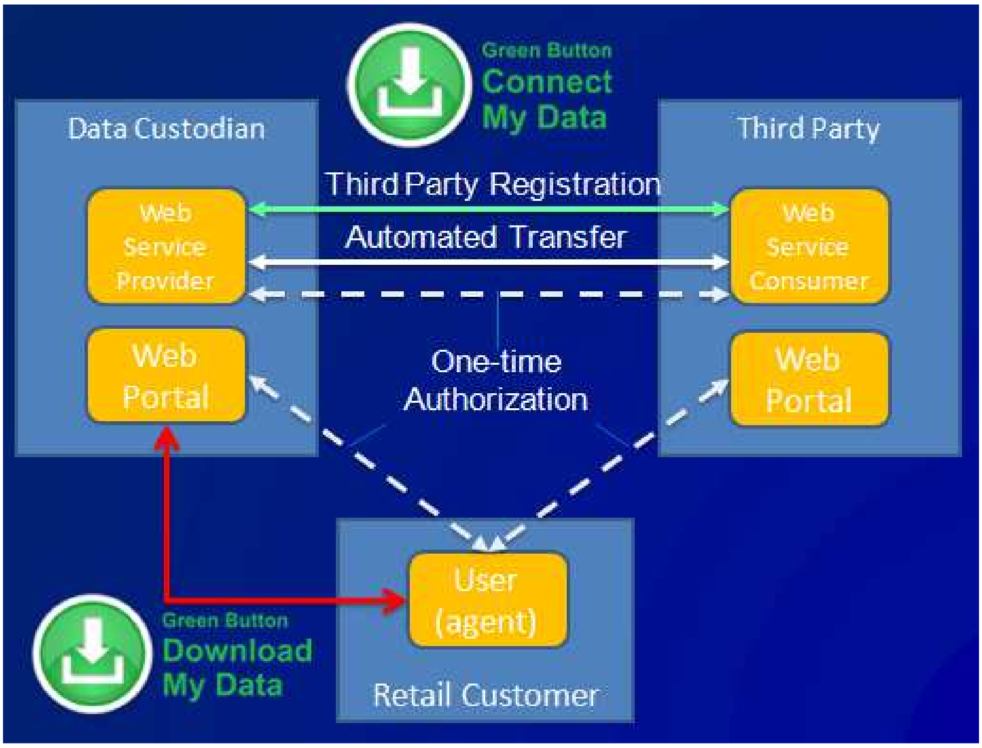

Figure 2: Overview of Green Button Connect My Data third party authorization process

Third Party Registration

California's utilities have all implemented Green Button Connect, including an authorization process that allows customers to give permission to the utilities to release customer data to the customers' service providers. Utilities and market participants are now working to streamline the process by which consumers indicate their choice and permissions.

In the collaborative effort, the participants adopted guiding principles for how customer authorization should be granted. The proposed principles are as follows:

1. **Full Data Set**: Standardize availability of a requisite set of data for historical and ongoing data access. Please see Appendix A for suggested data set.
2. **Synchronous Data**: Once a data request is authorized and authenticated, data is immediately delivered on-demand, upon authorization, (e.g. data begins streaming w/in 90 seconds of request).
3. **Instant, Digital Authorization**: A digital signature by the consumer via clicking on an acceptance button within a secure application where the consumer has provided identification details normally known only to that consumer, is valid for authorizing data sharing.
4. **Instant, Consumer-Centric, and customer friendly Authentication**: A third-party will not be held to a higher authentication standard than the standard to which the Utility holds itself. Accordingly, the Utility will authenticate using consumer-centric login credentials, for example, zip code and account # or Online Account username and password.
5. **Seamless Click-through**: A utility account holder will be allowed to begin and end the click-through process on the Third-Party website. This may happen without any requirement to log in to any other site/Process during this flow (e.g. checkbox) or may allow the user to remain in the third party website flow ,even in various authentication scenarios (login, signup, forgotten password, etc.), as in the case of OAuth[97] or open

[97] - OAuth is an online third-party authorization standard that allows an end user's account information to be shared with third-party services without exposing the user's sensitive authentication information (e.g., username, password, etc.). It also gives the customer full transparency into who is authenticating the customer and what data sharing the customer is authorizing. OAuth allows customers to use a familiar online experience (i.e., similar to services offered

authorization protocols. The click-through process shall be designed to be one-click and the third party may lead the customer request for the types of data and the time frame of data sharing. The customer may approve or reject such a request in its sole discretion.

6. **Strong Security Protocols**: Adopt strong security protocols. Data security may accommodate cloud-based systems. In addition, we recommend consideration of the security elements.

Conclusions

The CPUC has enacted foundational regulations to enable, on paper, a data-rich energy environment. However, there is significant work to be done yet for it to translate to a real market in which data is being actively utilized to create products and services. Raising awareness among end users is key to animating the market. Now is a good time to raise awareness on data access given that the CPUC is actively involved in the outreach efforts to prepare the customer base for a transition to default Time of Use (TOU) rates. Understanding usage and billing data is a key component of customer engagement to ensure a successful deployment. The CPUC should carefully evaluate the effectiveness of the goals being pursued by statewide efforts such as Energy Upgrade and several such customer education programs vis-à-vis the financial investments they currently entail. A consolidated approach to customer education may prove more efficient and cost-prudent from a rate-payer's perspective.

Standardization of the third party authorization process, data formats and access across the IOU territories would be an important fix to some of the technical challenges that currently face data access. The goal is to enable energy service product and service providers to tailor their offerings for the ultimate benefit of consumers. The CPUC is evaluating these barriers and supporting a process of standardization to enable a more efficient and accessible data environment.[98]

The results of these critical data access developments in California are significant increases in market activity, improved offers to consumers for products and services ranging from solar panels to demand response, and the ability to handle new regulatory requirements (such as the requirement in California that all new distributed solar customers take service on time-of-use rates, thus requiring solar providers to base their savings estimates on TOU, not flat, rates).

by Facebook and Google) to authorize the release of their data using a proven and secure system. This system also allows third parties to build to a supported industry standard, which promotes interoperability and quick development and innovation.

[98] - In late July 2017, the California Public Utilities Commission issued a draft decision on the click-through process for third-party authorization that adopts the principles described in this paper. As of August 3, 2017, the CPUC was scheduled to adopt the decision, called Resolution E-4868, on August 10, 2017.

References

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[4] Kaneshiro, B., California Public Utilities Commission Energy Division. *Customer Information Service Request Form (CISR) Issues Raised to Date,* Direct Participation Click Through Workshop, California Public Utilities Commission, August 24, 2016.

[5] Villareal, C., Minnesota Public Utilities Commission. *Balancing Privacy, Security, and Access.* Presented at Joint RMS/WMS Workshop II: Improving 3rd Party Access to Smart Meter Texas (SMT) hosted by Electric Reliability Council of Texas (ERCOT), October 16, 2016.

Appendix A

Data Set for Eventual Consideration

- Account Elements
- Account name (ACME INC. or JOE SMITH)
- Account address (123 OFFICE ST...)
- Account ID (2-xxx...)
- Outage block (A000)
- Service Elements
- Service ID (3-xxx...)
- Service address (123 MAIN ST #100...)
- Service tariff (D-TOU) (incl. any applicable demand response tariffs)
- Service tariff options (CARE, FERA, etc.)
- Service voltage (if relevant)
- Service meter number (if any)
- # of Service meters
- Historical bills (since beginning of service)
- Billing Elements
- Bill start date
- Bill end date
- Bill total charges ($)
- Bill total kWh
- Bill tier breakdown (if any)
- Baseline 1%-30%)
- Volume (1234.2)
- Cost ($100.23)
- Bill TOU kWh breakdown (if any)
- TOU period name (e.g. Summer Off Peak)
- Volume (1234.2)
- Cost ($100.23)
- Bill demand breakdown (if any, incl. options)
- Demand charge name (e.g. Summer Max Demand)
- Volume (1234.2)
- Cost ($100.23)
- Bill line items/options (sum should equal bill total charges above)
- Charge name (e.g. DWR Bond Charge)
- Volume (1234.2)
- Unit (kWh)
- Rate ($0.032/kWh)
- Cost ($100.23)
- Tracked line items
- Other charge name (e.g. Net In/Net Out)
- Volume (1234.2 in kWh)
- Unit (kWh)
- Rate ($0.032/kWh, if any)
- Cost ($100.23, if any)
- Payment Information
- Historical Intervals (since beginning of service)
- Start (unix timestamp)
- Duration (seconds)
- Volume (1234.2)
- Unit (kWh)
- Also: Capacity Reservation Level (CRL) for CPP/PDP customers, Demand Response program name and nomination, if fixed,
- Standby reservation if a customer has on-site generation, and sublap for wholesale nomination.
- Sub-Load Aggregation Point (sub-Lap)
- Pricing node (Pnode)
- Local Capacity Area

- Direct Access, CCA or Service Customer
- Identity and contact information of customer's LSE, MDMA and MSP.
- Utility's demand response program(s) and tariff schedule(s) in which the service account(s) are currently enrolled (if any)
- Estimated date of when the customer may be eligible to participate in DR Service w/o financial or tariff implications
- Customer 1 Digit meter read cycle letter

Addressing the gap between individual and system wide demand response programs

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Abstract

Electricity consumers may use demand response to reduce their bills, particularly in cases where local renewable energy systems are present. Similarly, grid managers may also pursue demand response to optimize the economic dispatch and investments on the electricity supply system. In isolated communities, the benefits of deploying such programs may be significant due to their insularity and typically higher costs for electricity generation. However, these two approaches may conflict with one another.

Furthermore, there is a knowledge gap on the benefits achieved by the end user with each of the previously described approaches. Although at the operational and communications level, multiple studies have already been developed to allow the central management of loads, there is still uncertainty on how to engage the consumers at the residential and small businesses levels in order for them to participate in centrally coordinated demand response programs.

Therefore, this work focuses on two objectives. First, it estimates the potential consumer and system economic impacts of these conflicting perspectives for insular areas. Second, it attempts to understand the availability of consumers to participate in such programs, by analyzing the technical and social limits of such participation and the factors that could ensure it, by conducting surveys to local consumers.

Results show when in presence of microgeneration systems the savings achieved differ by type of family, although being similar without microgeneration. Regarding the impact of DR programs, it may result in savings of up to 4% for the grid operator and up to 32.85 €/year for consumers, which may fall below the expected savings of users to participate in these types of programs. Both centrally and individual approaches to DR lead to savings to the end users, albeit being highest for the latest scenario. Nonetheless, and despite a clear lack of knowledge, consumers demonstrated interest in participating in price-based demand response programs.

Introduction

The increase in electricity demand and associated environmental impacts has led to the development of plans and legislation to reduce energy consumption and increase the use of renewable energy sources. Examples of this are the National Energy Efficiency Action Plans [1] and the National Renewable Energy Action Plans [2] that each European Union country has developed in order to fulfill the desired targets for 2020. Recognizing the importance of transitioning to a mainly renewable energy system, the European Union has begun to design a strategy towards 2050 [3].

However, the introduction of large shares of renewable energy sources (RES) in electricity systems still faces significant challenges. First, the electricity produced by MW is not as large as that produced by traditional generators using fossil fuels, with wind and solar having average capacity factors in the European Union of around 24% and 12% [4], respectively. Second, several RES have a high variability in production, both in spatial and temporal distribution. This means that the electricity system needs to be able to withstand periods with very high or lower electricity production from RES.

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Large transmission grids, energy storage systems or the introduction of flexibility in demand have been identified as enablers of high penetrations of RES [5]. However, while the investment in transmission grids and energy storage systems has been the most common approach to support the electricity production and consumption balance in systems with RES, both of these options may not be suitable for many systems. This is particularly the case in isolated electricity systems, which are not able to connect to another system and may not have the required natural conditions to install large scale and cost-effective energy storage systems, such as pumped-hydro storage [6].

Demand response, on the other hand, is a flexible and scalable instrument that may be deployed and result in direct benefits to both consumers and grid managers. Nonetheless, the introduction of demand response requires the participation of consumers in the management of the electricity grid, raising issues concerning the valuation of their participation and the benefits they should be provided with [7], [8]. Furthermore, as consumers may use demand response mechanisms to optimize their electricity consumption in order to reduce their bills [9], [10], there is still uncertainty regarding their overall acceptability to participate in demand response programs that focus on improving the management of the electricity system.

This study attempts to address the issues raised by analyzing the potential impact of demand response in isolated electricity systems from both a system wide and individual consumers' point of view. To evaluate the availability of consumers to participate in system wide demand response programs in alternative to individual programs, a survey was performed.

The paper is organized as follows: In the *State-of-the-Art* section an overview on demand response programs and main concerns when auditing the population on electricity demand are reported, while the *Methodology* section describes the demand response optimization model and scenarios, the case study and the survey preparation. On the *Results and Discussion* section, the modeling results for both case studies are presented and the survey responses are analyzed. Final statements are made in the *Conclusions* section.

State-of-the-Art

Demand response programs

Electric power demand suffers several significant changes during the day and, therefore, production facilities must be prepared to fully supply this demand that has been, traditionally, considered inelastic. Besides the increasing need for more flexibility in system operation, other factors such as climate change challenges, improvement of energy efficiency, greenhouse gas emissions mitigation and renewable sources promotion have also pressed for the participation of demand side management in power system operational procedures. Among demand side management activities, demand response (DR) strategies have been focus of much attention [11].

According to the ENTSOE [12], DR is *"a voluntary temporary adjustment of power demand taken by the end-user as a response to a price signal or taken by a counter-party based on an agreement with the end-user".* DR can be done during a short period (hours), having an impact on the system power balance, and can be seen as economical optimization of the electricity demand. DR executed during a longer period can also impact the energy balance and result in energy savings. Thus, it is possible to ascertain that DR has an important contribution in the increase of sustainability and in the development of a reliable and cost-efficient supply [13]. DR involves a series of actions that consumers can adopt as a response to certain conditions that occur within the electricity system [14]. For utilities, these type of programs play a crucial role in shifting their business model from a volume centered model to a tailored customer centered approach [13].

DR comprises two different mechanisms: incentive based and price-based programs. While the former sends quantity (curtailment) signals to end-users, mainly known as direct load control programs (DLC), the latter provides customers with price-signals promoting changes in consumption patterns based on time-varying rates [15]. DLC programs allow utilities to directly alter customer energy consumption, usually through a remote control device installed in a specific appliance offering users incentive payments for reducing demand in specific periods in response to a reliability event or high market prices [16]. Price-based programs, can include time-of-use tariffs (TOU), real-time pricing and critical peak pricing, and provide users with price signals to incentivize lower consumption levels in periods of high prices. These programs have the potential to become more predominant in the residential sector with the deployment of smart-meters [15]. Local generation, which involves the generation of electricity at customers' locations with the use of diesel or natural gas powered generators or renewable power installations such as solar PV arrays, can also be considered as DR [1]. These systems enable supplying demand at critical times contributing to reduce the need from the grid and, associated with workload management, have the potential to shed peak load and reduce energy costs.

The implementation of DR conveys several benefits, including its positive contribution for the integration of RES in power systems, to reduce forecast of peak demand [11], increase power system flexibility, more efficient use of system resources and assets and reduce system operating costs [17]. Furthermore, it can improve the performance of electricity markets by lowering and establishing more stable electricity prices and controlling market power, consequently, offering economic benefits to consumers [11]. Barriers have also been identified, mainly related with regulation issues (e.g. measurements and verification challenges, lack of real-time information, ineffective DR programs design, tariff structure), the fact that markets are designed in a centralized homogenous manner not appropriate for diverse and distributed nature of demand, and the lack of mechanisms for implementation [11][14][18].

While one of the main advantages of DR is the lack of major technological barriers [17], some studies [11][18] have identified the lack of advanced metering infrastructure, high cost of some technologies, lack of interoperability and open standards and the need for a platform enabling the consumer to respond to requests from the supply side as issues that need to be addressed. However, recent advances in technology have added value to the effectiveness of DR programs, such as smart meters [13]. Smart meters and advanced metering infrastructures are among the technology required to implement DR programs, having the capability of bi-directional communication between end-user and utility. Their penetration has been increasingly consistent throughout the world. Additionally, energy management systems deployed in end-users' sites are also essential to provide automated control for a more effective participation in DR [11].

The potential of deploying DR programs in isolated communities can be significant. Insular power systems rely on imported and fossil fuels not having the necessary characteristics to be considered sustainable [19]. Therefore, it becomes essential to correctly manage the grid variables involved between demand and supply in such areas, in order to guarantee the development of reliable and self-sustainable energy systems, promoting an efficient energy use on the demand side and contributing to the mitigation of fossil fuels dependency [6]. A study comparing three modeling tools and how they consider fixed and flexible loads in the dispatch optimization using the Corvo Island, Portugal as a case-study, indicated that a self-built model presented the best savings when using demand response strategies, leading to a 0.3% decrease in operation costs [20]. A demand response system installed in a remote community in BC, Canada, to promote the improvement of general dispatch efficiency led to energy reductions up to 3%, no changes in the level of service to the community and unexpected benefits of energy conservation with limited rebound [21].

Traditionally, DR programs have been mainly focused at the industry level, with the deployment of DLC and interruptible programs in most European utilities and a large variation of compensation mechanisms for industries [14]. Nonetheless, in 2013 a survey conducted by the Energy Research Council to 1.254 middle-market companies indicated that only 9% participated in DR programs and 28% were extremely or very interested in DR [22]. While there is significant experience with DR programs on large commercial and industrial customers to improve grid operations, lower energy prices and integrate renewable sources in the grid, it is the residential sector that holds a large proportion of DR potential [7]. As such, consumers engagement in DR programs is starting to become a pressing issue to face the rising requirements related with operational flexibility [9].

Residential consumers' engagement and willingness to participate in Demand Response programs

The successful implementation of DR programs relies highly on the participation of consumers, who will contribute to reduce overall power consumption in peak demand hours. Nonetheless, they control and decide if and how much they will participate in these programs [10]. However, there is still insufficient knowledge on households' behaviors and attitudes linked to DR, which has large implications on the development of customized solutions that may increase the potential for individual households [23].

Depending on the adopted mechanism, demand response may involve costs and measures that must be ensured by the consumer, who needs to engage in activities that might imply the loss of comfort (when they are required to reduce consumption in peak periods with high prices without changing patterns during other periods). Other mechanisms, however, might bear no cost, such as when consumers are required to respond to high prices by shifting some of peak demand to off-peak periods, or when using on-site generation, which does not require changes in behavioral patterns but contributes to reduce demand from the utility point of view [8].

In 2014, less than 10% of residential consumers in the USA participated in DR programs and only half were aware of their existence [7]. Several studies have addressed consumers' willingness to participate in DR programs exploring factors affecting acceptability and preferences of consumers through the conduct of surveys. Results from a questionnaire conducted in Sweden to 500 households to assess the potential increase in consumer participation in DR and micro-generation revealed that 60% and 41% of participants living in houses and apartments, respectively, were interested in improving energy habits. Price was the heaviest weighing factor to improve efficiency for those living in houses, while factors were more evenly distributed between price and environmental issues among users living in apartments. A slightly higher interest in participating in DR programs was found in users living in houses, due to their relatively higher electricity use and costs. Among the participants 24% were willing to participate in DR with bill reductions of at least 250SEK(26€)/month, indicative for the Swedish context that a relatively small compensation is required for DR participation [23]. In Australia, survey results indicated that TOU tariffs were unlikely to effectively reduce peak period consumption in households with children, due to their lack of flexibility and high consumption during higher peak periods, with 82% of respondents indicating that afternoon and early evening were the busiest and more complex time around the household [24]. In Britain, tariffs enabling DLC of heating were significantly more popular than TOU tariffs [25]. On the contrary, in Australia, self-professed distrust in utilities was identified as an important decision-making heuristic used by consumers when choosing to participate in new demand management technology, leading to lower willingness to engage in DLC programs [26].

The potential for demand response was assessed in a Dutch city based on real-life measurements using dynamic tariffs and smart appliances, informing households on tariffs a day ahead through a home energy management system. Results indicated the existence of flexibility of appliances use, such as dishwasher and washing machine, with load shifting from evening to midday by 31%. Simple and transparent design for dynamic tariffs was sufficient and effective to stimulate manual residential DR [27]. A study developed in Auckland, New Zealand, in 400 houses to test different Time of Use (TOU) tariffs between on and off peak periods revealed no significant differences between consumption patterns and that consumption was not linearly related to price changes, indicative that changes in consumption will be similar regardless of magnitude of price change [28]. An experimental DR pilot based on day ahead dynamic prices conducted in 58 Belgian households from September 2013 to July 2014 revealed a significant shift of flexible share of consumption to lower price periods, with dishwashers outperforming other appliances. However, a high variation in participants in both consumption and flexibility was also observed. Automated response from smart appliances reduced the comfort impact for users as well as the response fatigue concerns while improving the price response [29]. Utilities from 3 USA states (California, Michigan and Vermont) reached an average saving of 3% across 10 different peak events after engaging 150.000 of their customers in Behavioral Demand Response programs. Participants revealed a 74%-85% satisfaction and 6%-10% likelihood to express trust in the utility. Results from a North American dynamic rate program involving pre and post event personalized communications achieved a 5% average peak reduction in 200.000 households, with customers that received text alerts during peak events saving an average of 15% [7].

The engagement of consumers depends largely on their individual preferences in what concerns participation costs (what is asked of them) and benefits (compensation of participation). Consumers make decisions based on several criteria such as altruism, prosocial behavior, price risk, volume risk, complexity, loss of autonomy/privacy and financial compensation. Depending on individual preferences, different contracts might be appropriated to increase or maximize willingness to participate. Nonetheless, they might face challenges in selecting the right contract type and the best terms, identifying their preferences and they might not know how to quantify their load mix and how flexible it can be. Therefore, there is a need to establish tools and mechanisms such as price comparison tools, harmonization of contract design or data protection measures to empower consumers to make deliberate choices. DR changes should focus both on technology but also on contract types, because, by itself, technology will not ensure that consumers will become active [9]. Furthermore, it is important to bear in mind that DR might not be beneficial for all customers, with some being penalized for participating by facing high prices in peak hours that can lead to increases in monthly bill, while non-participants might benefit from the program without contributing it. Thus, consumers should be given access to informative tools, giving them knowledge on benefits of participating, advices on optimal use of appliances, and on pricing schemes that consider fairness criteria for participants and non-participants [10]. Considering the different characteristics, preferences, needs and expectations of the consumers, DR business models should be designed and adjusted according to these differences [23].

Methodology

In order to address the two goals previously described, two approaches were taken. First, the impact of Demand Response (DR) was addressed through the use of an economic dispatch model which calculates economic and energy impacts of DR, both on the grid manager and on the end-users. In parallel, an online survey was performed to understand the knowledge and willingness of the Portuguese population to participate in different possible DR programs. The survey was enriched with information about the possible economic benefits for each end user estimated using the previously mentioned model. **Figure 15** presents the methodology framework, which is detailed in the next subsections.

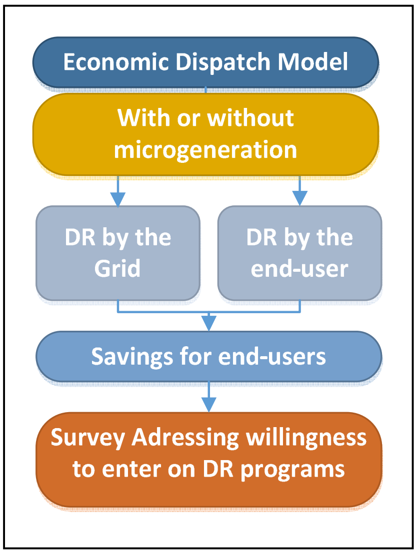

Figure 15 - Methodology framework

Model Description

The model used to evaluate the impact of DR in grid operation and end-users is an economic dispatch model, previously applied to the Terceira Island in Azores [30]. This model is designed to schedule a day-ahead dispatch, combining the unit commitment problem and a linear dispatch method, and taking into account operation constraints such as start-up/shut-down costs and time, variable renewable energy allowed in the system, fuel costs, etc. Thus, in generic terms the model obeys to Equation (1), having as outputs the production costs, CO_2 emissions and renewable energy shares.

$$Minimize\ [\,F_{total}(P_{total})] = \sum_{i=1}^{N} F_i(P_i) \quad (1)$$

where the objective function F_{total} is the total cost for supplying a certain load (P_{total}), which is the sum of generation cost $F_i(P_i)$ of each individual thermal unit *i* (in a total of *N*) generating a power P_i.

To account for demand response, the model is ran with two different optimization algorithms. Both optimizations are ran with and without the presence of solar PV microgeneration systems, to assess the potential that distributed generation would have in centralized and individual DR programs. The algorithms used are as follows:

- A genetic algorithm was used to optimize DR from the grid operator point of view, aiming to maximize the use of renewable resources and decrease operation costs. This optimization was first presented in [31] and then refined in [32] and [30]. It consists on creating a population *[nxm]* matrix, where each line is a DR chromosome [1x24], and each gene x_{nm} corresponds to the DR load allocated to a certain hour *m* (Equation 2), according to variable renewable energy availability (VRE). This chromosome is then added to the total demand (already subtracting previously appliances fixed loads) and its economic and energy impacts are tested in the economic dispatch model. The fitness of this chromosome is evaluated by its performance in complying with energy requirements, and it is penalized accordingly. Each chromosome is then the target of selection, cross-over and mutation processes, which will refine the optimum chromosome/DR profile, through *z* generations. In this work, a population size of 100 and generation size of 200 were considered.

$$\begin{gathered} given\ \ chromosome = [x_1 \quad \dots\ x_i \dots \quad x_m] \\ if\ \sum VRE\ (1{:}\,m) >\ flexible\ loads \\ x_i = \%\,VRE\ ; 0 \le x_i \le flexible\ loads \\ else \\ x_i = \%flexible\ loads \end{gathered} \tag{2}$$

- A linear programming algorithm was used to optimize the DR from the end-user point of view, to reduce their electricity bills. This optimization was previously developed in [30], assuming the use of a dual tariff (peak and off-peak prices), although in this work it is implemented with and without PV microgeneration systems. When in presence of microgeneration systems, the optimization can be summarized by Equation 3. For the case without PV systems, the optimization only reflects the shift of DR flexible loads to off-peak hours, in which the electricity price is lower. The optimized profile is then tested on the islands economic dispatch model.

$$\begin{gathered} \min\,[f(x)] = \textstyle\sum_{i=1}^{24} a_i x_i \\ \textstyle\sum_{i=1}^{24} x_i =\ Daily\ flexible\ needs \\ if\ PVgen(i) > fixed\ demand\ (i) \rightarrow x_i \le PVgen(i) - fixed\ demand\ (i) \wedge a_i = 0 \\ else\ \ \rightarrow x_i \le \max DR \wedge a_i = offpeak\ price \vee a_i = peak\ price \\ 0 \le x_i \le \max DR \end{gathered} \tag{3}$$

  where, *i* is the hour of the day, x_i is the energy of backup for a certain group of users, for a certain hour, a_i is the cost of the kWh imported from the grid, at certain hour, and *max DR* is the maximum shiftable load at each hour.

Data collection and analysis

The model was applied to study the impact of DR in insular areas, namely the Island of Terceira, in the Azores Archipelago, and the Island of Madeira, in Madeira Archipelago. The data collected is summarized in **Table 6**.

Table 6 – Data collection for the application to the chosen case studies

Data	Type	Source
Electricity Demand	Number of domestic users [nr] Total demand and domestic demand [MWh/year] Daily average total load profile Domestic tariffs applied	[33][34][35] [36]

Electricity Supply	Installed capacity per technology [MW] Energy supplied per technology [GWh]	[33]
Flexible loads	Identification of main domestic appliances [type] Percentage of houses with selected appliances [%] Electric profiles of each appliance and average demand per cycle [kWh/cycle] Nominal power [kW] Number of usages per week [nr/week]	[37]
Families	Identification of representative load profiles per type of family Percentage of families of each profile [%]	[38]
PV microgeneration	Daily PV production profile for a standardize 1 kW panel	[39]

Table 7, **Table 8**, **Figure 16**, **Figure 17**, and **Figure 18** report the energy systems of the islands of Terceira and Madeira for the parameters previously described. **Figure 19** presents the probability distribution function of the daily domestic energy demand profiles for the different types of families, with *Demand1* corresponding to families with 1 or 2 individuals, *Demand2* to families with 3 or 4 and *Demand3* to larger families.

Table 7 – Data on the domestic tariffs

	Electricity tariffs	
	peak	**off-peak**
	[€/kWh]	[€/kWh]
Terceira	0.1909	0.1002
Madeira	0.1889	0.0987

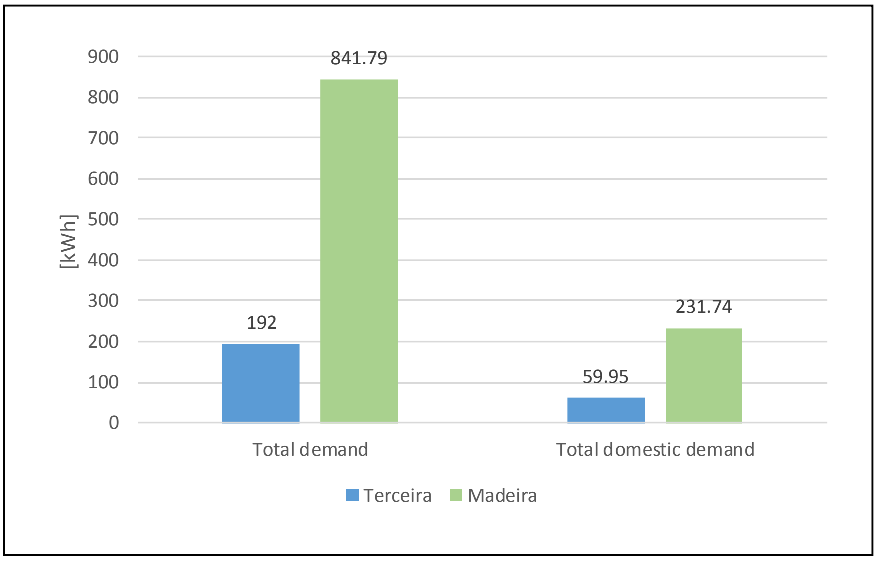

Figure 16 – Data on total and domestic electricity demand

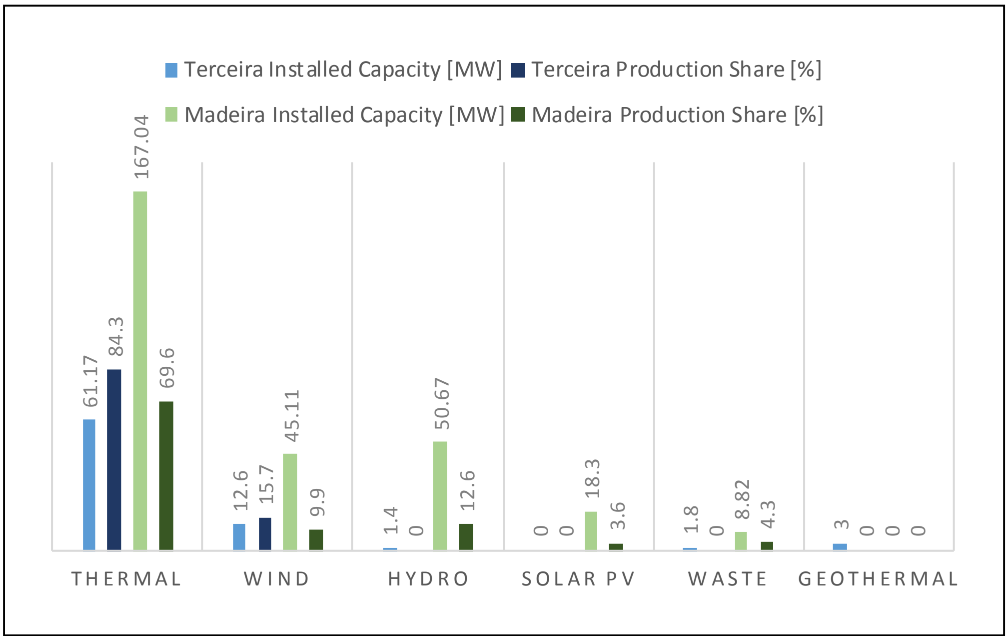

Figure 17 – Data on installed capacity and production[100]

Table 8- Data on flexible loads

Flexible loads		**Washing machine**	**Drying machine**	**Dishwasher**
Power [kW]		2.00	2.60	3.05
Energy per cycle [kWh]		1.30	3.60	1.40
Number of usages [nr/week]		3	2	4
Percentage of houses with [%]	Terceira	94.3	55.2	26.5
	Madeira	93.3	11.8	16.8

[100] Residual solid waste and geothermal power plants were recently installed in Terceira and that is why there is no data available on energy production yet.

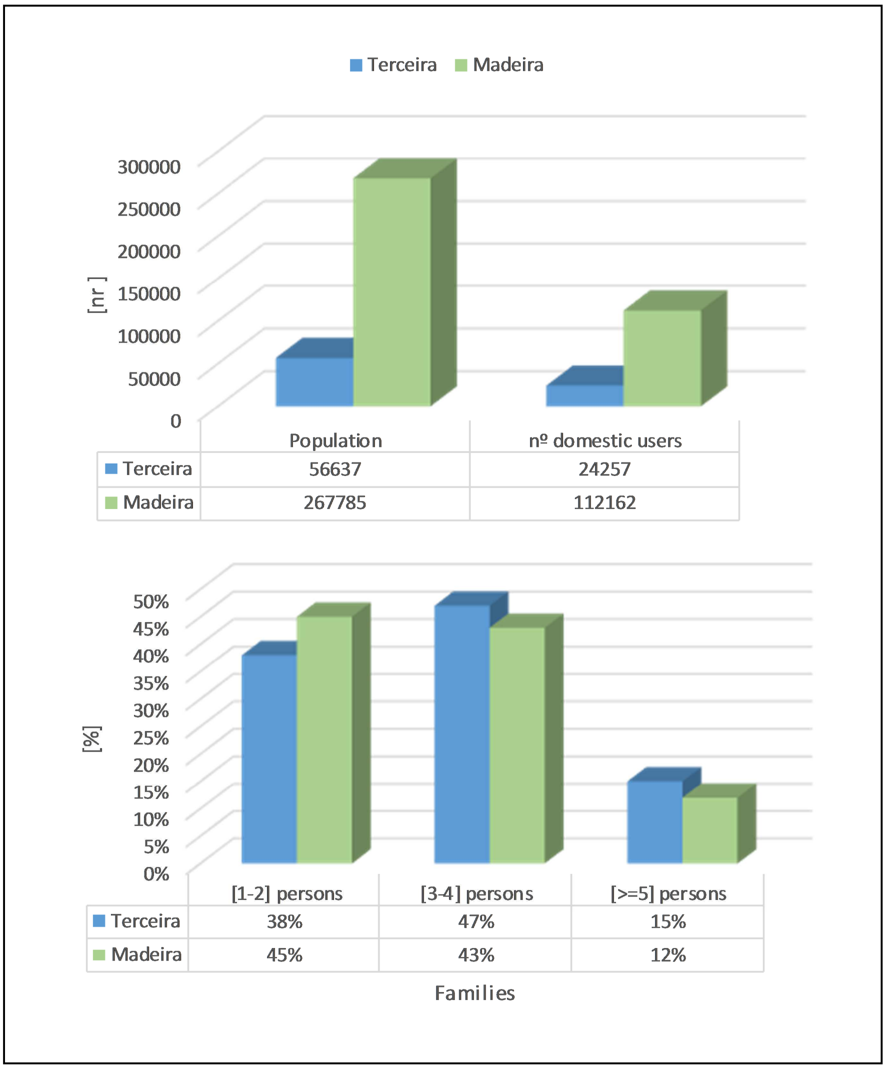

Figure 18 – Population data

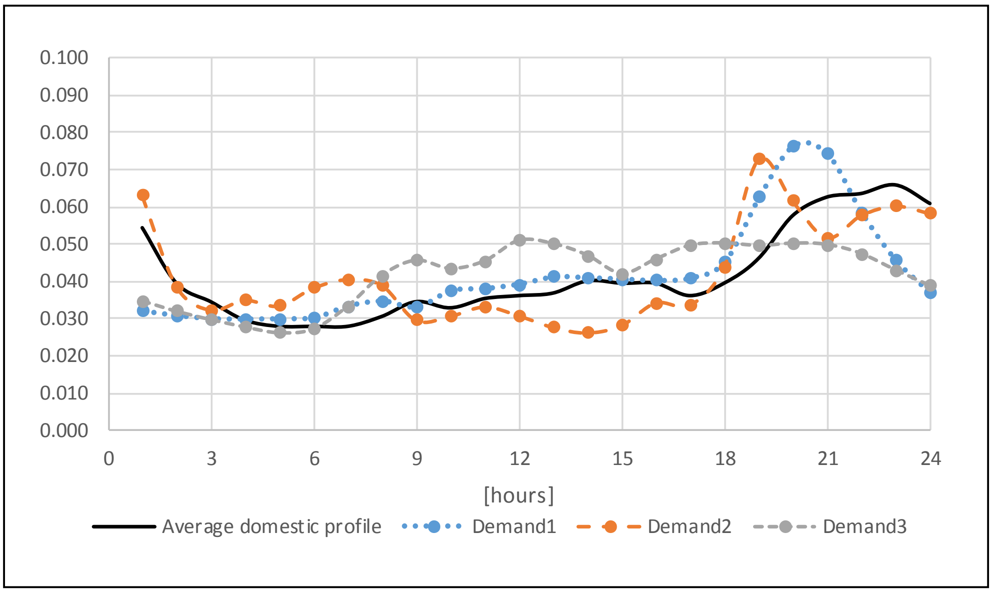

Figure 19 – Normalized Domestic Profiles

Scenarios Definition

In order to model and compare the impact of different DR mechanisms, five scenarios were designed based the existence of microgeneration and the implementation of grid DR or local DR programs. The scenarios are presented in **Table 9**.

Table 9 - Scenario Description

Scenario	**Microgeneration**	**DR Grid**	**DR local**
Base Scenario	-	-	-
Scenario 1	√	-	-
Scenario 2	√	√	-
Scenario 3	√	-	√
Scenario 4	-	√	-
Scenario 5	-	-	√

The Base Scenario intends to show the actual state of operation, while Scenario 1 intends to show the impact of deploying PV microgeneration systems in 100% of the houses. To test the potential of DR in presence of microgeneration systems, Scenario 2 and Scenario 3 consider the implementation of DR from a grid operator point of view and from an end-user perspective in order to take full profit of the PV system, respectively. Finally, Scenario 4 and Scenario 5 test the impact of demand response optimizations without the influence of microgeneration systems.

Survey preparation

One of the main aims of this work was to gather insights from a large number of citizens' perceptions, behavior and engagement in these programs as well as on energy consumption. As such, a questionnaire was developed as the main tool to collect this information, enabling the collection of information on socio-economic factors, linking consumers' preferences and behaviors with factors such as household income, educational level, housing characteristics, among others. The survey was designed to take up to 10 minutes to complete and was distributed between February and May 2017 through several promotion channels to the Portuguese population. These channels included energy agencies, state entities and social-media instruments.

The questionnaire was designed to address different issues and was, therefore, divided in several sections. The predominant format of the questions included multiple choice and checklists in which respondents were presented with several choices and had to select one or more options, depending on instructions. An initial section composed by 12 questions covered basic data on socio-economic factors about respondent and household characterization, collecting data on respondents age, gender, educational level, working status, number of people in the household, housing size, among others. This section was followed by a group of 15 questions related mainly to energy consumption knowledge and behaviors, focusing on aspects such as respondents' knowledge of household energy consumption, importance dedicated to energy efficiency and adopted energy saving practices. A final section dedicated to DR programs centering on consumers' knowledge of the existence of such programs, their willingness to participate, perceived benefits and barriers for participation and their preferences towards several programs. The survey also addressed consumers' expectations regarding economic savings potentially achieved by engaging in DR programs. This final section presented an initial text presenting the concept of DR to the respondent and was composed by 14 questions.

A total of 657 answers were collected over four months, of which 654 were considered valid. The survey was distributed all over the country, with 42% of the answers collected being from respondents from the mainland of the country and 58% from the islands. Taking into account that this work is focused on demand response potential impacts in isolated areas, the survey results presented are based on the answers collected from the islands. **Table 10** presents the characterization of the respondents. Additionally, 66% live in urban areas, 20% in suburban areas, 12% in rural (2% don't know how to characterize living area). Regarding home ownership 87.5% own a house, 9% are tenants, 0.5% live in social housing and 3% in other types of housing.

Table 10 – Demographics and Socio-economic characterization of respondents

Female (%)	Male (%)	Av. Age (years)	Av. Household size	Av. Number children per household
31	69	44	2.9	0.7

Results and Discussion

In this chapter, the results obtained from the modeling and survey are presented. First, the results of the scenarios modelling are described and compared. Then, an analysis of the survey responses is performed. Finally, a discussion is made combining the results obtained from both analyses.

Scenarios modeling results

Table 11 presents the impact on grid operation of the deployment of microgeneration systems in 100% of the domestic users of Terceira and Madeira Islands. It can be seen that the large scale deployment of microgeneration systems diminishes the need for thermal generation due to the increase of local electricity production, which is also consumed locally, by about 10% for both cases. However, the impacts in production costs are different according to each case study, as they are directly related to the dimension of the island. In this case, given that Madeira Island is considerably larger than Terceira the impact is of 19% compared to 7% costs decrease in Terceira.

Table 11 - Scenario comparison for the impact on the grid of Microgeneration

		Terceira Island			Madeira Island		
	Units	**Base Scenario**	**Scn1**	**Δ [%]**	**Base Scenario**	**Scn1**	**Δ [%]**
Energy Production	MWh	526.9	478	-9.3	2292.2	2039.2	-11.0
Production cost	€	49806	46573	-6.5	202057	170674	-15.5
Peak Demand	MW	25.3	25.1	-1.0	116.9	116.4	-0.5
Grid Shares							
Thermal	%	64.6	64.0	-0.9	68.6	65.4	-4.7
Total RE	%	35.4	36.0	1.6	31.4	34.6	10.3

In terms of savings for the end-users, **Figure 20** presents the absolute value of the savings per year achieved by each type of family for the case studies of Terceira and Madeira. As observed, *Demand 3* is the type of family with larger savings with the microgeneration systems, due to their load profile that best meets the solar PV production hours. However, for Terceira Island, *Demand 1* reports higher savings than *Demand 2*, which is justified by the fact that it has a higher self-sufficiency rate (energy produced and consumed locally) due the load profile distribution and since the same PV panel size was considered for every type of family.

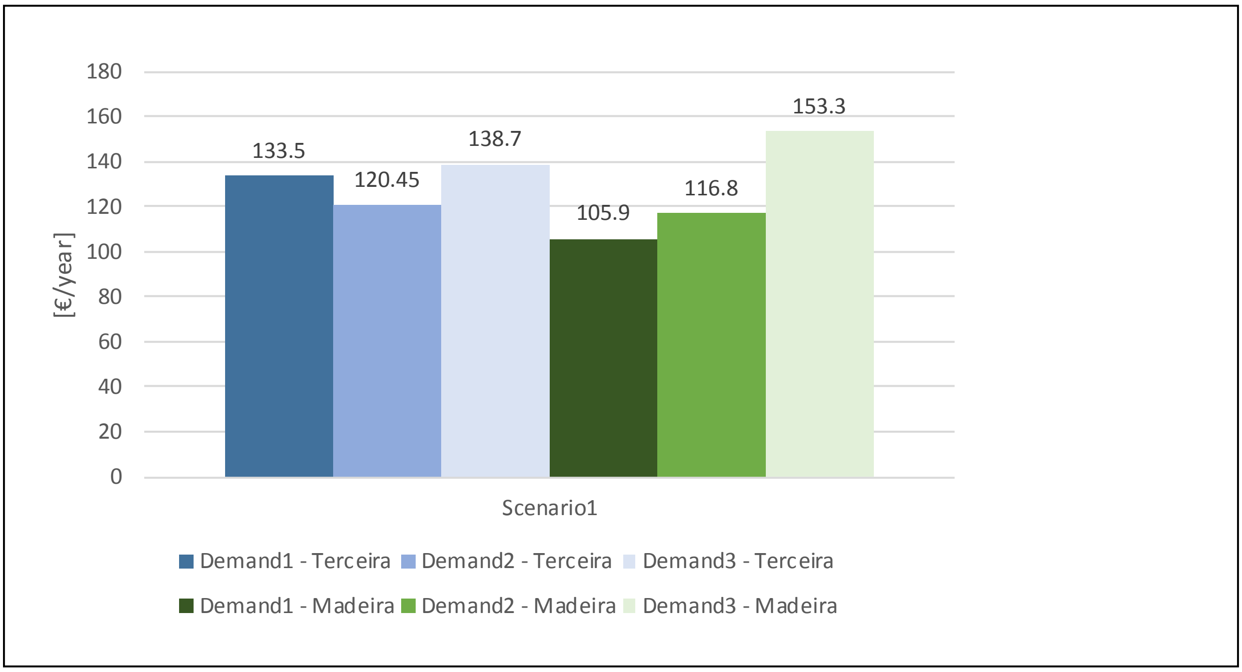

Figure 20 – Savings per year achieved with microgeneration for each family

Table 12 presents the comparison between Scenarios 1, 2 and 3 in order to assess the impact of introducing demand response together with microgeneration systems. The impact on the grid operation has a similar behavior within the islands, although the production costs decrease at a higher rate in Madeira, while the RE share increases more in Terceira Island. Scenario 2 was found to benefit more significantly grid operations in Terceira Island, by resulting in a higher decrease in cost and increase in share of RES, while in Madeira, the opposite was reported, and Scenario 3 was found to be more profitable. This can be explained by the way the GAs optimization model was constructed: as reported in Equation 2, the flexible loads are designed to take full profit of variable renewable energy, namely wind and solar, thus the model searches and finds the best feasible solutions when taking full advantage of these sources. However, when in presence of other dispatchable renewable resources, which can assure in a continuous way the off-peak hours of a load profile, there can be other also profitable solutions for allocating the loads in off-peak hours. This is what happens in Scenario 3, where the flexible loads are allocated individually during sunshine hours and off-peak hours, derived from the TOU tariffs.

Table 12 - Scenario Comparison for DR and microgeneration impact

		Terceira Island					Madeira Island				
	Units	**Scn1**	**Scn2**	**Δ [%]**	**Scn3**	**Δ [%]**	**Scn1**	**Scn2**	**Δ [%]**	**Scn3**	**Δ [%]**
Energy Production	Wh	78	78		78		2039.2	039.2		039.2	
Production cost		6573	5696	1.9	5943	1.4	170674	66177	2.6	64493	3.6
Peak Demand	W	5.1	3.7	5.4	3.7	5.2	116.4	12.6	3.3	12.8	3.1
Grid Shares											
Thermal		4.0	2.1	3.0	2.6	2.2	65.4	5.0	0.7	4.6	0.6
Total RE		6.0	7.9	5.4	7.4	3.9	34.6	5.0	1.2	5.4	2.3

Table 13 presents the impact of demand response strategies in systems without microgeneration. For Terceira, the highest decreases in production costs were observed for Scenario 5. This is justified by three facts: i) the centralized demand response program here considered is the direct load control; ii) the motivation for individual demand response relates to the dual tariff, with the end-users having a larger motivation to shift their loads to off-peak hours (from 22h to24h and from 0h to 8h), which leads to a considerable shift to the night period, and therefore a leveraging of the islands load profile; and iii) the optimization model favors the use of variable renewable energy. Given the larger scale of Madeira, where the domestic sector does not have such an influence on the overall demand, the centralized demand response achieves the best performance (Scenario 4).

Table 13 - Scenario Comparison for DR impact

		Terceira Island					Madeira Island				
	Units	**B ase Scenario**	**cn4**	**[%]**	**cn5**	**[%]**	**ase Scenario**	**cn4**	**[%]**	**cn5**	**[%]**
En ergy Production	Wh	5 26.9	26.9	0	26.9	0	2292.2	2292.2		2292.2	
Pro duction cost		4 9806	8725	2.2	8362	2.9	202057	197457	2.3	198917	1.6
Pe ak Demand	W	2 5.29	6.3	4.1	4.1	4.9	116.9	113.4	3.0	114.6	2.0
Grid Shares											
Th ermal		6 4.6	2.4	3.4	1.7	4.5	68.6	68.5	0.1	68.4	0.3
Tot al RE		3 5.4	7.6	6.1	8.3	8.2	31.4	31.5	.3	31.6	0.7

Figure 21 reports the savings achieved per type of demand profiles/families for each of the scenarios with demand response. As can be observed, the highest savings in Terceira are found in Scenario 5 (32.85€/year) and in Madeira in Scenario 3 (ranging between 14.60 €/year and 25.55 €/year), both cases in which DR is made from an individual point-of-view.

It is also interesting to see that the savings in the scenarios with centralized DR (Scenarios 2 and 4) are higher for smaller electricity systems (Terceira). On the other hand, when in presence of microgeneration (Scenarios 2 and 3), the savings are not equal for all the types of families, since their ability to practice DR will be influenced by their local production. For example, *Demand 1* in Madeira has null savings due to the inexistence of energy surplus leaving no room to shift demand.

Regarding scenarios without microgeneration (Scenario 4 and 5), the savings are much higher in Terceira than in Madeira, which is due to the effect of the night load shift which flattens the profile. Further, Scenario 5 (individual DR) presents equal savings for each type of family, which is explained by the assumption that every house, independently of the number of persons, has the same pattern of use of the washers and dryers, which constitute the flexible loads considered in this work.

In general, for all scenarios, higher savings are found for Terceira than Madeira, which can be justified by the type of load pattern of Terceira (mainly residential) which has a higher impact in the savings achieved, since the DR considered depends on the number of houses. However, overall, both users and the grid operator benefit from demand response programs, although with different levels.

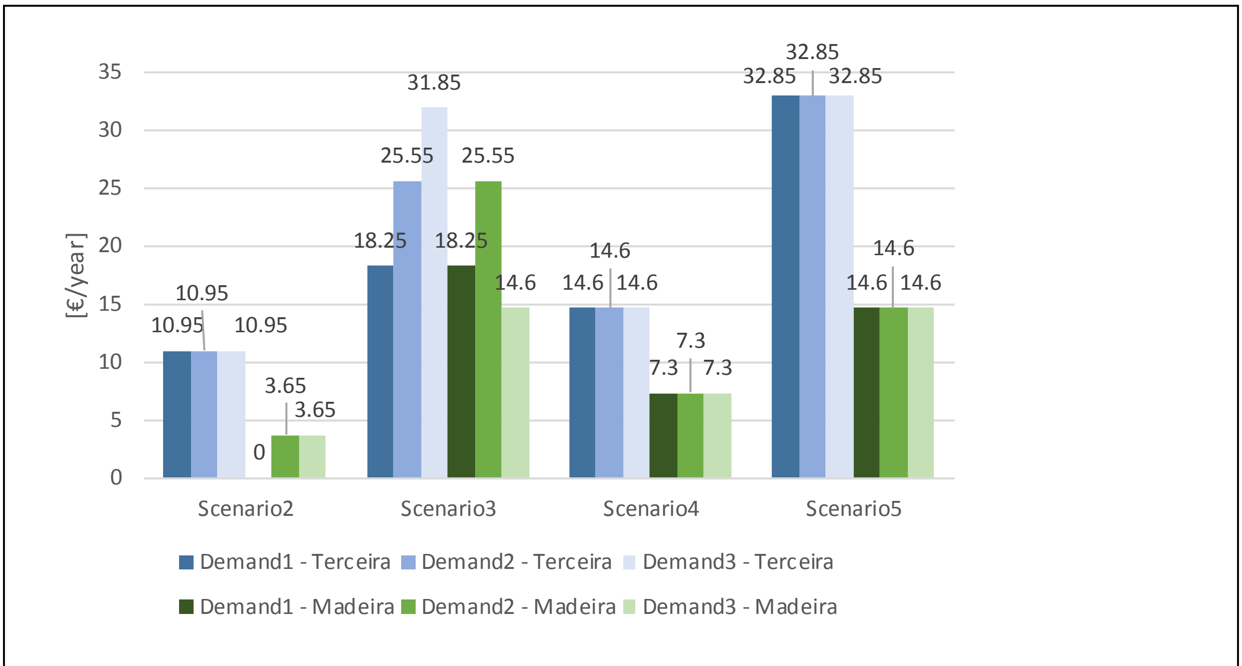

Figure 21 – Savings achieved per family for each scenario

In order to understand the impact of both approaches in the islands profile, **Figure 22** presents the allocation of flexible loads for the different Scenarios for the Madeira case study, since the model reports the same behavior for Terceira case study.

As can be seen, both Scenarios 2 and 4 have a larger volatility on the loads shifted, since the model is designed to take full profit of variable renewable generation. On the other hand, on Scenario 3 there is a clear tendency to take full advantage of microgeneration systems, with the loads accompanying the daylight hours. In contrary, when microgeneration systems are not considered and the demand response is done individually only recurring to the dual tariffs, there is a clear shift to off-peak periods.

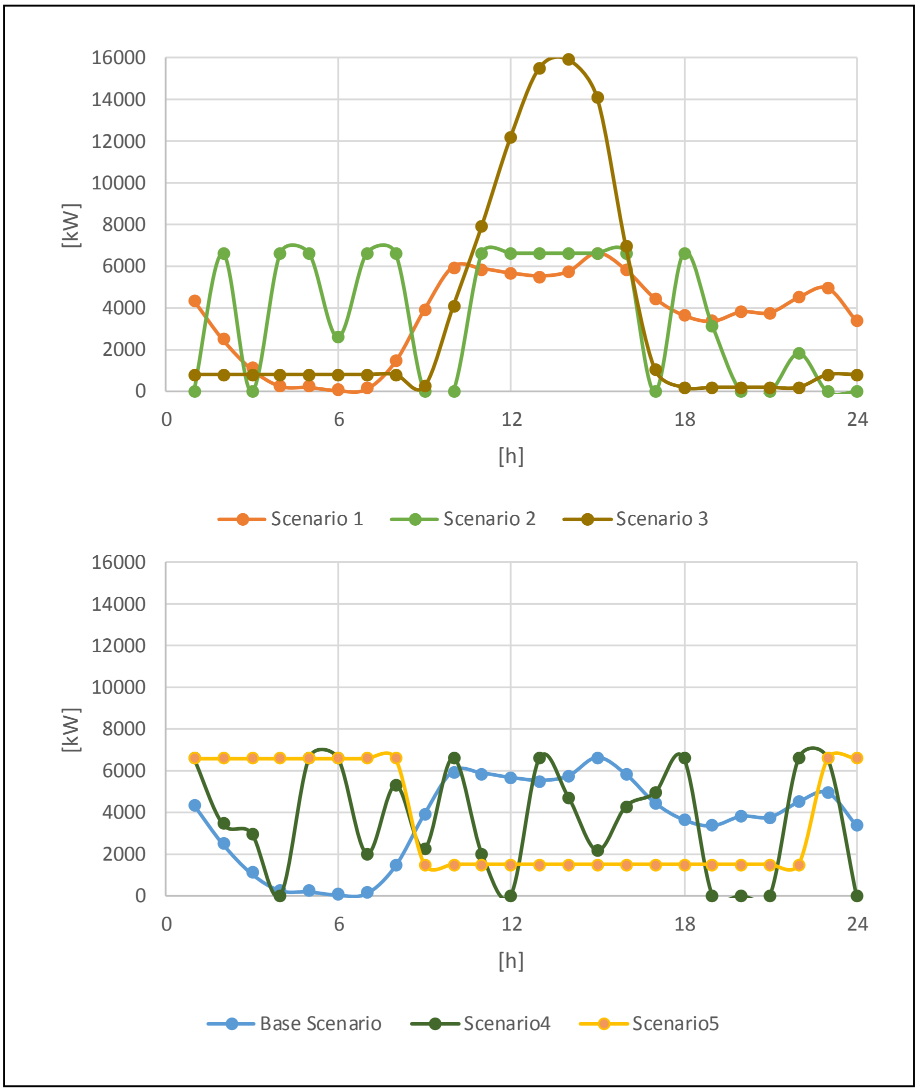

Figure 22 – Flexible loads profiles for each Scenario for Madeira Island

Survey Results

The results obtained from the analysis of the responses to the survey indicate that 81% of respondents are very or extremely concerned about their household energy consumption and 86% consider that it is very or extremely important to save energy, as can be seen in Table 14. However, ~9% and 49% indicate that they have a low or medium knowledge of their consumption, respectively.

Table 14 – Concerns about household energy consumption and importance attributed to energy saving behaviors

Level of concern about household energy consumption			**Level of importance attributed to energy saving behaviors**		
	n	**%**		**n**	**%**
Not concerned	4	1%	Not important	-	-
Somewhat concerned	11	3%	Somewhat important	1	0%
Concerned	54	14%	Important	51	14%
Very concerned	131	35%	Very important	88	23%
Extremely concerned	177	47%	Extremely important	237	63%
Total	**377**	**100%**	**Total**	**377**	**100%**

Among behaviors already practiced in the household to save energy, these include choosing new appliances according with the existing energy certification (18%), turning off lights when leaving a room (16%), maximizing appliances load, such as dishwashers and washing machines (14%), among others. The adoption of consumption saving behaviors is essentially related with economic factors, since 39% of respondents stated these were adopted to reduce the energy bill. Contribution to the sustainable environment and decreases in CO_2 emissions also stood out as reasons to adopt energy saving behaviors (17% and 27%, respectively).

Most of the respondents were not aware of the existence of DR (~85%), which is in line with previous findings [7], [22]. Those who have knowledge of DR indicated that awareness was promoted mainly by internet access (30%). **Figure 23** and

Figure **24** present the perceived benefits and challenges to adopt DR programs. As can be seen, once again monetary factors stood out as main advantage of adoption DR programs, with 18% of the respondents considering that participating will lead to energy bill reductions, followed by the possibility of energy consumption savings (16%) and consumption management improvements (15%). Nonetheless, concerns in participating in such programs were also indicated, mainly related with the lack of information or knowledge about programs (25%) as well as the perceived difficulty in changing consumption patterns or shifting consumption to other schedules (23%) and loss of privacy (14%), as can be seen in

Figure 24. Such results follow the trend found in the literature that bill reduction is considered the greatest motivation to engage in DR programs, and changing or shifting energy consumption patterns and lack of information as the main barriers for consumers [10][23].

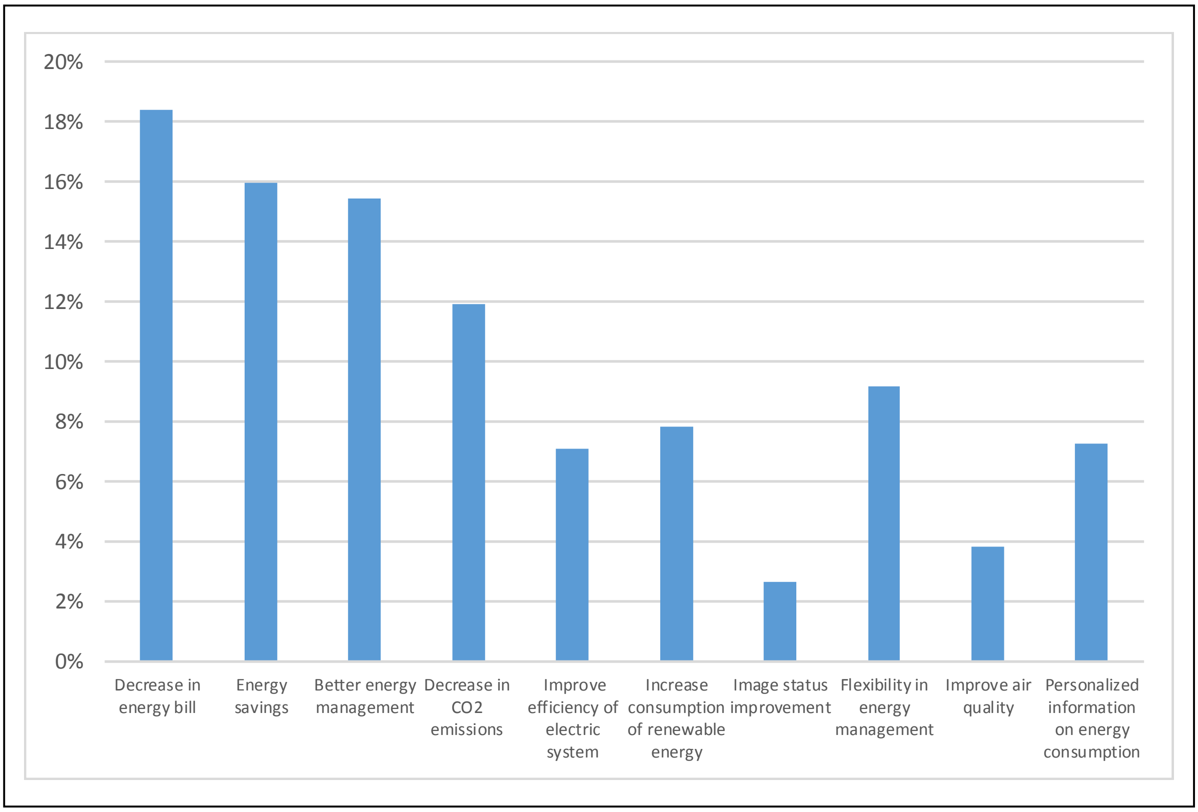

Figure 23 – Perceived benefits of DR programs

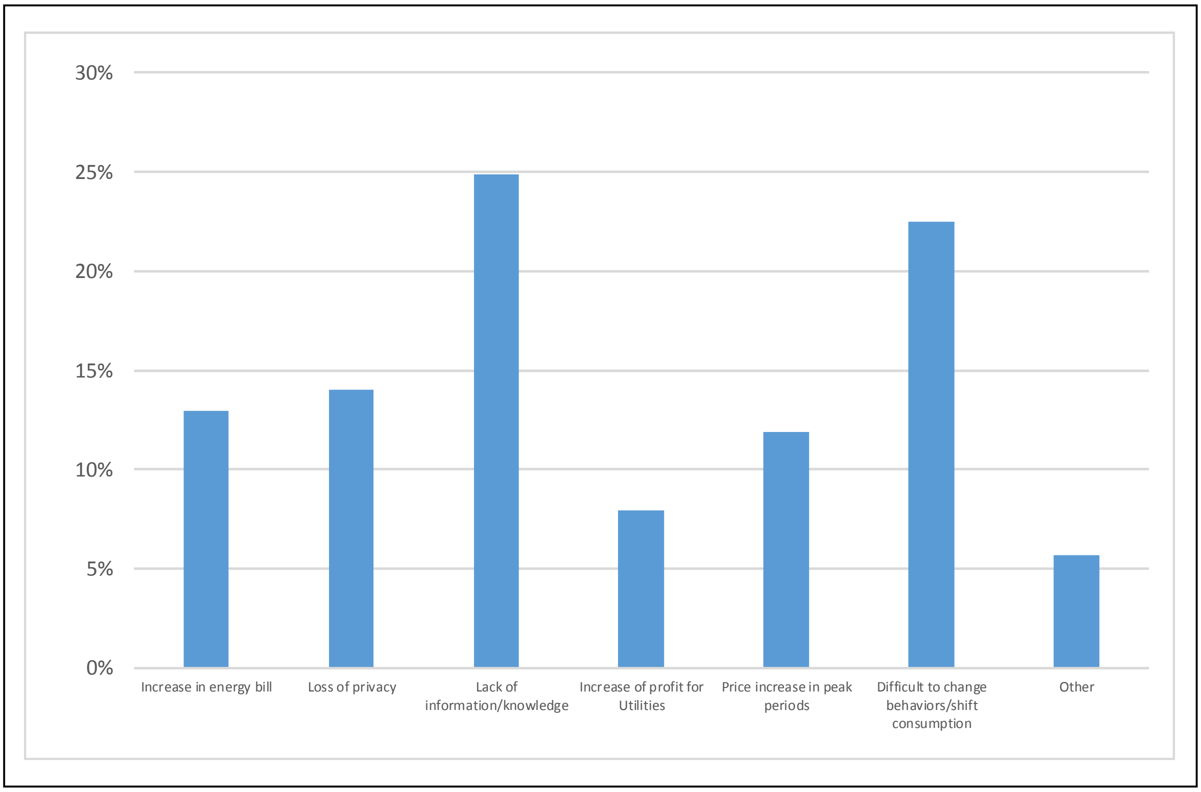

Figure 24 – Perceived challenges of DR programs

Table 15 presents respondents willingness to participate in DR programs, with results indicating that 11% of the participants consider they are already actively engaged in individual programs (either by taking advantage of microgeneration systems or shifting consumption to low demand periods) and 34% are willing to engage in such programs. In what concerns dynamic programs that are promoted by the Utility, **Table 15** reveals that 30% are willing to participate, 21% would not engage in these programs and 47% are uncertain. Among these, it is possible to ascertain that respondents are more willing to participate in price-based programs than in incentive-based programs, probably related with concerns with loss of privacy previously highlighted and potentially mistrust in utilities, following previous studies results indicating preferences in dynamic tariffs over direct load control programs.

Table 15 – Willingness to participate in Demand Response programs

	Individual programs	**Dynamic programs promoted by Utilities**	**Incentive-based programs**	**Price-based programs**	**Combination of incentive and price based programs**
No	14.06%	21.49%	31.83%	15.92%	19.89%
Yes	34.48%	29.97%	20.42%	38.99%	34.75%
Maybe	40.32%	47.21%	47.75%	45.09%	45.36%
Already adopted it	11.14%	1.33%	-	-	-

Nonetheless, when questioned about the different types of incentive and price-based programs they would like to participate, 44% indicated preference for incentives given through discounts in their monthly energy bill, 15% for critical peak rebates and 10% for day-ahead dynamic tariffs. These are indicative of the different expectations, preferences and needs that consumers have regarding DR, indicating the need for more educative tools in such programs and for contracts designed considering consumers' characteristics.

When questioned about their monthly saving expectations if they participated in a DR program, respondents indicated mainly values of 10€ per month (~21%) and 20€ (~21%). The final questions of the survey were related with willingness to participate in DR programs taking into account the economic impact found by the model for both individual (2 €/month) and dynamic programs (1€/month). Following the previous trend of respondents' preference for individual programs over collective DR programs, Table 16 indicates that 23% are willing to adopt individual programs if 2€/month saving could be achieved, 43% are not sure and 34% would not participate. On the other hand, if savings of 1 €/month could be achieved in a dynamic program, only 14% of consumers would be willing to engage, while ~49% would not participate.

Table 16 – Willingness to participate in DR programs based on model results for individual and collective programs

	Individual program	**Collective program**
No	34.22%	48.81%
Yes	23.08%	13.79%
Maybe	42.71%	37.40%

Concerning how consumers would like to receive information on DR, 33% would like to have access to information through emails, 21% in their monthly energy bill, 19% through mobile apps, while a mere 9% mentioned the use of devices installed at home. This might be indicative of issues related with privacy concerns and, particularly, of a lack of knowledge of the potential that these types of devices such as smart meters have in managing energy consumption and in facilitating the relationship between consumer and utility during the participation. Respondents revealed being available to shift consumption to lower demand periods particularly in what concerned the use of washing machine and dishwashers, 40% and 23%, respectively, following findings in the literature [27][29].

Discussion

The results obtained in this work demonstrate that there are still significant challenges to optimize electricity grid operations using demand response programs. First, there is an effective gap in the implementation of individual or system wide demand response programs, as individual homeowners may achieve higher savings if they optimize their electricity consumption individually. Second, there is a large lack of knowledge within consumers regarding what demand response is and how it may be implemented. Tackling this issue is surely one of the main steps that must be taken, in order to engage consumers in a DR program. Third, consumers envision that their participation in DR programs may require a change in habits or the loss of privacy, which may lower their acceptability in participating.

Given the expectations of consumers concerning the savings obtained from participating in DR programs, there is clearly a need to identify how some of the benefits obtained by the stakeholders involved in the value chain of electricity supply (from production to distribution and commercialization) may be passed on to final consumers. However, the preliminary results obtained in this work indicate that the impact of such programs in electricity systems might be very limited.

Nonetheless, the respondents from the survey also indicated that they would be more willing to participate in price-based programs with dynamic tariffs. The participation in such programs could yield additional benefits to both consumers and grid operators by resulting in a decrease in electricity demand, as a response of consumers to periods with high electricity prices.

Conclusions

Despite the recent interest in promoting demand response, there are still significant uncertainties concerning the full benefits that may be obtained for both consumers and grid operators, the type of programs that would have higher acceptability from consumers and how could their participation be fostered. In particular, there is a need to better understand how demand response programs may transition from individually based programs to system wide programs with a centralized optimization of demand.

To tackle these issues, this work estimates the savings that may be achieved in two isolated systems and presents some insights obtained through a questionnaire regarding the views of consumers on demand response programs. The estimated savings are calculated using an economic dispatch model coupled with optimization algorithms to simulate the implementation of individual or system wide demand response programs. The model is applied to a variety of scenarios that also compare the benefits with and without the large-scale deployment of PV microgeneration systems.

The results obtained demonstrated that the electricity systems would be able to obtain production cost reductions of up to 7% and 16% if PV microgeneration systems are deployed in Terceira and Madeira, respectively, while when implementing DR led to reductions of 2-3% for Terceira and 4 and 2% for Madeira when accounting, respectively, with microgeneration systems or not. Similarly, higher benefits were found to exist for final consumers in Terceira, reporting savings up to 32.85 €/year, when compared to consumers in Madeira, up to 25.55 €/year.

The survey showed that, despite an interest in reducing energy demand and bills, there are still several challenges that need to be addressed in order to promote demand response as a mechanism for a more optimized management of the electricity system. In particular, the expected value of savings, the lack of information and the fear of abdicating control or loss of privacy are the most relevant.

Future work will be performed to improve the detail of modelling methodologies to assess the impact of DR programs. A statistical analysis of the responses to the survey will also be performed when a larger number of answers is collected to assess potential correlations between consumers' socio-economic variables and household characteristics, such as household dimension, with willingness to participate in DR programs. This analysis may contribute to the design of more appropriate demand response programs.

Acknowledgements

Support from the IN+ strategic Project UID/EEA/50009/2013, as well as the Post-Doctoral FCT financial support (SFRH/BPD/96459/2013) is gratefully acknowledged.

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Evaluation of the performance of Aggregated Demand Response by the use of Load and Communication Technologies Models

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Abstract

The development of Demand Response in small customer segments is basic to achieve a more flexible demand in the horizon 2030-2050 because these segments account for up to 40% of the overall demand. The involvement of small segments is a difficult task because it requires the necessity to aggregate customer demand in energy/power packages. To overcome these difficulties, the aggregation of small customer segments needs both the development of new tools, the integration of other tools and, due to the complexity of the problem, the integration of knowledge from several areas (energy markets, appliances, automation, Information and Communication Technology, or mathematics, in our case, integrated into REDYD-2050, a research network funded by Spanish Government). The first step towards such a goal is the development of simulation tools. This paper deals with two important problems in residential DR: Firstly, the determination of the flexibility and response of the residential demand and second, how the performance of communications technologies can be analysed, and which is its effect on Demand Response characteristics. In this way, and specifically, the paper intends to show how the values and statistical distributions of dwellings, appliances and communication parameters can be considered and, moreover, how they can modify or limit the flexibility of demand response (power, energy, payback or rebound effects), and how to deal with these characteristics and limitations to facilitate the customer participation and response in several Electricity Markets.

List of Acronyms

AMI	Advanced Metering Infrastructure
AS	Ancillary Services
PBLM	Physically Based Load Modelling
CPF	Cumulative Probability Function
DNP3	Distributed Network Protocol
DR	Demand Response
EC	European Commission
EE	Energy Efficiency
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
ISO	(Independent) System Operator
LTE	Long-Term Evolution, a standard for high-speed wireless
NB-PLC	Narrowband Power Line Communications
NILM	Non-Intrusive Load Monitoring (also called NIALM)

PDF	In this paper, Probability Density Function
PJM	Pennsylvania, Jersey and Maryland regional transmission operator
PLC	Power Line Communications
REDYD-2050	Research network on Distributed Energy Resources and Demand
RIG	Remote Intelligent Gateway
RTO	Regional Transmission Operator
SCADA	Supervisory Control and Data Acquisition
SD	Standard Deviation, σ, of a set of data (e.g. model parameters)
TES	Thermal Energy Storage
TLS	Transport Layer Security
VEN/VTN	Virtual End/Top Node

1. Introduction

Residential customer segments (i.e. customers with contracted capacity less than or equal to 10kW) represent about 25% of the final demand of electricity in EU. If the researcher considers other small segments (commercial and industrial) the share reach 40% [1]. Unfortunately, the deployment of DR in these segments is very limited at present. Some barriers that explain this situation are well known: the specific legislation in each country, technical complexity of response and the education of customers on electricity markets (an excellent picture of this scenario and its evolution can be found in [2]). On the other side, the proposed rising share of green (and less predictable) generation by 2050 in the European Grid increases the need to develop new alternatives in demand and supply sides to face to this less flexible generation. The lower predictability in market and network operations means an urgent need for accruing customer flexibility to cope with this volatility of resources.

For years, the attitude was just throwing more supply resources at the power system. That simply does not work anymore from economic and technical points of view. In some of our electrical systems, the peak demand events occurring for less than 1 per cent of the time per year but a lot of networks are still planned according to the peak events because the potential of the demand-side is not considered. These situations explain the poor capacity factor (utilization factor) of resources in power systems with respect to other economic sectors, for example industry or transportation (around 75% in manufacturing sector in the US, 2016 [3], or from 88% to 96% in some European airlines or main freight railway lines). In this way, actual methods should change in the future in order to avoid unnecessary investments (fortunately, political authorities are aware with the problem). For these reasons, some incentives for the demand-side are being included in the EU regulation. For example, the article 15.8 of the Energy Efficiency Directive (2012/27/EU) [4] enables DR participation in wholesale and retail markets, including Balancing and Ancillary Services (AS) with the objective of removing the barriers for a broader deployment of Energy Efficiency policy. Technical specifications for participation in these markets must include aggregation of resources (i.e. allowing that small customers become engaged in DR in spite of power levels) "…in a non-discriminatory manner, on the basis of their technical capabilities". This objective is commonly admitted worldwide [5], [6].

The problem of applying DR policies beyond Energy Markets has been previously addressed in the literature, but some approaches present unrealistic limitations. One hypothesis is that "any consumer reducing his/her demand cannot sustain another reduction until the initial recovery interval is complete" [7]. This is not true. With regard to HVAC loads, the limit for DR reductions is their service, i.e. that indoor temperature is less than a predefined value with the user (e.g. 26ºC in the summer period). If the load is half way through the energy recovery period, after a DR control, perhaps the temperature will reach 23-24ºC, so the load could start a second DR period for different purposes (obviously, with other properties and characteristics). This fact opens a possibility to use loads for AS and Energy Markets simultaneously, but we need a model, not a black box but a PBLM, with the capability to respond both in short and medium term, as the one proposed in this paper. With respect to the architecture of the models to be presented in next sections, some general aspects must be considered. Firstly, in the literature, the main difference is the physical phenomena being considered. For instance, approaches such as [8] follow a model that only reproduces a simplified and inaccurate heat balance (heat losses/gains due to temperature gradient and electrical power conversion). The problem is that solar radiation through windows and walls are not a negligible factor in the modeling process of thermostatically controlled loads, for example in the South of Europe or in California. The proposed model can consider in more detail these heat flows. Second, for AS purposes, literature reports problems with delays in ICT; see [9]. In this way, the evaluation of load performance should consider an accurate modeling of ICT devices. Third, in some cases, the reader can found detailed models for loads and ICT, but the customer considered (and its demand level) does not need any aggregation [10]. New regulatory approaches (see EU, [6]) recommend that all customers need to be explored, and many customers need tools to aggregate their demand.

The solution of this problem needs a rational development of new and less expensive resources and not only from a material point of view (e.g. new software tools, information feedback from Smart Meters and customer education). The demonstration of customer capabilities is an important challenge for small and medium-sized segments, since their potential is undoubtedly of interest. Finally, it is also possible to take into account new solutions that are cost effective when synergies (economies of scale) are developed between energy policies: the integration of Energy Efficiency, Demand Response (EE&DR) and ICT [11]. Due to the necessity of taking into account the necessary synergies (from an economic point of view) and to afford the complexity of DR in these segments, a research network on DR (funded by Spanish Government), that engages seven research groups, was launched in 2015 with the objective of contribute to DR development. These groups develop research in key technologies (EE, DR, ICT, Control Engineering, Mathematics and Statistics) with the objective of developing and integrating methodologies to achieve a complete development of DR. This work presents some integrated tools that are being developed by REDYD-2050.

This paper is structured as follows: Section 2 introduces the characteristics of ICT networks for residential DR, and some problems such as latency; Section 3 deals with mechanical latency in loads with compressors; Section 4 presents a Physically Based Load Model (PBLM) and its aggregation to include the problems that have be presented in previous sections; Section 5 presents some simulation results, specially focussed to AS and, finally, Section 6 puts forward the conclusions.

2. ICT Performance and Latency

Different communications solutions can be used to provide DR services. At application layer, traditional SCADA protocols such as DNP3 can be used. This is the case of the RTO PJM, whose so-called Jetstream system uses DNP3 on top of TLS in order to secure data and setpoints exchange [12]. In the Jetstream system the DNP3 master runs in the PJM site, whereas the DNP3 client runs in the remote site, notably in the so-called RIG, which is used for aggregation purposes.

There are also application protocols specifically designed and developed for DR, OpenADR being the most well-known and widely used worldwide. OpenADR v2.0 is supported by the OpenADR Alliance [13] and has been accepted as standard by standardization bodies such as OASIS and IEC. OpenADR defines two types of nodes, namely: VTN (Virtual Top Node) and VEN (Virtual End Node). By combining them recursively, tree-wise topologies can be obtained, as Figure 1 illustrates. The OpenADR server shown in Figure 1 is managed by the ISO/RTO and works as VTN in the communication with the OpenADR client, which is managed by the Aggregator. The OpenADR client, in turn, runs a VEN for communicating with the OpenADR server and a VTN for communicating with the VEN running in the consumption infrastructures managed by the Aggregator.

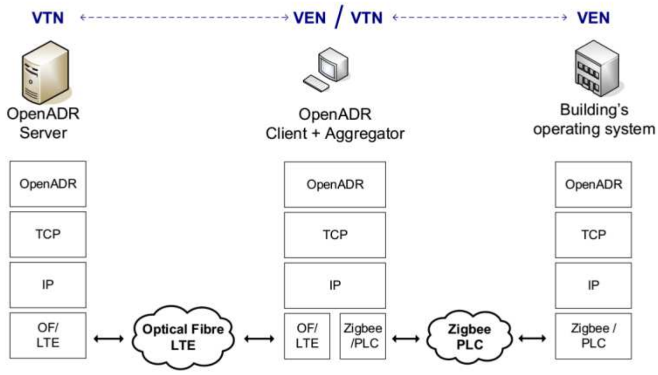


Figure 1. Communications architecture.

At lower layers, there are quite a few communications technologies that can be used in each of the communications segments of the typical communications architecture for DR shown in Figure 1. The selection of the most appropriate communications technology for each specific segment is influenced by the traffic characteristics and communications constraints of DR [13].

On the one side, the ISO/RTO and the Aggregators are typically far away from each other. The commands that the ISO/RTO sends to the Aggregators may require different time responses, ranging from a few seconds to minutes or even hours or days. Therefore, in this segment, broadband technologies over long distances are required, such as optical fibre or LTE. In order to increase reliability, redundant connections can be used in this segment.

On the other side, the Aggregators are typically close to their clients. The Aggregators may monitor the consumption infrastructures they manage by receiving low-frequency messages and may also send them time-constrained commands upon receiving ISO/RTO signals. So the volume and the pattern of the traffic are different in the uplink and downlink. In this segment, low-range technologies with lower data rates can be used, such as Zigbee or PLC.

PLC technologies are widely used in Smart Grid applications, in general, due to the advantages they present, such as the fact that they use the power cables as communications media [10]. NB-PLC (Narrowband PLC) technologies, in particular, are being widely deployed in the last mile of AMI mostly in Europe and China, but also in the US or Australia [16].

Regarding the application of NB-PLC technologies for DR, availability and latency stand out as key communications parameters.

The availability of this kind of networks is very sensitive to noise. However, the effects of noise can be mitigated by using filters that isolate the domestic electrical infrastructure from the power distribution network. Nevertheless, this would increase remarkably the costs associated to the infrastructure.

Reference [17] evaluates the performance of OpenADR over NB-PLC infrastructure using as metric the latency under three different types of noise. The results from simulations show that the round-trip latency is very similar for background and synchronous noise (median around 6.5 s and 7.5 s respectively), whereas it is almost double for asynchronous noise (median around 12 s). Although [17] concludes that such latencies make NB-PLC networks not suitable for DR products in the wholesale ancillary service markets, there are other research works that state that combined communications latencies up to 1 minute are acceptable for this kind of products [18]. Therefore, the results obtained in [17] will be taken as baseline for statistically modelling delays in the load simulations presented later in this paper

3. Mechanical latency

The second problem is the "lock-out" or mechanical delay of heating and air conditioning (HVAC) units. This mechanism is used to prevent a rapid recycling of a compressor avoiding mechanical damages. From the point of view of DR, it can cause an additional delay when applying ON/OFF and thermostat control signals, see [19]. To evaluate the effect and characterize from a statistical point of view this process, three residential HVAC appliances (ranging from 1kW to 3kW) have been monitored. To evaluate and validate models, customers demand have been recorded by an electronic meter and several Z-wave wall plug switches (with power meter feature, in this case manufactured by Fibaro [20]) which send data to PCs using an USB gateway. The hardware is managed with the help of software developed in one of the platforms use by the team: IP-Symcon [21]. This software allows sampling rates ranging from seconds to one minute. Usually, a pacer trigger from 5s to 1min has been used in elemental appliances with the aim of recording demand changes and validates load models. To evaluate mechanical latency, both IP-Symcon software and plug meters are able to perform immediate power reports, i.e. the user can define by how much the power load must change in percent to be reported to the main controller with the highest priority. In our case, several tests have been performed with 10% and 30% setting parameters for the measurement of residential HVAC (inverter) units. This test consisted on periodic changes in thermostat setting (up & down) which were sent to loads, and, moreover, On/Off functions of wall plug meters have been used to simulate cycling (note that some DR policies use switching control whereas others use thermostat control). Figure 2 shows one of these tests.

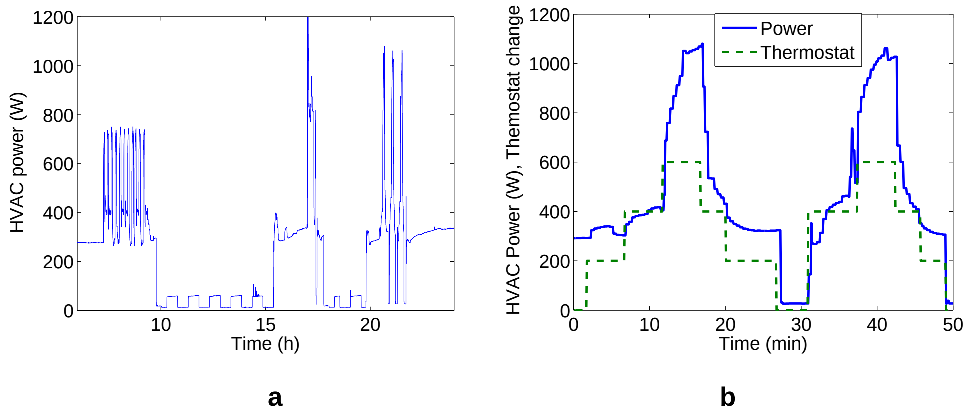


Figure 2. Test performed in a residential load to evaluate the effect of thermostat changes in latency and load demand: a) HVAC demand; b) Test period (from 19h30 to 20h30) and thermostat change (change ±1ºC and ±2ºC)

Figure 3 shows an histogram based on different delays recorded in tests similar to the one shown in figure 2 (note that the unit works as a Heat Pump). Results from histogram show that OFF/thermostats down times are slightly shorter than ON/thermostat up times. From the analysis of results, two uniform distributions have been chosen for simulation purposes: 10-40s for OFF control periods and 20-60s for ON control periods. Table 1 shows results and a comparison with commercial HVAC units analyzed and discussed in [10].

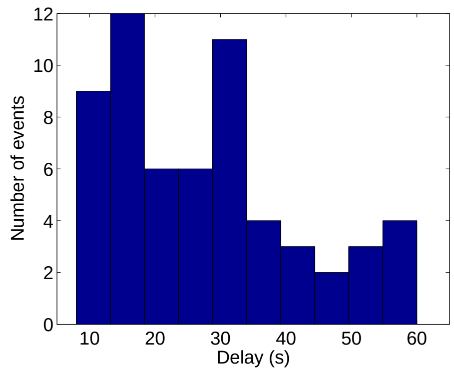


Figure 3. Histogram of delays in 2 kW HVAC test-unit (the load worked as Heat Pump)

Table 1. Up & down times in response to thermostat changes

Load	ON time delay	OFF time delay
Residential HVAC (≈ 2kW)	20s-1min	10-40s
Commercial HVAC [10]	≈ 30 s	≈ 30s

4. Methodology: Model Description and Integration

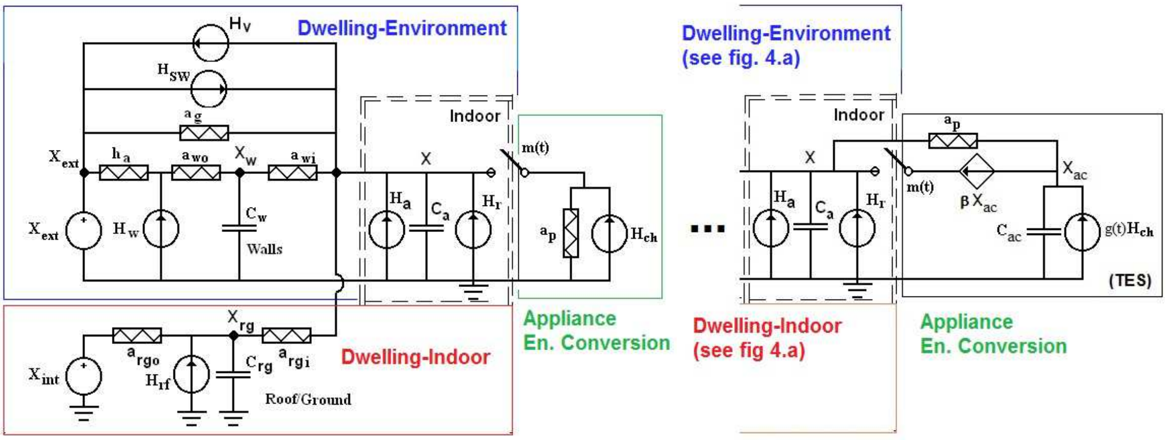
Since DR is complex for the demand-side (customers and, specially, energy aggregators), the philosophy adopted for modelling is to save time, information and resources and, consequently, use the same modelling basis for different DR policies, markets and loads, whenever possible. This seems affordable with the use of PBLM models that represent the processes occurring between load, environment and its service, involving physical information. Figure 4 presents two examples of this kind of models. All of these models usually have several components (sub-models) which use thermal-electrical analogies, for example:

- *Dwelling/environment*: parameters that represent heat losses/gains (conduction/convection through walls: h_a, a_w; the floor: a_{rg}; windows, a_g), ventilation losses/gains (H_V); as well as heat gains: solar radiation (H_{sw}, H_w); internal gains due to inhabitants (H_r) or appliances (H_a). Also, the model takes into account heat storage from the specific heat of walls (C_w), indoor mass (C_a) or roof/ground (C_{rg}).

- *The appliance*: and its energy conversion into heat (space heating), “cold” (air conditioning), or hot water. This is represented by a current source (H_{ch}) and is independent of the dwelling, see figure 4 where the same dwelling model "hosts" different appliances.

- *Control mechanisms (one or several) which drives the demand*: a thermostat in some loads, i.e., m(t) in Figure 4a, and m(t) and g(t) in figure 4b.

- *The state variables that usually are temperatures*: indoor (X), walls (X_w) and roof/ground (X_{rg}). In the case of TES appliances arises a fourth state variable of interest: the state of charge of storage, in this case the temperature of ceramic bricks (X_{ac}).



a **b**

Figure 4. Example of PBLM for residential dwelling (30m^2): **a**) Appliance: HVAC load; **b)** Appliance: TES load (ceramic bricks); dwelling sub-models are the same.

For instance, state-space representation for the model presented in figure 4a is:

$$\begin{pmatrix} DX_w(t) \\ DX(t) \\ DX_{rg}(t) \end{pmatrix} = \begin{bmatrix} -\frac{1}{C_w}\left[\frac{1}{(h_a+a_{w0})}+\frac{1}{a_{wi}}\right] & +\frac{1}{C_w a_{wi}} & 0 \\ \frac{1}{C_a a_{wi}} & -\frac{1}{C_a}\left[\frac{1}{a_g}+\frac{1}{a_{wi}}+\frac{1}{a_{rgi}}\right] & \frac{1}{C_a a_{rgi}} \\ 0 & \frac{1}{C_{rg} a_{rgi}} & -\frac{1}{C_{rg}}\left[\frac{1}{a_{rg0}}+\frac{1}{a_{rgi}}\right] \end{bmatrix} \begin{pmatrix} X_w(t) \\ X(t) \\ X_{rg}(t) \end{pmatrix} + \tag{1}$$

$$+\begin{bmatrix} \frac{1}{C_w(h_a+a_{w0})} & 0 & \frac{h_a}{C_w(h_a+a_{w0})} & 0 & 0 \\ \frac{1}{C_a a_g} & 0 & 0 & \frac{1}{C_a} & \frac{1}{C_a} \\ 0 & \frac{1}{C_{rg} a_{rg0}} & 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} X_{ext}(t) \\ X_{int}(t) \\ H_w(t) \\ H_{sw}(t)-H_v(t) \\ H_a(t)+H_r(t)+H_{ch}(t) \end{pmatrix}$$

where D is the differential operator and, coefficients, state variables and inputs have been described previously. A more detailed explanation of these coefficients is available in [11]. These models have been validated through measurements in individual customers.

4.1 Model aggregation

From the technical point of view, the participation of small customers in DR policies requires the estimation of the parameters included in equation (1) for a representative sample of customers, i.e. to perform an aggregation process (a summation of individual demands). Unfortunately, window or wall surfaces (and the losses or gains through them, e.g. a_g, a_w) are not the same for all the aggregator's customers, not even the rated power of appliances, and this makes more complex the process in the first insight. A first evaluation of individual model's parameters can be performed with the help of NILM methodologies and building codes. NILM and building codes are of interest because NILM ([22]) help the aggregator on parameter identification tasks in a range predefined by building codes requirements. Moreover, and through the development of the PBLM modeling process (see previous paragraph) this task becomes easier because energy heat flows and building standards help us to limit the search of possible values in equation (1) (in the near future standards and energy building certification [23] should contribute decisively to make easier this task), specially for 1/(C*a) terms (i.e. the ratio heat losses/heat storage of new and refurbished dwellings will trend to bounded intervals). Note that heat capacity (C) and losses/gains (a, 1/a) are related with surface and volume and this product of variables usually ranges in a narrow range of values (i.e. dwellings have similar time constants). Indeed, the conversion of energy verified in the appliance should be related with the losses in the dwelling (EE concerns also helps the modeling task, and demonstrates EE vs. DR synergies). For example, table 2 shows some of main dwelling parameters to obtain coefficients in state-space equation (1). Figure 5a shows the histogram of demand recorded in HVAC appliances whereas figure 5b shows the distribution used to consider this specific input in equation (1). A similar procedure is accomplished with the other coefficients and inputs [11].

Table 2. Parameters for the elemental load. Room volume: 30m^3; external walls 12.5 m^2; glazed area 3 m^2; internal wall 32.5 m^2; Orientation: Southwest; Location: Murcia (Spain).

Parameter (sub index in (1))	Windows (g)	External Walls (w)	Indoor (a)	Ceiling and ground (c,g)
1/a (W/(m^{2}ºC))	3. 5	4. 1.35	5. 2.25	6. 1.99
C (kJ/ºC)	7. N.A.	8. 2,192	9. 1,358	10. 12,304
Ha (W)	11. -	12. -	13. 200	14. -
H_{ch} (W)	15. -	16. .	17. 1,000 18. (COP 2.8)	19. -

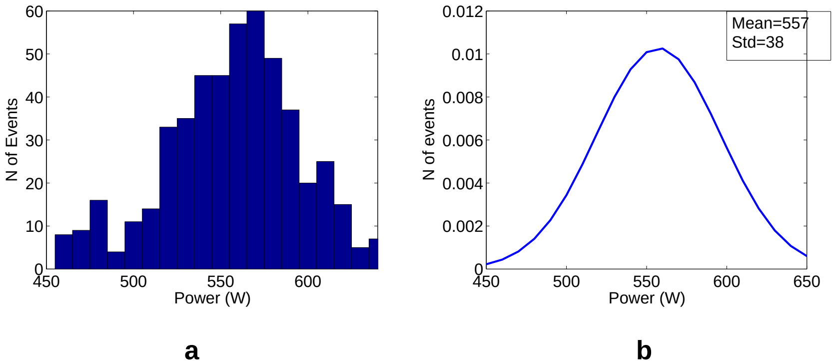


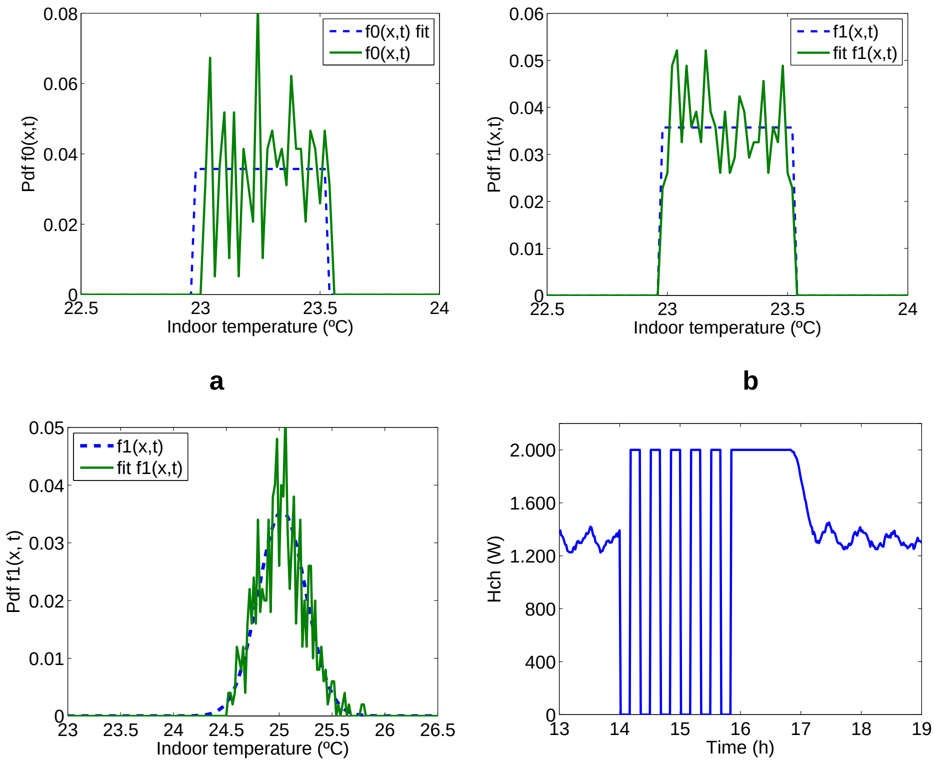
Figure 5. An example of random (input) variable used in (1): a) Energy demand to obtain $H_{ch}(t)$; b) Distribution function fitted from data in a)

Summarizing, the coefficients and input variables in the model (1) can be considered as random variables for a load group under the aggregator's control. In this way, the simulation of aggregated load needs Monte Carlo Methods for obtaining the overall demand. To get the aggregated demand, a conventional procedure is used. First, the random coefficients are sampled. Second, for each sample, a calculation with state-space equation (1) is performed to obtain state variables, and specifically the temperature inside the dwelling which drives the thermostat m(t) behavior and, consequently, individual demand. Due to the randomness in the inputs, the output for the aggregated load is also a random variable. Finally, the statistics of state variable X(t) is computed, which allows the estimation of the overall demand and dynamics of the aggregated load. It is advisable to define for each simulation time, two different pdf functions: $f_1(x, t)$ and $f_0(x,t)$. These functions will allow determining the probability that a load lies at temperature x in the time t with its energy conversion source $H_{ch}(t)$ in ON (m(t)=1, thus) or OFF (m(t)=0) state, i.e.:

$$
\begin{aligned}
f_1(x,t)dx &= \Pr\left[x \le X(t) \le x + dx \cap m(t) = 1\right] \\
f_0(x,t)dx &= \Pr\left[x \le X(t) \le x + dx \cap m(t) = 0\right]
\end{aligned}
\tag{2}
$$

4.2 Analysis of the effect of parameters' dispersion

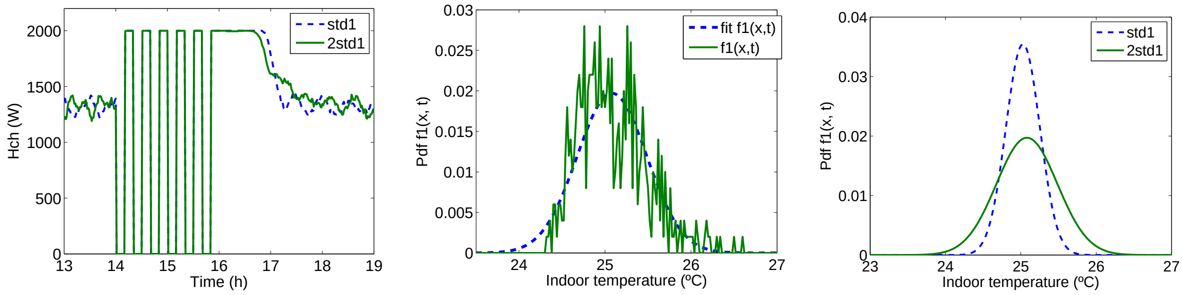
Figure 6 shows some examples of PDF functions (figures 6 a-c) for HVAC loads group being controlled from 14 to 16h (figure 6d). Before the control (at t=13h30), PDFs' suit a uniform distribution along the dead band of thermostat, in this case in the range [23, 23.5]ºC). When a control policy is applied (ON/OFF cycles) PDF function $f_1(x, t)$ fits a normal distribution whereas $f_0(x, t)$ does not exist, because all loads are recovering energy and service (i.e. m(t)=1, ON state, and dwellings are reaching the indoor temperature). Usually pdfs fit uniform and pseudo-normal distribution functions.



c d

Figure 6. Example of PDF functions for an aggregated load: a) $f_0(x, t)$ uniform in steady state; b) $f_1(x, t)$ uniform in steady state; a) $f_1(x, t)$ normal during payback period; d) Load response before and after DR cycling policy.

It is also interesting to evaluate the effect of parameter dispersion on load response. To evaluate this, the same control policy is applied to a new load group with the same parameters (see table 2) that the reference group but with a dispersion in Ha(t) (internal losses/gains, see table 2 and figure 4) twice the previous value (the value being considered for the simulation showed in figure 5, i.e. from SD1=0.25pu to 2*SD1). Figure 7 presents main results for this scenario. The aggregated load with the lowest dispersion in $H_a(t)$ exhibits a greater time for payback (recovery) and some damping after the control period (see figure 7a). Figure 7b presents $f_1(x, t)$ fitting a normal distribution at t=16h. It can be seen that standard deviation in $f_1(x, t)$ when the dispersion in parameter grows is twice the standard deviation reported in figure 6 (see figure 7c). These results are of interest for the aggregator because recovery time is relevant for the estimation of economic payback. Moreover, the value and shape of $f_1(x, t)$ is relevant for DR policies based on the change of thermostat set-points (see section 5).



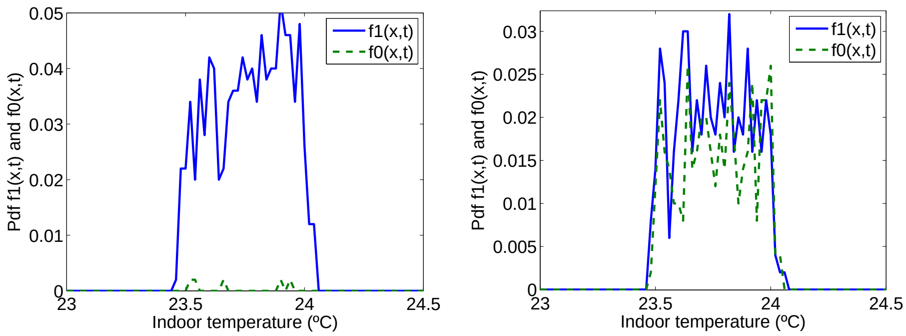
a **b** **c**

Figure 7. Results in control group when the value of SD in Ha(t) is doubled: a) Comparison of load response; b) a) $f_1(x, t)$ fitted to normal PDF according to SD values; c) a) $f_1(x, t)$ with fitted values to normal distribution

4.3 Modelling of ICT and mechanical delays

To obtain the aggregated demand when delays are taking into account, a similar procedure to the one described in paragraph 4.1 has been implemented. First, for each elemental load, the ICT delay value at the beginning of each control cycle is obtained by using a random variable (a normal distribution with mean 12s, and standard deviation 3s). Second, a mechanical delay is considered for each ON/OFF cycle according to values that have been presented in table 1 (in this case, by using a uniform distribution). Third, for each load, a different time simulation period is considered (this period is conditioned by the abovementioned delays), and equation (1) is solved to obtain the behavior of state variables, and specifically the temperature inside the dwelling (X(t)). The state X(t) is used to compute the thermostat operating state (m(t)) and the individual load demand. To perform the summation (aggregation) of electrical loads, and taking into account the fact that delays impose different time step simulation periods, a time step of 1 minute is considered for the presentation of results (this granularity of results depends on the application of load models, and it will be discussed in next paragraphs).

Again, and due to the randomness of inputs and coefficients in (1); and control policies (i.e. delay's effect), the output X(t) for the aggregated load becomes a random variable too. Finally, X(t) statistics are computed again, which allow the estimation of the overall demand and dynamics of the aggregated load. Figure 8 presents some representative results at the beginning of second control cycle (notice that theoretically all loads should change to ON without the consideration of delays, but these delays cause an error in the control target).



a **b**

Figure 8. Example of PDF functions for an aggregated load (simulation)**: a)** Only ICT delay is considered**; b)** Both delays (ICT and mechanical) are considered

It can be inferred (see figure 7a) that the effect of ICT delay in response (in 1 minute time basis, considering that Smart Meters use 1-minute interval metering for DR verification) is very low, because only 5% load "fails" and is not switched ON, i.e. load remains without control. On the contrary, the mechanical delay causes a higher error than in the previous case. About 50% of load group (this evaluation is done through PDF $f_0(x, t)$, see figure 7b) remains in OFF state, whereas 100% of loads were dispatched by aggregator (theoretically). This is not a problem for price DR policies because control periods last for some hours, but can be a problem when DR policies play in the range of seconds to minutes in AS markets (note that 2-4 second interval metering is usual in the case of DR policies for Ancillary Services).

5. DR SIMULATIONS

5.1 Requirements of AS and adaptation of aggregated load models

In section 4, elemental and aggregated load models were applied to simulate a typical ON/OFF control policy. In this paragraph, the goal is the use of these models for the development of DR policies in AS markets (maintaining the same main characteristics as the ones described in the paragraph 4, i.e. PBLM basis). In this scenario, it is required to follow an ISO regulation signal, and the best option to do that is to change the thermostat set-point, because this option allows a more continuous regulation of load demand. Figure 9 shows an example of two test regulation signals (2-second interval signal) used in PJM system [18] for customer flexibility qualification purposes. Obviously, in this case, load behaviour errors in the range of minute to minute are of interest and relevant from two points of view: customer qualification and DR revenue.

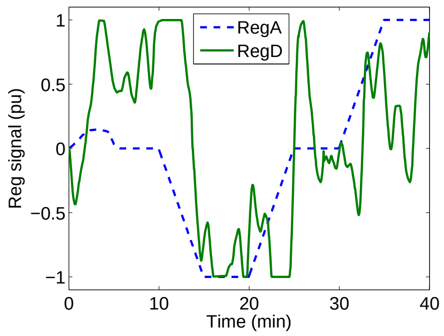


Figure 9. PJM AS Regulation "regA" and "regD" signals (before 2017).

Functions $f_1(x, t)$ and $f_0(x, t)$ (from now on, it will be considered fitted functions, for simplicity in the interpretation of results) can be used to determine the necessary changes in the thermostat set-point to achieve a load growth (drop) for the management of AS when typical over or under-frequency events appear in Power Systems. Figure 10a shows how the change of the thermostat setpoint (Heat Pumps in this example) can control the increase in demand (i.e., the number of appliances in the OFF state that should be changed to ON state). When the set-point grows (from X_- to X_{-n} and from X_+ to X_{+n}, see figure 10a) a number of loads migrate from the OFF to ON state ($m(t)=0 \rightarrow m(t)=1$). Note that grey area in figure 10a ($f_0(x, t)$ integral) represents the percentage of load that is switched ON (obviously, with a certain time delay, as has been explained in section 4.3).

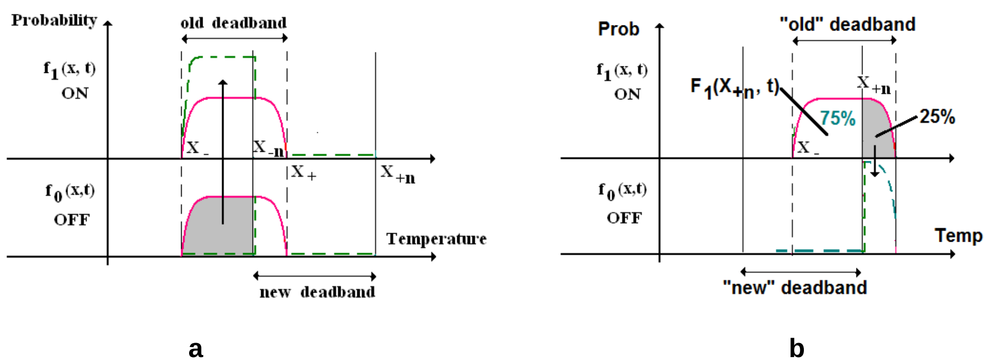


Figure 10. States ON and OFF and their probability “flows” during a change in the thermostat set-point (control group of Heat Pumps): a) Thermostat going up; b) Thermostat going down.

The implementation of changes in thermostat dead-band is easy in each elemental model. Once we get $f_1(x,t)$, through simulation, it is defined the proportion of loads in the control group (cg) switched "ON" at time t, $m_{cg}(t)$ (the so called operation state of average load into the control group). It can be computed easily by integrating $f_1(x,t)$:

$$\overline{m}_{cg}(t) = \frac{1}{N}\sum_i m_i(t) = \int_{-\infty}^{+\infty} f_1(x,t)dx \quad (3)$$

Sometimes, it is more convenient to work with the Cumulative Distribution Function (CPF) $F_k(x, t)$ associated to $f_k(x,t)$:

$$F_k(x,t) = \Pr\left[X(t) \le x \cap m(t) = k\right] = \int_{-\infty}^{x} f_k(\lambda,t)d\lambda; k = 0,1 \quad (4)$$

For example $f_0(x, t)$ integral (grey area in figure 10a):

$$F_0(x,t) = \Pr\left[X(t) \le X_{-n} \cap m(t) = 0\right] = \int_{-\infty}^{X-n} f_0(\lambda,t)d\lambda = load\ change \quad (5)$$

represents the target for load growth by the control of thermostat set-point.

The first simulation considered is a single thermostat change and return to its original state (the control group consists on 500 heat pumps with thermostat set-point [21, 22] ºC, and ICT and mechanical delays from table 2). In steady state 75% of controllable loads are in ON state (i.e. $m_{cg}(t)=0.75$). At t=15min, a change of set-point of +1.5ºC is sent to thermostat, see figure 11. Ten minutes later, thermostats returns to the original value (increment of - 1.5ºC). With the help of developed software, the user (aggregator) can compute and fit PDF functions, and finally, the operating state $m_{cg}(t)$. Results are presented in figure 11. It is interesting to state that the change of +1,5ºC in thermostat set-point causes a "walk process" in $f_1(x, t)$ because loads trend to follow the new service requested by thermostat, see figure 12a (a similar process can be deduced from figures 6b & c, in that case for cycling policies presented in section 4). In the same way, the change of -1.5ºC in thermostat set-point causes a reverse "walk process" in $f_k(x, t)$ because a lot of thermostats change to OFF state because dwelling heat losses drive an overall decrease in X(t) thorough the control group.

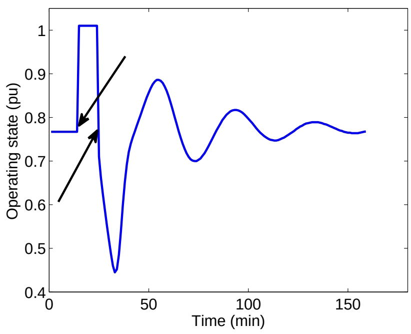
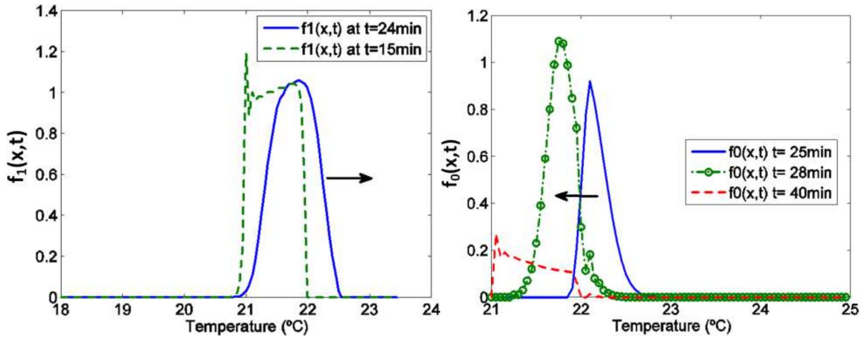


Figure 11. Operating state $\overline{m}_{cg}(t)$ of the control group considered (i.e. the power response in per unit). Arrows indicate the time start (t=15) and finish (t=25) of thermostat control.



a **b**

Figure 12. PDFs' walk process: a) Rise of thermostat and $f_1(x,t)$ "walk"; b) $f_0(x,t)$ with the thermostat on the way down

5.2. Response to static regulation signals

Figure 13 shows the load demand (continuous line) in response to a hypothetical test signal (dashed line), similar to the static regulation signal called "regA" in PJM system (see figure 9, dashed line). For simplicity, a rectangular wave which lasts 40min has been chosen. As aforementioned in section 5.1, the first growth of demand is easy to obtain because the only restriction to be accomplished is to raise the thermostat dead-band above the initial (steady-state) level (in this case 1.5ºC at t=15 min). To follow the first trailing edge of test signal, ten minutes ago (t=25min), the aggregator needs to reduce the load up to 25% ($\overline{m}_{cg}(t > 25\,\mathrm{min})$ = 75%, i.e. the original steady-state level).

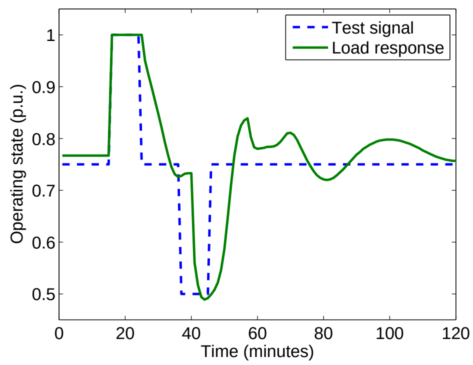
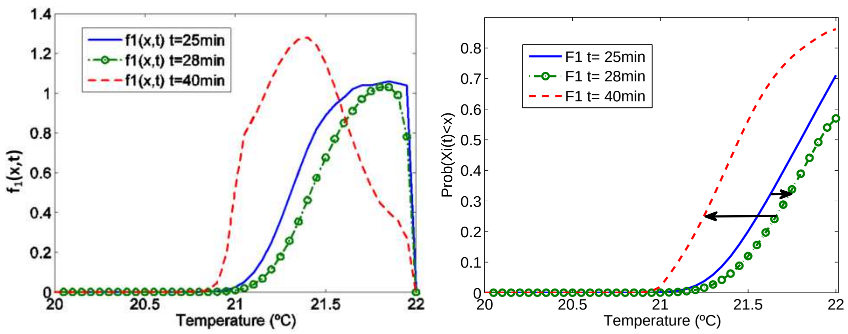
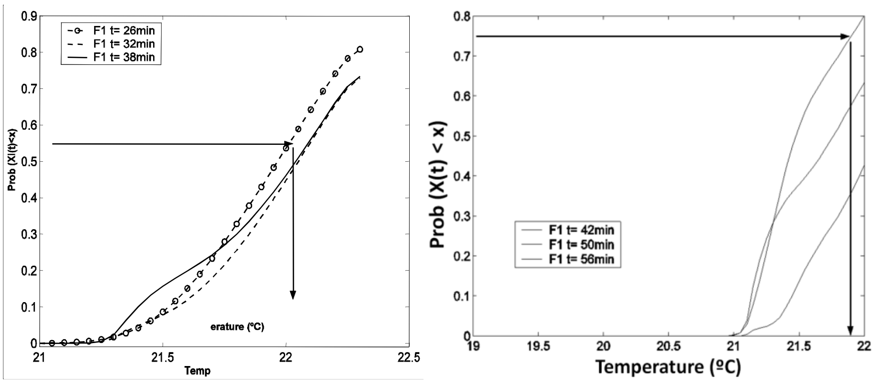


Figure 13. Aggregated demand response (simulation) to ISO test signal.



a **b**



c d

Figure 14. Definition of thermostat setpoint: a) PDF and b) CPFs during the trailing edge of test signal c) CPFs during the second trailing edge of test signal, and d) CPFs during the leading edge of test signal to reach original state.

As aforementioned, when all the load group is ON after the change of thermostat, the indoor temperature rises, and the PDF function $f_1(x,t)$ walks and goes to [21, 22.5]ºC interval (continuous signal in figure 11a; the arrow shows the forecasted displacement of from t=15 to t=20min). If the thermostat goes down, the aggregator follows the procedure described in figure 10b. It is necessary that 25% of loads switched on drop out (i.e. the new thermostat band fills 75% of loads, in this case 75% of $f_1(x,t)$, or in other words $F_1(x, t)=0{,}75$). This means the thermostat goes down about 1.0-1.2ºC at t=25min, because the upper side of dead-band should de centered at $F_1(x=22ºC, t=25min)=0.75$, and this would produce the desired load drop percentage (see in the figure 14b, continuous line, the value of temperature which gives $F_1(x,t) = 0.75$ is around 22ºC).

Again, around t=35min the aggregator needs to reduce load to follow the new leading edge in the proposed regulation signal (see figure 13, dashed line). An arrow is drawn at $F_1(x, t=36min)$ at the desired value 0.5 (50%); the intersection gives the new X_+ setpoint (see vertical arrow in figure 14c). Therefore, the solution is to reduce thermostat at about 0.2-0.3ºC (note that usually the resolution of thermostat is discrete and usually lies in the range [0.1, 0.5]ºC). Figure 13 shows the "success" achieved by the aggregated load to fit changes in reference signal. The last problem for the aggregator is how to return the load to the original value of demand when the ISOs test signal finishes, while the swing transient of the load is being reduced (figure 13, the interval starting from t=50min and finishing at t=100min). This can be done first by managing several load control groups (a well known solution in DR for economic and event responses) with specific thermostat references and changes of setpoints. The second question is what the new deadband value should be. The solution comes from the condition $F_1(x,t)=$ 75% (percentage of loads in ON state). In this case, the thermostat has to be reduced to 0.2-0.3ºC (following the procedure described in figure 14d).

5.3. Effects of response characteristics in performance scores

The effective participation of DR in AS (resource qualification) requires the fulfillment of certain conditions. Several ISOs (for example PJM [19]) use a performance scoring system to evaluate customers' revenue and also impose a threshold for potential resources. This scoring is based on the evaluation of three indices: accuracy, delay and precision of response. For each 10 second interval, PJM calculates correlation score as the statistical correlation function between test signal and response (in practice, the real operation signal), which measures the degree of correlation of signals. Delay score performs a comparison between the signals, evaluating the time T that gets the maximum correlation. This score is computed as:

$$Delayscore = abs\left|\frac{T - 5\min}{5\min}\right| \tag{6}$$

this mains that the maximum delay is 5 minutes and, in practice, T=1.25min could be a problem for resource qualification in the case of DR (e.g. PJM trends are to increase scoring threshold to 0.75). If this requirement is overcome, consequences in revenue should de analyzed. In our case, average delay is in the range of [20-50]s. The behavior of aggregated load group (damping) showed in figure 12, can cause an additional lack of correlation and the growth of parameter T. This fact justifies the need to improve modeling and refine methodology to achieve tools for aggregators and tools with the maximum performance. Different pilots with residential loads present similar conclusions [20].

Options to improve scoring are modifying existing communications to improve ICT delay or change load regulation mechanisms. Both are not likely to be cost effective just to improve DR in AS. The sole way to improve DR seems to increase customer revenue (through the participation of customers in several markets and DR options) while maintaining costs (use a common and cheap ICT framework). Another problem is to deal with uncertainties and disturbances in the dwelling-environment system due to changes in environmental conditions or changes in customer service. Both are potential causes of a lack of precision of response (third factor in scoring). As mentioned before, NILM methods developed by REDYD-2050 [22] can help in an early detection of these problems and their correction through a fast feedback to the model. Finally, reduce the computational time required for aggregation is another important concern for REDYD-2050 because the aggregator need the maximum time screen to forecast a portrait of possible scenarios for load response. The development of new methodologies to obtain new tools to infer and fit PDF is one of main concerns for this research network in the short term.

Conclusions

Electricity customers can obtain interesting benefits from energy management and trading with the help of an aggregator. The aggregator acts as an enrolling participant in DR and assists customers to understand and make more flexible their demand. Unfortunately, it is difficult to participate in the electricity market due to its complexity not only for the end-user but for aggregators. This paper presents improved methods for both actors (customer and aggregator) to understand, evaluate and overcome some barriers for DR markets. A simulation model (based on PBLM and Monte Carlo methodologies which are well known in conventional DR) has been adapted for its use in other DR policies. Specifically, it has been created to evaluate Energy and AS markets response of an important end-use in small segments: HVAC loads. The advantages of this approach are: the universality of the model (relevant for several markets and policies); the use of well-known individual models (PBLM), the robustness of the specific model for AS (i.e., it takes into account important variables such as the dynamic behavior and flexibility required in these markets), the analysis and consideration of electrical and mechanical latencies in the models (a concern to improve the accuracy in the response and the revenue), and finally the fast response and the interpretation of results to react to control signals (flexibility of response). Moreover, the idea of including load and ICT parameters makes the models more flexible than standard models presented in literature, and results even closer to reality. Through this combination of tools (load, aggregation and ICT models) the deployment of DR becomes easier and this will be valuable for price response and the management of frequency events in the short and medium term.

Acknowledgment

This paper is supported by Ministerio de Economía, Industria y Competitividad (Spanish Government) Grants ENE2015-70032-REDT, ENE-2016-78509-C3-1-P&2-P and EU FEDER funds.

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Do low-income electricity subsidies change peak consumption behavior?

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(Reproduced from proceedings of the 2017 International Energy Program Evaluation Conference, August 8-10, Baltimore, Maryland.)

Abstract

Increases in electricity consumption during peak hours place additional strain on the electric power system, which can be partially mitigated if foreseen years in advance. Smart meter data, with hourly resolution or better, allow improved characterization of the effects of various programs and other interventions on residential and system load shape. We characterize the load shape impacts of the California Alternate Rates for Energy (CARE) program, which provides 3.2 million households an average electric bill subsidy of 33% [1]. We use hourly electricity consumption data from roughly 30,000 randomly selected households from Pacific Gas and Electric service territory to estimate the hourly effect of enrollment in the CARE program on household electricity consumption using a fixed-effects regression model. We find that the CARE program is associated with an average increase in electricity consumption of 13% [11%, 16%]. The increase is relatively constant throughout the day, with no two hours statistically distinguishable from each other. We find suggestive evidence that the largest increase in electricity consumption in all three regions occurs between 7pm and 10pm, generally after summer peak demand. The overall increase is smallest in the cooler Coast, largest in the warmer Inland Hills, and in the middle in the hot Central Valley. These estimates of regional differences in the effect of the CARE program can help policy makers and utilities understand the energy effects of changes to low-income electricity subsidies.

Introduction and Background

Modern electric utilities are expected to reliably meet demand at all times with a fixed fleet of generators, and transmission and distribution infrastructure. Because electricity must enter the grid at the moment it is consumed, electricity consumption on or around peak consumption times can place much more demand on the system than off-peak consumption.

There is a substantial literature devoted to understanding the determinants of system-wide electric load shape, the distribution of electricity consumption over time. Several existing studies focus on bottom-up engineering estimates of the load shape effects of the dissemination of newer, more efficient appliances [2, 3] . More recent research attempts to measure the load shape effects of energy efficiency and demand response programs using hourly smart meter data [4, 5]. Many residential utility programs were not designed to influence load shape, but likely have load shape effects nonetheless. We are not aware of any efforts to quantify these effects in the peer-reviewed literature.

Some of the largest such programs provide low-income households with various forms of energy assistance. These programs range from emergency bill assistance such as that available through the Low-Income Home Energy Assistance Program [6], to weatherization and other efficiency measures such as California's Energy Savings Assistance program [1], to lump sum payments such as New

York's Home Energy Assistance Program [7], to direct price subsidies such as the California Alternate Rates for Energy (CARE) program [1].

We study the residential load shape effect of the CARE program, an electricity and natural gas subsidy available to California households with income below 200% of the federal poverty level. The program, which subsidized electric service in 3.2 million households in 2012 [1], provides a statewide average electric bill subsidy of 33%, or $29 per month [1]. Within the service territory of Pacific Gas and Electric, where our data come from, the average electric subsidy is 42%, or $40 per month [1]. California approved $4 billion in CARE expenditures for the 2012-2014 budget cycle, funded through a public purpose customer charge [1].

The intended effect of this subsidy is to make energy more affordable for millions of families, allowing them to enjoy a higher quality of life by lowering the cost of important energy services, such as lighting, refrigeration, heating, and cooling. Economic first principles suggest that the program should increase electricity consumption according to a price elasticity of electricity of demand. However, the effects of the program on residential load shape, and indeed overall energy consumption are poorly understood.

We anticipate that the greatest increases in electricity consumption will largely occur before, and particularly after normal working hours of roughly 7:00am-6:00pm, with some adjustment on both ends to account for commute time. Depending on commute time, this would likely coincide with partial peak demand, from 6:00-9:30pm, but likely would not overlap with summer peak periods of 12:00-6:00pm [8], which place greater strain on the electric power system. We do not have a firm prior expectation of the extent to which these changes in electricity consumption would be due to changes in household appliance stock or resident behavior.

We believe that an understanding of the load shape effects of low-income energy subsidies can provide utilities and energy policy makers with important insights, both for short-term and long-term planning. For example, deep decarbonization of the electric power system will likely require substantial investment in generation, transmission, and distribution infrastructure, which could easily raise the total cost of providing electric service. For instance, Southern California Edison's recent proposal to upgrade its distribution system to enable further renewable integration and smart grid applications is estimated to cost $1.5-2.5 billion from 2018-2020 [9]. Low-income subsidies, such as the CARE program, help ensure that these costs are distributed equitably through society. Still, these subsidies likely affect electricity consumption behavior, and thus long-term infrastructure needs. These effects should be understood and accounted for in resource adequacy planning.

A panel of smart meter data from northern California

In this work, we use a regionally stratified sample of smart meter data of approximately 30,000 households in Pacific Gas & Electric (PG&E) service territory from 2008 to 2011. The sample is drawn from all households in PG&E territory, including both single-family and multi-family residences. The data include 8,597 households from the Coast, 11,391 from the Inland Hills, and 10,217 from the Central Valley, three major climate regions in PG&E territory, displayed graphically in Figure 1A. This study period of 2008-2011 coincided with the roll-out of the smart meter program, so the number of households with smart meter readings in the dataset increases over time, as shown in Figure 1B.

The smart meter readings are communicated back to a base station, from which they are relayed back to PG&E. We use 15-minute smart meter readings, which we aggregate to hourly and daily.

This dataset includes two major household-related identifiers: a service point id, which identifies the location of the smart meter, and an account id, which identifies the customer (i.e., if a customer moves to a new house, the account id is maintained, but the customer will have a new service point id). Results below are in terms of electric service point id, which generally corresponds to a single household in a single location.

Households with smart meters were randomly sampled by PG&E at the end of the 2011. Data were gathered for each of these households for the duration of the period in which the household had an active smart meter. Figure 1B shows meter installation in our sample by region over time. As of August 2011, smart meters were installed for 4.7 million of PG&E's 5.25 million residential customers [10]. As a result, the dataset should be an unbiased sample of households in each region at the end of 2011. Earlier data are unbiased only to the extent that PG&E's smart meter deployment program can be considered random. Other than the staged deployment across regions, this assumption is not contradicted by any of our findings, but without access to PG&E's internal documents, the possibility of non-random selection cannot be ruled out.

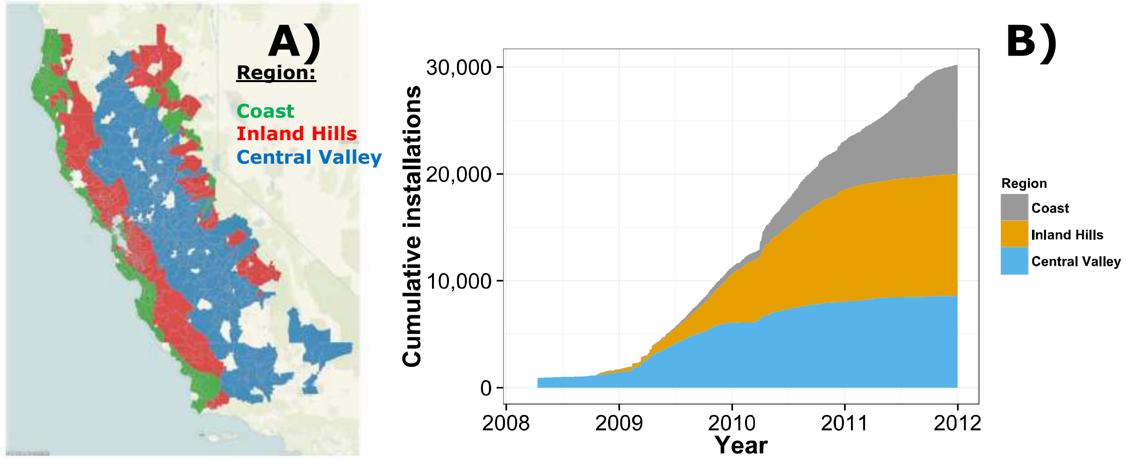

Figure 1. A) Regions in the PG&E service territory. PG&E randomly selected approximately 10,000 households from each of the region to construct the sample. Region classifications are based on climate, not geography, resulting in non-contiguous regions. Note: Figure from the Wharton Customer Analytics Initiative. B) Smart meter rollout for our sample, March 1, 2008 to December 31, 2011 by region. Deployment began in the Central Valley, followed by the Inland Hills, followed by the Coast. *Source:* [11].

In Figure 1B, we show the deployment of smart meters observed in our sample. In our sample, smart meter deployment began in the Central Valley, followed by Inland Hills, and finally by the Coast region. Region classifications are based on climate, rather than explicit geography. As a result, some far inland households are classified as "Coast" due to moderate climate. Toward the end of our sample period (end of 2011) our sample contains about the same number of households in each climate region.

PG&E Energy Efficiency and DSM Programs

During the study period, PG&E had several programs, such as energy efficiency, demand side management (DSM) and low-income programs. We control for participation in each of these programs to better isolate the effect of CARE. Key programs active during the period of observation include:

The **California Alternate Rates for Energy** (CARE) program is an energy subsidy, providing an average discount of 33% for low-income households in PG&E territory [1]. As mentioned before, we expect enrollment to increase electricity consumption due to lower prices.

The **Balanced Payment Plan** (BPP) program provides a bill smoothing service, in which the monthly bill is based on average consumption in the previous year. We expect this program to increase electricity consumption, particularly in the Central Valley, where the program allows households to smooth payment for highly seasonal electricity consumption.

The **Smart AC** demand response program provides a one-time $50 incentive payment, in exchange for installation of a device on the cooling unit that allows PG&E to cycle the unit off for up to 15 of every 30 minutes during peak load events. The program itself likely decreases electricity consumption, but our model may find a positive association with electricity consumption, as this program is essentially an indicator for the presence of air conditioning, and we are not separately controlling for the presence of air conditioning.

Rebate programs subsidize appliances, other residential energy-consuming devices, and retrofits. Customers receive efficiency rebates only after purchasing qualifying equipment or services and submitting an application to PG&E. Households are eligible to participate in the rebate programs multiple times. Our previous work has shown that rebate participation in this sample is associated with increases in electricity consumption in the Coast and Inland Hills, with no discernable effect in the Central Valley [11]. We believe this is due to households either purchasing appliances that they did not have before, or keeping and using older, more inefficient versions of the newly-purchased appliance.

The **Climate Smart** program allows households to purchase carbon offsets through PG&E via their monthly utility bill. We expect this price increase to translate to a decrease in electricity consumption.

The **Direct Access** program allows customers to purchase their electricity from alternative (non-PG&E) power providers. New customers have not been able to join the Direct Access program since the California energy crisis in 2001, though existing customers have been able to remain in the program. We expect that customers who remain on this program are receiving lower electricity rates than they would otherwise, providing an incentive for increased electricity consumption.

The **Smart Rate** program provides customers with a 3-cent per kWh discount in exchange for accepting a 60 cent per kWh rate during summer peak hours. We expect this program, which was relatively new during the sample, to correlate with a decrease in electricity consumption. The price signal could either encourage an increase or a reduction in overall electricity consumption.

The **Energy Savings Assistance (ESA)** Program provides free energy efficiency measures to households that meet similar eligibility criteria to the CARE program. Unfortunately, we do not have data on participation in this program. As of 2012, 59% of eligible households had participated in the ESA program [1]. This likely biases our results downward, as we cannot distinguish between increases in electricity consumption due to CARE, and decreases due to ESA.

PG&E Customers

The original dataset provided by PG&E includes smart meter electricity reading information and program enrollment. However, it does not include information on demographics at the household level. To overcome this limitation, we complement our dataset with 2010 Census data at the census block level. In Table 1, we provide the summary statistics of the census block data associated with each household in our sample. To be clear, if a household is associated with a location in census block *a*, we then associate that household observation with the median household value in census block *a*. The information displayed in Table 1 thus shows the median values for several demographic quantities across the sample of census block median characteristics for each household by climate region (Central Valley, Inland Hills, Coast and overall).

We observe that there are key differences across climate regions, with median home values in census blocks in the Inland Hills and the Coast regions being almost twice as large as those in the Central Valley. Similarly, the levels of median income in Census blocks in Central Valley are lower than in the Inland Hills or the Coast. The number of renters is higher in the Coast region, where the median home values are the highest. There is a striking difference in poverty rates between regions. The fraction of households below 150% of the federal poverty level is twice as high in the Central Valley as in the Inland Hills.

Electricity consumption in our sample by income and region

In Figure 2 we illustrate the daily electricity consumption over time and by climate region in our sample. We observe that the Coast has lower overall electricity consumption than the Inland Hills or the Central Valley, likely due in part to milder weather. We also note that the distribution of daily electricity consumption is tighter for the Coast and Inland Hills when compared to the daily distributions of electricity consumption for households in Central Valley. The summer spikes (largely attributable air conditioner use) are also notable in the Central Valley region. The large summer peak in the Central Valley illustrates the disproportionate contribution of that region to the overall residential peak consumption.

Table 1. Summary statistics for 2010 census block neighborhoods of households in the sample*. The Central Valley has the lowest incomes and home values. Below, “Poor” is defined as household income below 150% of the federal poverty level.

	Central Valley	Inland Hills	Coast	Overall
Median Home Value*	282,000	586,000	597,000	479,000
Median Income*	51,800	78,500	63,400	65,600
Median % Renters	34	32	51	38
Median % Poor	12	6	9	8
Median % w/ Bachelors (or higher)	17	38	40	32
Number of households	8,597	11,391	10,217	30,426

* These values are medians from our sample of Census block neighborhood medians. The values are top-coded by the US Census at $1M and $250k, respectively. We report the values rounded to the nearest $1000 for median home value, and to the nearest $100 for median income values. *Source:* [11].

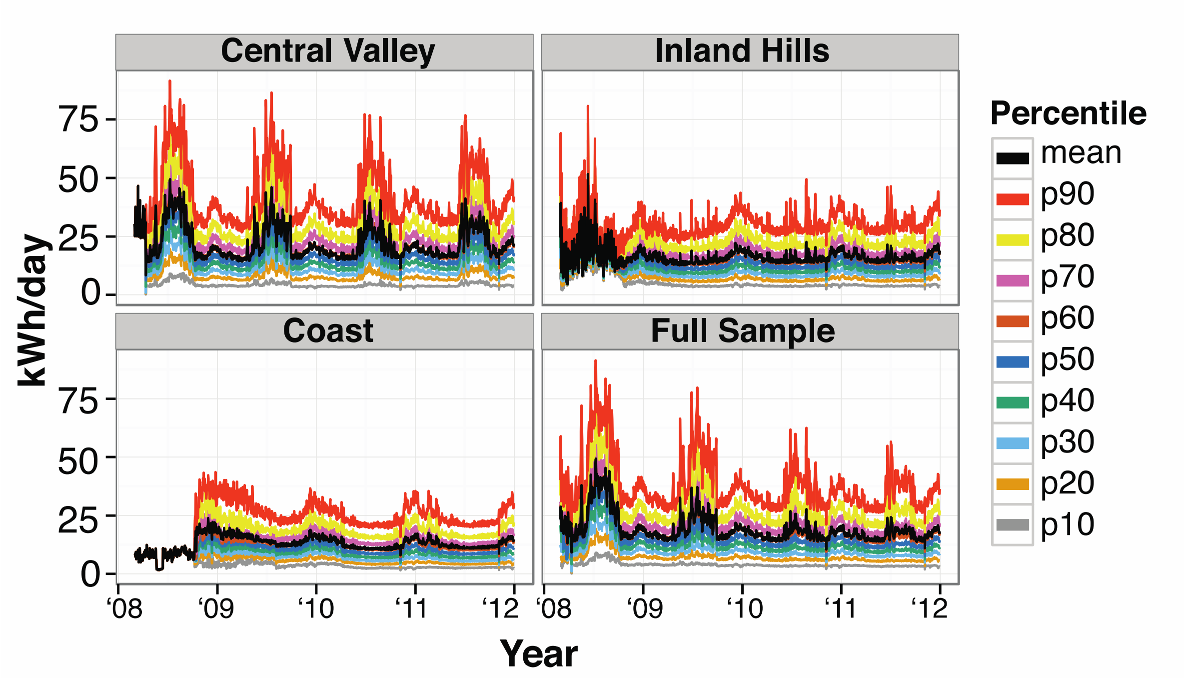

Figure 2. Deciles of daily household electricity consumption by region, from the 10th percentile to the 90th percentile, with the mean in black. All three regions have a small sample size in the first several months to one year, resulting in poorly-defined percentiles in some cases. *Source:* [11].

Who enrolls in energy efficiency, DSM and low income programs?

In Figure 3, we show the share of enrollment for all programs over time in our sample. We observe that the California Alternate Rates for Energy (CARE) program is the most prevalent program, with enrollments reaching 30% of the entire sample of households. This share is remarkable, as households must have income below 200% of the federal poverty level, or qualify for another means-tested low-income program such as Medicaid, to be eligible for CARE [1]. Of course, the goal of the CARE program is not to reduce electricity consumption or promote energy efficiency, but instead to ensure that low income households have affordable access to energy services.

By the end of 2011, 9% of households have participated in an energy efficiency rebate program, making it the second largest program in terms of peak participation. The Balanced Payment Plan (BPP), which provides a bill smoothing service, in which PG&E calculates the household’s average monthly utility bill and the customer pays a flat amount for each monthly billing cycle, comes third in terms of peak program participation, capturing less than 8% of all households in our sample at any point in time.

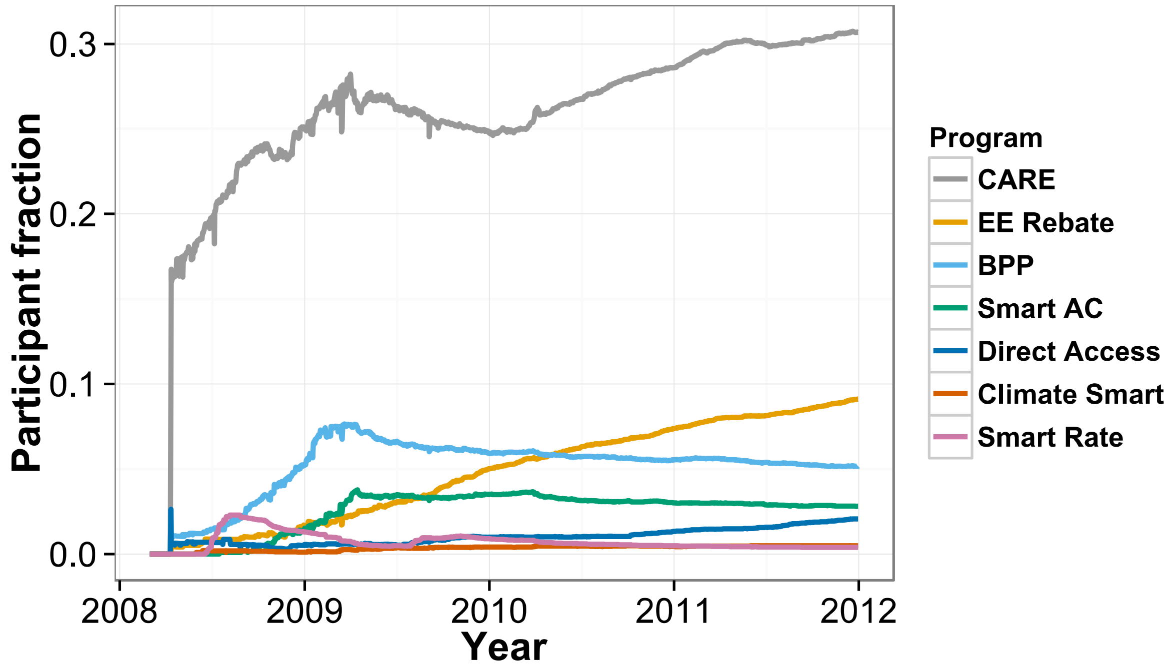

Figure 3. Enrollment rates in PG&E programs as a fraction of households in the dataset over time. The CARE low-income subsidy is by far the most prevalent. Energy efficiency rebates and the Balanced Payment Plan, BPP, are a distant second, followed by Smart AC. *Source:* [11].

In Figure 4, we display CARE program enrollment by region and income to understand differences in CARE participation by these factors. The values represent the share of households in the dataset that were participating the CARE program at that point in time.

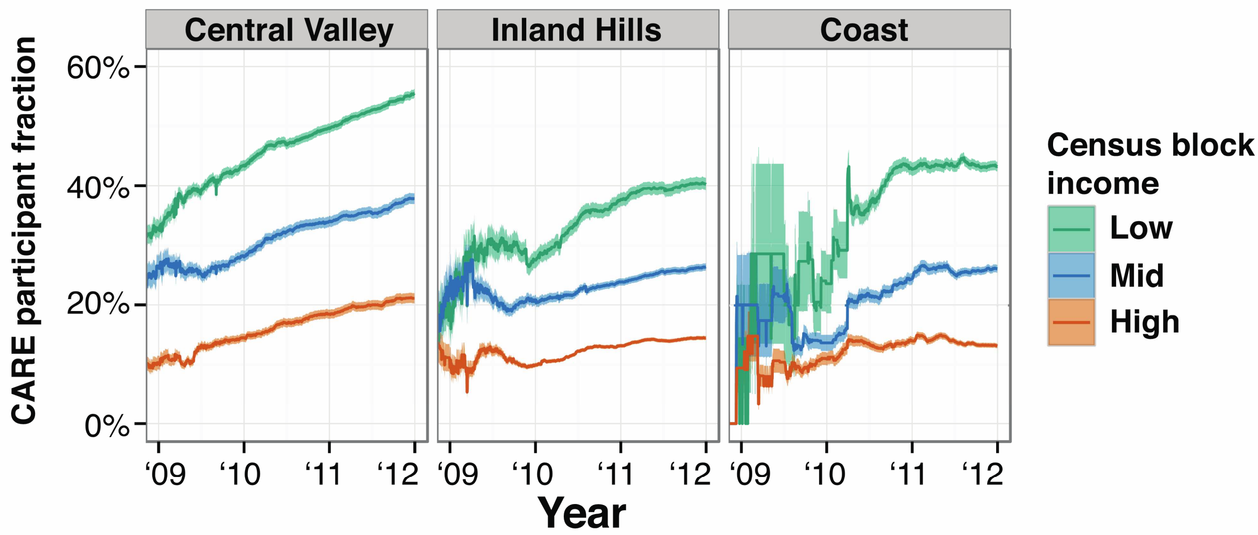

Figure 4. Enrollment rate in the CARE program as a fraction of all households in the dataset over time, by region and median census block median income, with thresholds of $52,252.33 and $81,572.00, the 1/3 and 2/3 fractiles of households in our sample respectively. Shaded areas are the 95% probability interval, considering sample error. Many CARE participants live outside low-income Census blocks. *Source:* [12].

We find that participation in the CARE program is prevalent across all three regions, but, unsurprisingly, primarily concentrated in low median income census blocks. CARE enrollment also increases substantially over the study period in all groups except high-income Census blocks on the

Coast. In households in low-income Census blocks in the Central Valley, CARE enrollment grows from just over 30% in 2009 to over 50% in 2011 (see Figure 4A). Similarly, in Census blocks with low median income in the Coast and Inland Hills, CARE program participation exceeds 40% in analogous households. The substantial increase in CARE enrollment over time may be attributable in part to the 2008 Financial Crisis, and the subsequent Great Recession.

Notably, in Census blocks with mid-range median income range, participation in CARE is still very high (about 40% in 2011 in the Central Valley, and about 20% in the Coast and Inland Hills regions). Even high-income Census blocks see CARE enrollment rates between 10% and 20% in 2011. Relatively high CARE enrollment in even relatively affluent areas is likely both a measure of local income inequality, and a product of language in CARE eligibility criteria that allows households participating in various social assistance programs to enroll in CARE regardless of income [13]. This may also reflect the program's randomized ex-post income verification process, which only selects a fraction, approximately 8% of participants annually, to verify eligibility for the program [14].

Methods

Because these data are observational, we must employ quasi-experimental methods, designating treatment and control groups, to estimate the effect of the CARE program on load shape and energy consumption. Due to an essentially flat overall time trend in electricity consumption, we apply the fixed-effects model below, as opposed to a difference-in-differences model, with the regression specification below. Our treatment group is all households actively enrolled in CARE (N ≈ 10,000). Our control group is all households not actively enrolled in CARE (N ≈ 25,000), including households that never enroll in CARE (N ≈ 20,000), and households that eventually enroll in CARE (N ≈ 5,000). Our model is:

$$\ln\left(kWh_{i,t,h}\right) = \alpha + \beta_j\left(Temp_{i,t,h}\right)_j + \gamma\left(CARE_{i,t}\right) + \delta_k(Time_t)_k + \zeta(TimeTrend_t) + \varphi_q\left(Program_{i,t}\right)_q + u_i + \varepsilon_{i,t}$$

$\ln(kWh_{i,t,h})$ is the natural log of household electricity consumption for household *i*, in day *t*, in hour *h*. *α* is a constant. *$(Temp_{i,t,h})_j$* is hourly linear and quadratic temperature controls, separately considering temperatures below or above 15 degrees C, using the index *j* to denote high or low temperature. *$CARE_{i,t}$* indicates whether household *i* is enrolled in CARE on day *t*. *$(Time_t)_k$* includes indicator variables for the day of the week and month of the year. *$TimeTrend_t$* is a time trend that captures any longer-term secular trend not included in day-of-week or month-of-year indicator variables. *$(Program_{i,t})_q$* indicates whether household *i* is enrolled in program *q* on day *t*. *u_i* controls for time-invariant household-level differences, such as different baseline levels of electricity consumption. *$\varepsilon_{i,t}$* is an error term, assumed to be normally distributed with mean zero.

Limitations

This fixed-effects model controls for differences between households that do not changes over time, such as whether the unit is a single-family or multi-family home. Limiting factors include unobserved variables that change differently over time for different households. The most important such variables include income and household occupancy, both of which are used to determine eligibility for the CARE program. For example, a family that has an additional child may become eligible for CARE as a result. In this case, it would not be possible to distinguish between a change in electricity consumption due to CARE, or due to the additional occupant of the household. The reverse is also true for households that experience a reduction in household size. As a result, the direction of the effect of this limitation on our results is not clear.

Similarly, changes in household income have the potential to bias the results in the either direction. If a household loses income, it may become eligible for CARE, but may also reduce electricity consumption due to the income elasticity of demand. The opposite is also true, for a household that experiences an increase in income, and subsequently becomes ineligible for CARE. Given that the sample contains the Financial Crisis and subsequent Great Recession, household incomes likely do change substantially over time. Literature estimates of the short-run income elasticity of electricity demand have a median of 0.15, a minimum of 0.04, and a maximum of 3.48 (*15*). Estimates of the long-run income elasticity of demand have a median of 0.92, a minimum of 0.02, and a maximum of 5.73 [15]. Bounding the effect of this limitation will require combining these elasticities with further analysis of the income dynamics of low-income and middle-income households.

Lastly, our results assume plausibly random deployment of smart meters. Apart from regionally staged deployment, we find no evidence of major non-randomness in important ways, but this cannot be ruled out. If deployment was not plausibly random, this could result in bias in either direction.

Results

We find that enrollment in the CARE program is associated with a significant increase in electricity consumption across the full sample, with a coefficient, shown in Table 2, of 0.12 [0.10, 0.15] (95% confidence interval), equivalent to an increase of 13% [11%, 16%]. Given the average bill subsidy of 42% [1], this corresponds to a price elasticity of demand of roughly 0.25, consistent with the mean short-run elasticity estimate from the literature [15]. In the three regions, the corresponding coefficients are 0.12 [0.085, 0.15] in the Central Valley, 0.16 [0.12, 0.20] in the Inland Hills, and 0.11 [0.04, 0.17] on the Coast.

Table 2. Effect of the CARE program on average household electricity consumption (coefficient estimates). CARE enrollment has the largest effect in the Inland Hills. Climate Smart is omitted in the Inland Hills and Coast due to collinearity with other covariates.

	Dependent Variable: ln(kWh/day)			
Independent Variable	Full Sample	Central Valley	Inland Hills	Coast
CARE	$1.2x10^{-1}$** ($1.2x10^{-2}$)	$1.2x10^{-1}$** ($1.7x10^{-2}$)	$1.6x10^{-1}$** ($2.0x10^{-2}$)	$1.1x10^{-1}$** ($3.2x10^{-2}$)
Rebate	$5.8x10^{-2}$** ($1.3x10^{-2}$)	$2.2x10^{-2}$ ($2.3x10^{-2}$)	$6.9x10^{-2}$** ($1.7x10^{-2}$)	$1.1x10^{-1}$** ($3.0x10^{-2}$)
BPP	$6.6x10^{-2}$** ($2.0x10^{-2}$)	$2.9x10^{-2}$ ($2.6x10^{-2}$)	$1.6x10^{-1}$** ($4.0x10^{-2}$)	$1.5x10^{-1}$** ($5.0x10^{-2}$)
Climate Smart	$-2.2x10^{-1}$ ($1.9x10^{-1}$)	$-1.8x10^{-1}$ ($1.9x10^{-1}$)	Omitted	Omitted
Direct Access	$8.1x10^{-2}$** ($3.0x10^{-2}$)	$1.0x10^{-1}$* ($4.7x10^{-2}$)	$6.0x10^{-3}$ ($3.1x10^{-2}$)	$1.1x10^{-1}$ ($7.0x10^{-2}$)
Smart AC	$4.7x10^{-2}$ ($2.6x10^{-2}$)	$5.6x10^{-2}$ ($3.6x10^{-2}$)	$2.6x10^{-2}$ ($2.8x10^{-2}$)	$3.0x10^{-1}$ ($2.8x10^{-1}$)
Smart Rate	$1.2x10^{-2}$ ($4.3x10^{-2}$)	$3.3x10^{-2}$ ($6.3x10^{-2}$)	$-3.6x10^{-2}$ ($4.2x10^{-2}$)	$7.3x10^{-2}$ ($2.7x10^{-2}$)
Daily Temperature Controls	Included	Included	Included	Included
Month Dummies	Included	Included	Included	Included
Day of Week Dummies	Included	Included	Included	Included
Intercept	2.7** ($9.6x10^{-3}$)	2.8** ($1.3x10^{-2}$)	2.6** ($1.3x10^{-2}$)	2.3** ($2.7x10^{-2}$)
Observations	18,329,664	7,222,330	7,323,276	3,659,844
# of groups, total	30,385	8,586	11,377	10,203
R^2 within	0.058	0.104	0.0272	0.026
R^2 between	0.032	0.003	0.0049	0.021
R^2 overall	0.046	0.055	0.013	0.0228

Robust and clustered standard errors in parentheses. ** p<0.01, *p<0.05

Figure 5 shows the estimated increase in electricity consumption due to CARE on an hourly basis, and by region. These full sample results present suggestive evidence that the measured increase in electricity consumption is higher later in the day, with the increase in electricity consumption between 8pm and 11pm roughly a third higher than the increase at 3am. The smallest increase, a coefficient of 0.09 [0.07, 0.12], or 9.7% [7.5%, 12.1%] occurs at 3am, while the highest increase, 13.3% [11.6%,16.4%], occurs at 9pm. Although each of the hourly coefficients is strongly statistically different from zero (p<0.001), the difference between any pair of hours is not statistically significant. Summer peak hours in California fall between noon and 6pm, with a partial peak ending at 9:30pm [8]. As a result, the largest increases in CARE electricity consumption do not coincide with the absolute peak demand, but are split between partial-peak and off-peak demand.

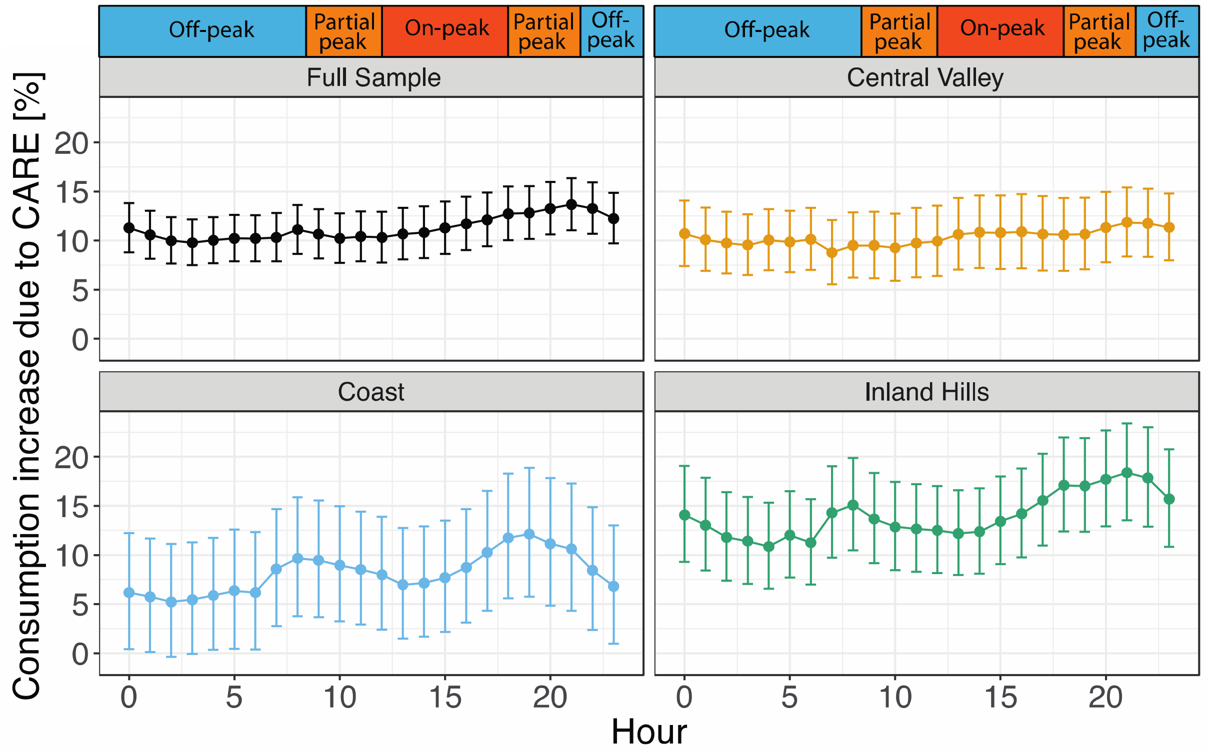

Figure 5. Hourly percent change in electricity consumption associated with enrollment in the CARE low-income energy subsidy program, derived from fixed-effects regression coefficients. In the full sample CARE enrollment is associated with a statistically significant increase of roughly 12% for all hours of the day, with a trough of 9.7% [7.5%, 12.1%] at 3am, and a peak increase, 13.3% [11.6%, 16.4%], at 9pm. CARE has the smallest effect on the on the Coast, with the highest effect in the Inland Hills.

When each of the three regions is considered individually, the results are similar. Figure 5 shows that there is an increase in electricity consumption associated with CARE in each region, and no pair of hours is statistically distinguishable from another. We see suggestive evidence that the morning and evening effects, which coincide with partial peak, but not with the overall system-level peak [8], are more pronounced in the Inland Hills and on the Coast, and that the effect of the CARE program is greater in the Inland Hills than in the Central Valley or Coast.

Conclusions and Policy Implications

This analysis demonstrates that a major low-income energy subsidy is, unsurprisingly, associated with a modest but non-trivial increase in electricity consumption. This is an indication that these programs are in fact working as intended, ensuring that households have affordable access to important energy services.

Our analysis of differences in the timing of increases in consumption, the load shape effects of the CARE program, suggests that the CARE program does not appear to be placing disproportionate strain on the electric power system during peak consumption periods. The largest increases in electricity consumption associated with the CARE program come at times that are generally somewhat later than peak consumption, but do coincide somewhat with partial peak demand. With that said, the electric power system, and its peaks, may change substantially as additional distributed energy resources are deployed to the grid.

Smart meter data present a historically unparalleled opportunity to characterize and understand residential electricity consumption behavior. We hope this analysis will help energy decision makers more accurately understand and model interactions between low-income subsidies, overall electricity demand, and long-term electric power infrastructure needs.

Acknowledgments

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1252522. This work was funded in part by the Center for Climate and Energy Decision Making (SES-0949710 and SES-1463492), through a cooperative agreement between the National Science Foundation and Carnegie Mellon University. We acknowledge and thank Pacific Gas and Electric Company, and the Wharton Customer Analytics Initiative for providing us with data.

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18 SMART METERS AND FEEDBACK SYSTEMS

Utilizing Flexibility of Hybrid Appliances in Local Multi-modal Energy Management

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Abstract

The energy transition towards renewable resources and distributed generation challenges our energy systems. Given the fact that many renewable resources are intermittent, a more flexible demand side may help to balance the energy generation and consumption. One way towards flexibilization is the introduction of energy management systems that optimize the utilization of energy in an automated way using measures of demand side management. So far, this flexibilization of the demand side focuses mainly on the provision and utilization of electricity. More promising is the introduction of smart grids that optimize the energy flows across all energy carriers. Multi-modal energy management is not limited to the provision of energy but includes also the utilization on the demand side. This paper addresses an integrated multi-commodity optimization of all relevant energy carriers. Hybrid appliances are investigated that may utilize not only electricity but also an additional energy carrier, such as hot water or natural gas, and thus provide additional potential for flexibility regarding the utilization of energy. This paper analyzes the effects of hybrid appliances in residential buildings that are equipped with electrical heating elements in combination with photovoltaic systems. Firstly, an overview of the different notions used in the context of multi-energy systems is given and appropriate terms are proposed. Secondly, the results of detailed bottom-up simulations of households are presented having automated building energy management systems that optimize the local utilization, conversion, storage, and provision of energy. The analysis includes self-consumption and self-sufficiency rates as well as possible cost reductions.

1 Introduction

The transition from fossil energy sources and mostly centralized electricity generation towards renewable energies and distributed generation challenges our energy systems. Given the fact that many renewable energy sources, such as solar and wind power, are intermittent and thus cause fluctuating generation, a more flexible demand side may help to balance the energy generation and consumption. In so doing, additional energy storage is needed, but its availability can be limited.

One way towards a more flexible demand side is the introduction of active energy management systems that optimize the utilization of energy in an automated way using measures of demand side management. So far, this flexibilization of the demand side focuses mainly on the provision and utilization of electricity. More promising is the introduction of multi-modal energy management, optimizing the energy flows across all energy carriers. This includes not only electricity but all energy carriers in buildings, e.g., all kinds of fuels and hot as well as chilled water, and enables a holistic optimization of the energy system taking technologies like district heating and cooling systems into account. In addition, this approach supports novel concepts, such as *power-to-X* or *X-to-power*, by providing a holistic management approach and thus facilitates the conversion of energy between the energy carriers, e.g., to enable the storage of electricity generated by photovoltaics or wind turbines in the gas grid [41], supporting *sector coupling*.

Multi-modal energy management addresses not only the provision but also the conversion and utilization of energy. Therefore, this paper investigates the integrated multi-commodity optimization of all energy carriers in a single building and evaluates the effects of hybrid appliances. Hybrid appliances may utilize not only electricity but also an additional energy carrier, such as hot water or natural gas, and thus provide additional flexibility potential of the building regarding the utilization of electricity. In this paper, this flexibility can be further improved by enabling the possibility to defer the appliances' operating times.

There are two major contributions of this paper: Firstly, the paper draws attention to the frequently inconsistent usage of the term *hybrid* (Section 2) and proposes a consistent terminology with respect to hybrid devices, systems, and services (Section 3). Secondly, the self-consumption and self-sufficiency rates as well as possible cost reductions of residential buildings comprising hybrid appliances are investigated by means of detailed bottom-up simulations using an automated building energy management system (BEMS) that optimizes the local utilization, conversion, storage, and provision of energy. To do so, an evaluation scenario of a smart residential building is defined (Section 4) and simulation scenarios of different appliance types, including two types of hybrid appliances, and varying local photovoltaic generation are evaluated (Section 5). In so doing, this work significantly extends first evaluation results of hybrid appliances presented in [43, 44].

2 Related Work: Hybrid Devices, Systems, and Operation Modes

Energy services serve useful purposes of the users, such as providing domestic hot water or cleaning dishes. At this, they consume so-called *useful energy* of *final energy carriers* [61]. In buildings, this usually includes multiple energy carriers, such as electricity and gas.

Nowadays, most devices utilize at least a small share of electricity. For instance, gas-fired condensing boilers utilize mostly natural gas to generate hot water and a small share of electricity for their device controllers and circulating pumps. In the sense of this paper, these devices are not considered to be hybrid ones. In contrast, real *hybrid devices and systems* may utilize or provide multiple energy carriers alternatively or in parallel as a functional principle, i.e., as their main energy carriers.

Unfortunately, the term *hybrid* is used not only in this context but refers also to other notions. Therefore, this section provides an overview of different notions before the next section proposes terms that may be used in the context of utilizing or providing multiple energy carriers in so-called *multi-energy systems* [36].

2.1 Hybrid Devices and Systems

In the literature and in practice, there are no commonly used uniform definitions of the terms *hybrid device*, *hybrid system*, or *hybrid operation*. Typically, the term *hybrid* refers to one of the following properties:

1. Utilization of at least two different alternative energy carriers [17, 34]
2. Usage of different technologies utilizing the same energy carrier in one device [9, 15]
3. Usage of different technologies utilizing different energy carriers in one system [12, 16, 34, 48]
4. Provision of multiple energy carriers by a single system [5, 35]
5. Provision of multiple energy services by one device instead of different ones [30, 43]

The following paragraphs describe various kinds of hybrid home appliances, systems, and operation modes in the context of residential buildings. A consistent terminology of devices and systems with respect to their utilization, conversion, and provision of technologies, energy carriers, and energy services is presented in Section 3.

2.2 Hybrid Home Appliances

In this paper, the term *hybrid appliance* refers to home appliances utilizing at least two energy carriers alternatively. Sometimes the term hybrid is also used to refer to appliances that combine several features into one device [4], e.g., conventional heating and microwave cooking, which does not necessarily include the usage of multiple energy carriers and is thus not consistent with the definition used in this paper.

Traditionally, to provide energy services, appliances utilize a single energy carrier, such as electricity, hot water, or natural gas, in their energy-intensive processes, which are mostly heating processes. Naturally, electricity is used in nearly all appliances, i.e., also in appliances utilizing mostly an energy carrier other than electricity, to power displays, controllers, sensors, or valves. However, these functions require only little electrical energy and are not a main functional principle.

By contrast, truly hybrid appliances utilize multiple energy carriers alternatively or in parallel as their main energy carriers. Particularly, the electrical energy that is utilized by the heating processes in dishwashers, washing machines, and tumble dryers may be partially or even fully substituted by hot water [43, 54, 57] or natural gas [3, 57]. In addition to these three appliances, hobs and ovens can be powered using electricity or natural gas, which is also possible within the same device though not yet commercially available [43]. In general, the availability of hybrid appliances is limited. Therefore, the work presented in this paper is largely theoretical and not verified by field tests, yet.

To automate and optimize the decision on the operation mode, i.e., the main energy carrier, hybrid appliances may be connected to a BEMS. This enables to take the local generation, variable energy tariffs, and the state of local energy storage systems, such as storage tanks and battery energy storage systems, into account.

2.3 Hybrid Heating and Cooling Systems

Although hybrid heating and cooling systems combining multiple heating or cooling technologies, respectively, in one integrated system are more popular [17, 48] than hybrid appliances, this paper focuses on appliances. However, this section provides an overview of some typical hybrid systems for heating and cooling because the hybrid operation modes that are presented below are related to these systems. Generally, there are many devices and systems that can be combined to an integrated hybrid system and provide one or multiple energy services, e.g., space heating, domestic hot water (DHW), and space cooling. Often, heat pumps are combined with electrical insert heating elements (IHEs) or with gas or oil boilers to provide sufficient thermal power in case of peak demands or low outdoor temperatures and thus low efficiency of the heat pumps [9, 29, 33, 49]. A detailed study about systems combining heat pumps and condensing gas boilers is given in [48].

Other hybrid heating systems include *cogeneration* systems, such as combined heat and power plants (CHPs) and fuel cells [7, 45], which are combined with boilers to cover demand peaks [14, 23]. *Trigeneration* systems add chilled water as a third energy carrier to the cogeneration of hot water and electricity. To do so, these systems typically combine a CHP with an ab- or adsorption chiller [10]. Sometimes, there is also an additional energy source, such as solar thermal energy. Usually, trigeneration systems are operated as cogeneration systems if there is no demand for space cooling.

When coupling cogeneration or trigeneration systems with energy storage systems, such as hot and chilled water storage tanks and battery energy storage systems, the provision of the energy carriers is partially decoupled from the provision of the energy service, i.e., space heating, space cooling, and local electricity supply [8, 53]. Then, a BEMS may decide about when and which device to operate and thus energy carrier to utilize with respect to economic and ecologic objectives, such as the minimization of total energy costs and emissions [59, p.8]. In case of CHPs, their heat-led or electricity-led operation is replaced by scheduled operation that considers heating as well as electricity demand. Similarly, the scheduling of the operation of the adsorption chiller and the CHP of a trigeneration system helps to increase the overall system efficiency and decrease energy costs [42].

2.4 Hybrid Operation Modes

In the literature and mostly in the context of operating heat pumps in heating systems, there are five different operation modes of hybrid devices, which refer to the number of utilized energy carriers, the number of used conversion technologies, and the parallelism of operation [15-17, 29, 49, 60]:

Monovalent Operation

In case of *monovalent* operation, there is only a single heating component, e.g., a heat pump, which operates without any auxiliary heating component, e.g., electrical IHE. Although a heat pump uses two energy carriers, electricity and environmental heat from air, groundwater, or ground, the latter is usually not regarded as a separate second energy carrier.

Bivalent Alternative Operation and Monoenergetic Operation

In case of *bivalent alternative* operation, there are two main heating components that work alternatively: above a certain temperature threshold only the heat pump is operated and below this temperature only the other heating component is used, e.g., a gas or oil boiler or an electrical heating element. In some cases, the operation of two heating components using the same energy carrier is called *monoenergetic operation* [60].

Bivalent Parallel Operation and Bivalent Partially-parallel Operation

Often, the main heating component, i.e., the heat pump, is used in parallel with another heating component when the heating power of the main component does not provide sufficient supply. Usually, an IHE element is used to generate the supplementary heat and thus the operation is mono-energetic, i.e., limited to a single energy carrier, because electricity is the only energy carrier except from environmental heat. In case of gas or oil boilers, two energy carriers are used. The term bivalent partially-parallel refers to a gradual transition from one heating component to another.

The efficiency and power levels of heat pumps and ab- as well as adsorption chillers depend on the temperatures of related storage systems and the ambient air. Therefore, scheduling such systems does not only affect their operation time but also their efficiency and operating points. An integrated and automated energy management that considers all these effects and, in addition, the interdependencies between the devices and systems may help to exploit opportunities, such as times of low or high outdoor temperatures, respectively, storing more efficiently generated energy carriers for later use, despite the standing losses. In so doing, this requires device models and the prediction of future demands and outdoor temperatures. Therefore, automated BEMSs and other methods of *Energy Informatics* may help to increase "energy efficiency beyond what engineering can do" [21].

3 Multi-modal Energy Management of Hybrid Devices and Systems

As the previous section points out, to date, there is no consistent terminology of hybrid devices, systems, and operation modes. Similarly, there is also no consistent terminology regarding the energy management of multiple energy carriers in (local) energy systems. **Table 17** presents an overview of the terms that are used in the contexts of energy management and of hybrid devices and systems. They refer to properties, such as the utilization or provision of different energy carriers, respectively, the usage of different energy sources, the combination of different distribution, conversion, or storage technologies, and the provision of different energy services.

Table 17 Overview of terms in the context of energy management of multiple energy carriers

Term	Exemplary references
Integrated energy systems	[52, 62]
Hybrid	[12, 15-17, 19, 43, 48]
Multi-carrier	[20, 41, 51]
Multi-commodity	[1, 5, 28, 38, 44]
Multi-energy	[19, 36, 40, 46]
Multi-fuel / dual-fuel	[2, 25, 36, 48]
Multi-generation / poly-generation / co- & trigeneration	[10, 11, 37, 39]
Multi-modal	[12, 44, 58]
Multi-product	[24]
Multi-service	[36, 47]
Multi-source	[24]
Multi-valent / bi-valent	[15-17, 34]
Multi-vector	[22, 32, 36]

3.1 Proposed Terminology for Hybrid and Multi-Energy Devices and Systems

Since the variety of terms complicates the scientific discussion, we propose the terminology given in **Table 18**. In addition to the standardization of terms, this terminology enables to refer more clearly to different hybrid devices and systems by defining terms for all stages of the energy chain. Although the table provides only the terms for hybrid and multi-energy devices and systems, the prefix "multi-" is substituted by "single-" in the opposite cases. Instead of using these prefixes, which come from Latin, the prefixes "poly-" and "mono-", which come from Ancient Greek, could have been used. However, most of the literature prefers the usage of prefixes that come from Latin (see **Table 17**). The proposed terminology avoids the ambiguousness of other terms, such as the different notions of "monovalent" and "monoenergetic" (see Section 2), and introduces terms that are structured along the energy chain, i.e., utilization, distribution, conversion, storage, and provision. Therefore, it may be used not only in local energy systems but also in large multi-modal systems that perform sector coupling.

Table 18 Proposed terminology for hybrid and multi-energy devices and systems

Description	Proposed term
Utilization	Multi-utilization
Utilization of multiple energy carriers	Multi-carrier utilization
Utilization of multiple energy sources	Multi-source utilization
Distribution	Multi-distribution
Distribution using multiple energy carriers	Multi-carrier distribution
Distribution using multiple links	Multi-link distribution
Distribution using multiple technologies	Multi-technology distribution
Conversion	Multi-conversion
Conversion of multiple energy carriers	Multi-carrier conversion
Conversion using multiple stages	Multi-stage conversion
Conversion using multiple technologies	Multi-technology conversion
Storage	Multi-storage
Storage of multiple energy carriers	Multi-carrier storage
Storage of multiple energy storage systems	Multi-system storage
Storage using multiple technologies	Multi-technology storage
Provision	Multi-provision
Provision of multiple energy carriers	Multi-carrier provision
Provision of multiple energy services	Multi-service provision

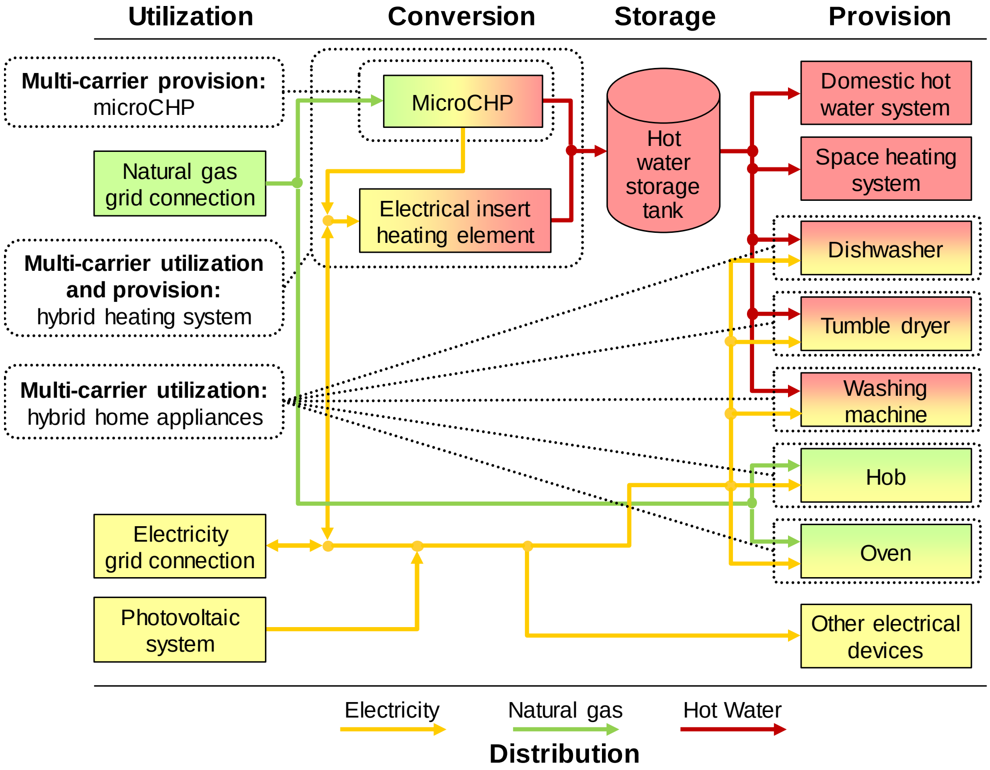

Figure 25 Smart residential building scenario as multi-energy system

3.2 Exemplary Multi-Energy System

As an exemplary multi-energy system, a smart residential building scenario is depicted in **Figure 25** using the proposed terminology: The small combined heat and power plant (microCHP) is a conversion system that enables *multi-carrier provision*. In combination with the electrical IHE, both devices are a hybrid heating system, i.e., a conversion system, that facilitates *multi-carrier utilization* as well as *multi-carrier provision*. The hybrid home appliances enable the provision of energy services as devices that perform *multi-carrier utilization*.

These are only some examples that may be found in buildings. Additionally, there may be *multi-service provision* by means of washer-dryers, *multi-technology conversion* using heat pumps and electrical IHE [6], *multi-source utilization* in case of multiple heat source for heat pumps [33], *multi-technology storage* in combined battery and supercapacitor energy storage systems that enable *multi-service provision* of electricity supply and ancillary grid services [27], and *multi-technology conversion* in trigeneration systems that use not only a microCHP but also a gas boiler [37].

4 Smart Residential Building Scenario

The specific smart residential building scenario that is used in evaluations is depicted in **Figure 26**. The single household comprises a photovoltaic (PV) system, a hot water storage tank with an electrical IHE that has controllable power levels, and (hybrid) household appliances. Electricity is utilized by the appliances, the electrical IHE, and other devices that are simulated as baseload. The hot water is consumed by the space heating and some of the hybrid appliances. The devices are managed by the BEMS that communicates not only with the devices and systems but also with the electricity and natural gas meters at the grid connection points. The specification of the simulated smart residential building scenario is given in **Table 19**. The framework that has been used to simulate and evaluate the smart residential building scenarios is open-source[101] and described in detail in [42].

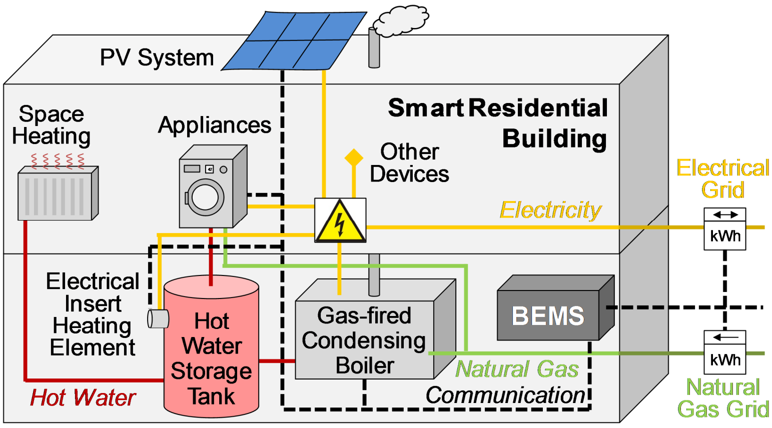

Figure 26 Overview of the smart residential building scenario used in the evaluations

4.1 Home Appliances

Home appliances are used in buildings to perform energy services related to *household functions*. Usually, they utilize a single energy carrier, such as electricity, hot water, or natural gas. In contrast, this paper considers hybrid appliances (see Section 3) as a possibility to increase the local flexibility with respect to the usage of different energy carriers. To allow for a detailed evaluation of their impact on the total costs and the local self-consumption as well as self-sufficiency regarding distributed generation, the usage of the appliances must be simulated realistically. Therefore, this paper uses statistical data on appliances usage as well as operation cycles and real load profiles.

Average Number of Appliance Operation Cycles, Program Selection, and Usage Times

The average numbers of appliance operation cycles per household and year largely depend on the number of persons per household [31, 50]. The values used in this paper are given in **Table 20** and based on statistical data [26, 27, 31, 42-44, 50, 54-57] as well as data measured and profiles recorded in our smart building laboratories [27, 42].

[101] http://www.organicsmarthome.org

Table 19 Specification of the simulated smart residential buildings

Smart residential building type	Four-person household
Yearly electricity consumption	4700 kWh
thereof: major appliances	1372 kWh
thereof: residual baseload	2628 kWh (simulated using SLP H0)
Simulated major appliances	Dishwasher, hob, oven, tumble dryer, washing machine
Minimum deferability	0 hours (all)
Average deferability	6 hours (dishwasher, tumble dryer, washing machine)
Maximum deferability	12 hours (dishwasher, tumble dryer, washing machine)
Efficiency in hybrid modes	η_{hybrid} = 0.77 (in comparison to electricity: 30% more)
	η_{hybrid} = 0.50 (in comparison to electricity: 100% more)
Photovoltaic system	Real profile recorded in Germany at a resolution of 1min
Electrical insert heating element	
Power steps	0.0, 0.5, …, 3.5 kW (8 power steps)
Efficiency	η = 1.0
Hot water storage tank (combined)	750 liters
Minimum tank temperature (top)	60°C
Maximum tank temperature (top)	80°C
Thermal loss	P_{loss} = 96 W * (θ_{tank} - 20°C) / 40 K
Tariffs	
Electricity, from grid	30 cent/kWh
Electricity, PV feed-in	10 cent/kWh
Electricity, PV self-consumption	0 cent/kWh
Electricity, CHP feed-in	9 cent/kWh
Electricity, CHP self-consumption	5 cent/kWh

To consider different programs, each appliance has at least two different appliance load profiles and the average yearly operation cycles are divided among them (see **Table 20**). The numbers of operation cycles are based on data provided in [13, 26, 50, 54]. The load profiles have been recorded in our laboratories. The usage times of the appliances are simulated using statistical data that distinguishes the day of the week as well as the time of the year to determine the probability that an appliance is used at a certain hour of the day. The average probability density functions of the appliances are depicted in **Figure 27**.

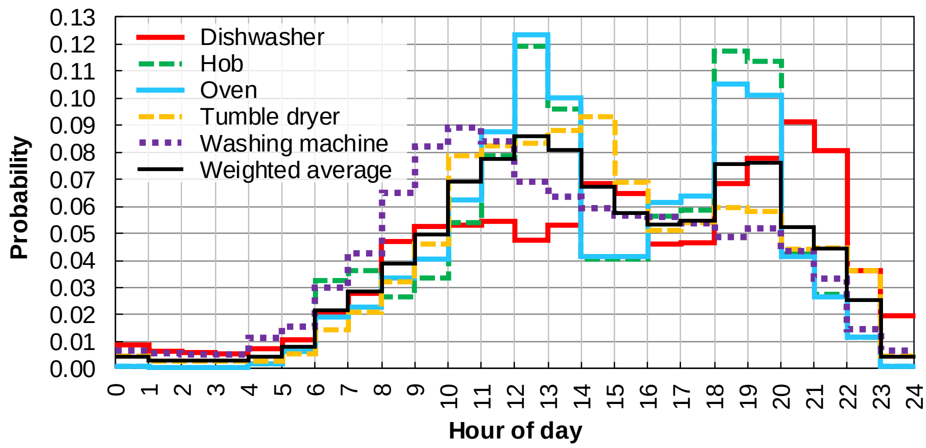

Figure 27 Average usage probability per major home appliance and as weighted average of the five appliances

Hybrid Operation Modes and Load Profiles

In this paper, the hybrid operation modes of the hybrid dishwasher, tumble dryer, and washing machine utilize heating hot water via an integrated heat exchanger. To be able to substitute all electricity that is utilized in the heating processes [57, p.40, p.55, pp.77f.], the hot water in the hot water storage tank has a comparably high temperature of at least 60°C. The hybrid hob and oven utilize natural gas as the alternative to electricity.

To date, there are no real load profiles of hybrid appliances available. Therefore, this paper assumes that the energy consumption profiles of natural gas and hot water are similar to those utilizing electricity but have about 30% or 100% higher loads, respectively (see efficiency in **Table 19** and energy consumption in **Table 20**). This is based on the fact that the utilization of hot water leads to additional thermal losses in the hot water supply system as well as the heat exchangers within the appliances. Furthermore, the utilization of natural gas is less efficient with respect to the local conversion when providing the energy service, i.e., the consumption of natural gas is usually significantly higher, i.e., about 100%, than that of electricity in heating processes [3, 18]. However, this paper assumes that there is a high potential for improvement regarding the consumption of natural gas in ovens and hobs as well as the reduction of thermal losses in the hot water distribution system. Therefore, this paper uses two different hybrid load profiles using a markup of 30% or 100%, respectively.

Table 20 Average appliance operation cycles per major appliance and year and energy carrier that is used in the hybrid operation mode of the appliances

Appliance	Average Operation Cycles per Year	Energy carrier hybrid mode	Energy consumption in kWh Conventional (electricity)	 Hybrid (electricity + other 30% / 100%)		
Dishwasher	310	Hot water				
Program 1	62		0.523	0.037	+	0.636 / 0.979
Program 2	93		0.927	0.100	+	1.091 / 1.681
Program 3	93		1.303	0.087	+	1.587 / 2.443
Program 4	62		1.547	0.140	+	1.839 / 2.833
Average			*1.083*	*0.091*	+	*1.298 / 2.000*
Hob	400	Natural gas				
Program 1	160		0.290	0.003	+	0.377 / 0.581
Program 2	160		0.648	0.006	+	0.843 / 1.298
Program 3	80		1.421	0.006	+	1.847 / 2.845
Average			*0.659*	*0.004*	+	*0.858 / 1.321*
Oven	200	Natural gas				
Program 1	80		0.757	0.008	+	0.974 / 1.500
Program 2	80		1.094	0.020	+	1.396 / 2.151
Program 3	40		1.435	0.145	+	1.677 / 2.582
Average			*1.027*	*0.040*	+	*1.284 / 1.977*
Tumble dryer	270	Hot water				
Program 1	54		1.457	0.144	+	1.724 / 2.656
Program 2	216		2.628	0.251	+	3.010 / 4.635
Average			*2.394*	*0.230*	+	*2.753 / 4.239*
Washing machine	360	Hot water				
Program 1	72		0.363	0.125	+	0.314 / 0.483
Program 2	180		0.654	0.188	+	0.613 / 0.944
Program 3	108		1.039	0.197	+	1.108 / 1.707
Average			*0.644*	*0.178*	+	*0.702 / 1.081*

Data given for a four-person household and based on [26, 27, 31, 42-44, 50, 54-57].

4.2 Photovoltaic System and Electrical Insert Heating Element

The residential building has distributed generation by means of a PV system. It is simulated using a recorded profile that is available in the BEMS simulation framework. It has been recorded in South Germany at a resolution of 1 min. This profile has been resized to a yearly generation of, e.g., 2000 kWh, 4000 kWh, or 6000 kWh, respectively. In the optimization, the PV generation is predicted using the average load profile of the previous 14 days. [42]

In this paper, an electrical IHE, which is also known as resistance, immersion, or screw-in heater, is used in a hot water storage tank to generate hot water. This approach is also called *power-to-heat*. Often, IHEs are used to support heat pumps or are combined with PV systems to utilize the surplus generation. Many IHEs may only be switched on or off, whereas the IHE in this paper has several power steps. It is based on the *EGO Smart Heater*, which has eight power steps from 0 kW to 3.5 kW in steps of 0.5 kW. For the sake of simplicity, it is assumed that it has an efficiency of 100%. [43]

4.3 Simulation Environment and Setup

This paper uses the *Organic Smart Home* (OSH) energy management and simulation framework that is open-source and available on *GitHub*[102]. Each configuration in the simulation and evaluation of the smart residential building scenarios has been simulated using 20 different random seeds to account for different randomized simulated behavior in the household. Overall, a total of 1440 simulation runs has been performed and is presented in the following section.

5 Simulation Results and Evaluation

This section presents the simulations results and evaluates them with respect to changes of the average yearly total costs, the self-consumption rate (SCR), i.e., the locally generated electricity that is also consumed locally, the self-sufficiency rate (SSR), i.e., the share locally consumed electricity that is also generated locally, the total electricity consumption, and the total natural gas consumption.

5.1 Simulation Results

The simulation results for four-person households comprising conventional, deferrable, hybrid, and hybrid deferrable appliances, an electrical IHE, and a PV system of various sizes are provided in **Table 21**. In case of the hybrid appliances, the results of the profiles utilizing 30% as well as 100% more energy than the conventional appliances are provided separately.

Table 21 Simulation results: average yearly total costs, self-consumption, and self-sufficiency in a four-person household (*n* = 20 per configuration)

Appliance setup	IHE	PV	Total costs in EUR	SCR	SSR	Electricity in kWh/a	Gas in kWh/a
Conventional	No	No	2348	–	–	4683	11793
Deferrable	No	No	2352	–	–	4694	11793
Hybrid 30%	No	No	2047	–	–	3147	13781
Hybrid deferrable 30%	No	No	2047	–	–	3150	13772
Hybrid 100%	No	No	2133	–	–	3147	14856
Hybrid deferrable 100%	No	No	2132	–	–	3151	14840
Conventional	No	2 kW	1931	54.3%	23.2%	4683	11793
Deferrable	No	2 kW	1930	55.1%	23.5%	4691	11793
Hybrid 30%	No	2 kW	1651	48.9%	31.1%	3147	13781
Hybrid deferrable 30%	No	2 kW	1651	49.1%	31.2%	3150	13775
Hybrid 100%	No	2 kW	1737	49.2%	31.1%	3157	14838
Hybrid deferrable 100%	No	2 kW	1737	49.4%	31.2%	3160	14826
Conventional	No	4 kW	1659	36.2%	30.9%	4683	11793
Deferrable	No	4 kW	1652	37.3%	31.8%	4690	11793
Hybrid 30%	No	4 kW	1412	30.2%	37.9%	3178	13740
Hybrid deferrable 30%	No	4 kW	1412	30.5%	38.2%	3192	13721
Hybrid 100%	No	4 kW	1498	32.5%	39.0%	3326	14499
Hybrid deferrable 100%	No	4 kW	1497	33.2%	39.5%	3366	14418
Conventional	No	6 kW	1421	27.3%	35.0%	4683	11793
Deferrable	No	6 kW	1413	28.1%	36.0%	4690	11793
Hybrid 30%	No	6 kW	1196	23.0%	42.1%	3276	13612
Hybrid deferrable 30%	No	6 kW	1197	23.4%	42.4%	3304	13575
Hybrid 100%	No	6 kW	1278	25.5%	43.5%	3507	14137
Hybrid deferrable 100%	No	6 kW	1278	26.2%	44.0%	3574	14005

[102] https://github.com/organicsmarthome/OSHv4/

Conventional	Yes	2 kW	2364	73.5%	21.0%	6979	9551
Deferrable	Yes	2 kW	2368	73.3%	21.0%	6988	9550
Hybrid 30%	Yes	2 kW	2184	71.7%	23.8%	6018	10816
Hybrid deferrable 30%	Yes	2 kW	2175	71.8%	24.0%	5970	10888
Hybrid 100%	Yes	2 kW	2243	71.7%	23.7%	6039	11474
Hybrid deferrable 100%	Yes	2 kW	2235	71.6%	24.0%	5973	11618
Conventional	Yes	4 kW	2172	59.2%	30.3%	7822	8728
Deferrable	Yes	4 kW	2170	59.4%	30.4%	7820	8737
Hybrid 30%	Yes	4 kW	2020	58.2%	33.3%	6993	9838
Hybrid deferrable 30%	Yes	4 kW	2010	58.3%	33.6%	6944	9914
Hybrid 100%	Yes	4 kW	2077	57.9%	32.8%	7056	10289
Hybrid deferrable 100%	Yes	4 kW	2067	57.9%	33.2%	6972	10472
Conventional	Yes	6 kW	1945	50.8%	36.6%	8311	8246
Deferrable	Yes	6 kW	1943	51.0%	36.8%	8317	8248
Hybrid 30%	Yes	6 kW	1803	50.3%	40.0%	7542	9298
Hybrid deferrable 30%	Yes	6 kW	1795	50.0%	40.1%	7480	9379
Hybrid 100%	Yes	6 kW	1865	50.1%	39.2%	7659	9601
Hybrid deferrable 100%	Yes	6 kW	1853	49.9%	39.6%	7563	9784

5.2 Visualization of Simulation Results depending on Size of PV System

Selected simulation results are visualized in **Figure 28** and **Figure 29**. The figures show the self-consumption and self-sufficiency rates depending on the peak power and thus yearly generation of the simulated PV system.

The results show that hybrid appliances decrease the self-consumption rate of locally generated electricity and increase the self-sufficiency rate for all simulated PV system peak powers. The change of the self-sufficiency rate in percentage points is nearly constant for all sizes of the PV system, except for very small ones.

In case of PV systems having a power exceeding 1000 W, the usage of the electrical IHE increases both rates significantly. The changes that are induced by the IHE are considerably larger than those by the hybrid appliances.

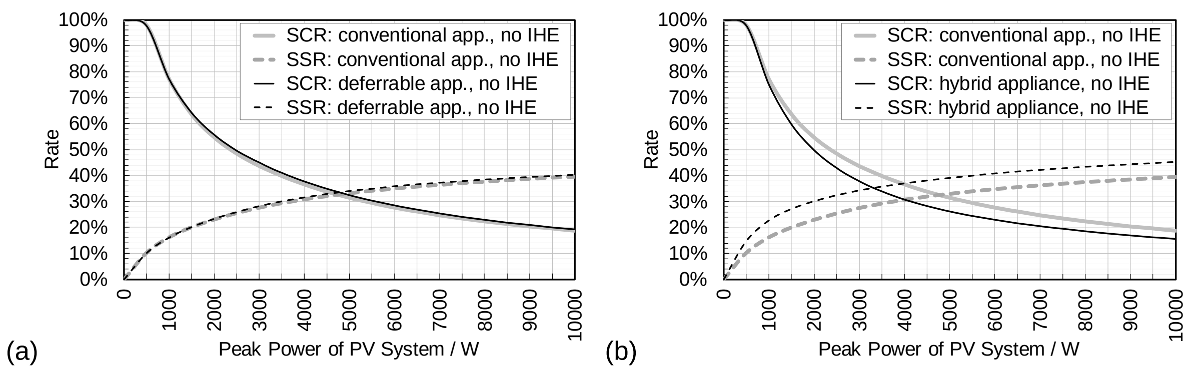

Figure 28 Simulation results: self-consumption and self-sufficiency rates depending on the PV system peak power in a four-person household using (a) conventional and deferrable or (b) conventional and hybrid appliances with η = 0.77

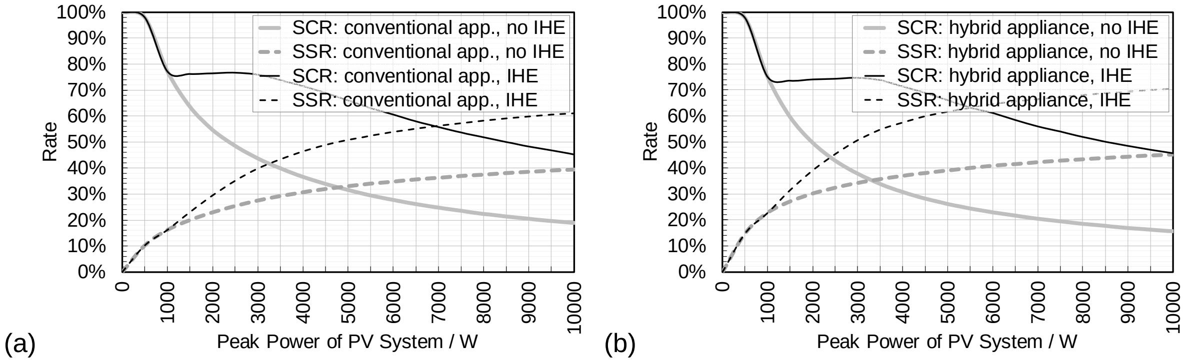

Figure 29 Simulation results: self-consumption and self-sufficiency rates depending on the PV system peak power in a four-person household using (a) conventional appliances or (b) hybrid appliances with η = 0.77 with and without electrical IHE

5.3 Evaluation and Discussion

In the simulations, the hybrid appliances lead to a significant cost reduction of about 150 to 300 EUR per year. Although the effect of a cost reduction is independent of the availability of the PV system or the IHE, the value of the cost reduction depends on the availability and the parameters of the other devices. Most of the savings are achieved by using less electricity and more natural gas, which has lower prices in the evaluation scenario. However, in case of sufficient local generation and a low hot water tank temperature, the appliances utilize electricity. When introducing a time-variable electricity tariff or other measures of demand response, the hybrid appliances may react dynamically and facilitate demand side management as demonstrated in [44].

In case of local generation, hybrid appliances reduce the self-consumption rate of the electricity, because most of the time it is substituted by another energy carrier that is used in the hybrid operation mode. Therefore, the overall electricity consumption in a four-person household is typically reduced by about a third. Making the hybrid appliances deferrable reduces the decrease of the self-consumption rate that is caused by the introduction of hybrid appliances.

The usage of the IHE increases the total costs. This is caused by the natural gas price, which is low when compared to the PV feed-in tariff. However, the IHE increases the self-consumption rate significantly and reduces the natural gas consumption, decreasing the consumption of fossil energy carriers and thus carbon dioxide emissions. Furthermore, the IHE helps to keep the self-consumption rate at about the same level, no matter whether there are conventional or hybrid appliances. In general, the IHE requires at least 500 W feed-in to the grid by the PV system to utilize any electricity at all. Therefore, the PV system must have a peak power of at least about 1000 W to provide enough electrical power for the IHE now and then.

Although increasing the total costs and the natural gas consumption, the results of hybrid appliances that are less efficient ("100%", η = 0.5) are similar to those that are more efficient ("30%", η = 0.77). This demonstrates that hybrid appliances are a promising approach towards sector coupling in buildings, even if they are locally significantly less energy-efficient than those using only electricity when providing the energy services.

It is important to note that the choice of the operation mode of the hybrid appliances depends on the relative structure of the electricity and natural gas tariffs. Because of this, the results are true for markets, in which the feed-in compensation for electricity is higher than the gas price. For instance, this is the case in the German market, but it is different in other countries or may change in future markets. Nevertheless, the results demonstrate the ability of hybrid appliances and IHEs to provide additional potential for flexibility regarding the utilization of electricity. This feature can be used to support the grid in future multi-modal smart grids by reducing the energy fed into the grid and reacting on dynamically changing consumption as well as feed-in tariffs.

6 Conclusion and Outlook

This paper introduces local multi-modal energy systems and proposes a terminology for hybrid and multi-energy devices and systems. In this context, the need for a local multi-modal energy management has been formulated. The potential of such a multi-modal energy management system has been demonstrated by performing bottom-up simulations of a smart residential building that is equipped with hybrid home appliances and an electrical insert heating element.

The results of the simulations show that hybrid home appliances that are managed by an automated building energy management system reduce the energy costs, decrease the self-consumption rate of locally generated electricity, and increase the self-sufficiency rate of the smart residential building. At the same time, the introduction of an electrical insert heating element helps to increase the self-sufficiency and keep the self-consumption rate at a high level if hybrid appliances are used.

Thus, the usage of electric insert heating elements and building energy management systems that optimize the operation of hybrid appliances in households leads to a higher flexibility of energy consumption by means of utilizing different energy carriers. This flexibilization will help to enable the transition in our energy system and the paradigm shift from “supply follows demand” to “demand follows supply”. Therefore, local multi-modal energy management systems promise to help to make the best possible use of existing fossil fuels, renewable fuels, power-to-X technologies, and thermal as well as electrical energy storage systems. For that reason, it would make sense to consider hybrid appliances as well as automated building energy management systems in future energy labeling.

Future work will address the integration of microCHPs, fuel cells, and battery energy storage systems into the simulations and the evaluation of them in combination with hybrid appliances. Additionally, to evaluate and demonstrate real hybrid appliances in practice, we work on integrating them into our laboratory buildings. In so doing, the results of the simulations presented in this paper may be verified by practical evaluations. In a next step, the developed concepts of a local multi-modal energy management system will be extended to a regional multi-modal energy management system that manages the multi-modal energy system on a regional scale, i.e., in a (sub-)urban distribution grid consisting of a variety of smart residential buildings, district heating, energy storage systems, and power-to-gas systems.

Acknowledgments

We gratefully acknowledge the financial support from the German *Federal Ministry for Economic Affairs and Energy* (BMWi) for the project *C/sells* (funding no. 03SIN121) within the research initiative *SINTEG* and the project *Advanced Decentral Grid Control* (funding no. 03ET7539F) within the initiative *Zukunftsfähige Stromnetze* as well as from the *Helmholtz Association*'s research program *Storage and Cross-linked Infrastructures*.

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A new approach for residential real-time energy feedback using a low-cost non-intrusive load monitoring framework

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Abstract

Most consumers know little about their home energy consumption. Providing detailed, personalized actions for saving energy is a key feature of in-home energy displays, encouraging consumers to reduce consumption. However, studies have shown inconclusive results regarding the effectiveness of commercially-available in-home energy displays, possibly due to providing delayed feedback without an effective consumption breakdown. Research shows that real-time residential energy displays lead to better identification of actions that affect energy consumption, compared to delayed feedback after one hour or longer.

Non-intrusive load monitoring is a well-known approach for measuring household energy consumption and automatically identifying individual plug loads. However, real-time disaggregation algorithms require high-resolution energy data and computational resources unavailable in most homes. Installing additional resources in homes to collect and analyze energy data would require a substantial investment and pose significant challenges. However, additional sources of information at home may enable feasible techniques to perform non-intrusive load monitoring.

This paper presents the implementation of a low-cost, real-time monitoring framework displayed on home televisions, named Energy Channel. This project was developed in collaboration with a Southern California utility company. The solution collects energy data directly from the local smart meter. This framework utilizes a home area network (HAN) and a mobile application to collect additional data and perform non-intrusive load monitoring. The proposed solution compensates for lacking additional sensors and high computational resources with additional sources of information, including historical consumption data, consumers' location, local weather, house properties, and consumer input via smartphone. This paper presents an overview of the framework, along with preliminary results of non-intrusive energy loads classification into predefined categories.

Introduction

Reducing residential energy usage is essential for proper implementation of the initiative for Zero Energy Building[103] in California. Energy consumption depends not only on what plug loads and attached systems exist within the home, but how the occupants use these devices and systems. However, most consumers still have little to no understanding about their energy consumption at home. Providing them with detailed information and personalized actions to save energy appears to be a key feature for further energy savings. However, prior studies with commercially available energy displays have shown mixed results that can lead to the conclusion that energy display are indeed effective. The differences of results among previous studies may be due to limitations such as providing delayed feedback and the lack of an effective consumption breakdown. [1], [2], [3], [4]. In partnership with Southern California Edison, the authors have developed and tested a low-cost, real-time monitoring framework to address these limitations.

Previous Work

Based on previous research, there is a set of features that seem to make energy displays more efficient and engaging:

[103] "An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy." Source: The National Institute of Building Sciences. *A Common Definition for Zero Energy Buildings.* U.S. Department of Energy, September 2015.

1. Research has demonstrated that energy displays with real-time data are useful and empowering for consumers in saving energy. Providing instantaneous feedback on household electrical demand allows consumers to immediately identify which devices are contributing to shifts in total energy use, and can reduce energy consumption by 5-15%. [1], [2]

2. When a set of interfaces with different sizes are provided to monitor energy consumption (i.e. desktop monitors vs mobile interfaces), consumers prefer larger screens, more graphical content, and access to more information. [3]

3. Any solution for boosting energy efficiency in residential environments should be easy to install and access, require little to no maintenance, and be easily integrated as a low-cost tool in the consumer's home.[4]

Objective

Based on the previous studies cited, the authors designed a new solution in an effort to address the limitations found.

1. To provide consumers with rapidly updated real-time usage, data can be collected directly from local sensor systems in the home: namely, a potential solution could take advantage of the current Advanced Metering Infrastructure (AMI) in place in a growing number of households in California; the utility's smart meter.

2. Consumers' preferences for large displays motivates the use of TVs to display energy data and consumption feedback. Using the TV as the primary interface provides a large energy display, central in most homes. Americans watched TV an average of almost five hours per day in 2015 [5], which motivates the use of this appliance to capture consumers' attention.

3. Easy access to the device can be achieved using TVs as an energy display, as it can be accessed by switching a channel or a video input. Most current TVs present powerful computational power and operating systems (e.g., Android) that facilitate running applications such as the one proposed in this project. Moreover, potential alerts displayed on the TV may have longer term impact than alerts that are just notified on devices or mobile.

In short, the project goal is to implement a "plug and play" device to bring real-time energy information to the television for display to the end user. The TV can serve as a simple and easy means of providing energy use feedback to consumers and maximizing energy consumption awareness at home.

Framework Overview: The Energy Channel

In the current project, the authors use market-available devices to assemble, implement, and demonstrate a proof-of-concept device. The proposed energy display is integrated mainly into the television, but also into a mobile app, which can greatly expand the range of locations from which consumers can access the solution. This solution is referred to as Energy Channel. As a first approach to build a proof of concept, an additional device, a TV interface "dongle", provides video input to the TV via HDMI, receiving and displaying information on energy use, energy costs, and other features, to engage consumers in increasing their energy efficiency.

Hosting Device

To allow consumers easy access, the proposed solution can eventually be integrated into the TV. This integration would be possible thanks to the emerging technology for Smart TVs, which provides operative systems in TVs (Android, for instance), which provides a convenient platform to run third party software. However, for this initial proof of concept, the authors used a TV dongle (minicomputer) that is provisioned with an HDMI video output to connect to the television. The minicomputers that host the Energy Channel are referred as the Energy Channel host, or EC-host. The authors have implemented Energy Channel on two different platforms so far: Windows 10 using an Intel stick, and Android 2.1 using a MK809 stick.

The EC-host interfaces with the TV using HDMI video input. USB input is used only for additional powering of the hardware. The targeted content of the Energy Channel is retrieved when the TV input corresponding to the device is selected.

Real-time Energy Data Collection

To collect energy data from the smart meter, the authors use a ZigBee-to-USB adapter. In this case, a market-available solution was chosen; the RAVEn unit developed by Rainforest Automation. The RAVEn unit is accessed and controlled by an application programming interface (API) directly from the EC-host. Energy data can be collected directly from the smart meter up to a maximum rate of one sample every five seconds. Additionally, historical energy information can be retrieved directly from the local smart meter at home, which provides up to three prior years of hourly data. If the smart meter was installed recently, historical data can be accessed through the Green Button initiative[104] using the home area network (HAN).

Input Device

For simplicity and cost reduction, Energy Channel does not require any additional peripherals on the TV to enable consumers' input. Instead, the authors implemented a web service in the EC-host, which allows customers to manage the framework through a web app and a mobile app. These applications are accessible through computers and mobile devices in the HAN, and they can be used to customize parameters of Energy Channel, such as notifications and colors. In addition, the mobile app is used to connect to the EC-host using Wi-Fi during the first installation. This provides an automated tool for the initial setup of the Energy Channel, making the setup easier and more intuitive for customers. During this automated initial setup, the EC configures the HAN to access the Ethernet and potential additional online services.

Notifications and Alert System

A smart system for notifications is embedded in Energy Chanel to occasionally notify consumers of new energy usage information such as budget alerts, potential savings, incentive programs and scheduled outages. The alerts include relevant information from the utility company, such as outages and "demand response" or "peak hour" events. The alerts can be retrieved in several ways. If consumers offer a phone number during the initial setup, Energy Channel can send the alerts via push notifications in the mobile app and via text message. Additionally, an LED light displays from the EC-host each time an alert has been triggered or when sensitive information is available. The consumer can then turn on the EC to view more detailed information. The notification system is centralized in the EC-host, which synchronizes the reception of the notification. Once the consumer accesses the information from one device (TV or smartphone), the EC framework marks that notification as seen and removes it from the other device.

User Engagement

The authors designed and implemented additional features in the interface which, based on previous research, should enhance user experience and keep consumers engaged in energy savings. Some of the additionally features included for users engament consist of visual aids, animations and a character-based game that measures the potential energy savings achieved. Energy Channel provides consumers with tailored advice to improve their energy consumption at home by integrating several sources of information, including high-granularity aggregated energy data, consumers' smartphone locations (if they allow this feature in the mobile app), house location and properties, and local weather. For example, Energy Channel can identify major appliances being used and suggest shifting their use to target off-peak hours, and can estimate potential energy savings by comparing historical data and usage of similar houses in the neighborhood.

Framework Implementation

As mentioned in the framework overview section, the authors implemented both a Windows version and an Android application to run the proposed proof of concept. However, both versions share the

[104] The Green Button initiative is an industry-led effort that responds to a White House call-to-action to provide utility customers with easy and secure access to their energy usage information in a consumer-friendly and computer-friendly format. Source: Department of energy. U.S. Government.

same structure, the main difference between them being the language for the backend implementation.

Figure 1 provides a diagram of the Energy Channel framework and the list of services included for data collection. The main data stream for the Energy Channel is the energy data. The EC-host (listed as microcomputer in Figure 1) uses a USB-ZigBee unit (RAVEn by Rainforest Automation) to connect with the home smart meter, collecting and storing the meter reading of "instantaneous power demand" into a local database every five seconds.

In addition to collecting the power demand, the EC-host gathers data from additional sources to provide a more effective picture of the consumer's energy usage, as well as providing helpful tips for homeowners. Energy Channel uses several web APIs to access the following services:

- Twitter, to retrieve the utility company's tweets regarding important messages such as notifications of outages. Tweets can be filtered by hash tag based on their importance and suitability to be displayed in the EC.
- Zillow, to gather features about the household and houses in the same area. This data is used to compare energy usage with similar homes in the area that are using the Energy Channel.
- Green Button, to collect historical energy consumption information if needed (that is, if past data on energy consumption cannot be gathered from the consumer's smart meter).
- The Weather Channel, to collect local weather information such as temperature, precipitation, humidity and wind.

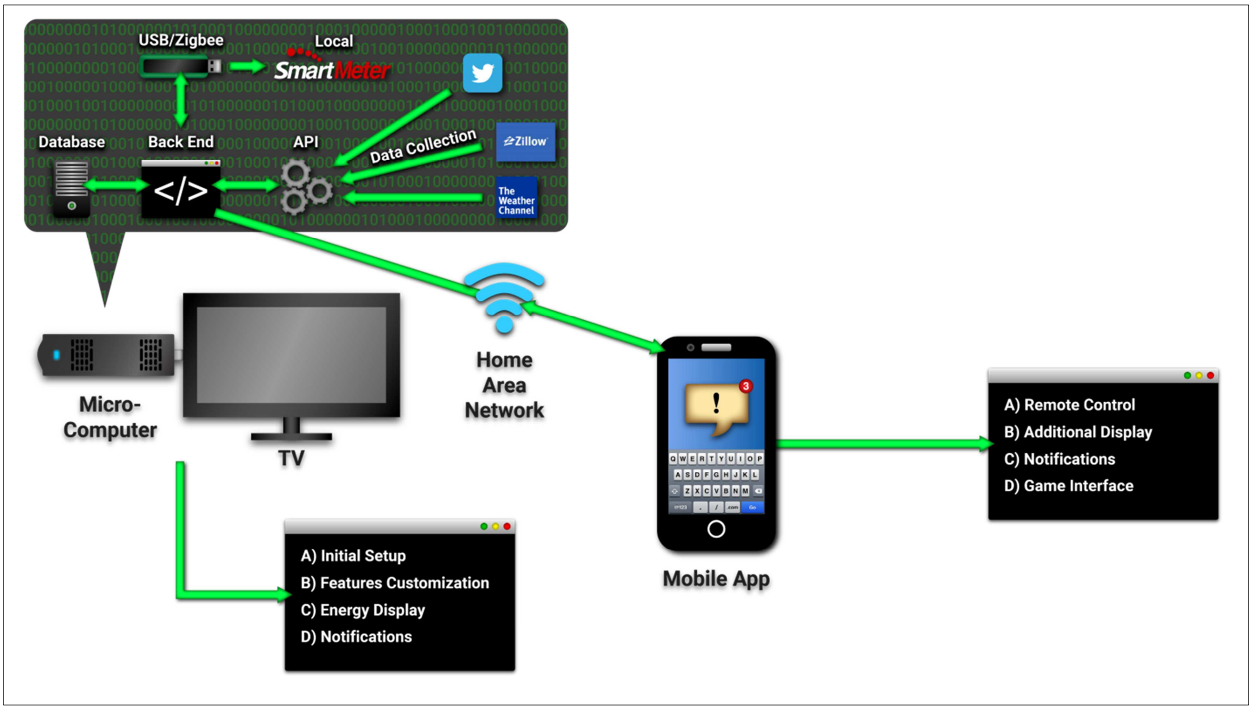

Figure 1. Overview of the Energy Channel framework

Back-end Implementation

Python is the language used here for back-end development in both Windows and Android environments. Python, an interpreted language, has no compilation time; this allows for speedy, incremental updates and tests. It is portable across platforms as well. The back-end in use is a SQLite database that stores the information retrieved from several sources, such as the smart meter for power demand, The Weather Channel for local weather, Zillow for house properties, and Twitter for updates from the utility company. It has one dependency, PySerial, which does not come with the standard Python distribution, but is available in Python's code repository. PySerial is used for communicating with the Rainforest RAVEn. It simplifies the interface between Python and the USB device. This software package was chosen over others such as PyUSB because it does not require any installation of a generic driver. By eliminating steps needed to build the application, it will be more portable and easier to test on multiple devices. The backend consists of three classes: Raven, SQLiteHelper, and ZillowSearch.

Raven is a class that handles the input and output with any Rainforest RAVEn device. It can create, send, and parse XML fragments to and from the device. There are several class methods, descriptions of which can be found within the source code documentation.

SQLiteHelper handles the storage and retrieval of data provided by the RAVEn unit. It uses SQLite, a software library that implements a self-contained, server-less, zero-configuration, transactional SQL database engine. SQLite offers several advantages over other database solutions such as PostgreSQL or MySQL. First, SQLite databases require no administration, which works well for embedded devices for Internet of Things (IOT) applications. Second, SQLite is a built-in of Python, which makes distribution of the application easier. A bonus of SQLite being part of Python is ease of data analysis: additional modules have been written for analysis of the data in an effort to disaggregate energy and analyze consumers' habits regarding energy usage.

ZillowSearch, as the name suggests, can search for data about a particular home and find comparable ones in the online Zillow database. Through using Zillow's API, we can find details about a consumer's home (mainly number of bedrooms and bathrooms, and square footage) with the goal of categorizing the household and comparing its energy usage to other similar homes in the neighborhood. This information is useful in data analysis. It was also used to implement a game-like feature that allows consumers to better understand their potential savings and encourages them to adopt energy-saving initiatives.

Certain small tasks can be performed with the custom module util.py: for example, getWeather, a function that can download weather data from OpenWeather for a particular zip code. This data will be used to help consumers adjust heating and cooling settings like air conditioning to use them more efficiently. It can also be used to save energy on lighting by utilizing the times listed for sunset and sunrise.

Energy Disaggregation

Non-intrusive load monitoring (NILM) is a computational technique for estimating the power demand of individual appliances from a single meter which measures the combined demand of multiple appliances. In a household, this would mean itemizing individual plug loads from a single residential smart meter. [6] Performing NILM is still challenging in residential environments, as previous research conducted in NILM required fine time-resolution data (i.e., several hundreds of data points per second) and long periods of observation to be able to disaggregate energy loads with reliable accuracy. The main reason is because the most effective algorithms currently in use for NILM are based on artificial neural networks (ANNs). ANNs are directed graphs where the nodes are artificial neurons and the edges allow information from one neuron to pass to another neuron (or the same neuron in a future time step). ANNs can be trained in certain categories or series of energy data. Given the number of undefined loads in a household, the number of neurons needed are extremely elevated, needing long training processes as well.[7] [8]

The Energy Channel framework is limited by the smart meter communication, which only provides one data point every five seconds. This resolution is not enough to perform accurate NILM. In addition, for data privacy, cost reduction, and easy deployment, the current framework does not include a cloud server where data could be collected, allowing it to be accessed by the additional hardware necessary to perform high-computational processes for energy disaggregation. Instead, the EC-host acts as a local database and web server. The processing resources of the EC-host are intended to be local, and therefore limited. Consequently, we can conclude that the proposed framework would not present enough resources to conduct energy disaggregation to the level of individual appliances.

Recognizing these limitations, the authors have identified a set of strategies to categorize loads using the presented framework. Instead of targeting energy disaggregation at the appliance level, the authors implemented a model for a "clustered disaggregation" that categorizing loads into four groups, providing consumers with a simplified breakdown consumption, yet helping them to better understand their energy data. The four clustered loads were defined as follows:

a) *Air Conditioning*, by itself, constitutes a category of loads given its high-power demand, characteristic pattern and strong correlation with the local outside temperature.
b) *Electrical Vehicle*, by itself, constitutes another category of load given its high-power demand
c) *Major appliances* are aggregated into a third category, including microwaves, clothes washers and dryers, dishwashers, refrigerators, and freezers. These loads pose a relatively high power demand and characteristic patterns of operation
d) Plug loads not considered in any of the three categories above constitute the fourth group: *Miscellaneous Electric Loads*. Most miscellaneous loads present short cycles of power demand under 1 kWh.

Figure 2 presents the implementation of the EC comparison page, where potential savings of disaggregated energy is compared with the average house in the neighborhood.

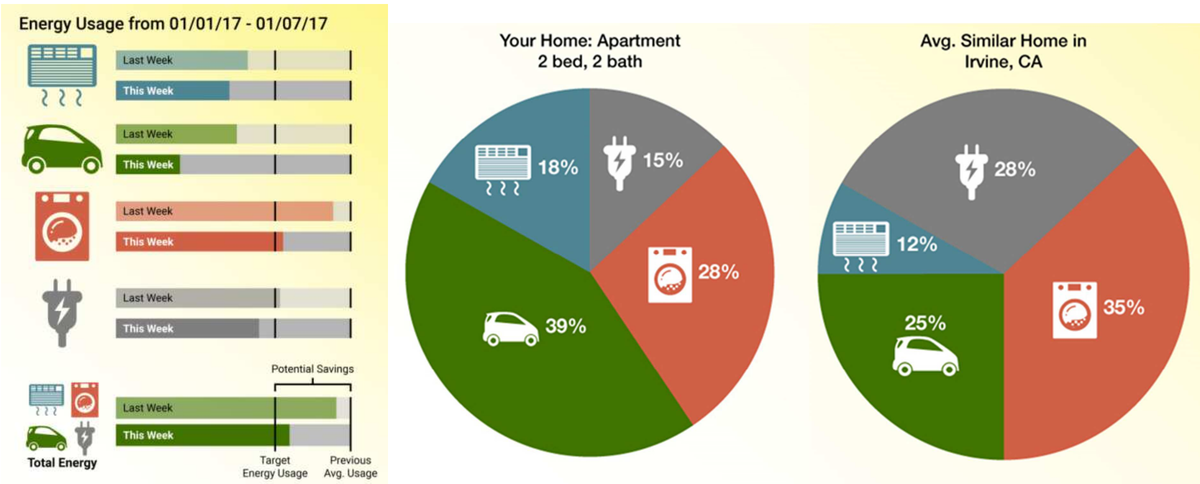

Figure 2. Presentation of clustered categories and potential energy savings.

Data Collection and Analysis Methods

As previously stated, accurately breaking down the household power demand into categories would normally require high computational resources and installing hardware, such as meters. This proposed solution compensates by incorporating additional sources of information, including historical consumption patterns, consumers' location (based on their phone's location), local weather, house properties, and self-reported appliances inventory. Based on these sources of information, we built three probabilistic models as follows:

- *House properties* such as location, footage, construction year, orientation, and number of bedrooms and bathrooms can be retrieved from online databases such as Zillow. This data allows the selection and weight of attributes that greatly impact the expected energy consumption behavior of a given household, and it creates a specific model of energy usage based on the house properties. For instance, this information would help with the prediction of the pattern of cooling and heating systems based on the local weather.

- *Consumers' occupancy pattern* information will create a second model based on the number of people living at the house, and the life pattern of each occupant. The life pattern models are based on the time that occupants spend at home and the activities that they perform when they are at home, allowing the model to better predict the demand distribution [9]. The authors' previous efforts for modeling consumers' patterns at home included a set of sensors to record events (Authors, 2016). In the present work, the approach was to use a mobile app for consumers to occasionally input relevant information and allow the framework to track consumers' location, building more accurate models for each occupant's pattern and user habits patterns regarding the use of appliances. The basic principle is to occasionally present a consumer with an initial guess of the loads that may be in use at a particular moment when that consumer is at home. Then, the consumer can mark whether the list is accurate or not, inputting that feedback directly into the learning algorithm.

- The third and the last model includes an assessment of the total *loads and services* that are present in the house. A database of generic load patterns of appliances is included in the EC-host, which will be used to build the model of total loads and services in the household. The EC mobile app provides an intuitive and friendly interface to survey consumers to voluntarily input this data in order to build this model. It will periodically and progressively present consumers with specific questions regarding the type and number of appliances present in the house.

Gathering the information needed to implement the three probabilistic models presented enables, by inference, an accurate categorization of events that can be categorized in the clustered loads presented. There are several techniques to implement this categorization.[10] Among them, using artificial neural networks and self-organizing maps were found to be the most successful for this project goal.[10], [11]

Exploratory Data Analysis

The first proof-of-concept of Energy Channel was developed in September 2016 and tested with smart meter data collected from two households located in Orange County in California. The goal was to pilot the EC framework and test the accuracy of the simplified disaggregation for categorizing the power demand, based on the techniques presented in this work. This section presents the methods used to collect the data from the two households and build the probabilistic models that enable the clustered disaggregation.

For testing the accuracy of the implemented algorithm, all data regarding household properties, consumers' patterns, and loads and services was introduced by the researchers without using the EC mobile app, by surveying the occupants. Also, individual meters were strategically installed in several appliances to collect discrete data for later comparison and evaluation of the results of the proposed clustered disaggregation. Table 1 and Table 2 shows data regarding household properties and loads information respectively.

House	Footage	Location[105]	Orientation	Bedrooms	Bathrooms	Garage
1	1,326	Tustin, CA	SE	3	2	Attached
2	847	Irvine, CA	NNE	2	1	Detached

Table 1. Participants' household properties retrieved from Zillow API.

House	Refrigerators	Dishwasher	Microwave	Dryer	EV	TVs	Pool	PC	Smart Therm.	…
1	2	1	1	2	1	3	1	2	1	…
2	1	1	1	1	0	2	0	3	0	…

Table 2. Some of the loads present in each participants' household

To allow the EC framework to build patterns of usage by occupancy in each house, participants installed the EC mobile app and signed up as occupants of the house, allowing the app to perform location tracking through their phones. In addition, consumers needed to create a basic profile where they indicated daily activities that they perform, such as working at home, laundry, or using media, which includes music, TV and video games. Using additional sources of information such as historical energy consumption, outside temperature, and thermostat settings, the EC framework can build patterns of probability of use of appliances when different occupants are expected to be at home. It is

[105] Location data in Table 1 was originally retrieved as latitude and longitude for high-accuracy, but it was converted here to preserve confidentiality.

important to note that the location tracking of participants' phones does not constitute a warranty of occupancy by itself, but can be used to estimate an occupancy pattern over time.

Figure 3 represents three different distributions for household 2 in a given weekday: probability of use of appliances (top), occupancy pattern (middle), and local outside temperature (bottom).

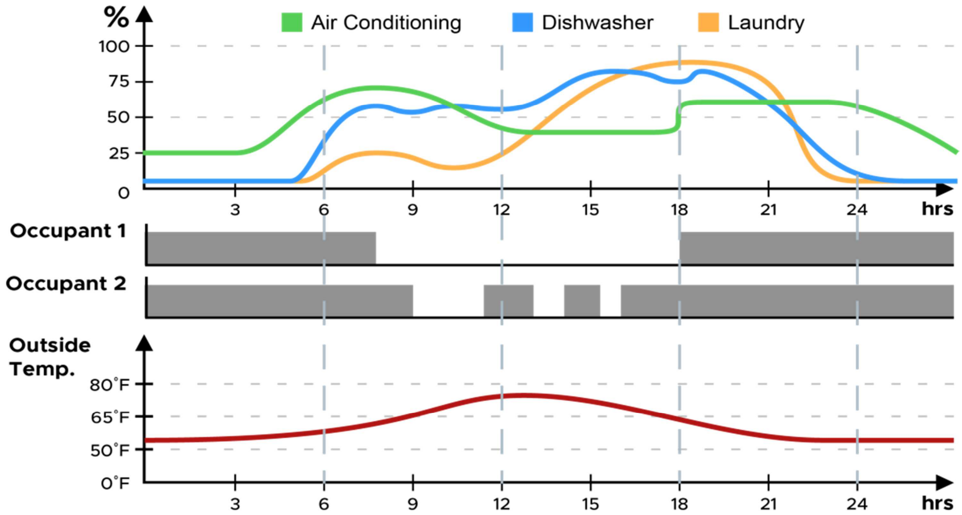

Figure 3. Probability of use of appliances in household #2 on a weekday.

It can be argued that is extremely difficult to differentiate many small loads turned on at the same time from a single major appliance. In addition, the success of algorithms for simplified disaggregation, as the one presented here, may vary depending on each household and consumers' habits. However, given the distribution of use of appliances and the occupants' habits in the two participating households, the resulting identification of categories was satisfactory in the initial pass. Figure 4 presents the accuracy rate for the clustered disaggregation compared to observed data on usage for 3 months of data collected on the two households. Without retrofitting the system (left chart in Figure 4), the algorithm can predict all clustered categories with accuracy of 54% or higher, with the EV being the most accurate category, given the magnitude of the load. A load as large as an EV provides a unique signal that allows the algorithm to identify it regardless of the concurrence with other loads in use.

Although not implemented in the original EC framework, the authors simulated a feedback system where consumers would occasionally receive push notification in the mobile app to confirm the recent use of a major appliance. This allows the EC to improve the accuracy of the initial simplified disaggregation based on a learning process. Assuming this verification was answered by occupants at least 3 days a week for four weeks during random days and times when substantial increment in energy consumption was detected, the accuracy of clustered disaggregation would improve considerably, as shown in Figure 4. The success of appliance detection would increase 8 points, pushing the accuracy of the rest of categories as well. Assuming retrofitting the system with occupants' feedback during a 30-day training period, and based on this simulation, the average accuracy of the EC framework would be 71%, which may be acceptable for customers' satisfaction with the EC application and engagement on energy-saving initiatives.

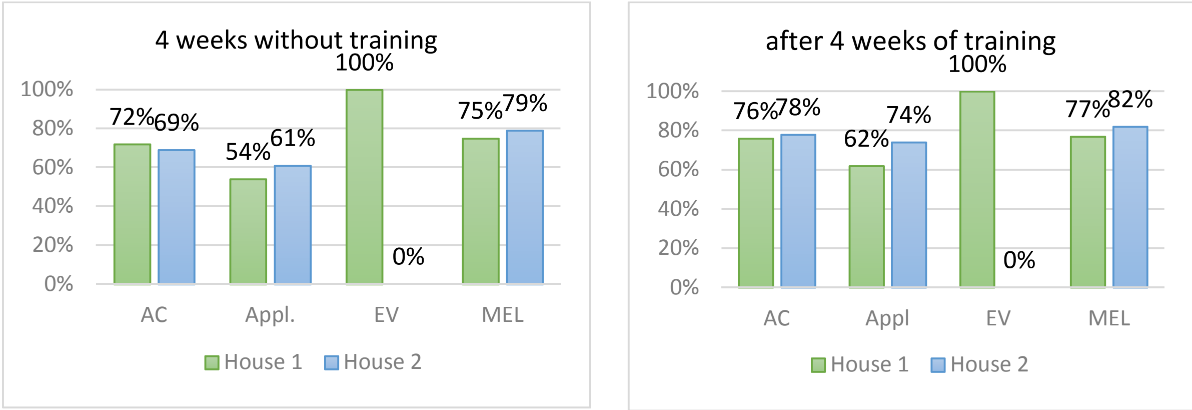

Figure 4. Accuracy of Clustered Disaggregation with and without training data

Front-end Implementation

The front-end is a cross-platform desktop application built using Electron.[106] The authors chose Electron because it can create native desktop apps with web technologies such as HTML, CSS, and JavaScript, which are popular technologies used in web applications that enable the efficient implementation of customized visual elements such as animations and several type of charts. The use of these technologies will also facilitate customers accessing the energy display interface from multiple devices within their HAN, such as web and mobile apps. Charts including bar and pie charts were implemented using D3.[107]

The EC front-end for the TV application consist of two sections. The right section of the interface always shows the instantaneous power demand, including the daily average and projected demand for that day. The left section automatically iterates through a sequence of four pages. Figure 5 presents one of the pages of the EC interface on the TV, the monthly energy usage comparison. Each page in the right section presents relevant information on the household energy consumption as follows:

1) Weekly energy usage: It presents a bar chart that enables comparison with previous periods. Consumers can compare differences in their energy consumption with previous days and weeks, facilitating the identification of causes that rise energy consumption.
2) Monthly energy usage: It presents a bar chart like the weekly energy usage, but arranged by month periods instead.
3) Neighborhood Comparison energy usage: It is used as a way of engagement in potential energy savings when customers realize that their energy consumption is substantially higher that the average in their community for similar households. For engagement purposes, the comparison is hidden if the user’s energy consumption is actually lower than the average.
4) Potential savings: As presented in the framework overview section, the authors implemented an algorithm that estimates the potential energy savings of a household based on occupancy, neighborhood average, and number of appliances present in the house, as well as previously recorded energy use patterns. This potential savings is used in the gamification features that consumers can enable in the mobile app to be challenged with daily energy savings goals.

[106] Electron, also known as “Atom Shell” is an open-source framework developed by GitHub (https://electron.atom.io).
[107] D3 is a JavaScript library for implementing dynamic, interactive data using SVG, HTML5, and CSS standards (https://d3js.org/).

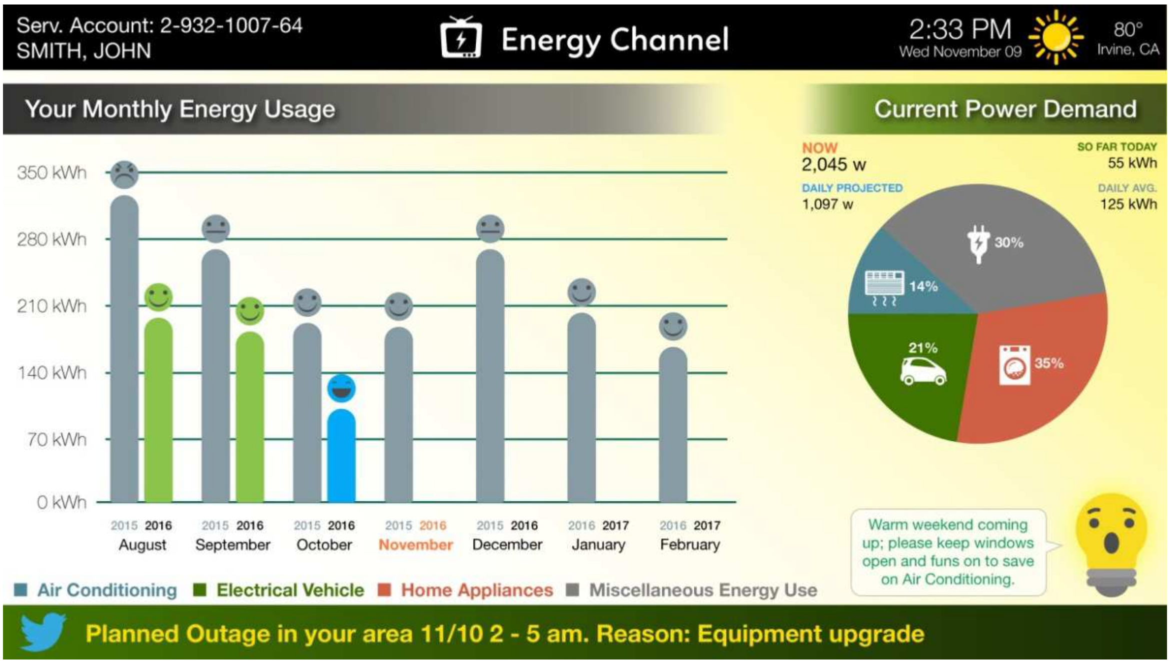

Figure 5. Energy Channel Front-end screenshot - Monthly Energy Usage comparison

Similar to the EC TV app, the EC mobile app was built using Cordova, a cross-platform mobile application framework. Like Electron, Cordova can create native apps using web technologies such as HTML, CSS, and JavaScript. This commonality allowed for sharing and reusing functionality across the mobile and desktop apps. Specifically, the mobile app was implemented to provide consumers with two functionalities: an additional interface to check their EC data and a platform to receive tailored notification. The notification feature of EC delivers information as a regular system of push notifcation and it uses FCM.[108]

The EC mobile app provides information about the clustered instataneous power demand and the potential savings. It also includes the gamification feature that enables users to measure and track their achievement on energy savings. Figure 6 presents two screenshots of the EC mobile app regarding the gamification features, where potential energy savings are presented for each category.

[108] Firebase Cloud Messaging (FCM) is a cross-platform cloud-based messaging service provided by Google currently at no cost. (https://firebase.google.com/docs/cloud-messaging)

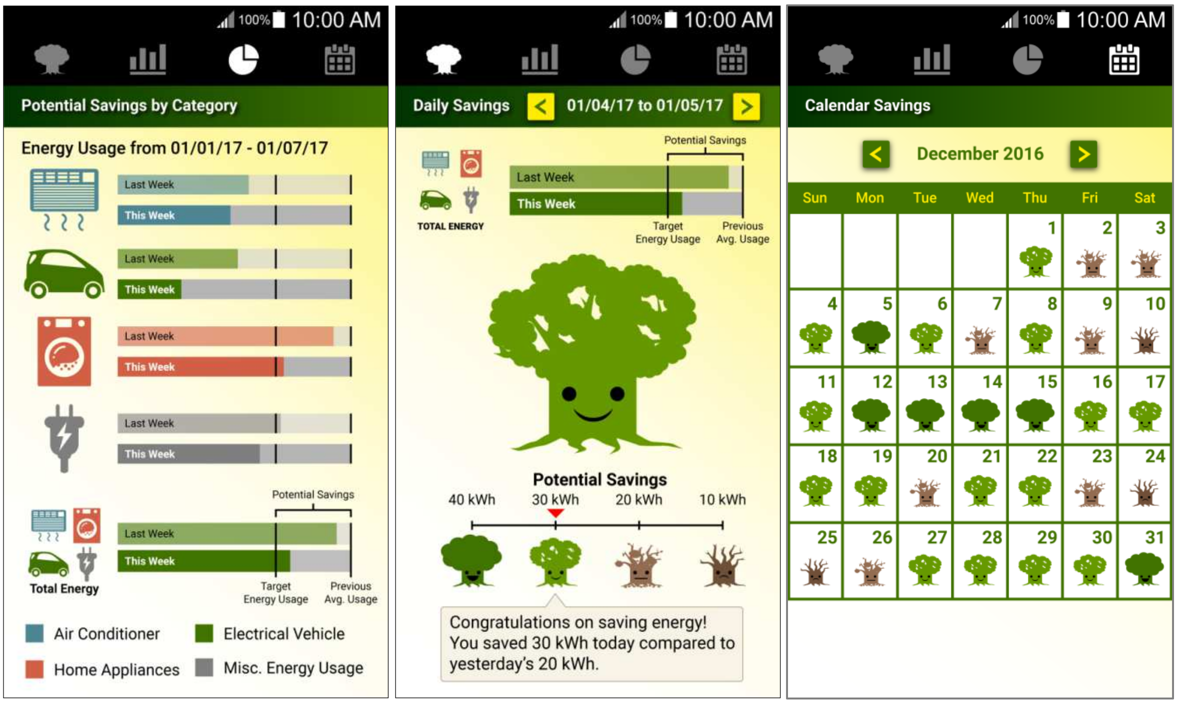

Figure 6: Energy Channel Mobile app - Gamification of Potential Energy Savings

Discussion and Future Work

Energy Channel presents the potential to enable easier access and show more meaningful energy data than a simple monthly bill from the utility. EC can help consumers better understand their energy consumption and identify actions to manage that consumption more efficiently. The EC-host can also serve as an effective gateway that integrates and controls energy management systems, performs energy disaggregation, and improves residential demand/response behaviors. To evaluate the potential of Energy Channel, more participant households, consumer feedback, and testing periods are required. The authors are currently designing an extended field trial that will include the installation of the EC in 15 households, which will allow diverse scenarios and more varied data to evaluate and further improve the current EC framework. The evaluation will focus on how the EC engages consumers through effective energy savings upon acting on immediate actions to be performed by the consumers. It is also expected to conduct further evaluation on the retention of behavioral changes adopted towards energy savings.

The new generation of Smart TVs would be an ideal platform into which Energy Channel could be integrated. The next generation of TVs will include higher computational power and improved operating systems that can be part of the residential network, serving as a hub and interface for smart device interaction in home energy management systems. Finally, home automation extends Energy Channel to plug loads. Aggregated consumption can be broken down to each device, enabling remote control of home appliances, improvement of demand-response programs, and automatic adoption of the identified energy savings.

In addition, customer engagement could be increased through incentives programs to use EC during the training period, and also offering additional entertainment channels like social media. Social networks and especially comparison to similar others can be a source of motivation for consumers. With the right influence, power saving competitions and challenges hosted on Social Media pages may be expected to go viral, hence greatly strengthening public awareness on energy efficiency.

Conclusion

Energy Channel is an energy display presented on the TV and associated web and mobile apps. It translates smart meter readings into categorized loads using NILM algorithms for clustered disaggregation applied to information retrieved from several sources, such as local smart meter, web API's, and mobile apps, making energy data more relevant and useful to customers. The current proof of concept for Energy Channel targets the set of features found relevant by previous researchers as follows:

1. Providing a plug-and-play solution that requires minimal effort by consumers to install, access and operate.
2. Using the most convenient and largest screen at home -- the television -- which allows a comfortable layout for displaying all relevant energy information without the need of browsing content.
3. Displaying real-time energy information at a high sampling rate.
4. Incorporating a set of features promoting consistent engagement in energy efficiency.

In conclusion, Energy Channel offers great promise for engaging consumers by addressing the limitations of other commercial in-home energy display devices. EC provides clear advantages such as plug-and-play installation, inexpensive technology and ease of use. Although further evaluation of the EC features is needed, the present work sets the scene for the next generation of non-intrusive energy displays at home.

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Residential Consumer Driven Energy Management and Feedback

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Abstract

Current Energy Management Systems (EMS) utilize monetary incentives to drive residential load demand. Appliance scheduling is then evaluated based on the type of appliance load, if deferrable or non-deferrable, under the constraints of current price and appliance initiation wait times. Such systems do not take into account human behavior with respect to scheduling convenience. We examine how resident activities of daily living inform energy usage at any given time. By taking human behavior as a driver of consumption, EMS can improve appliance scheduling and home energy efficiency without compromising resident comfort. Furthermore, bidirectional communication between the EMS and the consumer can provide the resident with valuable energy usage feedback with respect to daily living, thereby bolstering consumer acceptance of demand response programs. In this study we present the state of art in EMS technology in the context of current demand side management programs and propose a resident behavior centric EMS framework for the scheduling of appliances given consumer, appliance, grid, and environmental parameters.

Introduction

The traditional grid maintains a delicate balance between supply and demand. The generation and distribution of electricity of the current power system supplies the absorbing active and reactive load demand. To ensure a reliable “smart" grid, the supply-demand balance must be adaptable to renewables, electric storage, electric transportation, and traditional demand [1].

While most controls are inherent to the electronic circuitry at the generation and distribution stage (i.e. frequency control generators and power converters), fluctuations in load demands must be offset with intermittent generation to avoid grid overload and potential sags. While energy storage solutions such as super capacitors and vanadium redox batteries have been proposed to counteract load noise [2] expense in terms of physical and infrastructural cost render energy storage solutions unfeasible compared to traditional generation [3].

Integration of renewables to the traditional grid while beneficial, increases variability and controllability of load balances as renewables are susceptible to transient availability based on environmental factors. Despite this, the Senate Bill 1078 established the Renewables Portfolio Standard program requiring 20% renewable energy by 2017 [4]. Furthermore, California's RPS program seeks to increase energy acquisition from renewables to 33% by 2020 [5]. The push for successful renewable integration complicates traditional power system performance by introducing noise to the line. As is, the power grid is susceptible to control error due to noise on the order of +/- 100MW. By integrating 20% more distributed renewable energy sources control errors increase several times the existing error. 33% integration, as encouraged by California's RPS, would result in over +/-3000MW of control errors to the existing grid [6]. With the shift to 33\% renewables, existing grid infrastructure would set off protective devices, thereby interrupting power flow to residents and resulting in blackouts. Demand Response [DR], however, is an immediate, cost-effective, and significant improvement to grid balancing and smoothing of transients caused by renewables as it does not require significant infrastructure. Navigant estimates that DR can directly reduce CO_2 emissions by 1 percent equivalent to 19.5 million metric tons [7].

Demand Response

Current demand side management presents voluntary and direct utility control options for residents seeking to curtail their load consumption. On the voluntary side, the utility may offer rebates to consumers that replace their appliances with more energy efficient devices. Electric pricing is also used to steer demand. Direct options for residential demand side management include the installation of controllers that the utility can control remotely should the power system be under excess load demand.

Voluntary utility control through pricing incentives, encourage consumers to shift loads to off-peak hours to flatten spikes in demand. Time of use (TOU) pricing sets electric prices according to time of day while dynamic pricing relies on real-time power system conditions based on metering data. The goal of these demand side programs is to influence consumption patterns thereby achieving a manageable load profile.

Direct utility load management employs the use of Automated Demand Response Controllers at the disposal of the power utility in the industrial sector. AutoDR controllers are inexpensive compared to the alternative of ramping up generation to meet supply demands or storing excess energy in expensive batteries that require special infrastructure and installation. In the industrial and commercial context alone, Grid balancing ancillary services to counteract intermittent and non-dispatchable renewables, could double load shedding potential between .42 and 2.07 GW via fast Auto Demand Response. The cost of implementation represents about 10% of the deployed costs of grid scale battery storage [8]. While current openAutomaticDR controllers exist for load shedding of discretionary loads associated with heating and cooling in exchange for utility rebates for the industrial sector, the residential sector has remained mostly unaddressed due to privacy limitations. However, 22% of US total energy consumption is from the residential sector [9]. Since fast AutoDR development has proved successful in the industrial sector, it necessitates availability to the residential sector for loads other than discretionary heating and cooling loads in exchange for rebates.

Both voluntary and direct utility control of residential loads have been met with limited acceptance since current programs do not take into account behavioral motivations for participation. Passive control requires the end-user to be engaged with utility alerts, local pricing schemes, personal daily consumption patterns, as well as future consumption patterns in order to make decisions with respect to when or how long a particular appliance should run. In direct control schemes, the end-user compromises autonomy of a particular appliance, most commonly the HVAC system raising concerns with respect to privacy. In both cases, current demand response programs do not incentivize energy efficient behaviors enough to maintain significant program enrollment.

Energy Management Systems

To increase demand response penetration to residential end-users, both voluntary and direct load control require engagement with end-users without compromising convenience. To alleviate issues concerning autonomy infringement, direct demand-side management must focus on allowing the end user to control utility consumption decision [10].

To address this, consumer load shifting based upon the monetary incentives set by the utility, necessitate the use of automation to control and schedule household appliances which can absorb or generate power via “smart home” systems that provide two-way communication between the consumer and the utility. The energy management system (EMS) offers the convenience of automation introduced in direct utility control or demand side management under pricing constraints used in voluntary programs. In this framework, the end-user may install a home EMS that optimizes the scheduling of appliances based on pricing similar to a thermostat with respect to set point temperature.

In current art presented, energy management systems and models are proposed through simulated case studies with a limited number of appliances that are both resistive or generative. EMS frameworks are built via optimization methods to minimize costs and maximize end-user benefits.

Cost-Benefit Optimization

Proposed work in EMS focus on cost-benefit optimization with respect to electricity pricing as well as user convenience in terms of appliance scheduling wait times. In other words, constraints with respect to consumer comfort values are presented in the form of availability of energy for appliances or parameters recommended by the power supplier. For example, [11] develops an energy management model for distributed energy resources using coevolutionary particle swarm optimization of a benefits-cost function. The appliances to be scheduled represent must-run resistive loads as well as loads associated with PHEVs, temperature systems, and pool pumps. In this framework, the consumer must define the monetary benefit of a unit of energy usage for the system to quantify personal comfort based on ambient temperature, water temperature, and PHEV charge. These parameters then determine the cost of “undelivered services,” taking into account acceptable temperature gradients, water discharge, PHEV discharge under the constraint of tariffs set by the utility. In [12], a taxonomy of appliance types depending on elasticity with respect to power requirements and memory restrictions, is established as a measure of utility indirectly representative of consumer satisfaction. Mixed integer nonlinear programming techniques are then used to perform a tradeoff analysis between maximal utility and minimal cost.

Load Disaggregated Optimization

Load Disaggregation provides end-users with appliance level consumption feedback in contrast to current aggregate load information. In this scheme, appliance load curves are given directly through smart devices and monitoring equipment or are derived from the aggregate consumption in what is known as non-intrusive load monitoring. In [13] residential loads are classified as shiftable and nonshiftable “must-run” loads in the context of autonomous distributed demand-side energy management. [13] applied informed game strategies to total loads in distribution. In appliance scheduling problems, the characterization of discrete or continuous smart appliances becomes important in the optimization technique of choice. [14] used both chance-constrained and robust techniques. [15] continued this body of work by modeling households using 10 smart energy hubs and modeled cases where resident consumers are unlikely to compromise comfort for energy curtailment. Models optimizing and examining the tradeoff between energy savings and thermal comfort level with respect to schedulable and fixed loads were studied in [16].

Consumer Classification

Scheduling based on pricing optimization benefits from consumer classification which takes into account variations in end-user consumption behaviors. In [17], residential energy consumption is classified by a cost-efficiency value which varies for three different consumer behavior profiles. The behavior profiles are qualitative based upon the combinations of appliances and their respective “task cycles'' based on operation. Therefore, consumer behavior, rather than being directly assessed, is indirectly built in to the utility function based on a deadline parameter (the device must activate after a certain period of time irrespective of price) as a measure of user consumption satisfaction under time of use pricing. Further, the utility, or importance assigned to a particular appliance, must again be set by the user. Results indicate that load shifting increased residential cost efficiency. However, the efficiency and resident comfort tradeoff was not assessed. Similarly, [18] developed a utility-centric heuristic-based Evolutionary algorithm to optimize load profiles for day-ahead load shifting. Though results showed that residential consumers had the highest level of tolerance for load shifting, the inconvenience of doing so was similarly not assessed. In [19] an objective function with respect to a utility variable is minimized under daily consumption constraints in the form of ramping up and down limits on hourly levels. In the case study presented, a utility value, representative of the consumer, is set as a constant, when in reality, utility may be variable depending on the type of consumer.

Other game theoretic approaches are based upon whether a resident participates in dual metering programs as a consequence of distributed generation via PV cells or other distributed energy resources. In this scheme, disaggregation or characterization of power line loads becomes of interest. [20] seek to disaggregate appliance loads from the overall power consumption of a single household following survey queries by using duration-specific HMMs. Aggregate power line observations are complex in terms of traceability to specific device characteristics. In other words, more than one appliance could generate similar observations in terms of power information alone. While this may be beneficial in terms of identifying inefficient appliance models, census type surveys of household demographics and appliances are undesirable and inconvenient to residential consumers despite its importance in analyzing these effects on consumption.

End User Behavior Centric Approaches

While the aforementioned optimization frameworks for EMS provide consumers with energy usage information under the constraints of pricing, appliance wait times, and individual appliance usage, such information without a behavioral context may not impact the user to significantly change long-term energy habits. For demand response to benefit from residential EMS, the system needs to take into account the end user. In other words, activities of daily living must be recognized as a major player in consumption choices. The optimization framework must then take resident activities into account prior to scheduling under current popular demand response constraints.

In the work presented by [21], energy patterns were detected using data mining techniques on sensor data retrieved from a smart home testbed. The testbed was fitted with event-triggered sensors such as motion detectors, air and water temperature sensors, power monitors, and other analog sensors. Data collected over several months was analyzed and clustered into normal behavioral patterns and anomalies. Pattern variances and frequencies were then assessed. Results showed that the activities of testbed inhabitants had a correlation with time of day, detected movement, and appliance activation thereby resulting in unique power usage patterns depending on the individual. While the data was not used for the purposes of control [21] did create a web-based application that provided visual passive feedback to the end user with respect to their usage patterns.

Proposed Behavior Based EMS

In this section we elaborate on previous work presented in [22] and [23] which introduces resident behavior as the driver of energy usage patterns and an essential element of feedback for current demand response systems. In these works, user behavioral activity patterns directly influence consumption through activation of appliance operational cycles. The appliances at any given moment contribute to the aggregate consumption, therefore sequences of particular activities unique to a user can be utilized in demand response programs to both classify end-user usage in addition to allowing the end-user a more active role in the system.

To successfully implement a resident behavior based home EMS we need to identify key components of the system in terms of input and output. The EMS agent must acquire sensory data from the environment in terms of the aggregate consumption, user comfort preferences, and the state of the current grid. Based on this data, the EMS can infer resident activity patterns and evaluate the sequences against a dictionary of reference models built into the system and updated with new resident information over time. The EMS is then able to predict future resident activities and consumption states, based on the best fit activity model allowing it to use model predictive control to aid the resident in the scheduling of appliances. The key players of the system are described as follows.

The Resident

Central to the proposed EMS is the resident. In this approach, control of appliances is not based solely on monetary savings in lieu of utility programs such as dynamic pricing or time of use pricing for electricity. Such an approach is desirable as it takes into account the resident's schedule which is subject to change as well as their comfort which is a function of their current home activity. Home activities, however, are difficult to assess without privacy concerns. In other behavioral based models building sensor installation of cameras and motion detectors are required to determine activity events. This also presents an infrastructural cost as the residence must be retrofitted with additional devices. In the proposed EMS, we recognize that this may not be realistic, and use probabilistic inference to determine human activity sequences using aggregate consumption data which is available to the advanced metering infrastructure (i.e. "smart meter") provided by the utility. Examples of these activities include leaving the home, hygiene, cooking, dining, dressing, sleeping, resting, working out, and cleaning. We can also predefine common sequences of behaviors based on behavioral data or likelihoods of one activity following another. For instance, a particular resident sequence may be "hygiene," "dress," "cook," "dine," and "clean." In practice, these behavioral sequences will be learned with use as the system acquires new information with respect to user interaction. A library of past model sequences can be built to assess the current resident state. Note that these activities of daily life cannot be assessed directly by examining the resident load curve at any given time.

Household Appliances

To get a better perspective of how activity may influence consumption patterns, we take an inventory of the appliances available in a single household and categorize them based on their operating duration and dependency on a particular activity of daily life.

We examine the load curve of each individual device using manufacturer specifications and sub-metered device curves. Based on the operational curves we identify power states that the appliance may be in during its use. We can then derive a Markov transition matrix based on the likelihood that when activated, a specific device is in a particular power state. In other words we can analyze the individual appliance load curve and count the frequency of transitions that occur from one power state to another in a time series. Since the frequency is scaled by the total number of state transitions, the value is between 0 and 1, indicative of a probability. An example of individual appliance state transitions is provided in Figure 1.

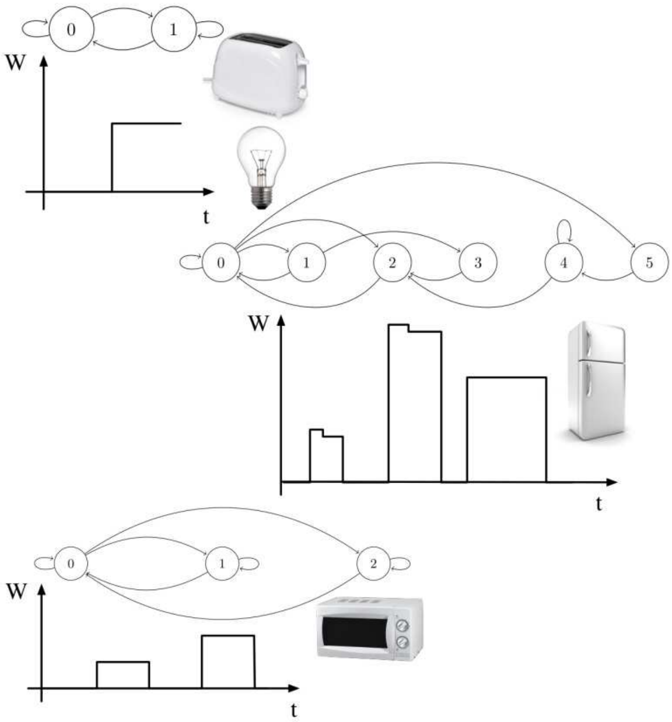

Figure 1: Appliance power consumption curves approximated from manufacturer data and sub-metered data. Operational states are identified. Each device is characterized by transitions that occur between identified states and are represented as finite state machines.

Following individual appliance power consumption characterization as a Markov chain, the appliances are then categorized according to activity dependencies. In other words, there are common electric appliances that a consumer may use for a particular activity at a given time. For example, for the activity "clean," a resident is more likely to use the vacuum, steam cleaner, washing machine, dryer, or dishwasher. Note that while the resident is "cleaning" they may use one, all, or any combination of the appliances aforementioned. Some appliances such as the refrigerator do not have direct activity dependencies as they are required to be on at all times. Also the set of appliances per activity are not exclusive to one another. In other words, an appliance may be dependent on more than one activity of daily living. For instance, the home security alarm system may be on when one has left the home or when one is sleeping. Lights are grouped in the set of all activities of daily living since any activity may be performed by the user past daylight hours.

We may also categorize appliances based on duration of operation. We identify appliances on whether they are short-term activity dependent devices, long-term activity dependent devices, or long-term activity independent devices. Examples of short term activity dependent devices include the toaster, the blender, the coffee maker, and the electric kettle. These appliances all depend on the activity cook and are characterized as resistive on-off devices. Long-term activity dependent devices are appliances that require more time to complete operation and may extend beyond the length of time that a user is in a particular activity. For example, the resident may activate the washing machine while in the activity clean, but may complete cleaning tasks and move on to rest while the washing machine is in it's spin cycle. Long-term activity dependent devices are the central appliances the EMS seeks to control since once activated they "must-run."

The Grid

The state of the grid is made available to the EMS through existing AMI infrastructure provided by the utility. This state may be defined in terms of utility grid alerts or pricing schemes. Grid alerts may come in the form of load shedding initiatives during high load conditions to prevent brownouts, tiered energy program power thresholds, or information with respect to dynamic pricing or time of use pricing. The information received by the EMS from the utility is necessary in terms of establishing aggregate power consumption preferences given the residents desire to enroll in any of the aforementioned demand response programs.

Environmental Factors

Environmental factors included in the EMS consist of comfort parameters that may be based on temperature, humidity, external weather conditions, time of day, season, and other factors. For example, weather conditions may affect the ambient temperature of the household which depending on a resident consumer's activity may require immediate activation of heating or cooling from the HVAC irrespective of load aggregate consumption threshold the particular household may have programmed into the system to meet a specific energy tier program. Other environmental factors such as a social gathering may also require the resident to prefer comfort over power consumption optimization in scheduling a particular appliance.

EMS Appliance Scheduling and Control

We describe a resident behavior based home EMS that learns habitual behavior patterns of the individual resident, assesses the pattern sequence against a library of behavior models, and predicts future aggregate consumption values based on expected resident activity. In the event of an appliance activation request, the predicted consumption is compared to external constraints set by the utility and comfort constraints set by the consumer. If the predicted consumption does not impinge on these constraints, the user's request is fulfilled and the device is scheduled to run. If not, a backlog of the request is maintained to schedule the device to run at a later time when the aggregate consumption is within constraints desired by the user.

Resident Behavior Sequence Classification

We classify the user behavior sequence by analyzing the instantaneous aggregate consumption and calculating the maximum likely model by analyzing the joint probability of a sequence of power observations given a particular activity state for each reference model in a dictionary of possible user activity sequences as aforementioned. The model itself is built as a hierarchical hidden Markov model where the observation states are defined by the aggregate power consumption, and the hidden states are the joint appliance-activity states. After a training period where the system identifies the resident activity sequence model based on the maximal likelihood, the system continues to receive updated consumption information and uses the activity sequence model parameters to predict future consumption states to assess whether an appliance activation request may be met given consumption and user comfort constraints.

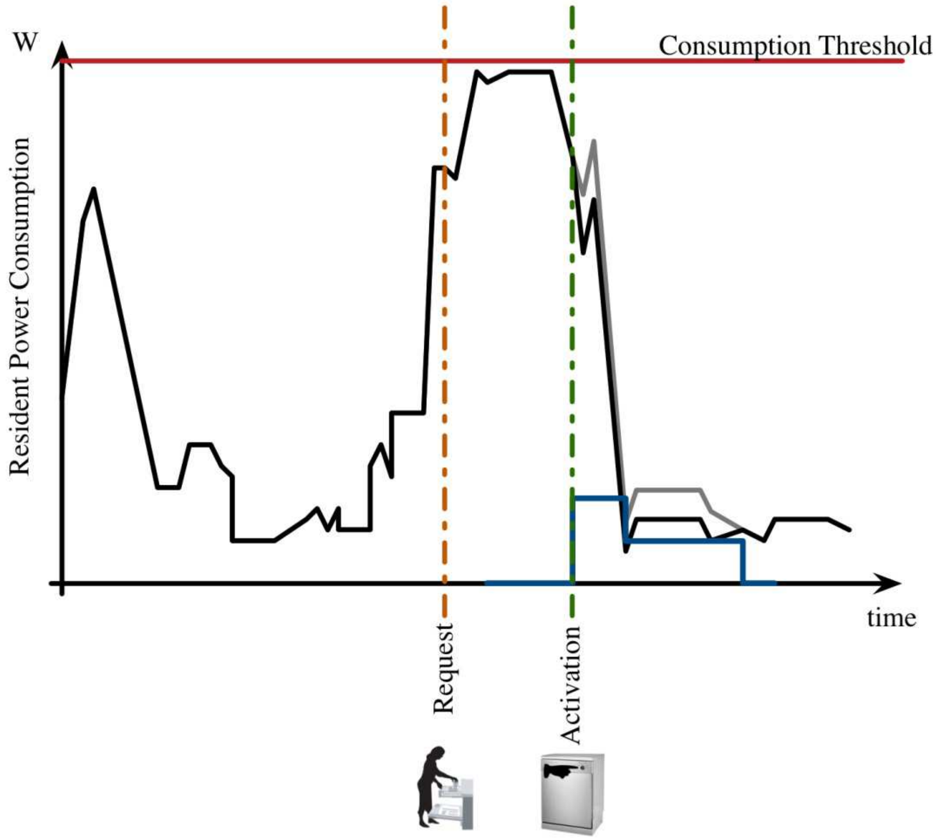

Figure 2: Appliance scheduling following activation request based on behavior-centric EMS. The blue curve represents the load curve for the appliance which is superimposed to the black consumption curve to produce the aggregate load following activation.

Appliance Energy Request

We illustrate a particular user EMS interaction given long-term activity dependent appliance initiation request in Figure 2. Following activity sequence classification, the EMS can assess energy requests made by the resident for long-term activity dependent appliances. We seek to control this particular category of appliances since they operate for longer durations and can affect future consumption trajectories with respect to grid and user comfort constraints.

When the user requests the activation of an appliance, the EMS calculates the probability of the aggregate consumption exceeding a consumption threshold given the current wattage observation and estimated reference model. It does this by assessing the probability over the duration of the requested appliance operation. In other words, if the appliance requires 40min to run, the system will predict the future aggregate consumption based on the behavioral activity sequence for the next 40min and determine whether the consumption should the energy request be made will exceed the threshold. If it is determined that the consumption will exceed the threshold, activation of the device is delayed. Upon receipt of the updated power consumption observation, the EMS will repeat the calculation until it is safe for the long-term activity dependent device to be activated. Once the device is activated the resulting load curve is within the consumption threshold.

User Comfort

The resident may enforce preferences with respect to the consumption threshold depending on how willing they are to accept delay in activation. In other words, the resident has a degree of freedom concerning appliance scheduling by defining the probability with which they will accept consumption threshold violations. This provides the user with a means to override the EMS despite the convenience of automation enabling the consumer to make informed energy decisions and remain in control of device scheduling.

Concluding Remarks

In conclusion, current demand side management programs allow for end users to enroll in direct and voluntary load-shedding programs. In voluntary programs the utility uses pricing incentives to steer load behavior indirectly. These programs require disciplined engagement on the part of the user since they have to keep track of pricing, grid alerts, current load, and future loads with respect to the activation and operational duration of household appliances. More active direct utility control programs allow end-users to install autoDR controllers in the home to control non-discretionary loads associated with heating and cooling. In both cases, end-user enrollment remains low due to lack of convenience or privacy concerns. To alleviate the current situation, the EMS presents the end user with the ability to take advantage of bidirectional communication between the utility and the smart meter, thereby allowing the user to schedule appliances under pricing constraints. EMS scheduling can be greatly improved upon by incorporating human behavior into the control loop to allow the resident comfort and convenience under different pricing schemes. We examine the state of art and propose a resident-centric EMS using a model predictive control framework that takes into account human daily activities, home appliance inventory, grid alerts, and environmental factors in the form of human comfort. The EMS then evaluates an appliance energy request and optimally schedules the appliance given the current aggregate power consumption, user model classification, and inferred residence state.

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doi: 10.1109/TSG.2017.2661991.

KJ-NC-28961-EN-N

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doi:10.2760/113534

ISBN 978-92-79-77174-3