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Contents

8 DISTRIBUTED ENERGY GENERATION

Technical and Economic Assessment of Solar Photovoltaic and Energy Storage Options for Zero Energy Residential Buildings

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Abstract

In the last decade, the cost of photovoltaic (PV) power has sharply decreased and its easy integration into buildings has led to a fast-growing penetration in several countries. However, in residential buildings, PV generation and electricity consumption do not have the same variation profile. Such mismatch brings the need to export to the electrical grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption. Additionally, the appearance of tariffs that foster the self-consumption and penalize the injection of energy into the electrical grid increases the need to provide cost-effective solutions to enable the matching between energy generation and consumption. It is possible to use electrical appliances as a demand response resource in order to minimize such problem, but its impact is not enough to ensure a high self-consumption level. Therefore, the opportunity of using energy storage systems to store surplus generation for later use is becoming increasingly attractive. New solutions for residential energy storage have been appearing on the market in recent years and the need of periodically replace electric vehicles (EVs) batteries will lead to a large number of batteries available in the upcoming years. These batteries could be used in secondary applications, such as residential PV energy storage.

This paper assesses the technical and economic impacts of PV generation and energy storage in Portuguese residential buildings considering zero energy goals. For the average Portuguese residential building, the achieved self-consumption level, as well as the associated economic impacts were assessed considering different sizes of PV systems, in order to determine the optimum installed PV power size. The self-consumption level and the economic impact was then assessed considering new and repurposed (from EVs) lithium-ion batteries with different sizes for a zero energy building (considering the same yearly generation and consumption levels). The cost-effectiveness of the different energy storage solutions was then assessed, considering the actual and future costs, in order to determine the optimum energy storage size. It was concluded that the cost-effectiveness can already be achieved with systems using repurposed batteries and with small size new batteries and can be ensured in the near future with medium size new batteries.

1. Introduction

The efforts to reduce the use of fossil fuels and greenhouse gases emissions related to electricity generation have been leading to a fast increase in the deployment of renewable generation, not only as bulk generation, but also as distributed local generation, using mostly photovoltaic (PV) solar power systems. In the last decade, the cost of PV power has sharply decreased and its easy integration into buildings has been leading to a fast-growing penetration in several countries around the World [1]. However, since the output of PV power is determined by variable meteorological processes, outside the control of the generators or the system operators, unlike conventional generating capacity, solar generated electricity cannot be reliably dispatched or perfectly forecasted, and exhibits significant temporal variability. Additionally, in residential buildings, the PV generation and electricity consumption do not have the same variation profile and such mismatch brings the need to export to the grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption [2].

These aspects are a source of inefficiency and create problems on the electrical grid management and can even be a source of economic losses to the end-user in situations in which the price paid by the consumed energy is higher than the price received by the energy injected into the grid. Most European countries have legislation allowing self-consumption and the sale to the grid of surplus energy generated by photovoltaic systems. Therefore, given that a PV system produces in excess during the hours of higher solar radiation and that this energy is sold to the grid at a very low price (typically equal or lower than the wholesale market price), the self-consumption of the generated energy should be maximized. The self-consumption is already cost-effective in several countries in the absence of subsidies [3].

Such situation increases the need to provide cost-effective solutions to enable the matching between energy generation and consumption. If properly controlled, several residential appliances can be used as a demand response (DR) resource, therefore contributing to minimize the mismatch between the generation and consumption [2]. Washing and drying appliances can be rescheduled to periods of surplus on the energy generation coming from renewable sources, thus matching consumption with renewable generation. The thermal loads (cold appliances, water heating or space conditioning) can be interrupted during shorts periods of time, without major reductions of service quality, to avoid the most unbalanced situations between generation and consumption, compensating the effects of the variability and randomness of the renewable resources availability. However, its impact for achieving a high self-consumption level is very limited [4].

Therefore, energy storage has emerged as an attractive solution for this new paradigm, since it can compensate the intermittency of renewables by storing energy during periods of high generation to be later used during periods of high demand [5]. A consequence of this business opportunity is the development of new solutions for residential energy storage, mainly using lithium-ion batteries systems due to their versatility in smaller scale applications. Such solutions have been appearing in the market in recent years, gradually increasing the implementation of these systems [6]. Nevertheless, despite the continuous fall in battery prices and a forthcoming decrease in the price of energy storage technologies, they still are an expensive asset.

The secondary use of batteries, coming from a first use in electric vehicles (EV) might be one answer for this problem. The number of EVs on the roads is increasing due to their environmental benefits and their positive impact, as a flexible load, on the electrical grid management by contributing to integrate renewables fluctuations [7]. Simultaneously, the need of periodic replacement of the battery in order to not affect the vehicle performance, will lead to a large number of batteries available in the upcoming years. Though these batteries do not possess the required capacity for transportation usage, they still retain 70-80% of their original capacity and therefore they have enough capacity to be used in secondary applications, such as energy storage in the residential sector [8].

This paper assesses the technical and economic impacts of PV generation and energy storage in residential buildings. For the average Portuguese residential building, the achieved self-consumption level, as well as the associated economic impacts were assessed for different sizes of PV systems, in order to determine the optimum installed PV power for buildings without energy storage. Then, the impact of energy storage is assessed for a zero energy building (considering the same yearly generation and consumption levels), taking into account the seasonality that leads to days with higher generation and days with higher consumption. Such assessment considers lithium-ion batteries with different sizes and two options: new batteries and repurposed batteries from EVs. The different solutions are assessed regarding its impact on the minimization of energy exchange between the household and the grid. The cost-effectiveness of the different solutions is then assessed, considering the actual and future costs of storage technologies, to determine the optimum size and to verify the viability of the implementation of these storage systems.

The remainder of the paper is structured as follows. Section 2 presents the sizing of the PV generation and energy storage systems. Then, Section 3 presents the considered generation and storage system, as well as its control. Section 4 presents the assessment of the impact of different PV systems and energy storage capacities (considering new and repurposed batteries) on the self-consumption.

Section 5 assessed from the economic point-of-view the scenarios presented in Section 4. Finally, Section 6 summarizes the paper, emphasizing its main conclusions.

2. PV Generation and Energy Storage Sizing

2.1 PV Generation

In order to achieve a zero energy building it is important to know how much renewable generation is needed. Therefore, a PV system was sized to the average Portuguese household. The survey on energy consumption in the residential sector, developed by the National Institute of Statistics and the Direction-General for Energy and Geology [9], assessed the average consumption of electricity per household in Portugal as 3673 kWh/year, which is about 10 kWh/day. Such survey also assessed the ownership rates of each type of appliance in the Portuguese households. Then, the electricity consumption breakdown in EU households was used as reference [10] and adapted to the Portuguese reality using the ownership rates of each appliance.

To have a generation level enough to ensure this average electricity consumption, the PV system was designed in PVSyst [11] in order to achieve a minimum generation level of 3673 kWh/year, considering the solar radiation conditions in Coimbra (Portugal). The designed PV system has a total power of 2.4 kWp and is constituted by two strings of five panels (each panel with 240 Wp) in series. In order to assess different sizing options, three additional scenarios were designed, able to ensure 75%, 50% and 25% of the average electricity consumption. Table 1 presents the installed power and the yearly energy generation in the 4 considered scenarios.

Table 1: Installed Power and Yearly Generation

Scenario	**100%**	**75%**	**50%**	**25%**
Power (kW)	2.4	1.8	1.2	0.6
Generation (kWh/year)	3673	2755	1837	918

2.2 Energy Storage

It was previously assessed that to ensure a good level of generation and consumption matching, considering the seasonality of generation and consumption, an effective energy storage capacity of 60% of the average daily consumption is needed [12]. Therefore, to the average Portuguese household the needed effective capacity of the energy storage system is about 6 kWh. Additionally, to avoid a quick degradation of the batteries, the state of charge (SoC) should not be lower than 30% (increasing the needed capacity to 8.57 kWh). Considering the use of lithium-ion batteries with an efficiency of 92%, the needed minimum output storage capacity is 9.32 kWh. However, the standard value available on the market is 10.2 kWh. Therefore, to achieve a nZEB level in an average residential building, the use of a PV system with 2.4 kWp and an energy storage system of lithium-ion batteries with 10.2 kWh was considered.

Repeating the same assumptions, the system was also sized for different effective energy storage capacities, considering 100%, 80%, 30% and 15% of the average daily consumption. Table 2 presents the required energy storage capacities, as well as the standard values available on the market that were considered in the assessment.

Table 2: Required and Standard Energy Storage Capacity

Scenario	**100%**	**80%**	**60%**	**30%**	**15%**
Required Capacity (kWh)	15.5	12.4	9.3	4.7	2.3
Standard Capacity (kWh)	16.6	12.8	10.2	5.1	2.4

It was also considered the used of repurposed batteries from EVs. Nowadays, most EV batteries have 10 to 85 kWh of capacity [8]. Table 3 presents some options of batteries for different electric vehicles on the market and their remaining capacity after automobile use, considering a degradation up to 70% of the initial capacity. It can be verified that all the presented options, and their respective capacity for second life applications can fulfil the storage needs of an average Portuguese household. However, for further analysis, the battery of a Nissan Leaf, due to its larger market share, and the battery of a Citroen C0, because of its smaller capacity and yet capable of offering the storage needs of a Portuguese household, were considered. Therefore, only the batteries with a second life capacity of

16.8 kWh (large reused battery) and 10.2 kWh (small reused battery) are used in the assessments presented in Section 4 and Section 5.

Table 3: Initial and Remaining Capacity of Batteries from Different EVs

Electric Vehicle	Initial Capacity (kWh)	2^{nd} Life Capacity (kWh)
Tesla Model S	85.0	59.5
Nissan Leaf	24.0	16.8
BMW i3	18.8	13.2
Chevy Volt	16.5	11.6
Citroen C0	14.5	10.2

3. PV Generation and Energy Storage System

Figure 1 presents the proposed configuration to the grid connected PV generation and battery storage system. The PV array is connected to the DC bus by a boost converter with the duty cycle controlled to ensure the maximum power point tracking (MPPT) using an incremental conductance algorithm. The MPPT algorithm ensures that the PV panel always provides the maximum power, regardless the load connected to its terminals, playing an important role for this kind of solar energy utilization, since it increases the PV panel efficiency. Its implementation is done through a DC-DC converter, and the operating principle consists in regulating the converter duty cycle in order to regulate the voltage (or current) output, extracting, thereby, the maximum power from the panel. The lithium-ion battery is then connected to the DC bus by a bidirectional DC-DC converter. The battery charging and discharging processes is ensured by the bidirectional DC-DC converter which operates in buck mode, during the charging process, and in boost mode, during the discharging process. The duty cycle of the bidirectional DC-DC converter is controlled according to the amplitude of the needed charging or discharging current. The DC bus is connected to the grid and loads by an inverter, controlled by the hysteresis current [13].

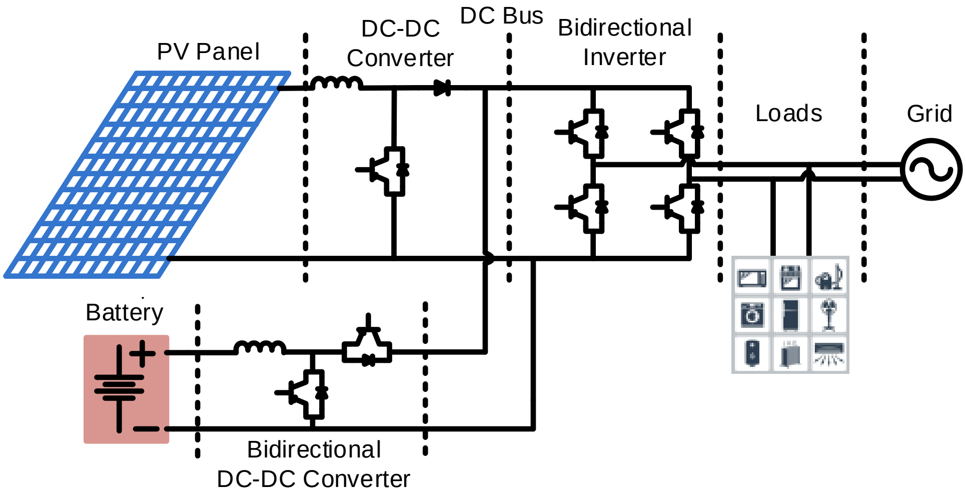


Figure 1: PV Generation and Energy Storage System

The control of the battery charging and discharging process is done considering as main objective the minimization of the power flows between the household and the grid. To ensure such objective, the priority is the self-consumption of the generated energy, being the surplus generation stored. Therefore, only the energy that cannot be consumed or stored is injected into the grid. Simultaneously, there is consumption of energy from the grid only if the generated and stored energy is not enough to ensure the demand. The second objective is the minimization of the energy bill and therefore when a consumption of energy from the grid is inevitable, the energy is consumed in the period with lower costs (details presented in Section 5), being such energy stored in the battery for later use. The considered priorities on the energy storage optimization process is presented in Table

4. In order to increase the battery lifespan a minimum SoC of 30% was considered. Therefore, the useable capacity is 70% of the rated capacity.

Table 4: Priorities of the energy storage optimization

Battery	Generation > Demand	Generation < Demand
SoC = 30%	1. Needed generation to loads 2. Remainder generation to storage	1. Available generation to loads 2. Remainder energy need received from grid
30% < SoC < 100%		1. Available generation to loads 2. Available stored energy to loads 3. Remainder energy need received from grid
SoC = 100%	1. Needed generation to loads 2. Remainder generation to grid	

The global system, its individual components (PV panels, batteries, etc.) and its management and control system were modelled in MATLAB/Simulink, as presented in Figure 2. Details about the developed model can be found at [13]. Such model was then used to simulate the system operation with different PV generation and energy storage capacities, being the results presented in Section 4.

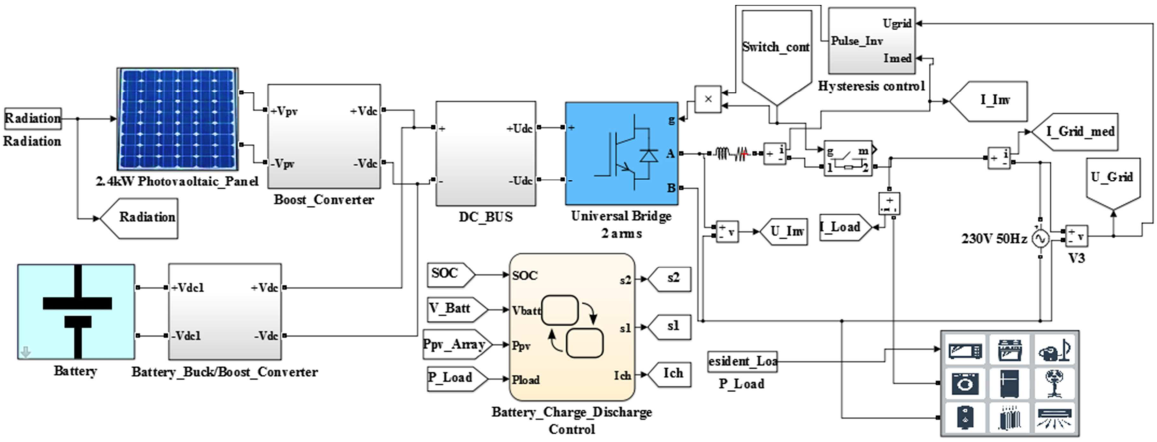


Figure 2: MATLAB/Simulink Model of the System Control

4. Self-Consumption Assessment

4.1 PV Generation

The system was simulated for a typical residential household in Coimbra, during one year (the considered period was July, 1st to June, 30th), using real data of solar radiation and electricity consumption. Figure 3 presents the daily variation of the PV generation (considering 2.4 kW of PV power) and the electricity demand for the household in October. In such month, the average daily generation and consumption levels are similar, but the PV generation occurs in a period of low demand and therefore it is mainly exported to the grid, being the needed energy later imported from the grid.

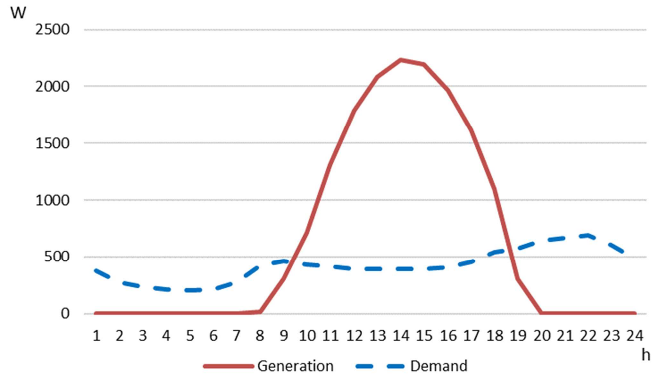


Figure 3: Daily PV Generation (2.4 kW of PV power) and Demand in October

The four scenarios of PV sizing described in Section 2 were simulated, as well as a baseline scenario without generation, leading to the results presented in Table 5, being H2G (House-to-Grid) the energy generated in the household and injected into the grid and G2H (Grid-to-House) the energy consumed in the household imported from the grid. The percentage of H2G is calculated relatively to the total generation and the percentage of G2H is calculated relatively to the total consumption. As can be seen, in a household with 2.4 kW of PV power, 58.9% of the generated energy has to be injected into the grid and 60% of the consumed energy has to be imported from the grid, leading to a self-consumption level of only 41.4%. Decreasing the size of the PV system, leads to an increase on the self-consumption, being possible to achieve a self-consumption of 97.6% with an installed power of 0.6 kW. The total exchange (H2G + G2H) also increases, but its percentage of the total generation and consumption does not present a relevant variation.

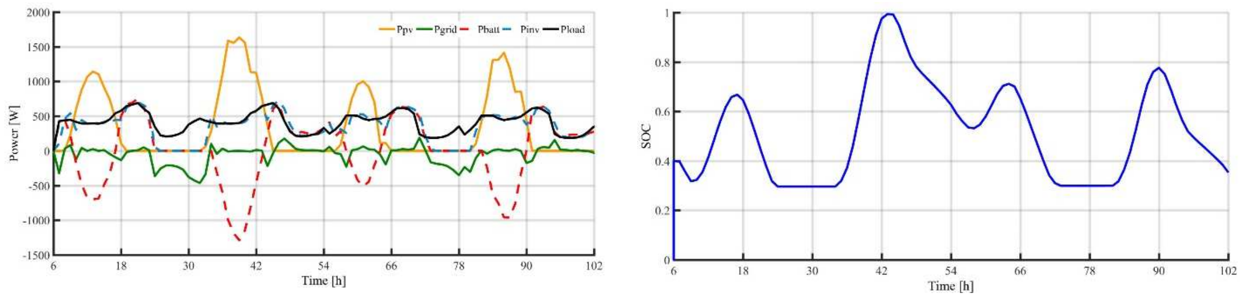
Table 5: Energy Exchange Between the Household and the Grid for Different Scenarios of PV Generation

Scenario	**100%**	**75%**	**50%**	**25%**	**0%**
Power (kW)	2.4	1.8	1.2	0.6	0
Generation (kWh/year)	3670	2760	1840	918	0
H2G (kWh/year)	2160	1370	533	22	0
H2G (%)	***58.9%***	***49.5%***	***29.0%***	***2.4%***	***0.0%***
G2H – On-peak (kWh/year)	1290	1350	1470	1780	2570
G2H – Off-peak (kWh/year)	920	940	980	1040	1100
G2H (kWh/year)	2200	2290	2450	2820	3670
G2H (%)	***60.0%***	***62.2%***	***66.7%***	***76.7%***	***100.0%***
Total (kWh/year)	4370	3650	2980	2840	3670
Total (%)	***59.4%***	***56.8%***	***54.2%***	***61.9%***	***100.0%***

4.2 Energy Storage with New Batteries

The system was then simulated for a PV generation of 2.4 kW (able to ensure 100% of the electricity consumption in average year) and considering the five scenarios of energy storage described in Section 2. Figure 4 presents one example of simulation for the 60% case (battery of 10.2 kWh), presenting the first four days of October.

As can be seen in Figure 4(a), in different days, there are periods with energy consumed from the grid (negative grid power) and other periods with energy injected into the grid (positive grid power). During the first day, the generation is lower than the demand and, as can be seen in Figure 4(b), the battery state of charge reaches its minimum value, leading to the consumption of energy from the grid. On the second day, the generation is higher than the demand and the battery state of charge reaches the maximum value, leading to a small injection of energy into the grid. On the third day, the conditions are again similar to the first day (lower generation than consumption), and therefore the minimum state of charge is reached, leading to the consumption of energy from the grid.



(a) (b)

Figure 4: Simulation Results for October (a) Power Flow in the PV Panel, Battery, Inverter, Household and Grid; (b) Battery State of Charge

Figure 5 presents the monthly variation of the energy exchange between the household and the grid for the five scenarios. As can be seen, in winter months, energy is always consumed from the grid (G2H) and during the summer, energy is always injected into the grid (H2G). However, by decreasing the battery size there is an increase on the energy injected into the grid and on the energy consumed from the grid, due to the lower storage capacity. For the smaller batteries, there are also situations with injection of energy into the grid and consumption of energy from the grid during the same month.

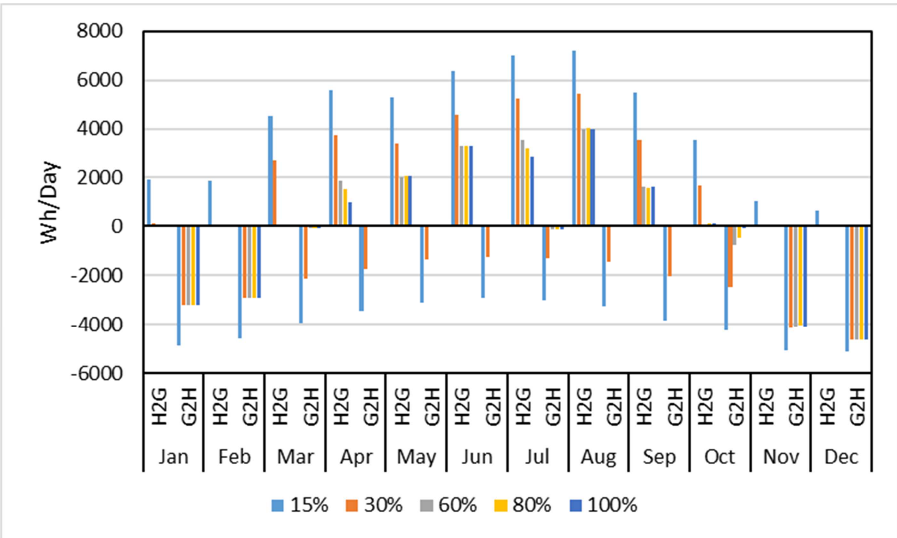


Figure 5: Monthly Variation of the Energy Exchange Between the Household and the Grid for Different Scenarios of Energy Storage

Table 6 presents the yearly energy exchange between the household and the grid for the five scenarios. As can be seen, in a household with a 16.6 kWh battery, only 12.4% of the generated energy has to be injected into the grid and 12.4% of the consumed energy has to be imported from the grid, leading to a self-consumption of 87.6%. Decreasing the size of the energy storage system, leads to a decrease on the self-consumption (in the absolute value and percentage), achieving a minimum of 58% with a storage capacity of 2.4 kWh. The total exchange (H2G + G2H) also increases with the use of a smaller battery. As previously explained, the implemented control strategy ensures that when a consumption of energy from the grid is inevitable the energy is only consumed in the period with lower costs, being such energy stored in the battery for later use. However, this cannot be achieved with all batteries, since with the smaller batteries (2.4 and 5.1 kWh) the capacity is not enough to store all all the required energy in off-peak periods.

Table 6: Energy Exchange Between the Household and the Grid for Different Scenarios of Energy Storage

Scenario	**100%**	**80%**	**60%**	**30%**	**15%**
Capacity (kWh)	16.6	12.8	10.2	5.1	2.4

H2G (kWh/year)	457	483	500	934	1540
H2G (%)	***12.4%***	***13.1%***	***13.6%***	***25.4%***	***42.0%***
G2H – On-peak (kWh/year)	0	0	0	65	830
G2H – Off-peak (kWh/year)	457	468	485	807	613
G2H (kWh/year)	457	468	485	872	1440
G2H (%)	***12.4%***	***12.7%***	***13.2%***	***23.7%***	***39.3%***
Total (kWh/year)	914	951	985	1810	2990
Total (%)	***12.4%***	***12.9%***	***13.4%***	***24.6%***	***40.7%***

4.3 Energy Storage with Repurposed Batteries

The system was also simulated with a PV generation of 2.4 kW (able to ensure 100% of the electricity consumption in average year), but considering the two scenarios of repurposed batteries. Table 7 presents the yearly energy exchange between the household and the grid for the two scenarios. As can be seen, in a household with a repurposed battery with 16.8 kWh of second life capacity (large reused battery), only 12.4% of the generated energy has to be injected into the grid and 12% of the consumed energy has to be imported from the grid, leading to a self-consumption of 87.6%. Decreasing the size of the energy storage system, leads to a decrease on the self-consumption, achieving 84.9% with a storage capacity of 10.2 kWh (small reused battery).

Table 7: Energy Exchange Between the Household and the Grid with Repurposed Batteries

Scenario	**Large Reused Battery**	**Small Reused Battery**
Capacity (kWh)	16.8	10.2
H2G (kWh/year)	454	556
H2G (%)	***12.4%***	***15.1%***
G2H (kWh/year)	427	468
G2H (%)	***11.6%***	***12.7%***
Total (kWh/year)	881	1020
Total (%)	***12.0%***	***13.9%***

5. Economic Assessment

In order to assess the economic impact for the studied systems, a typical Portuguese household with an installed power of 6.9 kVA (in normal low voltage) and a time-of-use tariff with two periods was considered. In a similar way to several European countries, the Portuguese regulation for self-consumption of locally generated electricity allows for a paid price of the energy injected to the grid of 90% of the average monthly price of the Portuguese spot electricity market. The prices for the time-of-use tariff and for the energy injected into the grid (average prices in 2016) are presented in Table 8.

Table 8: Bi-hourly Tariffs for the Electricity Consumption and Energy Injected into the Grid

Grid to House		**House to Grid**
Off-Peak (11 p.m. - 8 a.m.)	On-Peak (9 a.m. -10 p.m.)	-0.03546 €/kWh
0.1259 €/kWh	0.2437 €/kWh	

The annual costs were calculated through equation (1) by adding all the costs throughout a year, where C_{OP} is the consumption in off-peak hours (kWh), P_{OP} is the price of energy during off-peak hours (€/kWh), C_P is the consumption in peak hours (kWh) and P_P the price during these hours (€/kWh), IE is the injected energy in the grid (kWh) and P_{IE} is the price paid for the energy injected into the grid by the energy supplier (€/kWh).

$$Yearly\ Cost\ (€) = C_{OP} \times P_{OP} + C_P \times P_P - IE \times P_{IE} \quad (1)$$

The economic assessment was done by calculating the NPV (net present value), using equation (2), and the payback, using equation (3), where CF_i are the cash-flows for the year i (€), r is the discount rate (%), n is the lifetime (years), p is the immediate period before the cumulative cash-flows turn positive (year), CF_p is the cumulative cash-flow for the period p (€) and CF_{p+1} is the cumulative cash-flow for the period $p+1$ (€).

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+\mathrm{r})^2} \quad (2)$$

$$Payback = p + \frac{CF_p}{CF_p - CF_{p+1}} \quad (3)$$

5.1 PV Generation

The yearly cost considering the operation of the different PV systems was assessed with equation (1), as presented in Table 9. A reference scenario, without PV system was also included.

Table 9: Yearly Energy Cost for the PV Systems and a Reference Scenario

Scenario	Grid Consumption (kWh)		Energy Injec. (kWh)	Yearly cost (€)
	On-Peak	Off-Peak		
2.4 kW PV System	1290	916	2160	353
1.8 kW PV System	1350	941	1370	398
1.2 kW PV System	1470	984	533	463
0.6 kW PV System	1780	1040	22	564
Without PV	2570	1100	0	766

Table 10 presents the costs for the PV systems (data obtained from Portuguese installers), including a yearly operation and maintenance cost (based on data from real installations). The benefit was calculated through the difference in the yearly cost between the selected and the reference scenarios. The NPV and payback were calculated considering a discount rate of 5% (typical value in the Portuguese market) and a lifetime of 30 years. As can be seen, all systems are cost-effective, presenting a positive NPV. However, the 2.4 kW system (able to ensure 100% of the electricity consumption in average year) has a relatively long payback due to the impact of a large share of energy injected into the grid. Therefore, smaller systems have a smaller payback, being the best result
(8.5 years) achieved with the 0.6 kW PV system. Considering such results, the 1.2 kW PV system (able to ensure 50% of the electricity consumption in average year) can be considered the best solution, due to its higher NPV and good payback.

Table 10: Cost and Benefits, NPV and Payback for Different PV Systems

Scenario	System Cost (€)	O&M Cost (€/year)	Benefit (€/year)	NPV (€)	Payback (years)
2.4 kW PV System	4400	22.0	413	1610	16.9
1.8 kW PV System	3350	16.8	368	2040	13.3
1.2 kW PV System	**2300**	**11.5**	**303**	**2180**	**10.3**
0.6 kW PV System	1320	6.6	203	1680	8.5

5.2 Energy Storage with New Batteries

The economic impact was then assessed for a PV generation of 2.4 kW (able to ensure 100% of the electricity consumption in average year) and considering the five scenarios of energy storage. The yearly cost considering the operation of the five different energy storage systems was assessed with equation (1), as presented in Table 11. A reference scenario, without energy storage system (only with a PV system of 2.4 kW) was also included.

Table 11: Yearly Energy Cost for Different New Batteries and a Reference Scenario

Scenario	Grid Consumption (kWh)		Energy Injec. (kWh)	Yearly cost (€)
	On-Peak	Off-Peak		
16.6 kWh Battery	0	457	457	41.3
12.8 kWh Battery	0	468	483	41.9
10.2 kWh Battery	0	485	500	43.3
5.12 kWh Battery	65	807	934	84.4
2.4 kWh Battery	830	613	1540	225
PV Only (2.4 kW)	1290	916	2160	352

Table 12 presents the costs for the energy storage systems in 2017, including a yearly operation and maintenance cost. The actual cost of the energy storage systems was estimated considering a battery cost of 480 €/kWh [14] and an additional cost of 15% for the battery management system (it was considered as baseline that the PV systems and respective inverter was already installed), leading to a total cost of about 550 €/kWh. However, the storage costs forecasts point in the direction of a fast decrease of the costs, due to the growing mass market associated with electric vehicles, being the forecasted cost for lithium-ion batteries in 2020 about 175 €/kWh [14]. Considering the additional costs of the battery management system, the total projected cost for 2020 is about 200 €/kWh (Table 13). The benefit was calculated through the difference in the yearly cost between the selected and the reference scenarios. The NPV and payback were calculated considering a discount rate of 5% and a lifetime of 12 years (considering one cycle/day). A sensitivity analysis considering a 10.2 battery with different costs and discount rates can be found at [13].

Table 12: Cost and Benefits, NPV and Payback for Different Energy Storage Systems in 2017

Scenario	System Cost (€)	O&M Cost (€/year)	Benefit (€/year)	NPV (€)	Payback (years)
16.6 kWh Battery	5740	57.4	311	-3040	45.6
12.8 kWh Battery	4420	44.2	310	-1700	26.2
10.2 kWh Battery	3530	35.3	309	-826	17.7
5.1 kWh Battery	**1770**	**17.7**	**268**	**451**	**8.9**
2.4 kWh Battery	828	8.3	128	229	8.8

Table 13: Cost and Benefits, NPV and Payback for Different Energy Storage Systems in 2020

Scenario	System Cost (€)	O&M Cost (€/year)	Benefit (€/year)	NPV (€)	Payback (years)
16.6 kWh Battery	3490	34.9	311	-770	17.2
12.8 kWh Battery	2690	26.9	310	-39.2	11.8
10.2 kWh Battery	2150	21.5	309	569	8.9
5.1 kWh Battery	**1080**	**10.8**	**268**	**1200**	**4.8**
2.4 kWh Battery	504	5.0	127	581	4.7

As can be seen, considering the costs in 2017, only the two smaller batteries (2.4 and 5.12 kWh) are cost-effective, presenting a payback (about 8.9 years) lower than their estimated lifespan. However, by considering the forecasted costs for 2020, the 10.2 kWh also becomes cost-effective and there are improvements on the economic indicators of all batteries. Comparing the results, the best solution is the 5.1 kWh battery, since despite presenting a slightly higher payback than the 2.4 kWh battery, it has a much larger NPV and, simultaneously ensures a better technical impact (increase on the self-consumption).

5.3 Energy Storage with Repurposed Batteries

With the goal of estimating the actual cost of acquisition of repurposed batteries the SAE International (Society of Automotive Engineers) defined a range between 34 and 118 €/kWh [15]. Due to the tendency of cost reduction, the minimum cost of 34 €/kWh was used in the assessment. The need of a battery management system (BMS) capable of controlling the charging and discharging cycles of the battery and hence maximize its lifespan was also considered. The encapsulation and installation costs (considered as other costs) were defined as 5% of the total cost. The final price of acquisition for the end consumer for an energy storage system with repurposed EV batteries is presented in Table 14.

Table 14: Cost of the Storage System with Repurposed Batteries

Scenario	Battery (€)	BMS (€)	Others (€)	Total (€)
16.8 kWh Reused Bat.	571	1500	104	2180
10.2 kWh Reused Bat.	345	1080	71.3	1500

The yearly cost considering the operation of the different energy storage systems with repurposed batteries was assessed with equation (1), as presented in Table 15. A reference scenario, without energy storage system (only with a PV system of 2.4 kW) was also included.

Table 15: Yearly Energy Cost for Different Repurposed Batteries and a Reference Scenario

Scenario	Grid Consumption (kWh)		Energy Injec. (kWh)	Yearly cost (€)
	On-Peak	Off-Peak		
16.8 kWh Reused Bat.	0	427	454	37.7
10.2 kWh Reused Bat.	0	468	556	39.1
PV Only (2.4 kW)	1290	916	2160	352

Table 16 presents the costs for the storage systems with repurposed batteries, including a yearly operation and maintenance cost. The benefit was calculated through the difference in the yearly cost between the selected and the reference scenarios. The NPV and payback were calculated considering a discount rate of 5% and a lifetime of 12 years (considering one cycle / day). It was verified that for the two studied battery storage systems the payback is smaller than their estimated lifespan, being therefore cost-effective. Comparing the two options, the best solution is the reused small battery (10.2 kWh), since it ensures a smaller payback (5.6 years) and a larger NPV. A sensitivity analysis considering different costs and discount rates can be found at [16].

Table 16: Cost and Benefits, NPV and Payback for Systems with Repurposed Batteries

Scenario	System Cost (€)	O&M Cost (€/year)	Benefit (€/year)	NPV (€)	Payback (years)
16.8 kWh Reused Bat.	2180	2.18	315	593	8.8
10.2 kWh Reused Bat.	**1150**	**1.50**	**310**	**1270**	**5.6**

6. Conclusions

This paper assessed the technical and economic impacts of PV generation and energy storage in residential buildings. For the average Portuguese household, different PV system were sized in order to ensure 100%, 75%, 50% and 25% of the average electricity consumption, which is achieved with 2.4, 1.8, 1.2 and 0.6 kW of installed power, respectively. Then, considering a scenario with a PV system able to ensure 100% of the average electricity consumption, energy storage systems were sized in order to ensure 100%, 80%, 60%, 30% and 15% of the average daily electricity consumption with lithium-ion batteries, which is achieved with 16.6, 12.8, 10.2, 5.1 and 2.4 kWh of capacity, respectively. It was also considered the option of repurposed batteries from EVs, being considered the battery of a Nissan Leaf (16.8 kWh) and the battery of a Citroen C0 (10.2 kWh).

The considered PV generation and energy storage system, as well as its control were presented. Such control was implemented considering as main objective the minimization of the power flows between the household and the grid and the minimization of the energy bill, by concentrating the energy consumed from the grid in the period with lower costs. The system was then simulated during one year, considering the several options of PV and energy storage sizing. Considering a PV system with 2.4 kW the self-consumption level is only 41.4%, but decreasing the size of the PV system leads to an increase on the self-consumption, being possible to achieve a self-consumption of 97.6% with the 0.6 kW PV system. All systems are cost-effective, but the smaller systems have a smaller payback, being the best economic indicators achieved with the 1.2 kW PV system.

With the energy storage scenarios, it is possible to achieve a self-consumption level of 87.6% with the 16.64 kWh battery. Considering the costs in 2017, only the 2.4 and 5.1 kWh batteries are cost-effective, but considering the forecasted costs for 2020, the 10.2 kWh also becomes cost-effective, being the best economic indicators achieved with the 5.1 kWh battery. With the repurposed batteries, it is also possible to achieve a self-consumption level of 87.6% and 84.9% with the 16.8 kWh and 10.2 kWh batteries, respectively. The two systems are cost-effective, being the best economic indicators achieved with the 10.2 kWh battery. Therefore, systems using repurposed batteries and systems with small size new batteries are already cost-effective and medium size new batteries are also going to be cost-effective until 2020.

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Current Source DC/AC Converter for Renewable Sources

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Abstract

Transformerless inverters are being widely used in low power grid-connected photovoltaic (PV) generation systems. Transformer elimination has many advantages; it reduces cost, size, weight, and also increases the whole system efficiency. However, once the transformer is removed, there is no galvanic isolation between grid and PV array and, as a consequence, a leakage current may appear due to the photovoltaic panel parasitic capacitance to the ground, resulting in prohibitive electromagnetic interference and security issues. This paper presents a novel current source DC/AC topology in order to reduce this ground leakage current. It is established that the neutral line of the grid is the same as the negative terminal of the PV system, eliminating this way, any possibility of leakage current through this terminal.

Introduction

Grid-connected photovoltaic (PV) systems often include a low-frequency transformer between the conversion stage and the grid. This transformer guarantees galvanic isolation between the grid and the PV system, eliminates leakage currents between the PV system and the ground and ensures that no direct current (DC) is injected into the grid. However, because of its low frequency (50-60 Hz), the transformer is bulky, heavy, and expensive (because it has more elements and material). In addition, it reduces the overall efficiency of the conversion stage [1]-[4]. Transformerless inverters eliminate these drawbacks. Unfortunately, if the transformer is removed, it is generated a varying common-mode voltage (CM) and leakage currents or common-mode current ($i_{leakage}$) can flow through the inverter, its output filter, the grid impedance and the PV panel parasitic capacitances C_{p1} and C_{p2} to the ground, as shown in Fig 1 [5].

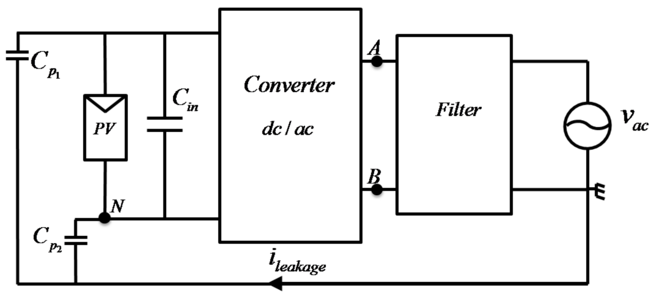


Fig. 1. Block diagram that illustrates the leakage current path in a transformerless inverter.

The CM voltage, V_{CM}, the modulation strategy, and the value of the parasitic capacitance greatly affect the value of leakage current [6]. This leakage current may reduce the power conversion efficiency, increase the grid current distortion, deteriorate the electromagnetic compatibility (EMC), and give rise to the safety threats [2]; for instance, higher current harmonic, higher losses, and electromagnetic interference (EMI) issues [5]–[15].

Several solutions that do not generate variable V_{CM} voltages have been proposed for use in transformerless PV systems: in [16], a summary of strategies to suppress leakage currents is presented. One solution is the use a modulation technique that not generate a variable V_{CM}, like Bipolar Sinusoidal Pulse Width Modulation (BSPWM) [16]. Another solution is disconnecting PV array from the grid when V_{CM} varies, several topologies have been proposed with this idea like H5, H6, HERIC and those shown in [17]-[18]. Another solution is clamping the PV array to the neutral point of the grid by connecting one inverter terminal output to the neutral point of the grid, like the half bridge inverter.

This paper presents a novel topology with low leakage current. However, in this case, it is a current source DC/AC converter, with the advantages of featuring low switching *dv/dt* and reliable over-current/short-circuit protection. The proposed topology establishes that the negative line of the grid is directly connected to the negative terminal in the PV system, maintaining its voltage constant and generating in this way, an ideally zero leakage current.

The proposed topology and its analysis are discussed in the second section, where the control by hysteresis is discussed in a simulated way. In the third section the simulation results are presented, finally, some conclusions are made.

Proposed converter topology

The circuit diagram of the converter is shown in Fig. 2. The main idea is that the neutral terminal of the grid is connected straight to the negative terminal of the PV array and the converter is a current source DC/AC one. It is composed by six power MOSFETs (S_1, S_2, S_3, S_4, S_5, and S_6), with just a combination of two of them conducting in each switching state. The converter also includes two capacitors and two inductors (C_f, C_{out}, L, and L_f).

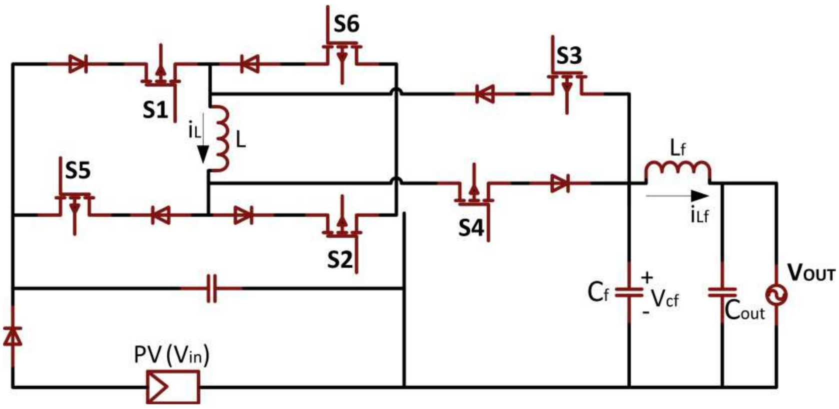


Figure 2. Circuit diagram for the proposed topology.

The converter has five switching states, depicted in Table I. The behavior of the voltages and currents of interest are summarized in Table II, indicating if its value increases or decreases.

Table I. Switching states

	Subcircuit A (+)	Subcircuit B (-)	Subcircuit C (0)	Subcircuit D (0)	Subcircuit E (0)
S_1	**On**	Off	**On**	Off	Off
S_2	Off	**On**	**On**	Off	Off
S_3	Off	**On**	Off	Off	**On**
S_4	**On**	Off	Off	Off	**On**
S_5	Off	Off	Off	**On**	Off
S_6	Off	Off	Off	**On**	Off

Table II. Behavior of voltages and currents of interest

	Subcircuit A	Subcircuit B	Subcircuit C	Subcircuit D	Subcircuit E
i_L	Increases if V_{in} is greater than V_{Cf} otherwise decreases	Increases	Increases	Decreases	No Change
V_{Cf}	Increases if i_L is greater than i_{Lf} otherwise decreases	Decreases	Decreases	Decreases	Decreases
i_{Lf}	Increases if V_{Cf} is greater than V_{out} otherwise decreases	Increases if V_{Cf} is greater than V_{out} otherwise decreases	Increases if V_{Cf} is greater than V_{out} otherwise decreases	Increases if V_{Cf} is greater than V_{out} otherwise decreases	Increases if V_{Cf} is greater than V_{out} otherwise decreases

Operating mode.

The proposed converter is modulated by means of a Sinusoidal Pulse Width Modulation to eliminate de leakage current [16]. In order to obtain a unipolar output a sinusoidal modulator signal is compared with two triangular carrier signals, obtaining two auxiliary control signals, A and B. Signal A is obtained comparing the modulator against the upper carrier and signal B is obtained comparing the modulator against the lower carrier. These waveforms are shown in Fig. 3 (a low frequency signal was used to illustrate the operation).

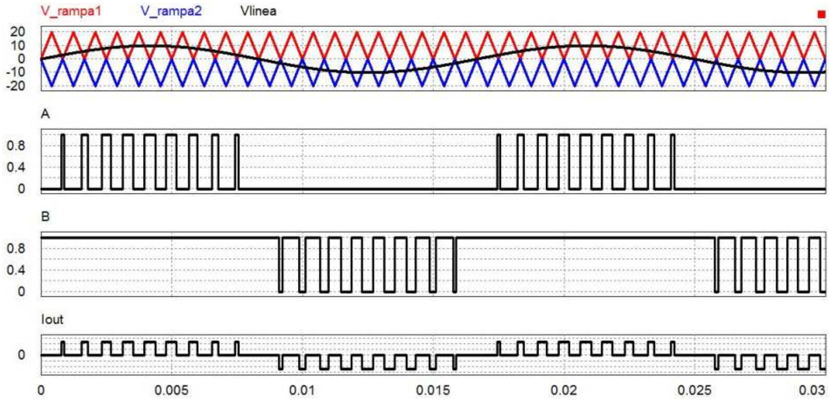


Fig. 3. From top to bottom, PWM pattern generation, control signal A, control signal B and output current I_{out}.

If signals A and B are simultaneously at a logic high level, a positive output current I_{out} will be obtained, which corresponds to subcircuit A. If signals A and B are simultaneously at a low logic level, a negative output current I_{out} will be obtained. This corresponds to subcircuit B. In both cases the inductor current i_L increases.

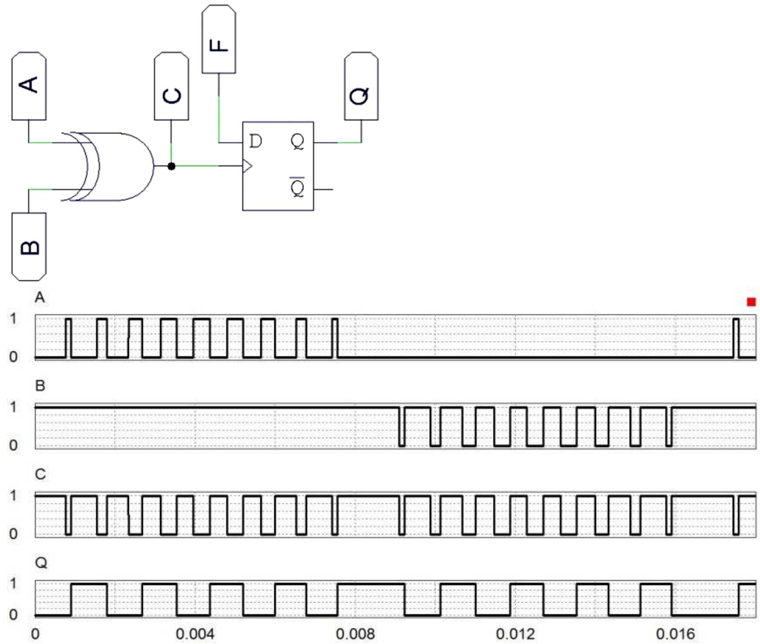
While A and B are simultaneously at different logic levels, a zero output current I_{out} will be obtained, which corresponds to any of the subcircuits C, D or E. The current in the inductor L is increased, decreased or maintained respectively. A particular subcircuit C, D or E is selected by an appropriate controller, with the premise of maintaining the inductor current i_L at a desired constant value, as in any current source converter.

Inductor Current Control

A XOR logic gate is used with signals A and B as inputs to obtain an auxiliary output signal C. This signal is at a high logic level at any zero output current I_{out} and is the *CLK* input to a D-type positive edge triggered flip flop, which will divide the frequency of C by half. The D-type output signal is named signal Q, When the current level i_L is greater or less than desired, the F signal of the flip flop will be switched, as can be seen in Fig. 4 (a low-frequency signal was used to illustrate the operation).

This new signal Q allows us to differentiate at least two cases for the zero output current state. By means of signals A and B, it is indicated that a zero must be produced at the output current. If signal Q is at a high logical level, we will use subcircuit C, and if signal F is at a low logical level, we will use the subcircuit D. This will allow us to increase and decrease the current of the inductor L, to maintaining it constant.

The value of the inductor current i_L is kept at a desired value by means of a hysteresis controller. It has been defined a hysteresis window of 0.04 A, around a constant current of the inductor L equal to 2A. A combinational logic circuit is employed to determine the final control signals of the switches, where the signals A, B, F and the hysteresis controller are considered.



a)
b)

Fig. 4. Circuit and auxiliary signals. a) Auxiliary circuit, b) From top to bottom signals A, B, C, and Q.

The value of the inductor current i_L is kept at a desired value by means of a hysteresis controller. It has been defined a hysteresis window of 0.04 A, around a constant current of the inductor L equal to 2A. A combinational logic circuit is employed to determine the final control signals of the switches, where the signals A, B, F and the hysteresis controller are considered.

Simulation results

The proposed system was numerically simulated in order to confirm the operation of the proposed system. The system parameters are shown in Table III:

Table III. Values for simulation

L	$5\mu H$	C_f	$10\mu F$	L_f	$2\mu H$	C_{out}	$1\mu F$
	Sine wave voltage for PWM	10 V	Triangular voltage for PWM	±20 V	PV Voltage (V_{in})	120 V	
	Line Frequency	60 Hz	Triangular Frequency for PWM	60 kHz	V_{out}	120 V	

Signals A, B, I_{out}, and i_L, with the proposed hysteresis controlled, are shown in Fig. 5. In order to illustrate the operation at steady state of the system, the Fig 5.a shows the signals at several periods. In Fig. 5.b a zoom of the same signals is shown. As it can be observed the system operates as proposed.

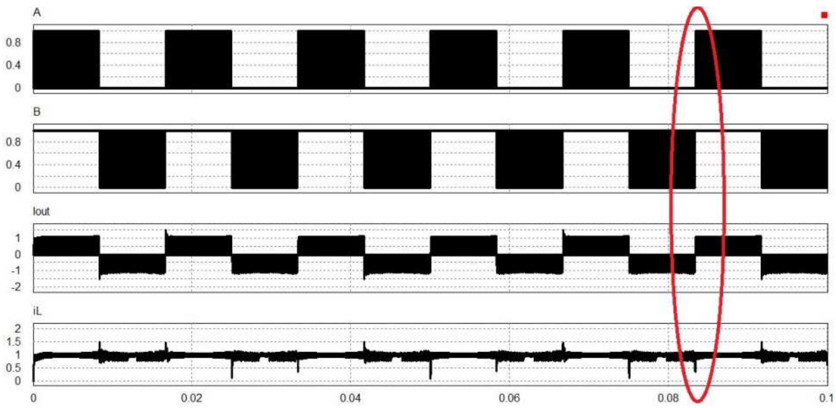
The signals V_{out}, I_{out}, and i_L are shown in Fig. 6. As it can be observed, the current of the inductor L is controlled between of the signal of hysteresis around the desired level. The voltage and the current are operated with a CLC filter. The output signals can be viewed clearly sinusoidal and in phase with the grid. The leakage current in the solar panel is almost zero, as can be seen in Fig. 7.

Conclusions

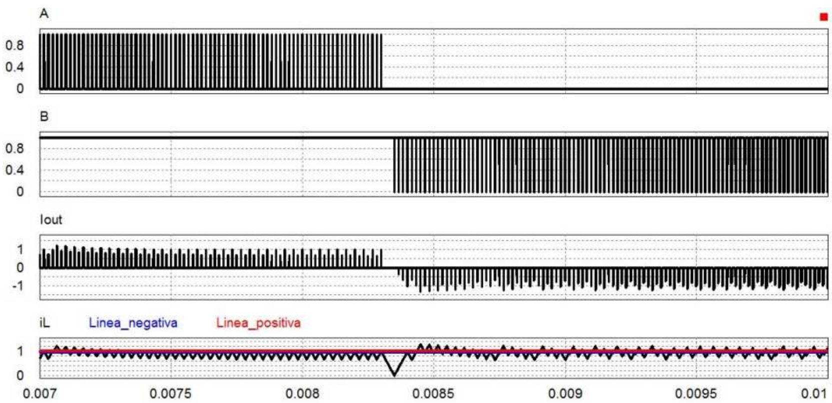
This work presents a new topology that has the purpose of reducing the problems caused by the leakage current presented in transformerless PV systems connected to the grid. The proposal consists of a current source DC/AC topology.

The results of the simulation have verified the performance of the proposed system, demonstrating that it is capable of generating the desired current with an almost zero leakage current.

Eliminating the transformer increases efficiency by up to 3% and eliminates the cost of it, the conversion stage or power stage is still maintained, so its cost is practically the same.



a)



b)

Fig. 5. From top to bottom: Signals A, B, I_{out}, and i_L, a) Complete signals in several periods, b) Zoom of the signals of a).

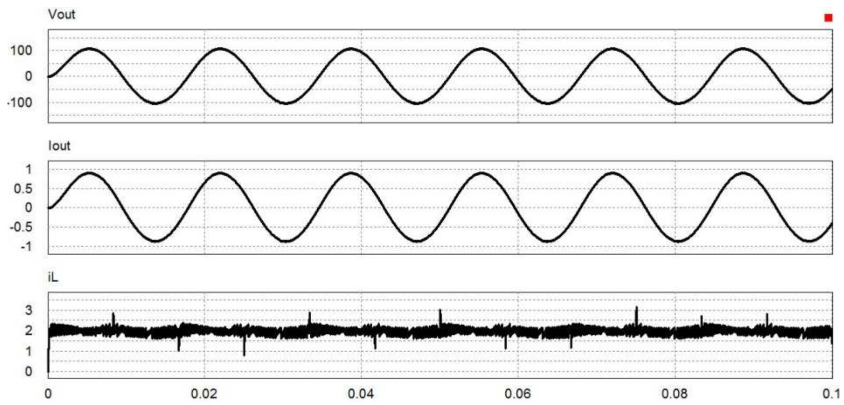


Fig. 6. Operation at startup and steady state. From top to bottom: V_{out}, I_{out}, and i_L

Fig. 7. The leakage current

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Estimating PV Technical Potential and Financial Feasibility for Educational Buildings in the United States

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Abstract

Electricity generation in the United States presently accounts for roughly 35% of total U.S. carbon emissions each year. Renewable energy technologies, specifically solar photovoltaics, can significantly reduce emissions of CO_2 and other harmful pollutants, which have asymmetric negative effects for at-risk populations such as asthmatics, the elderly, and low-income families. Although there is a significant literature on the quantified costs and benefits of installing solar PV throughout the residential and commercial sectors, little is known regarding solar PV's potential among educational institutions. Our research identifies the technical potential and financial feasibility of installing PV on educational facilities throughout the U.S. with a particular focus on the societal and environmental benefits associated with offsetting traditional electricity generation methods. We perform at benefit-cost analysis of each educational building in the U.S. for which we have LIDAR-estimated roof space (n = 38,022) and aggregate results at the state-level. Preliminary results suggest that PV energy generation is highest in the Southwest and lowest in New England. Furthermore, PV has the highest health and environmental benefits in regions where it is offsetting carbon-intensive and high-polluting technologies such as coal-fired power plants in the Midwest. Preliminary results also suggest that installing rooftop PV on educational buildings will result in negative net-benefits for the schools and positive social-benefits for society.

Background

In 2016, approximately 64% of total electricity generated in the United States (U.S.) came from fossil fuel sources, while less than 1% came from solar photovoltaic (PV) electricity generation [1]. Due to this mostly fossil fuel dependent electricity portfolio, electricity generation accounts for approximately 35% of total U.S. carbon dioxide (CO_2) emissions each year [2]. Distributed generation technologies such as solar PV can significantly reduce emissions of CO_2 and other harmful pollutants, which have asymmetric negative effects for at-risk populations such as asthmatics, the elderly, and low-income families.

To fully characterize the costs and benefits of installing distributed generation technologies, one should consider the perspective of the customer installing the system as well as society. Vaishnav et al. performed such an analysis on currently installed residential and non-residential distributed solar generation leveraging the Tracking the Sun database [3]. They estimated marginal public benefits as avoided damages from reducing emissions of CO_2, SO_2, NO_x, and $PM_{2.5}$ by offsetting traditional fossil fuel electricity production first by calculating avoided emissions in each eGrid region using techniques outlined in Siler-Evans et al. and secondly by translating emissions reductions to damage reductions using two integrated air quality models: AP2 and the EASIUR model [4,5,6]. They found public benefits exceeded the public costs of the various incentives and subsidies offered to system owners for less than 10% of the systems installed, when considering discount rates of 2% and 7% [3]. Their detailed assessment of historical rebates and incentives also unveiled a disproportionate flow of rebates and incentives to counties with higher median incomes [3]. Ultimately, they found private and social costs and benefits to vary widely across the U.S. based on varying retail rates, solar resource, existing electricity generation portfolios, and available rebates and net-metering policies [3].

Although there is a significant literature on the quantified costs and benefits of installing solar PV throughout the residential and commercial sectors, little is known regarding solar PV's potential among educational institutions. According to the Commercial Building Energy Consumption Survey (CBECS) database, educational buildings account for 11% of total U.S. building electricity consumption and 14% of building floor space [7]. Educational facilities, especially higher education, have set goals for reducing energy consumption and promoting sustainability. For instance, the DOE's Better Buildings Challenge includes higher education facilities in their goal to reduce building energy consumption by 20% compared to a 2010 baseline [8]. If federal commitment to energy conservation and climate change initiatives, like the Paris Agreement, diminish under the current administration, other private and local initiatives will likely persist [9]. For instance, Bloomberg Philanthropies and others have committed to producing the $15 million promised by the U.S. for the U.N.'s Climate Secretariat for the Paris Agreement [9].

Colleges and universities have also taken initiatives to improve sustainability on campuses and the Association for the Advancement of Sustainability in Higher Education (AASHE) developed a tool to track this progress: Sustainability Tracking, Assessment, and Rating System (STARS) [10]. The Princeton Review also provides a rating of schools based on their green practices [11]. To improve campus sustainability, several major universities such as Carnegie Mellon University and Stanford have established their own greenhouse gas (GHG) emissions inventories [12,13]. In fact, the University of California Office of the President (UCOP) has pledged to become carbon neutral, or emit zero greenhouse gases from its buildings and fleet vehicles, across each of the 10 universities in the system by 2025 [14]. The UCOP hopes to lead other colleges and universities to similar sustainability goals by demonstrating a path to achievement through expanding energy efficiency initiatives and increasing its reliance on renewable energy.

Our research identifies the technical potential and financial feasibility of installing PV on educational facilities throughout the United States with a particular focus on the societal and environmental benefits associated with offsetting traditional electricity generation methods. We employ a cost-benefit analysis (CBA) to determine which counties in the U.S. will gain the most social benefits from installing solar PV on their educational facilities and for which of these institutions PV projects are financially feasible.

Approach

The primary output of this model is a cost-benefit analysis (CBA) for each educational institution in the U.S. aggregated at the state-level. In this paper, we address the following research questions:

1. What is the total potential electricity generation from solar PV on all U.S. educational buildings for which we have LIDAR data?
2. What are the total lifetime cost and benefits – both private and public – of rooftop solar PV systems installed on all U.S. educational buildings for which we have LIDAR data?

The following subsections describe the data we rely on to develop our CBAs.

Available roof space

To measure technical potential of PV on all U.S. educational buildings, we use the address, faculty and students counts from three National Center for Education Statistics (NCES) datasets: Integrated Postsecondary Education Data System (for higher education institutions) [15], Common Core of Data (for K12 public institutions) [16], and the Private School Universe Survey (for K12 private institutions) [17]. This results in a total of 134,137 educational institutions.

We then produce estimates of available roof space for each institution in our dataset. To do so, we first rely on NREL light detection and ranging (LIDAR) estimates [18]. NREL uses LIDAR data in combination with GIS methods and statistical modeling to estimate suitable rooftop space for solar PV for some buildings in the U.S.; these space estimates were available for roughly 28% of all of the schools listed in the NCES data (n = 38,022 schools). Thus, for those institutions where NREL estimates are available, we use their values. In the future, we will estimate the rooftop space for the remaining institutions separately.

Figure 1 shows all the institutions that are listed in NCES that are considered in our analysis; the black diamonds highlight the educational institutions' observations from NREL LIDAR data.

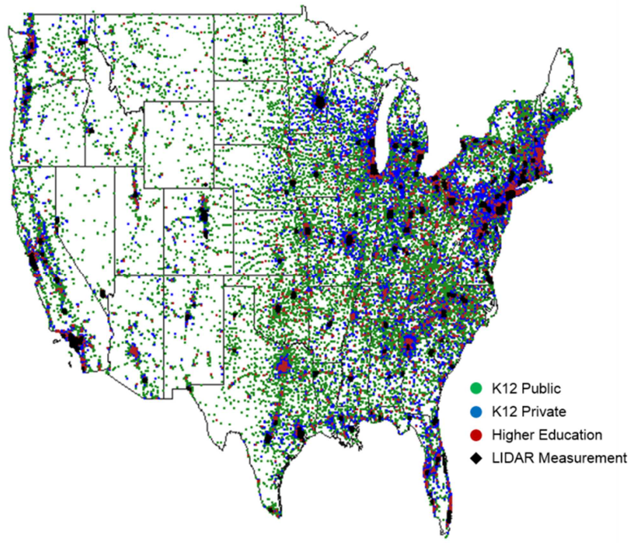

Figure 6. Map of U.S. schools in the NCES datasets: Integrated Postsecondary Education Data System (higher education), Common Core of Data (K12 public), and Private School Universe Survey (K12 private). After excluding schools with reported latitude and longitude values falling outside of the U.S. boundaries, we have combined building dataset of 134,137 schools to consider.

PV-generation modeling

We use a method outlined in Lorenzo [19] and also used in Vaishnav et al. [3] to estimate hourly electricity generation at each of the 936 locations for which we have solar irradiance data made available from NREL's Typical Meteorological Year (TMY3) data [20]. Each school is assigned to the geographically closest TMY3 site and we calculate the power output for the systems installed on each roof for each hour of a typical year. We use the hourly load profiles for "secondary schools" compiled by the U.S. Department of Energy (DOE) for each of the TMY3 locations [21]. We assume that all electricity generated offsets consumption and during periods that generation exceeds consumption, we assume excess generation is sold back to the grid.

Installed price of system

The LBNL Tracking the Sun dataset provides information on historical system installation prices representing 85% of all residential and non-residential solar PV systems installed cumulatively through 2015 and 82% of systems installed in 2015 in the U.S. [22]. We use the data for 2015 projects and focus on school, government, and non-profit installations. This resulted in approximately 600 projects out of the roughly 800,000 projects captured in the dataset. These projects represent ten states in the U.S., with the top three being California, Maine, and Arizona [22]. Our mean project cost in our reduced dataset is $4,080/kW or $750,600 overall. We use this mean value to estimate project costs for all systems in our combined school building dataset for which we have LIDAR data.

PV system rebates and net-metering policies

To determine available rebates, we reference the DOE database of state incentives for energy efficiency and renewable energy, DSIRE [23]. We consider only rebates that are explicitly made available to schools in each state and that are offered at a $/kW rate. If the rebate isn't made available at the state-level, but there exist multiple utility-level rebates, we use the most conservative rebates. In our analysis, rebate values range from $100/kW to $1,200/kW and capacity limits range from 5 kW to 1 MW. Figure 2 depicts all state-level PV rebates available to schools as of July 2017.

Similarly, we use DSIRE to determine which states allow net metering, make it explicitly available to schools, and at which rate they value excess generation. Offset electricity consumption is summed for each building for each year and then multiplied by the state-average 2015 commercial retail rate [24]. Electricity sold back to the grid can be valued at two rates, which we consider bounding cases: (1) the state-average 2015 commercial retail rate and (2) the hourly state-average locational-marginal price (LMP) for 2015. Currently, we are assuming that net-metering is available for schools in every state and that excess generation is valued at the LMP. In the future, we will incorporate state-specific net-metering policies, also depicted in Figure 2.

We do not include the Investment Tax Credit (ITC) since it only applies to residential, commercial, industrial, investor-owned utility, cooperative utilities, and agricultural PV projects [25,26].

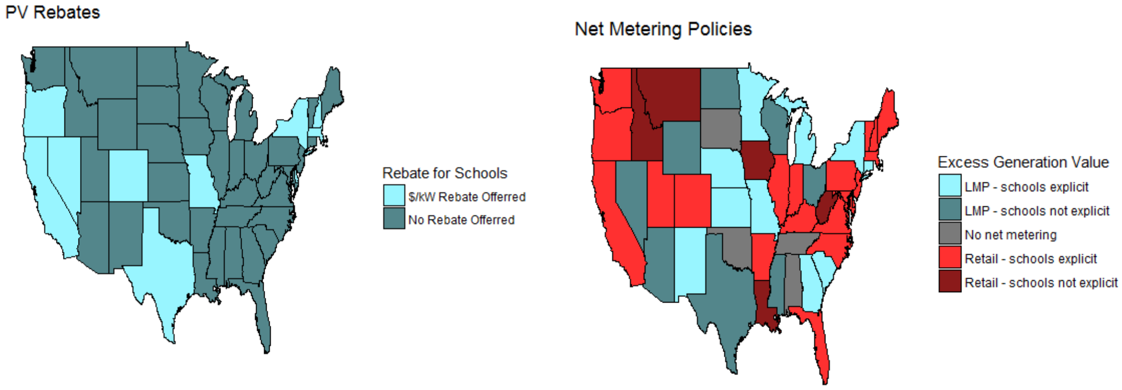

Figure 7. Available school PV rebates and net metering policies at the state-level. The maps are informed by the DSIRE website and represent policies effective as of July 2017.

Valuing health and environmental benefits

To quantify health and environmental benefits resulting from offsetting traditional fossil fuel electricity generation, we use the method outlined in Vaishnav et al. [3]. We estimate marginal public benefits as avoided damages from reducing emissions of CO_2, SO_2, NO_x, and $PM_{2.5}$ first by calculating avoided emissions in each eGrid region using techniques outlined in Siler-Evans et al. [6] with 2016 emissions values for each U.S. fossil fuel power plant greater than 25 kW [27]. Next, we translate emissions reductions to damage reductions using two integrated air quality models: AP2 and the EASIUR model [4,5]. These models estimate the dispersion of pollutants and the resulting concentration in all U.S. counties and then rely on dose-response functions to estimate physical impacts. Finally, they monetize the impacts by using estimates for such inputs as the value of statistical life and the value of lost commodities. We use these models to calculate offset air quality and greenhouse gas damages from a 1 kW system for each TMY3 location for each hour of a year, summed for an annual estimate. This annual estimate is then multiplied by the system capacity for each school in that particular TMY3 location. Since we assume a 20-year system life, 2017-2035 damages are approximated by 2016 estimates. In summary, Table 1 depicts all data inputs for our analyses.

Table 17. Data inputs for the cost-benefit analyses.

Variable	Source	Reference
Building Counts		
Higher Education (N = 7,647)	Integrated Postsecondary Education Data System	[7]
K-12 Public Schools (N = 102,799)	Common Core of Data	[8]
K-12 Private Schools (N = 26,983)	Private School Universe Survey	[9]
Solar Irradiance	NREL TMY3 Data	[14]
Building Load Profile	DOE Commercial Reference Buildings	[15]
Project Costs	LBNL Tracking the Sun	[6]
Rebates	DSIRE	[16]
Electricity Rates	EIA 2016 Commercial Rates	[17]
Available Roof Space	NREL LIDAR data	[3]
Societal & Environmental Damages	AP2 Model	[22]
Societal & Environmental Damages	EASIUR Model	[23]

Lifetime costs and benefits

The CBAs are completed at the school-level and aggregated at the state-level. We are primarily interested in two CBAs: one with the school as the decision-maker and one with a public policy decision-maker. Costs to the school include the system price minus any available rebates (Eq. 1) and benefits include the present value of the electricity generated each year that the system is in operation (assume 20-yr lifetime) (Eq. 2). Social costs include any rebates made available to the schools (Eq. 3); social benefits include the present value of monetized benefits associated with the reduction in CO_2, SO2, NO_x, and $PM_{2.5}$ (Eq. 4). The social costs equation outline in Eq. 3 are for instances where excess generation is valued at the LMP.

$$SchoolCosts_s = i_s - g_s \quad \text{(Eq. 1)}$$

$$SchoolBenefits_s = \sum_{y=2016}^{y=2036}\left(\left(\sum_{h=1}^{h=8760}(o_{s,h} \times p_{s,y}) + \sum_{h=1}^{h=8760}(n_{s,h} \times l_{s,h})\right) \times d^{(y-2015)}\right) \quad \text{(Eq. 2)}$$

$$SocialCosts_s = g_s \quad \text{(Eq. 3)}$$

$$SocialBenefits_s = \sum_{y=2016}^{y=2036}\left(\left(\sum_{h=1}^{h=8760}\left((o_{s,h} + n_{s,h}) \times m(2016)_{s,h}\right)\right) \times d^{(y-2016)}\right) \quad \text{(Eq. 4)}$$

In these questions, I_s is the total system *s* installation cost, g_s is the rebate, $o_{s,h}$ is offset consumption in hour *h* of a typical meteorological year, $n_{s,h}$ is electricity sold back to the grid, $p_{s,y}$ is the state annual-average retail price of electricity (set to the latest available year: 2015) where the system is installed, $l_{s,h}$ is the average LMP, $m(y)_{s,h}$ is the marginal health and environmental damage, and *d* is the annual discount factor set at 2% and 7% for both the school and social CBAs. Ultimately, the CBAs for the schools and society are arrived at with Eq. 5 and Eq.6:

$$SchoolNetBenefits = \sum_{s}(SchoolBenefits_s - SchoolCosts_s)\ \forall\ aggregation\ unit \quad \text{(Eq. 5)}$$

$$SocialNetBenefits = \sum_{s}(SocialBenefits_s - SocialCosts_s)\ \forall\ aggregation\ unit \quad \text{(Eq. 6)}$$

Preliminary Results and Discussion

PV technical potential on U.S. educational buildings, for which we have LIDAR data
From the schools for which we have LIDAR data, we estimate a total installed power electricity generation potential of 1,700 GW or 2,500 TWh of annual energy generation. However, we expected our estimated total technical potential for installing PV on all U.S. educational buildings to be less than the total technical potential estimated by NREL for rooftop PV on residential and commercial buildings. NREL found the total national technical potential of rooftop PV to be approximately 1,100 GW of installed capacity or 1,400 TWh of annual energy generation [18]. Therefore, we plan to compare the PV-generation modeling of Gagnon et al. with Lorenzo and Vaishnav et al. to see which differences may cause our estimate to be larger than Gagnon et al.'s estimate of the total potential.

Lifetime costs and benefits of PV on U.S. educational buildings, for which we have LIDAR data
Only considering the schools for which we have LIDAR data and assuming a 7% discount rate for schools and society, we find school net-benefits to be -3,571,000 million USD and we find social net-benefits to be 730,000 million USD. Figure 3 represents the cumulative distributions for each PV project from the perspective of schools and society at a 2% and 7% discount rate.

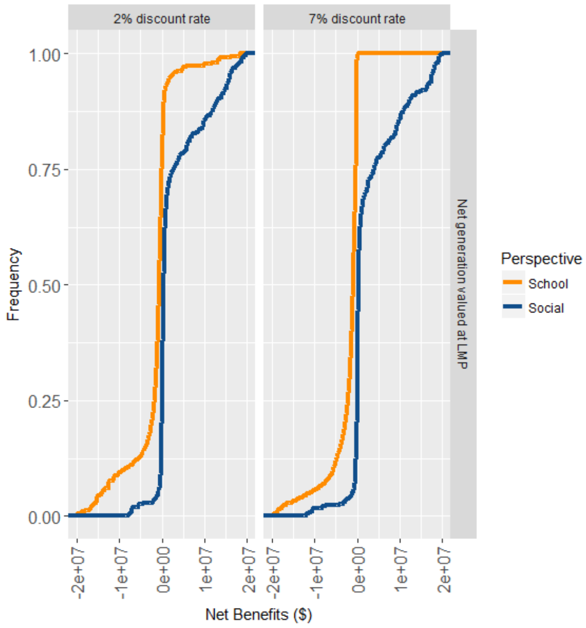

Figure 8. Cumulative distribution plots of each PV project from the perspective of the schools (orange) and society (blue) assuming a 2% (left) and 7% (right) discount rate. In both plots, we assume excess generation is sold back at the LMP. These plots only consider schools for which we have LIDAR data. Currently, school net-benefits are generally negative and social net-benefits are generally positive.

Following a previous study by Siler-Evans et al., we anticipate energy output to be highest in the Southwest and lowest in New England [6]. Furthermore, we expect solar PV to have the highest health and environmental benefits in regions where it is offsetting carbon-intensive and high-polluting technologies such as coal-fired power plants in the Midwest. Preliminary results from the roughly 38,000 schools for which we have LIDAR data suggests that regional trends are going in the direction that we expect, as shown in Figure 4.

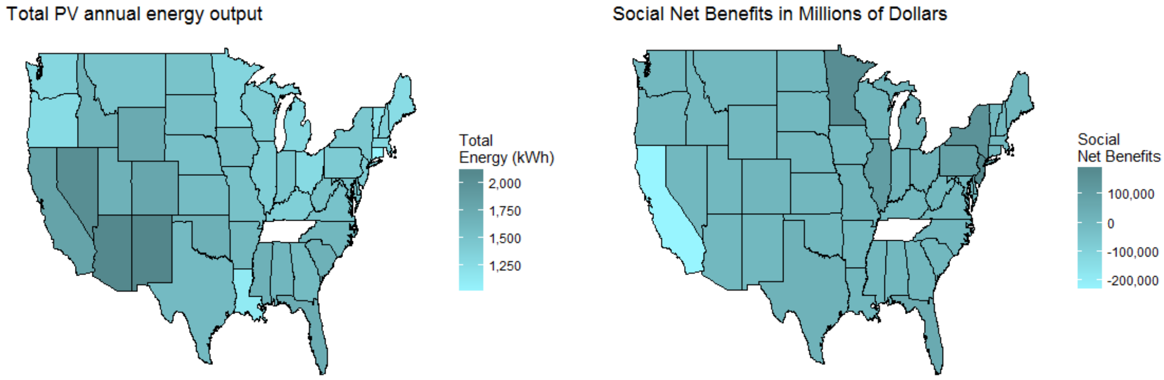

Figure 9. Maps of total PV electricity generation in kWh and total social net benefits in million USD aggregated at the state-level. These maps represent results from the roughly 38,000 schools for which we have LIDAR data. As expected, electricity generation is highest in the southwest where solar resource is highest and social net benefits are highest in regions where PV generation offsets electricity generated by fossil fuel power plants. We do not have LIDAR data for Tennessee; hence it is blank on both maps.

In the future, we plan to estimate roof space for the remaining school dataset that falls outside of the LIDAR measurements. Then, we plan to replicate this analysis for the full dataset of 134,000 schools. We also plan to estimate the annualized per-kilowatt costs and benefits of solar PV systems installed on all educational buildings in the United States. Finally, we plan to perform a sensitivity analysis on the CBAs to determine how results vary in relation to inputs such as discount factor, net-metering policies, and the value of excess generation (e.g. retail vs. LMP).

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9 STANDARDS AND LABELS

Applying Standards and Labeling Principles to Clean Cookstove Programs in Ghana

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Abstract

Standards and labeling (S&L) have been proven an effective tool for transforming the market for many efficient end-user products in many countries. Similarly, the application of best practice principles and experiences from S&L programs, such as analysis of market data, product testing and stakeholder engagement, can also facilitate the transition to clean and efficient cookstoves and fuels. CLASP has partnered with the Energy Commission of Ghana and the Global Alliance for Clean Cookstoves to carry out a series of standards and labeling projects to increase the penetration of clean cookstoves. One of the activities was to set performance tiers for the forthcoming cookstove labeling program in Ghana. This paper will present initial findings, recommendations, and lessons learned from this project. Specifically, this paper aims to 1) assess the difficulties and challenges for setting cookstove performance tiers, including lack of market information, limited product and testing data, and the difficulties in estimating impacts; 2) explain approaches and assumptions used in setting the performance tiers; and 3) summarize how S&L principles and experiences are being applied in the tier-setting process to provide a starting point for future tier revisions.

Introduction

Inefficient traditional cookstoves and open fire are still being used as the primary means for cooking for nearly three billion people in developing countries, posing serious environmental and health threats such as deforestation, loss of biodiversity, climate change and diseases due to indoor air pollution exposure. With over 70% of households using biomass cookstoves and 70% of forests eliminated in Ghana [1], transitioning to clean and efficient cookstoves is of the highest priority for Ghanaian policy makers. In fact, one of Ghana's conditional mitigation policy actions for its Nationally Determined Contributions (NDC) was to expand the adoption of market-based cleaner cooking solutions.

Standard and labeling programs have been proven effective in transforming home appliances market towards higher efficiency in many countries. Ghana is one of the first countries in Africa to introduce S&L program for major household appliances, including air conditioners, refrigerators, TVs and lighting products. The Ghanaian S&L program successfully helped Ghana to reduce energy consumption. The star label brand is also well recognized in the country. The Energy Commission of Ghana is currently developing an S&L program for cookstoves based on the success of on-grid programs as well as the star label brand. The Ghanaian cookstove S&L program will likely to include a minimum energy performance standard (MEPS) and a labeling program that is based on the existing Ghana star label brand. CLASP is supporting the Energy Commission in the cookstove S&L program development process. Once approved, the Ghanaian program will become one of the first cookstove S&L programs in the world and the standard-setting process will provide valuable lessons to policy makers around the world.

Objectives and Approach

This overall objective of this project is to propose a set of thermal efficiency and emission levels for the upcoming cookstove S&L program in Ghana.

The best practice for setting up S&L programs normally begins with a data-collection phase, followed by an analysis phase and then the standards-setting process. Policy makers may assess the existing product performance levels to determine where the standards and performance levels should be set and how many products on the market will be eliminated. The performance levels for each tier should be set based on the energy saved, the cost effectiveness, and the acceptability to consumers of incremental costs. The draft performance levels will go through multiple rounds of reviews by stakeholders before being finalized. The overall objective is to encourage the market transformation towards high-efficiency products in a cost-effective manner and to maximize national level energy saving impacts.

However, robust data and analysis may not always be available. The cookstove market in Ghana is fairly nascent and readily available market data is limited. Resources for carrying out in-depth market data collection and technical analysis are also limited. Therefore, we attempt to use a simplified approach to develop an initial set of cookstove performance levels, leveraging existing international tier levels and global cookstove performance data. This is intended to provide a first step to a longer-term and iterative process that aligns the tiers/levels with a comparative labeling program.

The specific objectives of the tier-setting are as follows:

Define label scope – whether the label should apply to a specific cookstove type (i.e. technology-specific) or all cookstove types including biomass, liquefied petroleum gas (LPG) and ethanol cookstoves (i.e. technology-neutral);

Set appropriate thermal efficiency levels for the label based on subset of international levels;

Set appropriate emission levels for the label based on subset of international levels.

What we learned and recommended

Defining the Label Scope

Cookstoves are a very complex product category from a standards and labeling perspective, due to the wide range of different technologies and fuel types. As such, one of the key questions to consider is whether to apply one label that is applicable across all technologies and fuels (technology-neutral approach) or different labels for each stove technology and/or fuel (technology-specific approach). It is recommended that the Ghana cookstove labeling program should adopt the technology-neutral approach and include all technology and fuel types, such as wood, charcoal, LPG and ethanol stoves. The following is a summary of advantages of using a technology-neutral labeling approach for cookstoves:

- **Potential to influence large segment of urban households to switch to LPG**: Over 1.7 million urban households (i.e. approximately 28% of all households in Ghana[1]) have access to LPG but the market share of LPG stoves is only 20% [1]. A labeling program that includes LPG stoves may encourage consumers to switch to LPG or other clean fuel (e.g. ethanol) stoves.
- **Simplicity of implementation**: Using one label facilitates monitoring and implementation.

[1] Total number of households in Ghana was reported to be 6,097,956. [1]

- **Ease of understanding**: Communication campaigns are simplified, as consumers need only understand one common label that encompasses stoves using different technologies and fuels.

- **Market impacts will match program intentions**: This approach will encourage consumers to move to more efficient stoves, beyond what could be achieved within specific technologies. Technology neutral approach also sends a clear market signal that more efficient technologies are encouraged and higher efficiency products will be rewarded with higher tiers on the label.

- **Level playing field and enhance competitiveness across technologies**: All products that deliver the same service (in this case cooking service) can be compared directly against each other using the same metrics. Clean cookstove manufacturers or distributors gain a competitive edge, distinguishing themselves from their competitors.

- **Enhance competitiveness of clean technologies**: **Marketing and branding**: The technology-neutral label approach establishes the legitimacy of energy efficiency (and emissions) and allows clean cookstove manufacturers or distributors to better market and brand their products against those lower efficiency products.

Setting Appropriate Thermal Efficiency Levels

One of the most common measures of stove performance is thermal efficiency, which refers to the fraction of heat produced by the fuel that made it directly to water in a pot placed on the coosktove. A higher thermal efficiency indicates a better efficiency to transfer the heat produced into the pot.

The following resources and data were used as inputs to set the thermal efficiency tiers:

- International Working Agreement (IWA) Tiers of Performance[2]

- Draft Ghana biomass cookstove standards *DGS 1112:2015;*

- Analysis of global aggregated cookstove performance datasets[3];

- Summary of current technology and product performance available on the market in Ghana.

A total number of 192 data points for thermal efficiency was gathered, including all types of stoves and fuels. It can be observed from Figure 1 that the performance distribution of cookstoves roughly follows a normal distribution, which is typical for many energy-using products[4]. This information allows us to set the performance tiers based on the following general guidelines:

- A small percentage of the best-performing products will occupy the highest tiers;

- A percentage of worst-performing products will be eliminated from the market;

- An even distribution of average-performing products which will occupy the middle tiers

[2] The IWA Tiers of Performances is the interim international guidelines for cookstove performances. The IWA Tiers cover efficiency, total emissions, indoor emissions as well as safety. IWA tiers range from 0 to 4, with tier 4 being the highest level of performance.
The goal is to provide a common and easy-to-understand terminology for governments, donors, investors, and consumers to make decisions about technology options.

[3] The data primarily consisted of the *Test Results Database* and *Stove Database* from the Clean Cooking Catalog, and complemented by performance and test data from a few other studies.

[4] Several LPG cookstoves reported in this data set can achieve a thermal efficiency of more than 70%.

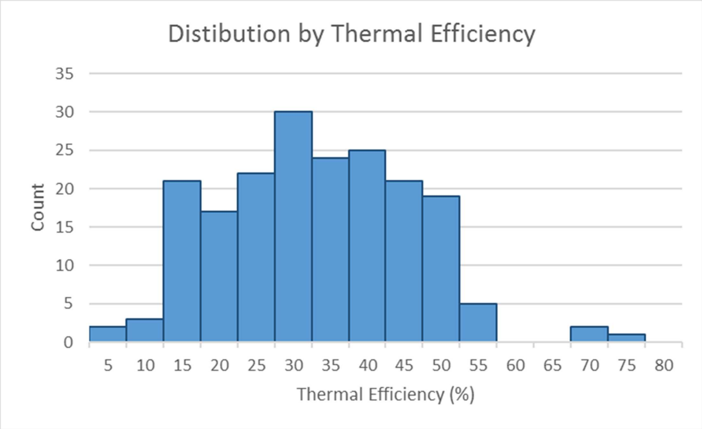


Figure 1. Distribution of Cookstoves by Thermal Efficiency

Based on the general guidelines mentioned above, we proposed thermal efficiency levels for each tier of the Ghana cookstove labeling program to start at 20% with 10% increment for each star level. The 20% cutoff will eliminate approximately 23% of the worst-performing products on the market. Moreover, the proposed cutoff exceeds the requirements for IWA Tier 1 thermal efficiency level which is 15%.

Table 1. Proposed thermal efficiency levels for each of the label's star levels

Star	Thermal Efficiency	Note
Five Star	≥60%	Five Star can only be achieved by LPG, or other clean fuel stoves (e.g. ethanol)
Four Star	≥50%	Four Star can be achieved by LPG or ethanol fuel stoves and also some high efficiency charcoal or wood stoves
Three Star	≥40%	Two Star and Three Star can be achieved by many improved charcoal and wood stoves available on the Ghana market
Two Star	≥30%	
One Star	≥20%	One star

Due to limited availability of Ghana-specific data, global data were used, under the assumption that the cookstove market in Ghana may have similar characteristics as the global market. Ideally, more accurate and Ghana-specific data should be collected in the future to evaluate the appropriateness of the proposed tier requirements.

Figure 2 illustrates the potential impact of the proposed tiers on the cookstove market for each type of cookstove. Any product with below One Star performance level (approximately 23% of all products) will not be able to participate in the labeling program. The proposed tiers can provide a reasonable distinction between various cookstove technologies thereby encouraging the market to shift towards higher efficiencies, as indicated in Table 1.

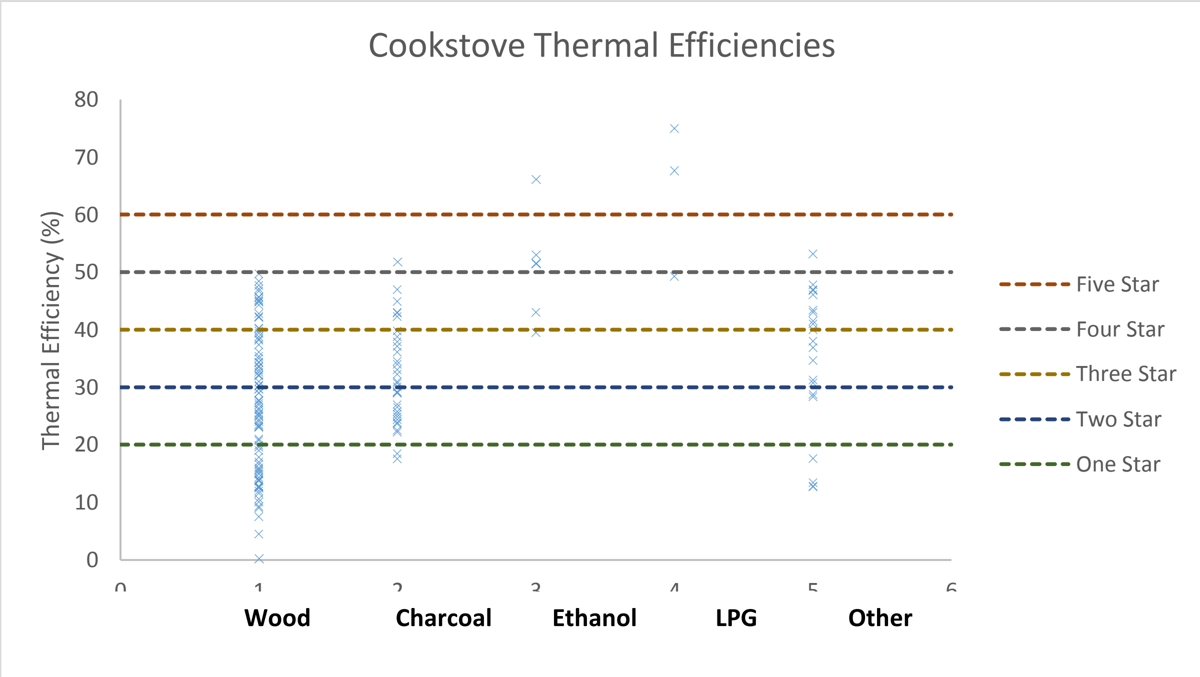


Figure 1.

Recommended Approach for Emissions

There are key differences in the process of setting tiers for thermal efficiency and emissions. Emissions are relevant to health risks rather than energy savings, and unlike energy efficiency and energy savings, the relationship between emissions and health risk is not linear. This means incremental improvements in the emissions levels of cookstoves do not result in proportional reductions in health risks. Therefore, using a market-based approach and an even range of tiers (both used to set thermal efficiency tier levels) may not be appropriate for setting emission tiers. Given the complexity of the relationship between emissions and health risks, it is recommended that the Ghanaian policy makers follow international bodies, such as the World Health Organization (WHO) [2] or International Standards Organization (ISO) [3]. Current international practice uses the following specifications for emission tiers detailed in Table 2.

Table 2. Tiers of Performance for Emission

IWA Tier	PM2.5			CO	
	RR	**mg/MJd**	**Normalized Emission Rate (mg/min)**	**g/MJd**	**Normalized Emission Rate (g/min)**
Tier 4	1.0	5	0.23	3	0.16
Tier 3	1.5	68	3.1	8	0.35
Tier 2	2.0	137	6.3	11	0.50
Tier 1	3.0	513	23.5	16	0.73
Tier 0	>3.0	>513	>23.5	>16	>0.73

RR: relative risk; MJD: mega joules delivered.

Given high levels of variability in current emissions testing worldwide, it is recommended that Ghanaian policy makers use a voluntary endorsement approach for labeling emissions. Tier 2 emissions (i.e. PM2.5 < 137mg/MJD and CO < 11 g/MJD) are being considered as the minimum threshold for the voluntary emission label – the shaded area in Figure 2. Approximately 24% of the cookstoves data points collected in this study can meet Tier 2 PM2.5 requirement and would therefore be eligible for the voluntary endorsement label.

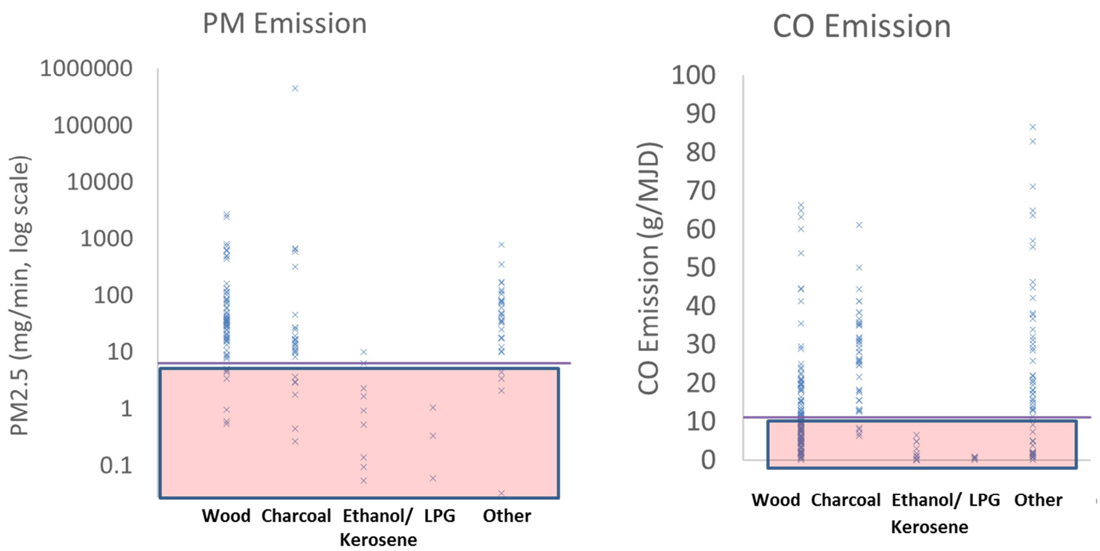


Figure 2. Proposed emissions levels

What Happens Next

As mentioned in earlier sections, the cookstove market and performance information in Ghana is rather limited, and therefore, we have used a simplified approach to set the tier requirements.

The recommended tier levels are only a starting point for the Ghanaian cookstove standard and labeling programs.

- EC has conducted additional cookstove testing in Ghana. Most commercially available cookstoves on the Ghanaian market have been tested and a database will be developed for EC's reference.
- EC is currently engaging with the international cookstove testing working group and ensure the test protocol is in alignment with international or regional test procedures wherever possible.
- EC has decided to first launch the minimum performance standards for cookstoves, including both minimum thermal efficiency and minimum emission requirements. A separate labeling program will be developed by EC later on.
- EC has held a workshop with cookstove industry players to discuss the appropriate tier levels; Followed by the discussion, EC decided to adopt an minimum thermal efficiency level of 25%, which is even more ambitious than the proposed 20% thermal efficiency cutoff.
- EC has decided to adopt the IWA Tier 2 as the minimum emission requirements.

Based on our past experience from appliances and lighting S&L programs, we recommended the following steps to be taken in the future to evaluate and revise the Ghana cookstove S&L programs:

- Identification of resources for ongoing program promotion and marketing, policing and enforcement, and updating test procedures and information about new technologies on the market. Include, if possible, links to programs sponsored by other government or non-governmental organizations that can increase incentives and resources for promotion.

- Development of an evaluation plan at the beginning of the program. Process and impact data to be collected and utilized to improve the program.

- Revise standards and labeling program and performance thresholds if needed.

Limitations

One major limitation of this study is that the recommended tier requirements are developed based on global data points instead of Ghana-specific data points. The Ghana cookstove market may not be the same as the global market. Therefore, the recommended tier requirements might be over- or underestimated. However, as we mentioned earlier, this simplified approach can still provide policy makers with a starting point for their labeling program in absence of detailed data. Policy makers will need to continue to evaluate and review the program as more data become available.

Another limitation is that the data were collected from various sources and the test protocol used from different literatures or databases might be different. The test results may not be comparable.

Lastly, due to the limited data, we did not carry out a cost-benefit analyses to study the effectiveness of the proposed tier requirements. This study should be carried out in the future to ensure the cookstove labeling program can bring net positive impact to Ghana.

Conclusion

A technology-neutral approach to labeling cookstoves, one that includes all fuels types, is recommended due to the complexity and diversity of technologies on the cookstoves market. Final tier levels and minimum performance levels for thermal efficiency and emissions will be decided during the S&L process lead by the Energy Commission of Ghana.

Regarding opportunities for future initiatives, there is a critical need for more performance data at the country level for both thermal efficiency and emissions. Country-specific data is crucial for developing an S&L program, and the underlying labeling tiers, to transform effectively the Ghana market. In addition, continued efforts to build technical capacity of testing centers and improve accuracy of emissions testing will enhance the impact of comparative (tiered) labels, which in theory can help move consumers toward higher performing cookstoves.

References

[1] Global Alliance for Clean Cookstoves. (2012). *Ghana Market Assessment – Sector Mapping.* Can be downloaded at: http://cleancookstoves.org/binary-data/RESOURCE/file/000/000/162-1.pdf

[2] World Health Organization. (2014). Indoor air quality guidelines: household fuel combustion

[3] International Standards Organization. ISO 19867 – Harmonized laboratory test protocols. (Under development).

Regional Harmonization of Energy Efficiency Standards for Appliances

Steve Kukoda, International Copper Association and Patrick Blake, UN Environment

Abstract

This paper will demonstrate the methodologies that led to the first regionally harmonized standard in Southeast Asia through the Association of Southeast Asian nations (ASEAN) for room air conditioners, and ongoing efforts to expand the project to include other appliances. Further, the paper will demonstrate how the ASEAN project is being replicated in other regions.

The paper will introduce newly created United for Efficiency (U4E) Policy Guides and roadmaps for lighting, refrigerators and air conditioners (as well as for motors and distribution transformers) that, when implemented, will lead to total market transformations towards energy efficient appliances. At the heart of these market transformations are mandatory minimum energy performance standards (MEPS) and associated policy frameworks, including creative financing mechanisms.

Action is needed in the developing and emerging economies, in particular, where MEPS are often non-existent or inadequate. Without intervention, these developing economies will lock-in inefficient appliances that will exacerbate climate change and make unstable grids even more so.

The projects covered in this paper will help enable regional blocks of countries to make significant contributions towards their Nationally Determined Contributions (NDCs) as part of the global climate change agreement, while at the same time taking stress off electrical grids and mitigating the need for investments in new power generation.

Introduction

The goal of this paper is to demonstrate the success of the first regional harmonization of standards (for room air conditioners) in the ASEAN region, and to demonstrate how the United For Efficiency initiative is committed to taking the lessons learned from the ASEAN SHINE initiative and scaling-up to regions beyond the ASEAN.

ASEAN SHINE is a public-private partnership between the UN Environment and the International Copper Association (ICA), with primary funding from the European Commission's Switch Europe. ASEAN SHINE is implemented under the steering of the ASEAN Member States and has been recognized as a key Dialogue Partner by the ASEAN Ministers of Energy Meeting (AMEM). ASEAN SHINE adopts a holistic approach to market transformation, by using mechanisms including policy, regulations, capacity building along the supply chain, and awareness raising among end-users.

ASEAN SHINE currently works on standards harmonization across ASEAN for air conditioners and lighting products. Achievements to date include:

•Agreement by ASEAN Member States to harmonize test methods for air conditioners to the international standard ISO 5151:2010

•The agreement and adoption of a "ASEAN Regional Policy Roadmap for Harmonization of Energy Performance Standards for Air Conditioners"

•Individual National policy roadmaps for air conditioners developed and adopted by ASEAN Member States to achieve regional harmonization.

•Capacity building programs for manufacturers and testing laboratories

•Consumer awareness campaigns and tools, including air conditioner selection software and AC SELECT Application to help retailers and consumers see the important economic benefits of purchasing higher efficiency air conditioners.

•The establishment of ASEAN SHINE Lighting Technical and Policy workgroup;

•The agreement of ASEAN Member States to establish harmonized standards for lighting products in the region.

With financial support from UN Environment and the European Union, ASEAN SHINE has completed a study to prepare for the expansion of ASEAN SHINE to include the following products: Continuation of Lighting, Refrigerators, Electric Motors, Distribution Transformers Solar PV and Solar Thermal.

ASEAN SHINE is a direct support initiative of United For Efficiency (U4E), a public-private partnership founded by UN Environment, the International Copper Association, the UN Development Program, CLASP and the Natural Resources Defense Council. U4E is focused on market transformations towards energy efficiency appliances and industrial equipment: air conditioners, refrigerators, motors, distribution transformers, and lighting. U4E recognizes the positive (and ongoing) outcomes of ASEAN SHINE in harmonizing standards across regions and looks to replicate the SHINE model in other regions.

Background

In April 2016, 175 countries signed the historic Paris Agreement, in which each country pledged its national commitment in reducing greenhouse gas emissions, known as the nationally determined contributions (NDCs). Among various strategies in achieving the NDC goals, appliance energy efficiency is one of the easiest and most cost-effective ways to reduce energy demand and greenhouse emissions.

The International Energy Agency (IEA) published a report that states half of the actions needed to achieve the Paris agreement could come from energy efficiency. Importantly, these actions do not require investments in new technologies, but rather a commitment to scale-up existing energy efficiency technologies.

Energy efficiency in domestic appliances (and industrial equipment) is universally critical. This is particularly true in the developing world, where standards for appliances are often either absent or woefully inadequate compared to currently available technologies. The figure below shows the status of mandatory minimum energy performance standards (MEPS) globally for residential air conditioners and refrigerators, and for motors and distribution transformers.

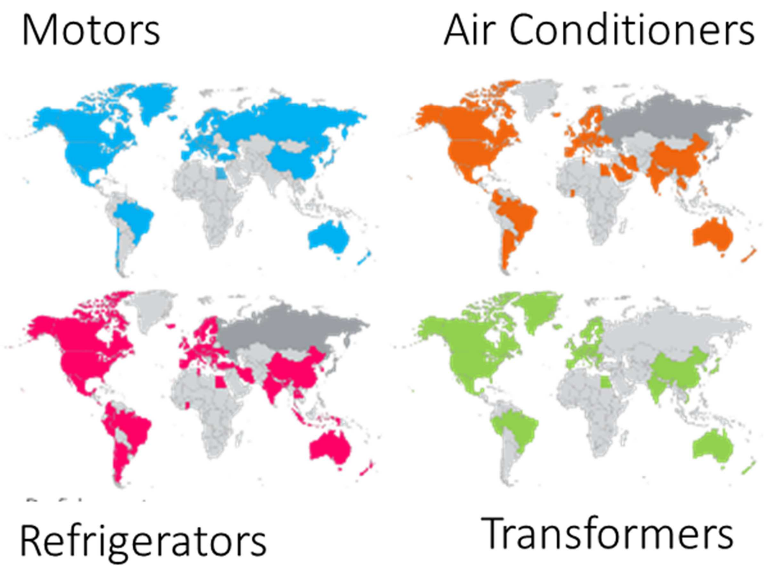
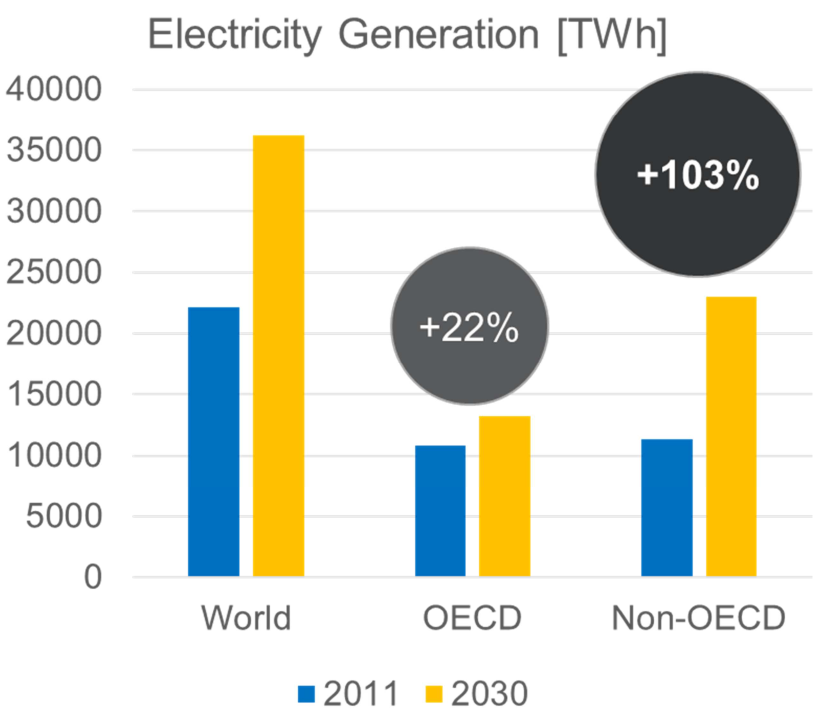


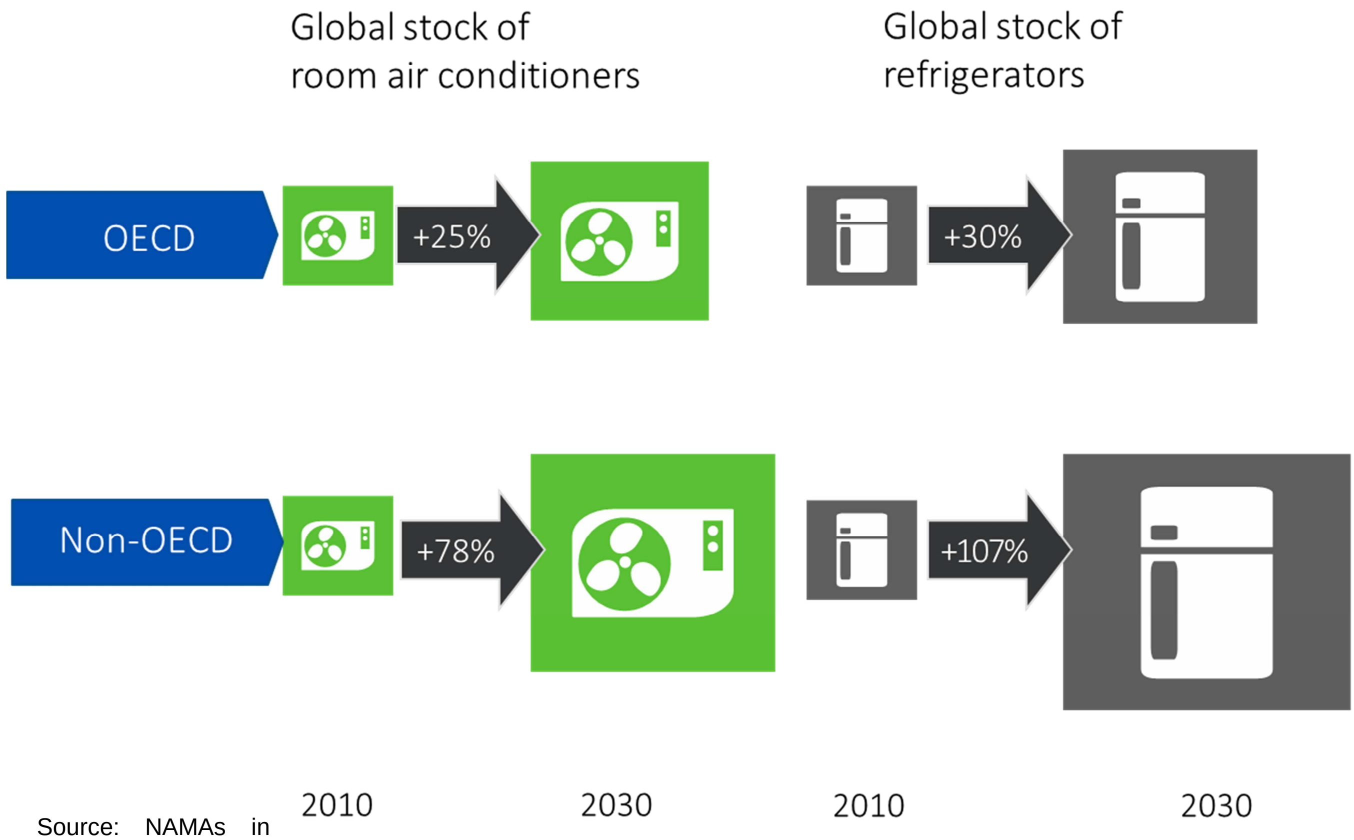
Figure 1: Status of Mandatory MEPS Worldwide. Source: UN Environment Program

This simple chart is color-coded to show where mandatory MEPS are currently present; if a country has a color, MEPS are in place. We can see the grey areas – which indicate mandatory MEPS are currently not in place – are primarily limited to non-OECD countries, and it is in these countries were demand growth for appliances will far outpace the developed world. According to the IEA, global electricity consumption will grow by 60-percent between 2011 and 2030[5]. When this overall growth is segmented into OECD and non-OECD countries, a striking picture emerges:



[5] International Energy Agency World Energy Outlook 2013

The data shows electricity consumption in the non-OECD growing at a rate nearly five-times that of the OECD[6]. This demand largely will be driven by a growing middle class (sometimes referred to as a “spending class”), expected to grow from two billion people to five billion people in the same timeframe [7]. This growing middle class will greatly increase demand for residential appliances, such as air conditioners and refrigerators. As is the case with overall electricity consumption, demand for appliances in the non-OECD will greatly exceed demand in the OECD:



Source: NAMAs in the refrigeration, air conditioning and foam sectors: A technical handbook”, GIZ, 2013; LBNL BUENAS, 2014.

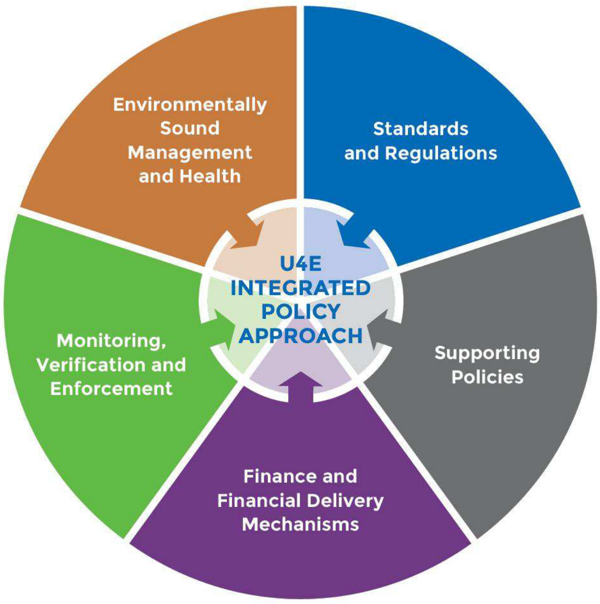
We can see a more than tripling of demand in the non-OECD versus the OECD for both refrigerators and air conditioners. As noted earlier in this paper, non-OECD countries generally do not have MEPS, so the potential exists for one billion refrigerators and air conditioners to be sold without MEPS, which would have significant and adverse effects on the Paris climate change agreement.

Accelerating Market Transformations Towards Energy Efficient Appliances and Equipment

United For Efficiency (U4E) is a public-private partnership (PPP), formed in 2014 to accelerate the global transition towards energy efficient products. Manufacturing partners to the initiative include ABB, Arçelik, BSH Hausgeräte GmbH, Electrolux, MABE, Neonlite (MEGAMAN brand), Osram, Philips Lighting and Whirlpool Corporation. Partner organizations include the Copenhagen Center on Energy Efficiency, GIZ, China National Institute on Standardization, Global Efficient Lighting Challenge, OLADE, National Lighting Test Center China, Southern Africa Power Pool, Big EE, and Top Ten International Services. Partners support U4E with global outreach, technical expertise, market intelligence and training for government officials.

[6] International Energy Agency World Energy Outlook 2013
[7] Brookings Institute

U4E is built on the success of the en.lighten initiative, which to date has helped more than 60 countries commit to phasing-out inefficient lighting technologies; this is making a positive impact on one billion people around the world. en.lighten introduced the Integrated Policy Approach, which is now updated under U4E for the other appliances and equipment. The U4E approach mimics the successful Integrated Policy Approach introduced through en.lighten and includes five main pillars:



1. **Standards and Regulations** (including MEPS) cover a collection of requirements defining which products can be sold and those that should be blocked from the market. They form the foundation from which to ensure the success of any efficient lighting transition strategy.
2. **Supporting Policies** include labelling schemes replacement programs and other market based instruments; and information and communication campaigns to change end users' behavior. These are necessary to ensure the smooth implementation of standards and regulations, and to achieve a broad public acceptance.
3. **Finance and Financial Delivery Mechanisms** address high first-cost challenges of energy-efficient products. These include economic and fiscal instruments, such as rational electricity prices and tax breaks. Financing incentives address initial incremental costs through, for example, dedicated funds and electric utility on-bill financing.
4. **Monitoring, Verification, and Enforcement** includes effective monitoring of product efficiency, verification of declarations of conformance, and enforcement of regulations.
5. **Environmentally Sound Management and Health** is crucial to minimize any environmental or health impacts. Mercury and other hazardous substance content standards should be established in line with global best practice. Special attention should be given to the development of a legal framework for environmentally sound, end-of-life activities.

This integrated policy approach has been successfully introduced to more than 60 countries by en.lighten. U4E seeks to build upon the success of en.lighten by transferring the integrated policy approach to residential appliances and industrial equipment. The goals of U4E are, by 2030:

- 10% reduction in global electricity consumption
- 1.25 giga-ton reduction in CO_2 emissions annually
- Creation of $350 billion USD in savings to users of more-efficient products
- Avoidance of $500 billion in investments in new power generation

Both U4E and en.lighten align with the UN's Sustainable Energy for All (SE4ALL) initiative, and these programs serve as the official Energy Efficiency Accelerators for appliances and lighting, respectively, under SE4ALL. The SE4ALL EE Accelerator platform was established to meet the SE4ALL goal of doubling the rate of improvement in energy efficiency. Other high-impact areas addressed by the SE4ALL EE Accelerator platform are: Buildings Efficiency; District Energy; Transport and Motor Vehicle Fuel Efficiency; and Industrial Energy Efficiency.

Regional Harmonization of Standards

In order to accelerate market transformations towards energy-efficient products, U4E is focused on a model that will encourage regional blocks of countries to harmonize on MEPS.

Regional harmonization offers multiple benefits. They allow countries, private sector and consumers to avoid the costs of duplicating testing and performance information required on package and other requirements. Stakeholders thus benefit from the removal of this administrative trade barrier and are able to leverage the better prices and choice of goods associated with the larger economies to which they are harmonized. If countries have different requirements, it is difficult and time consuming for a manufacturer to carry out the necessary tests for each specific country. Harmonization enables multiple national markets to be accessible for the cost of only one test. It also enables lower product cost as manufacturers can leverage their production volume across multiple markets.

Working within a region and with different organizations (e.g. government, private sector, civil society) can result in more effective outcomes. Such cooperation leads to positive results through sharing resources for energy-efficient product policies and programs. Energy-efficient product and policies programs are initiated each year at local and national levels, which can inadvertently duplicate effort, conflict, or cause confusion. A regional cooperation initiative helps to coordinate such programs. Conflict can be avoided and results can be achieved in a cost-effective manner.

For a regional cooperation initiative to be successful consensus among the stakeholders is important. The following are suggestions for how to promote regional cooperation:

- Conduct roundtables and other consensus-building activities to reach agreement about particular issues, policies, guidelines, standards, and related subjects;
- Identify liaisons in each country to be point of contact and lead on local activities;
- Establish bilateral activities with another country in the region;
- Conduct in-person and online events to share experiences and information; and
- Develop infrastructure for communication between stakeholders.

For promoting energy-efficient products, regional cooperation can include:

- Developing a regional efficient product roadmap to identify areas of cooperation and ways to share resources and build regional markets for efficient products;
- Establishing or harmonizing specifications and standards that include energy performance and quality criteria;
- Coordinating around monitoring, verification and enforcement activities, e.g., verification of labels, mutual recognition of test results, or sampling and checking regulations (MEPS) and standards compliance;
- Expanding test facilities to reduce costs and build a network of professionals, with some countries potentially specializing in certain aspects of testing;
- Establishing regional resources for environmentally sound management, including collection and recycling schemes and information programs.[8]
- Pooling resources and making use of the available structures and capacities within regions to improve the effectiveness, mutual reinforcement, and synergy between the various country programs, making them more cost effective and impactful.

[8] The Basel Convention and many national laws establish strict guidelines for the movement of hazardous wastes to other countries, but exceptions can be made if certain conditions are met by the proposed programme. A country or group of countries planning to collaborate in the establishment of a regional recycling programme should consult with the Basel Convention Secretariat and its Regional Centers to obtain information and guidance.

Regional Harmonization Case Study: ASEAN-SHINE

U4E's approach to regional harmonization is proven to work. Through the SHINE initiative, the ASEAN region has agreed on the region's first harmonized standard (room air conditioners). Achievements of SHINE include:

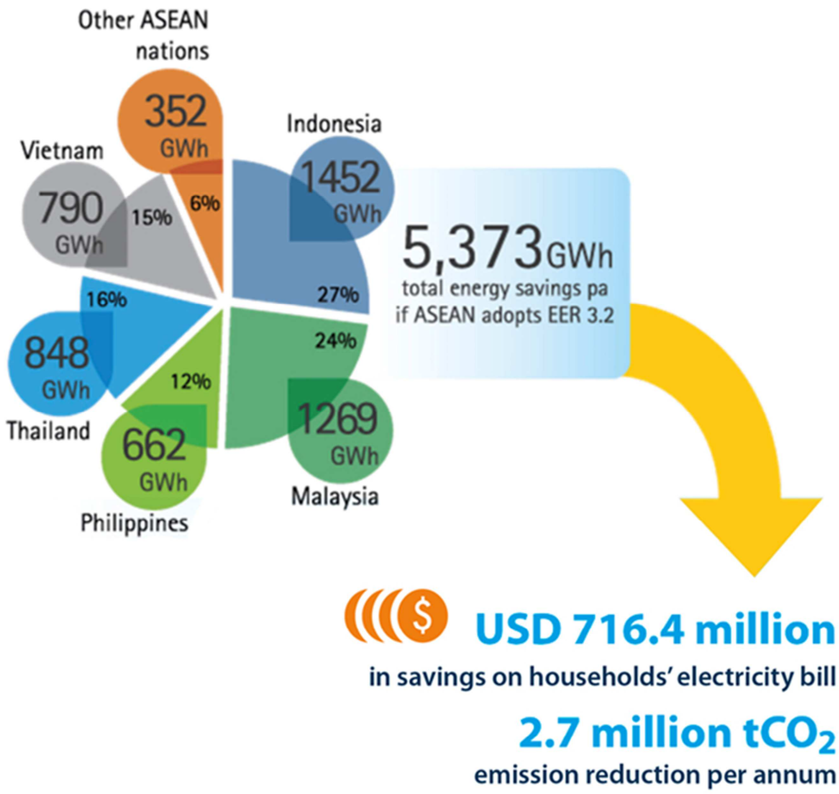
- All ASEAN member states to use ISO 5151:2010 for the testing method for air conditioners by 2017, and adoption of ISO 16358 by 2020
- A Regional Policy Roadmap was endorsed by 10 ASEAN member states (Ministers of Energy Meeting, AMEM) ASEAN Member states agreed to increase MEPS for ACs over time
- Training for testing laboratories from Thailand, Malaysia, Indonesia, Philippines, Vietnam increased capacity to perform testing according to ISO5151:2010 and implement ISO 17025

A Joint Ministerial Statement following 34th ASEAN Energy Ministers Meeting, September 2016, reads:

"The Ministers agreed to pursue the dynamic collaboration with Dialogue Partners in the area of energy efficiency and conservation and acknowledged the continued implementation of the ASEAN-SHINE programme."

SHINE is a partnership between the UN Environment Program and the International Copper Association. It was formed in 2010, with funding from the Asia Pacific Economic Cooperation (APEC) and the European Union.

The impact of harmonized standards, based on MEPS set at China's energy efficiency rating (EER) level of 3.2 are enormous:



Source: UN Environment

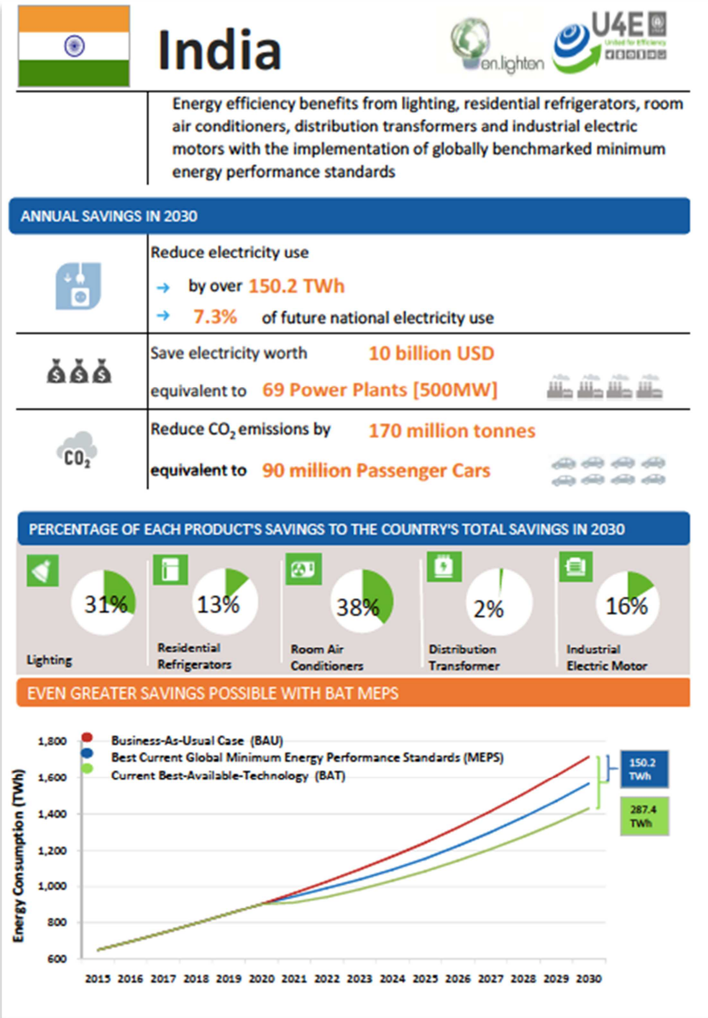
With the successful adoption of MEPS for room air conditioners, the ASEAN is looking to harmonize on the other products covered by U4E.

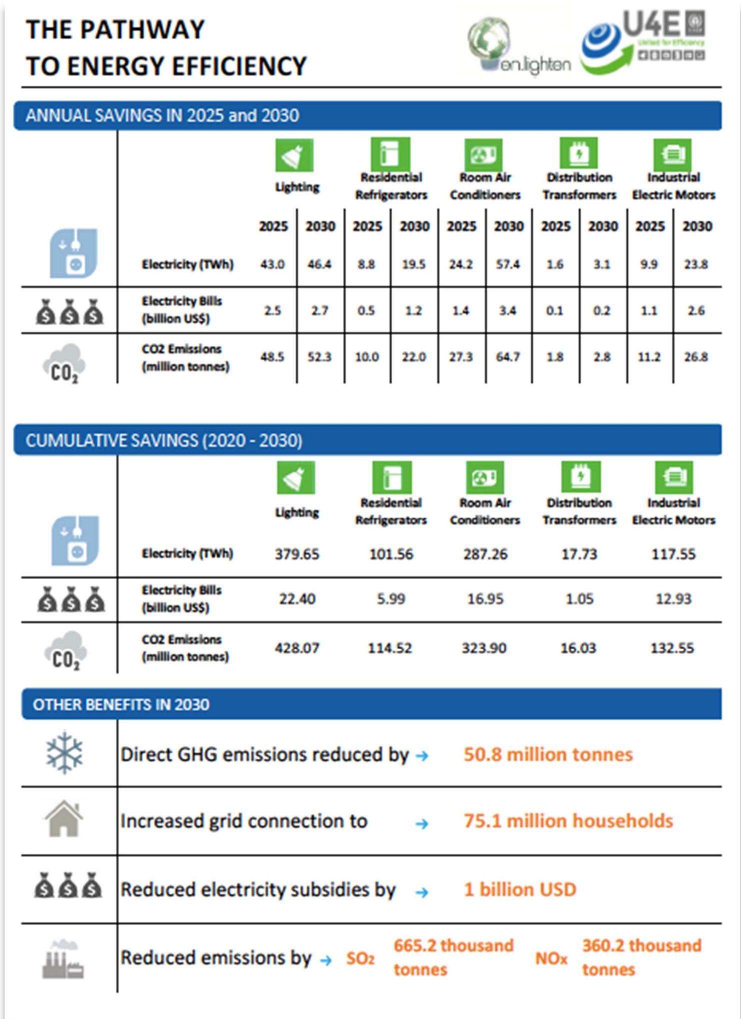
Replicating the ASEAN-SHINE Model

With success and momentum in the ASEAN region, U4E is replicating the regional harmonization work of SHINE in other regions, through scaling-up the Integrated Policy Approach of en.lighten. For example, the member countries of the Central American Integration System (SICA) region have agreed to harmonize on MEPS for lighting, air conditioners, refrigerators, street lighting and motors. The regional MEPS align with existing standards in Mexico, and include regionally harmonized product labels. Regional U4E projects are in process in the Southern Africa Development Community (SADC) countries, as well as in the Pacific Island States.

To help countries to understand the potential of the U4E integrated policy approach, 150 country-specific assessments were completed. Each shows a country its potential reductions in electricity consumption and CO_2 emissions, dollar-savings to consumers, and avoided investments in new power generation. An example for India is shown below. The country assessments are the main advocacy tool for U4E. They help the initiative to secure political commitment, and to encourage the development of national projects to accelerate the deployment of energy-efficient lighting, appliances and equipment.

Example of U4E Country Assessmen





THE PATHWAY TO ENERGY EFFICIENCY

ANNUAL SAVINGS IN 2025 and 2030

	Lighting 2025	Lighting 2030	Residential Refrigerators 2025	Residential Refrigerators 2030	Room Air Conditioners 2025	Room Air Conditioners 2030	Distribution Transformers 2025	Distribution Transformers 2030	Industrial Electric Motors 2025	Industrial Electric Motors 2030
Electricity (TWh)	43.0	46.4	8.8	19.5	24.2	57.4	1.6	3.1	9.9	23.8
Electricity Bills (billion US$)	2.5	2.7	0.5	1.2	1.4	3.4	0.1	0.2	1.1	2.6
CO2 Emissions (million tonnes)	48.5	52.3	10.0	22.0	27.3	64.7	1.8	2.8	11.2	26.8

CUMULATIVE SAVINGS (2020 - 2030)

	Lighting	Residential Refrigerators	Room Air Conditioners	Distribution Transformers	Industrial Electric Motors
Electricity (TWh)	379.65	101.56	287.26	17.73	117.55
Electricity Bills (billion US$)	22.40	5.99	16.95	1.05	12.93
CO2 Emissions (million tonnes)	428.07	114.52	323.90	16.03	132.55

OTHER BENEFITS IN 2030

Direct GHG emissions reduced by →	50.8 million tonnes
Increased grid connection to →	75.1 million households
Reduced electricity subsidies by →	1 billion USD
Reduced emissions by →	SO_2 665.2 thousand tonnes; NOx 360.2 thousand tonnes

U4E Policy Guide Books

The most recent advancement for U4E is the development of Policy Guides for each of the five products (lighting, air conditioners, refrigerators, motors, distribution transformers) addressed by the initiative. A consultative process was used to developed the guides by establishing an Expert Taskforce for each of the five focus products. Each Expert Taskforce had participants from over 20 organizations, including international organizations, environmental groups, international manufacturers, government officials and academic institutions.

The balanced Expert Taskforces results in credible guidance that is very effective in reducing uncertainty, and measurably helps countries adopt policies that make good economic sense and help reduce carbon emissions.

These comprehensive tools provide step-by-step roadmaps on the implementation of U4E's integrated policy approach. The steps of the Policy Guides are outlined in Annex I and electronic copies of the guides can be found at http://united4efficiency.org/resources/publications/.

The implementation of the U4E Policy Guides requires capacity-building in countries, along with financing and other resources. As of this writing, twelve countries are progressing to implement the U4E Integrated Policy Approach, with funding from the Global Environment Facility (GEF).

Early Replacement of Inefficient Products and Environmentally Sound Disposal

While policies for energy-efficient products are critical, policies alone are insufficient to transform markets quickly. In 2015, less than 30-percent of appliances and 10-percent of motors in the installed base were covered by MEPS[9]. A primary reason is a lack of policies and incentives that provide enabling frameworks for the early replacement of functional, yet less-efficient products. Air conditioners and refrigerators have product life cycles of ten or more years. An installed motor can remain in use for more than two decades. A distribution transformer may not be replaced for more than three decades. Further, repairs to malfunctioning products generally bring them back to functional performance levels inherent to the time of original manufacture. Or worse, products are repaired only to the point of functionality, with degraded performance from when new.

Capacity-building for early replacement of appliances and industrial equipment needs to gain awareness, along with associated actions that ensure the installed base of less-efficient products are being replaced with newer, more-efficient ones. The single biggest barrier to this effort is a dearth of financing. Here governments, financial institutions and manufacturers can form partnerships that provide enabling environments that lead to policies to accelerate early replacement. Education is critical to this effort, including case studies that provide solid data on payback times and lifetime-cost savings for early replacement of products. However, again, the first cost must be overcome.

Creative financing mechanisms include:

- No- or low-cost loans to governments
- Rebates for higher-efficient products
- On-bill incremental financing of products
- Others

The early replacement of less-efficient products provides all the inherent benefits of energy efficiency: reduced CO_2 emissions, consumer electricity bill savings, reduced stress on electrical grids, and avoidance of new power generation. From a climate change mitigation perspective, it is vital that policies for early replacement include provisions for safe and environmental disposal of the old equipment; shipping used, inefficient products to less-developed countries only transfers greenhouse gas emissions to another country, while also saddling that country with unnecessarily high electricity consumption.

U4E is engaged with financial institutions to provide financing packages for countries that will accelerate the early replacement of inefficient appliances and equipment. For example, U4E is partnering with the Copenhagen Center on Energy Efficiency to convene a series of workshops in 2017 that brings together financial institutions (private sector banks, development banks, foundations, etc.) to gain commitments for in-country financing of early replacement of appliances and industrial equipment.

Recycling used, less-efficient appliances and equipment ensures these products will never be reused, and many of the materials contained within can be repurposed for other uses. Some of these materials are finite global resources and recycling will help countries to better manage their resource requirements.

The recycling process must ensure the environmentally friendly collection and disposal of ozone-depleting substances and persistent organic pollutants, such as refrigerants found in refrigerators and air conditioners, mercury in lighting, etc.

[9] International Energy Agency Energy Efficiency Market Report 2016

Conclusions

Best-practice sharing with en.lighten (on the proven benefits of the Integrated Policy Approach) and ASEAN SHINE (on the successful regional harmonization of an energy efficiency standard for room air conditioners) are enabling United For Efficiency to accelerate market transformations towards energy-efficient appliances and industrial equipment. U4E is making progress on regional harmonization of standards in the LAC and SADC, and other priority regions have been identified. These market transformations will allow countries to significantly reduce their CO_2 emissions, while at the same time creating economic development for individuals and businesses, and mitigating investments in new power generation (and taking stress off existing electrical grids). Through partnership with financial institutions, U4E is driving policies that aim to accelerate the early replacement of inefficient products.

The work of U4E is critical as without intervention, a majority of developing world countries will continue to drive demand for inefficient products that will dramatically increase CO_2 emissions, unnecessarily increase electricity demand, and put unneeded cost burdens on individuals and businesses through high energy bills.

Annex I U4E Policy Guides Table of Contents

Consumer Preferences and Response to Cookstove Label Designs

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Abstract

Three billion people in low- and middle-income countries use cooking fuels and technologies that pose health risks associated with household air pollution, and environmental impacts associated with GHG emissions and deforestation. In response, efforts are underway across the globe to transition households to cleaner, safer, and more fuel-efficient cookstoves. The government of Ghana is planning to launch a new national performance standards and labeling (S&L) program for improved cookstoves, in an effort to increase the uptake of ICS across their urban and rural populations. This paper discusses a component of the process for developing the Ghana improved cookstove label, specifically the informed design of the visual label. The paper includes the approach and methodology, as well as qualitative findings from consumer research on preferences and comprehension of draft cookstove labels and an existing Ghana energy efficiency label.

Introduction

More than seventy percent of Ghanaians use biomass fuel for cooking and are exposed to harmful pollutants emitted by the incomplete combustion of biomass (firewood, charcoal, agri-waste, etc.). Around 13,400 deaths occur per annum in Ghana from smoke related illnesses attributable to household air pollution from the use of biomass for cooking. [10] Due to their high exposure to cookstoves in the home, children under the age of five are considered most vulnerable.[11] In Ghana and around the world, the market for improved cookstoves and alternative fuels is nascent. Many national and international initiatives are already underway to make better cookstoves and alternative fuels available to Ghanaians, including private manufacturer initiatives through profit-based business models, non-governmental initiatives, and ongoing government initiatives. Most of these programs focus on charcoal stoves and the approximately thirty-two percent[12] of households that rely on charcoal as a primary cooking fuel. In urban areas, liquid petroleum gas (LPG) has significant market penetration as a cooking fuel, with about twenty-two percent of households – or about thirty-six percent of the urban population – using LPG as their primary cooking fuel.[3]

The government of Ghana recognizes the dire harm caused by open fires and traditional stoves and is seeking to transition consumers from traditional biomass stoves to improved stoves by developing and implementing performance standards and labels (S&L) for biomass cookstoves. To assist the development of the labeling portion of this initiative, the Energy Commission of Ghana (regulator for the energy sector including biomass fuels and end-use devices) partnered with the Global Alliance for Clean Cookstoves (Alliance) and CLASP to transfer and apply best practices from energy efficiency labeling programs for *on-grid* appliances (i.e. electric appliances such as air conditioners and refrigerators). A consumer research project was undertaken to inform the design of the label for the proposed cookstove S&L program.

The rationale for undertaking market research to inform label design reflected both best practice for electrical appliances, and the need to address a data gap – very limited research is available anywhere on consumer comprehension, behavior, and attitudes towards, and in response to, cookstove labels. This information is essential for the Ghana Energy Commission to design an effective cookstoves label that will resonate with cookstove consumers, and inform broader policy interventions, including standards and labeling awareness campaigns.

While some Ghanaian consumers are already familiar with energy labels on refrigerators, air conditioners (ACs) and compact fluorescent lamps (CFLs), cookstoves are used by almost all households, including rural communities, which may not be familiar with existing energy efficiency labels. Any potential lack of familiarity or misunderstanding of labels by consumers could present a risk to the program and broader clean cooking initiatives. Even those familiar with labels could struggle to interpret cookstove labels, which will need to convey simultaneously two primary product performance measures: emissions, which convey overall health and environmental impacts, and efficiency, which conveys fuel savings and economic impacts.

Disclaimers:
1) The label presented in this paper is a draft version.
2) The results from the research presented in this paper are in draft form and may not be consistent with the final results.

[10] Global Alliance for Clean Cookstoves (GACC), at: http://cleancookstoves.org/country-profiles/focus-countries/1-ghana.html
[11] WHO, Indoor Air Thematic Briefing 2, p2 available at: http://www.who.int/indoorair/info/briefing2.pdf
[12] Ghana Statistical Service, 2014. Ghana Living Standards Survey Round 6 (GLSS 6) Main Report

Approach and Methodology

The objective of the consumer research was to investigate household and institutional users' response to the Energy Commission's draft cookstove labels, in the following areas:

1. Label comprehension,
2. Relevance of label information to user,
3. Understanding of benefits of improved cookstoves.

In addition, participants were asked about their:

4. Familiarity and comprehension of existing product performance labels (such as the energy efficiency label for refrigerating appliances, which has been on refrigerating units in Ghana since 2009).

The ultimate goal of this research was to identify a label design that is most effective at influencing consumers to purchase improved and more efficient cookstoves.

The study was performed by Kantar Public (a social research private organization), and included qualitative mini focus group discussions and in-person interviews administered in consumer's houses or institutions. The focus groups and household interviews were administered to a representative sample of the adult population aged 16 and older who are considered heads of their households. The sample was drawn from four regions across Ghana – Greater Accra Region, Ashanti Region, Western Region, and Northern Region. A non-representative sample of relevant institutional decision-makers were interviewed as well, but did not participate in the focus group discussions.

Focus groups were composed of small groups of eight (8) cookstove users led through an open discussion by a skilled moderator from Kantar Public. Each focus group section lasted for about 60 minutes. The focus groups were predominately homogeneous with respect to user's primary cookstove type at home (e.g. traditional charcoal users). In total, 12 focus groups were carried out with 96 household participants across the four regions.

Table 1. Focus group discussions with target household participants

Region	**Consumer Segments**		
	Urban – High Income	**Urban – High/Middle Income**	**Rural – High/Middle Income**
Greater Accra	1 x Ci 1 x C&L	1 x C 1 x C&L	1 x F 1 x C&F
Ashanti			1 x F 1 x C&F
Western		1 x C 1 x C&L	
Northern			1 x F 1 x C&F
Total	*2*	*4*	*6*

F: Firewood stove user
C: Traditional charcoal stove user
Ci: Improved charcoal stove user
L: LPG stove userC&L: Charcoal stove & LPG stove user
C&F: Charcoal stove & Firewood stove user

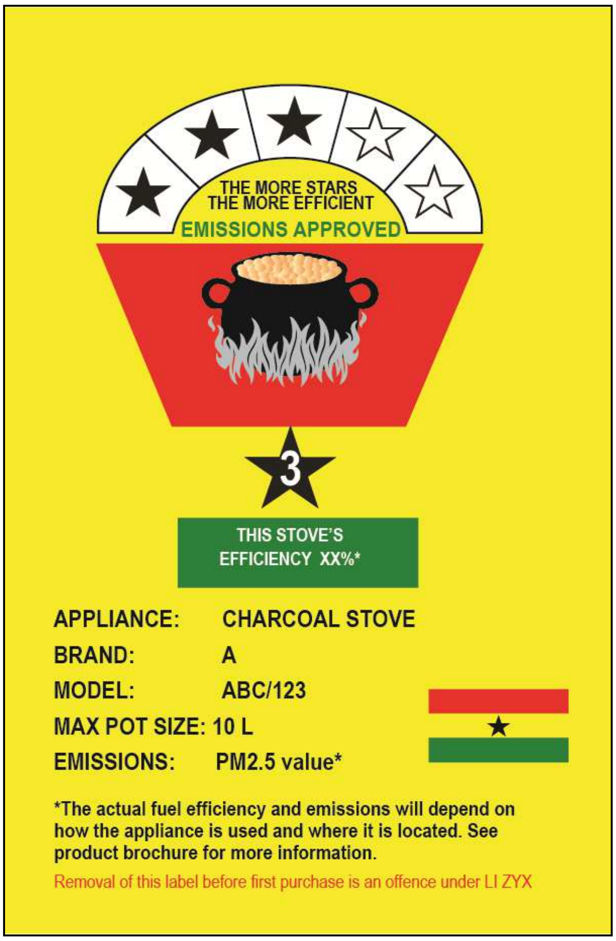
In addition to the focus groups, 26 in-person interviews were conducted with both household users and institutional users. Institutional users consisted of individuals representing local restaurants, secondary schools, government hospitals, and stove retailers.

Table 2. Interviews of target household and institutional participants

Type of participants	**# of Interviews**
Households	6
Institutions	
Local restaurants	4
Secondary schools	4
Government hospitals	4
Retailers	8
Total	*26*

Multiple draft labels, each improved or changed slightly based on previous consumer interviews, were presented to participants to stimulate conversation and responses.

Figure 10: Example of an early-stage cookstove label presented to participants



What we learned

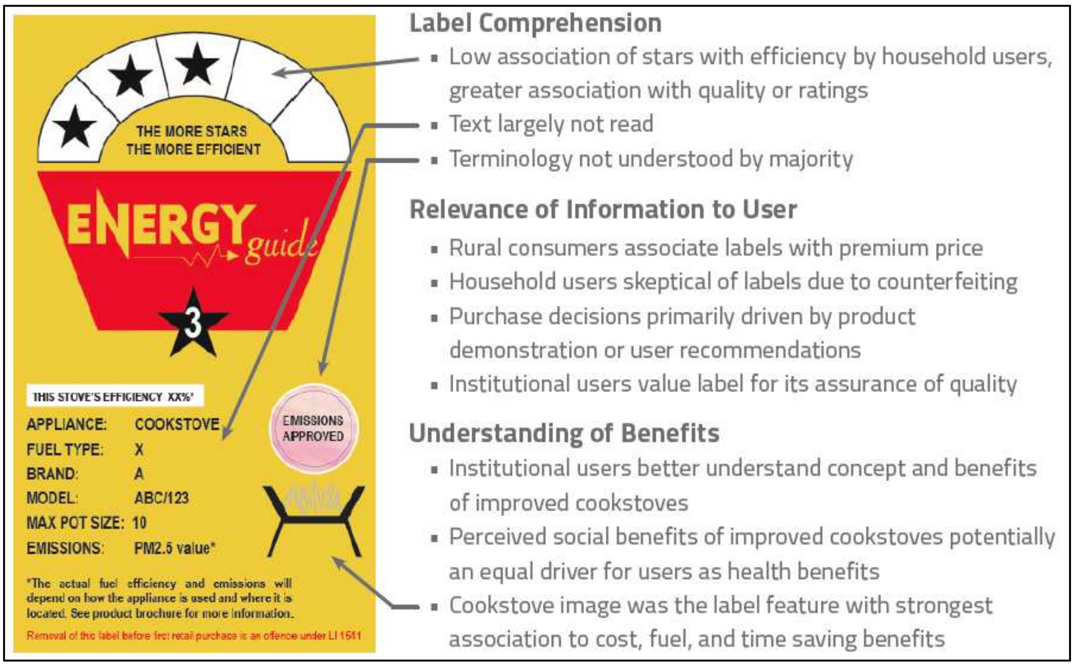
Results from the focus groups and interviews provided insights into the following topics/areas of interest (from the original list on page 2), which are summarize in Table 1. Some of these findings can also be found in Figure 2.

Table 1. Results from qualitative focus groups and home interviews

Topic	Results from Participants/Consumers
1. Label Comprehension	- When presented with the draft cookstove label, household user responses indicated a low association between the number of stars on the cookstove label and performance of the labeled cookstove. - Household participants generally associated the number of stars with product quality. - The majority of participants either do not read or are not able to read text on the label.
2. Relevance of Label Information to User	- Rural participants associated labels with a corresponding price premium for the labeled product. - Household users were sceptical of labels generally due to the large prevalence of counterfeit products on the Ghanaian market. - Participants indicated that their product purchasing decisions are primarily driven by product demonstrations or word-of-mouth recommendations from trusted users. - Institutional users value labels for its assurance of quality.
3. Understanding of Benefits of Improved Cookstoves	- The icon or image representing the cookstove on the label was the label feature that participations most strongly associated with cost, fuel, and time saving benefits. However, it is unclear what the relationship between the image and those benefits are from the results. - Compared to household participants, institutional participants better understood the concept and benefits of improved cookstoves. This appeared to also be correlated with the higher levels of education of institutional participants. - The perceived social benefits of improved cookstoves – most notably the perceived mitigation of quarrelling with neighbours in tight living quarters over emissions from cooking – is potentially an equal motivator household users to purchase improved cookstoves as perceived health benefits.
4. Familiarity and Comprehension of Existing Product Performance Labels	- Household consumers reported a low association between label stars with product energy efficiency. - Participants indicated that information on energy labels did not significantly drive their decisions or influence attitudes around the choice of electric appliances.

Figure 2 depicts a more recent evolution of the draft Ghana cookstove label, after inputs were made in response to preliminary results from the consumer research.

Figure 2: Summary of consumer responses to the proposed cookstove label



Analysis and Conclusion

Given the nascence of the improved cookstove industry in Ghana, a national standards and labeling program as well as other quality assurance initiatives offer opportunities to move consumers towards cleaner cooking methods. Results from consumer research indicate that consumers believe cookstove labels can help them make informed decisions but may be limited due to consumer's low confidence in product "endorsements" because of high rates of counterfeiting. Anti-counterfeiting measures and labels designed with minimal reliance on text to communicate messages should be considered.

In addition, consumer awareness of the concept of product performance, especially efficiency, and subsequent fuel and cost savings (for both cookstoves and electric appliances), appears low. Therefore, any product performance label may require significant consumer awareness campaigns to optimize.

Future initiatives and opportunities to expand on the consumer research of cookstove product performance labeling in Ghana are recommended. There is a critical need for more product performance data at the country level, for both thermal efficiency and emissions of cookstoves. Country-specific data is crucial for developing an S&L program, and the underlying labeling tiers to effectively move the Ghana market toward cleaner stoves. In addition, continued efforts to build technical capacity of testing centers and improve accuracy of emissions testing will enhance the impact of comparative (tiered) labels, which in theory can help move consumers toward higher and higher performing cookstoves. Labeling efforts in Ghana should also consider consumer's limited familiarity and understanding of performance labeling concepts. Finally, institutional user may be an easier audience to study in future consumer research for label design due to their greater familiarity and understanding of product performance labeling.

Multivariate Regression as a Transparent Method for Providing Allowances in Energy Efficiency Requirements

Dan Baldewicz and Mateusz Malinowski, ICF

The energy use of products depends on their features, which we refer to as functional adders. Energy requirements typically differentiate products by functionality, decreasing stringency with the number and complexity of features. The ENERGY STAR program requirements for consumer electronics provide an example of this, listing allowances for key adders (features), such as networking and data storage, in addition to capacity (size or speed). However, setting appropriate allowances is complicated, especially as products continue to grow more complex. This paper shows how multivariate regression can bring transparency to the process.

Isolating the energy impacts of a particular feature typically requires sequential tests with the feature on and off. If the feature cannot be turned off, destructive tests may be required. Even then, the features can interact with each other as well as shared product components such as the processor or power supply, impacting their real-world power draw. For example, a higher-featured computer graphics card may result in lower power at the mains because it is offset by the higher efficiency of the power supply now operating at higher load. Accounting for these interactions would require numerous tests with different combinations of features enabled.

Multivariate regression methods permit a different approach. Rather than examining the impacts of features on a single product, multivariate methods examine multiple products with different combination of features simultaneously. They reveal the impact of individual features on power draw and identify features that may not need their own allowance because they can be grouped with other features, allowing for a simpler set of requirements with as few allowances as necessary. These methods are more flexible and more transparent than the alternatives and build off commonly used simple linear regression used to fit performance requirements to capacity in programs around the world.

Introduction

Product Requirement Systems

When developing voluntary or mandatory energy efficiency or energy conservation requirements, program managers choose a system to describe the products that are in scope, relating product features to minimum efficiency or maximum power draw or energy consumption. The simplest system, where all products are given a single performance limit, is easy to understand but may not reflect the range of product performance in the marketplace. For example, requirement that all televisions draw no more than 30 watts would miss the range of sizes available and the impact of size on power draw.

Expanding upon this approach, program managers can divide up the scope by product features and set constant limits for product subtypes or classes. For example, TVs with a diagonal size below 40 inches would meet one requirement (e.g., 30 watts), while ones with a diagonal size greater than or equal to 40 inches would meet another (60 watts). This approach works well so long as the product classes are small enough to capture key product characteristics without being too numerous to make the resultant requirements difficult to use. For example, two TV product classes based on size would be too few to capture differences in performance unrelated to size, but a class at every inch of diagonal size would be too many.

The next step would be to make the requirement proportional to a key product feature, such as TV size, rather than constant. In effect, this results in an infinite number of classes, but can be expressed neatly as an equation or even incorporated directly into the efficiency metric. For example, the ENERGY STAR Eligibility Criteria for Displays contain energy requirements that are proportional to capacity (resolution and area) [1], while the requirements for clothes washers are constant but expressed in terms of an Integrated Modified Energy Factor, which is a function of capacity. Specifically, IMEF is “The quotient of the cubic foot (or liter) capacity of the clothes container divided by the total clothes washer energy consumption per cycle . . .”[2].

Finally, the two approaches can be combined: providing different proportional requirements for various classes or subtypes. Figure 11, below, shows the above-referenced ENERGY STAR displays requirements varying across several product classes.

Figure 11 Illustration of an energy requirement proportional to resolution, *r*, and area, *A*, divided among different classes [1].

Area (in^2)	**E_{TEC} Max (kWh)** Where: A = Viewable screen area in in^2 r = Screen resolution in megapixels The result shall be rounded to the nearest tenth of a kWh for reporting
A < 130	$(6.13 \times r) + (0.06 \times A) + 9$
130 ≤ A <150	$(6.13 \times r) + (0.69 \times A) - 72.38$
150 ≤ A <180	$(6.13 \times r) + (0.21 \times A) - 0.50$
180 ≤ A < 200	$(6.13 \times r) + (0.05 \times A) + 28$
200 ≤ A <230	$(6.13 \times r) + (0.03 \times A) + 31.33$
230 ≤ A <280	$(6.13 \times r) + (0.2 \times A) - 7$
280 ≤ A <300	$(6.13 \times r) + 49$
300 ≤ A <500	$(6.13 \times r) + (0.2 \times A) - 11$
A ≥ 500	$(6.13 \times r) + 89$

Although the displays classes are based on area, as is the requirement, the requirement or metric typically scales with a continuous product characteristic such as capacity, while the classes are based on binary characteristics, as seen in Figure 12, below.

Figure 12 Illustration of classes based on binary product characteristics (e.g., automatic defrost, ice maker, etc.; table abbreviated) [3]

Product Class	Annual Energy Consumption Base Allowance, AEC_{BASE} (kWh/year)
Full-Size Refrigerators and Refrigerator-freezers	
1. Refrigerator-freezers and refrigerators other than all-refrigerators with manual defrost.	7.19 * AV + 202.5
1A. All-refrigerators—manual defrost.	6.11 * AV + 174.2
2. Refrigerator-freezers—partial automatic defrost.	7.19 * AV + 202.5
3. Refrigerator-freezers—automatic defrost with top-mounted freezer without an automatic icemaker.	7.26 * AV + 210.3
3–BI. Built-in refrigerator-freezer—automatic defrost with top-mounted freezer without an automatic icemaker.	8.24 * AV + 238.4
3I. Refrigerator-freezers—automatic defrost with top-mounted freezer with an automatic icemaker without through-the-door ice service.	7.26 * AV + 294.3
3I–BI. Built-in refrigerator-freezers—automatic defrost with top-mounted freezer with an automatic icemaker without through-the-door ice service.	8.24 * AV + 322.4

Figure 12, above, only reproduced 7 of 32 refrigerator and freezer product classes showing that this system can still be unwieldy, demonstrating a need for additional flexibility. This can be provided by a base plus adder approach, where the product scope is divided into subtypes, each of which is given minimum (base) performance requirements, but product features that require additional energy (adders) are provided further energy allowances. In theory, this allows any base to be combined with any subset of adders, resulting in a customized energy requirement appropriate for the product, Figure 13 illustrates the ENERGY STAR approach to classifying set-top boxes using base plus adder allowances.

Figure 13 ENERGY STAR Version 5.0 Set-top Box specification requirements showing a base plus adder approach (adder table abbreviated) [4].

Base Type (Use Topmost if Multiple Apply)	Allowance (kWh/year)
1. Cable DTA	37
2. Cable	50
3. Satellite	50
4. Multichannel Video Programming Distributor (MVPD) Internet Protocol (IP)	40
5. Thin-client / Remote	7 (Applicable after January 1, 2018)
6. Over the top (OTT) Internet Protocol (IP)	7

Additional Functionality	Allowance (kWh/year)
Advanced Video Processing	0
Advanced Video Processing – Additional	0
CableCARD	15
CableCARD – Max One Additional	15
Digital Video Recorder (DVR)	35
DOCSIS 2	25
DOCSIS 3.0 (May be also applied to DOCSIS 3.1 devices)	45
HD	0

Setting Adder Allowances

While the base plus adder framework is the most flexible, setting the allowances for the base (minimum requirements) and each adder (feature) is not straightforward. Three lab-based methods include:

1. Measuring the energy use of two related product models that differ only in the presence or absence of an adder;

2. Measuring the energy use of the same product model with the adder turned on or off; and

3. Measuring the energy use of the adder itself, either removed from the product or through dc measurements inside the product.

The first method is the most accurate but hinges on manufacturers offering similar products that differ by a single feature and also require purchasing multiple models for test. The other two methods introduce inaccuracies and require further measurements and calculations to capture system interactions: standby or overhead power of the adder (method 2) or ac-dc conversion losses (method 3).

At a minimum, a product model would need to be tested in several states with various features enabled and disabled, to quantify the energy use of each feature and set appropriate allowances (whether at the median level or market best). These tests would then need to be repeated for models across the range available in the market. One key benefit of analytic methods is that it avoids this complex, time-consuming, and costly testing.

The regression methods discussed in the remainder of the paper use existing test data and information about presence or absence of adders to estimate relationships between the adders and energy consumption.

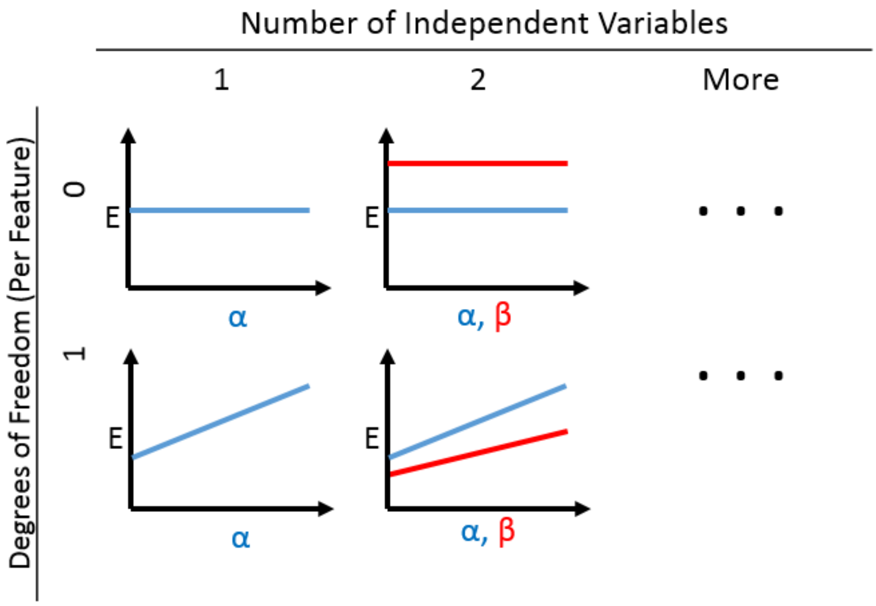
Linear regression can effectively determine relationships between a single dependent (Y) and independent (X) variable, in this case the energy use and presence of adders. This process could be repeated multiple times with different combinations of independent (X) variables. This approach runs into key limitations when attempting to address all of the independent variables at once, since each linear regression for one variable will inadvertently include effects from other variables. Multivariate regression addresses this issue directly, allowing all of the significant independent variables to be considered in one analysis run.

Multivariate regression is used across a wide range of sectors, including electrical capacity planning, oil supply/pricing estimates, and the biological sciences (see the Journal of Environmental Health, the Journal of Environmental Science, and the Journal of Science of the Total Environment to name a few). We note many of these sectors have key equations or models that depend on a number of different parametric factors, which logically leads to the use of modelling approaches that can handle these factors simultaneously. An academic search of past EEDAL conferences, Journal of Energy, and Journal of Applied Energy demonstrated that simple (i.e., single-variable) linear regression was far more common than multivariate linear regression in efficiency work.[13] We hope that our work will demonstrate the similarity between currently used simple linear regression methods and multivariate regression, demonstrating how to adapt simple linear regression strategies to multivariate approaches when advantageous.

[13] Two examples of multivariate-regression applied to efficiency can be found in [13] and [14].

Constructing a Product Feature Equation

Figure 14: A depiction of an energy modeling relationship, with different numbers of features and dimensionality of each feature.



Note that feature relationships in a modeling equation can be constants (0 degrees of freedom in Figure 4) or functions (1 or more degree of freedom in Figure 4). In the remainder of the paper, we will describe our model of set-top box (STB) energy consumption, where each adder is assumed to have a constant energy requirement if present in that product. We model a consumer electronics product as a relationship between product energy use and the energy use of the base (minimum requirement) plus the energy use of each adder (feature).

As an illustration, consider a satellite set-top box, which provides no additional features beyond receiving content. Such an STB would qualify only for the base allowance, and its energy consumption would only be a function of that base. Next, assume that this STB is modified to decode higher compression data streams, such that now its energy consumption is a function of the base and a High Efficiency Video Processing (HEVP) adder.

We extend this process over all features believed to result in energy consumption. By associating each feature individually, we implicitly assume that the energy requirements of each feature is not correlated with other features, thus constructing a linear model with no interactions. When we identify a feature group that we cannot reduce into components, we add this feature group as a single adder, maintaining the simplicity of the model.

Figure 14 demonstrates how an energy use model could be built up for a product from a base and adders for each unreducible set of features. Once all meaningful bases and adders have been identified for a group of products and a regression model built up, multivariate regression can be used to estimate the base requirements and quantify the average contribution of each adder to the energy consumption of models in the dataset. These results are then used to establish allowances.

Multivariate Regression

Simple linear regression models the relationship between dependent variable Y and independent variable X via the following equation:

$$Y = \beta_0 + \beta_1 X + \epsilon \quad \mathbf{(1)}$$

$$where\ \beta_0\ and\ \beta_1\ are\ constant\ coefficients\ and\ \epsilon\ is\ the\ irreducible\ error$$

In simple linear regression, we refer to β_0 as the intercept and β_1 as the slope.

This framework can be extended to additional variables/features to model more complex relationships between Y and variables X_1 through X_p. This multivariate regression equation can be written as[14]:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_P X_P + \epsilon \quad \mathbf{(2)}$$

$$where\ \beta_0, \beta_1, \beta_2, \beta_P\ are\ constant\ coefficients\ and\ \epsilon\ is\ the\ irreducible\ error$$

Interpreting these coefficients, β_0 is the intercept, and each β coefficient is the effect of an independent variable on the dependent variable holding all other variables constant [5, p. 72]. In our feature energy estimation analysis, the base requirements of a product without incorporating adders/features is this intercept β_0. Coefficients applied to a feature variable (product has or does not have feature) can be interpreted as the energy use of this feature. A negative coefficient would indicate that a feature reduces overall energy consumption.

Multivariate linear regression is the calculation of the optimal coefficients for a given equation model and data. Equation **(2)**, is then solved via a least squares optimization problem to determine the values of the coefficients which have a minimum Residual Sum of Squares (RSS). This regression process is carried out via a linear algebra calculation, where the optimal coefficients, known as $\hat{\beta}$ are given by:

$$\hat{\beta} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T y \quad \mathbf{(3)}$$

$$Where\ \boldsymbol{A}\ is\ the\ matrix\ of\ independent\ variables\ (predictors)$$

$$and\ y\ is\ the\ dependent\ variable\ (response)\ vector$$

Software packages performing this calculation generally output both the coefficient values and the residuals (how well each data point compares to the model) [6, p. 86].

We used the open-source statistical programming language R for our analysis. R has all the necessary statistics and modeling tools necessary to perform multivariate regression. From the statistics package in R, the lm() function allows a user to specify a multivariate linear model both with and without interactions between predictor variables [7]. As mentioned above, we assumed that the predictors are independent. This model is specified in R as: y ~ x1 + x2 + x3 … x_p.

Results of a least square regression via most major software packages return values for each coefficient and additional measures of performance, including p values, t-ratios, and statistical significance for each coefficient, and R^2 , and Adjusted R^2 for the entire model. T-ratios quantify the influence of an explanatory variable, larger t-ratios for a given variable indicate that the influence of this variable on the model is larger than other terms [8]. The p-value, which is calculated based on the t-ratio, is an indicator of the possibility of a chance occurrence of the result, smaller p values are more

[14] We assume that each STB feature will have its own independent adder energy requirements, thereby dropping all interaction terms in the regression model, leading to the form in **(2)**.

preferable to large ones [8]. The most important of these for model validation are R^2 and Adjusted R^2, which quantify the proportion of variability of Y explained by variables $X_1,\ldots,X_p$ [6, p. 70]. Both measures range between 0 and 1, with 1 indicating ideal performance. They are further defined in (**4**) and (**5**), below [6, p. 226].

$$R^2 = 1 - \frac{RSS\ (Residual\ Sum\ of\ Squares)}{TSS\ (Total\ Sum\ of\ Squares)} \quad \mathbf{(4)}$$

$$Adjusted\ R^2 = 1 - \frac{RSS/_{(n-d-1)}}{TSS/_{(n-1)}} \quad \mathbf{(5)}$$

Adjusted R^2 is designed to incorporate the number of variables n and number of model of predictors d into the R^2 measure, eliminating the issue that R^2 will always increase as additional terms are added, which would reduce the value of the metric for overall model performance [6, pp. 224-226].

About the Dataset(s)

Several product types were present in the STB data: Cable, Cable DTA, Satellite, MVPD IP, OTT, Thin-Client. There are product type clusters: simple 1 room boxes, fully featured STBs intended for running terminal node STBs, terminal node STBs which do not require a full feature set. Data available was from multiple sources, Version 4.1 ENERGY STAR data, industry Voluntary Agreement data, and in some cases, specific test data for individual or groups of products [9].

The Regression Problem for STBs

The dependent variable is a continuous variable, product energy use in kWh.

The independent variables are:

1. Product bases (product type power requirements)—categorical variable; and
2. Adders (feature power requirements—binary variables.

Low numbers of products in each category recommend not creating a test/training data split.

Note that we assume that adders are independent, uncorrelated (no duplication between features), and have minimal interaction effects, as discussed in the previous section: Constructing a Product Feature Equation.

Stepwise Feature Selection

Although Figure 13 only shows 8 set-top box specification adders, the Version 4.1 ENERGY STAR specification that was used as a starting point for the modeling of STB performance had 16 adders [10]. The Amendment No. 1 to the Voluntary Agreement for Ongoing improvement to the Energy Efficiency of Set-top Boxes (Tier 2 VA) had over 17 (some of the 17 could be claimed multiple times) [11, pp. 45-46].

To reduce the number of predictors, we used a forward stepwise procedure to construct a model with optimal performance with the fewest possible number of adders. The stepwise process relies on Akaike Information Criterion (AIC), which describes dependent variable variation accounted for by independent variables with an additional penalty per term in the model [5, p. 472]. This AIC function is designed to improve upon the performance of Adjusted R^2 when models with multiple terms are compared [6, pp. 224-226, 12]. This is particularly important as models which favor more terms tend to perform sub-optimally, by incorporating too much noise in the data to predict accurately (overfitting).

Resulting Dataset

The STB Dataset had 136 rows of data (spanning 6 categories) and effectively 11 unique adders (6 additional MIMO Wi-Fi adders are present). These adders fall into a number of categories:

1. **Conventional STB adders.** Some adders are well-understood, often traditional STB features, such as DOCSIS and CableCARD, which are ubiquitous components of Cable STBs; we have a starting estimate for these variables but wanted to know if their energy use had. Sometimes these features are present in such a high percentage of the dataset (>90%) that they should be removed and calculated as a part of the base allowance. HNI was one such feature in MVPD IP STBs.
2. **Overlapping with other specifications.** Some of these adders are well understood from overlap with multiple specifications and product areas, and can be adjusted out of the energy use and feature set to reduce the number of variables to be analyzed for the benefit of the model. For example, Wi-Fi.
3. **New features.** Some features are relatively new features (Ultra High Definition (UHD), DOCSIS 3.0), with limited availability in the dataset (note these could be considered near zero variance predictors).
4. **Regression estimated feature groups.** Some features are intended to capture a group of potential energy and hardware requirements, and are mostly determined by regression (Multi-room, Multi-stream).
5. **Base Levels.** Estimating the base power or energy needed for the core product is a key priority in this analysis, and is contained in the intercept of the model. It is important that we keep our feature set as small as possible to ensure that we are not overwhelming our available dataset with noise/uninformative predictors. Note that the multivariate regression analysis will provide the average base level (i.e., 50% for a normal distribution), and this may need to be adjusted manually, e.g., reducing the base requirements to capture the highest performing 25% of models.

Regression Results

See Figure 15 for an example output from a multivariate regression model for Multi-Channel Video Provider Internet Protocol (MVPD IP) Set-top Boxes. The thick red box in the figure highlights:

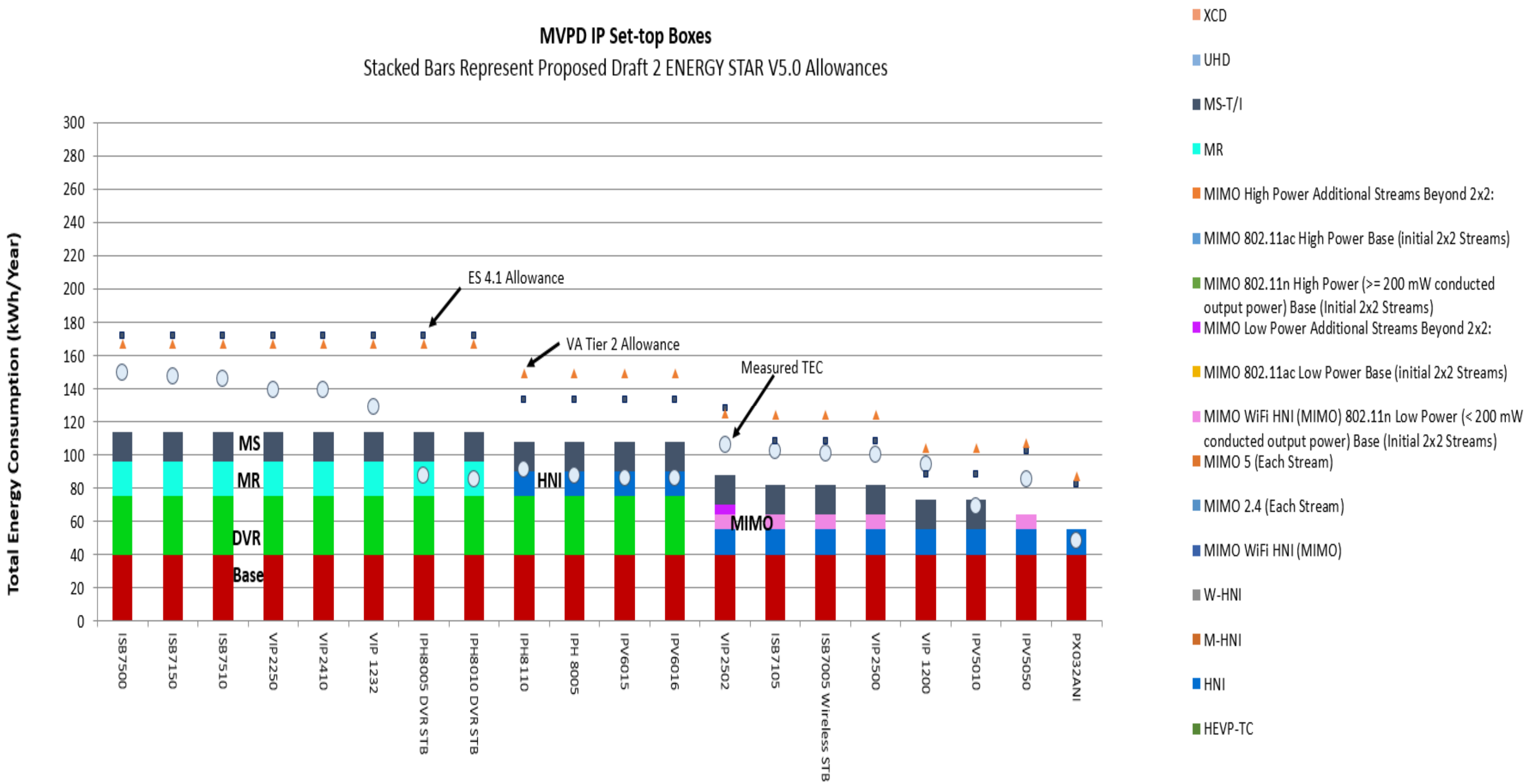
1. The base types (Cable is identified as Intercept (β_0), while “SCRUBBED.TYPEMVPD_IP” and “SCRUBBED.TYPESatellite” refer to the difference between MVPD IP and Satellite bases and Cable). The adders are listed
2. The adders (CableCARD (CC), digital video recorder (DVR), multi-room (MR), multi-stream cable/satellite (MS.C.S), and multi-stream terrestrial/IP (MS.T.I))

Figure 15 Regression Output from a Multivariate Linear Regression of MVPD IP Set-top Boxes.

```
> NONTHINALL.lmyear <- lm(TEC_CNTL_V4~CC+ DVR+ MR+ MS.C.S + MS.T.I +SCRUBBED.TYPE, data=NONTHINALL)
> summary(NONTHINALL.lmyear)

Call:
lm(formula = TEC_CNTL_V4 ~ CC + DVR + MR + MS.C.S + MS.T.I +
    SCRUBBED.TYPE, data = NONTHINALL)

Residuals:
    Min      1Q  Median      3Q     Max
-58.907 -17.381   2.203  19.448  64.432

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)              58.531      9.078   6.447 4.71e-09 ***
CC                       37.265      9.833   3.790 0.000264 ***
DVR                      35.807      8.280   4.324 3.78e-05 ***
MR                       21.132      6.820   3.099 0.002557 **
MS.C.S                   19.230      9.382   2.050 0.043150 *
MS.T.I                   22.282     19.834   1.123 0.264092
SCRUBBED.TYPEMVPD IP    -12.481     20.556  -0.607 0.545186
SCRUBBED.TYPESatellite   -9.306     11.213  -0.830 0.408672
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 26.08 on 95 degrees of freedom
Multiple R-squared:  0.7139,    Adjusted R-squared:  0.6928
F-statistic: 33.87 on 7 and 95 DF,  p-value: < 2.2e-16
```

Figure 16 shows one of these validation plots, also for MVPD IP products.

Figure 16 MVPD IP Adder and Base results, plotted with TEC usage.



Note that the features are clustered between product groups, e.g. products which have DVR and Multi Stream and Multi Room, non-DVR products with MIMO Wi-Fi, and basic models on the far right.

Note that each product in Figure 16 is shown with a corresponding TEC level dot, and if the level is above the top of the bar chart, the model does not meet the requirements. When a regression model base level is tuned to incorporate ENERGY STAR performance requirements (top 25% products), we ensure that the model is not unfairly penalizing a subset of products with groups of features. Examining Figure 16, we note that there are several distinct product groups, and there is a percentage of passes and failures in each group. In some cases, the energy variation of a certain product subset is similar enough that a greater than average subset of products will pass a level; this is preferable than the alternative of tightening the requirement such that all the products in this group would fail. These manual adjustments are occasionally needed to ensure that sections of product scope are not inadvertently lost to requirements that are too stringent in this subset. We note that an important part of applying multivariate regression models to specification requirements is the validation component, which confirms that the model is properly covering the entire product scope of the specification.

Conclusion

Our approach was able to evaluate the dataset and provide feature energy use estimates, so mathematically and programmatically, it was a successful implementation of an advanced approach to a generalizable problem. We recognize that the use of regression is agnostic to product sector; this approach would work just as reasonably in lighting, HVAC, and appliances as it did in set-top boxes. We also note that regression methods should be selected and tuned to the data and problem that the user is solving, as in many cases, data preprocessing and careful feature selection is essential to obtaining an accurate model of product energy use. In cases where more products are available in the dataset, we advise that a testing and training dataset could be split out to validate the model further.

On a technical note, use of the AIC in multivariate linear regression is effective, but as the number of adders (features) increases, especially with a similar number of rows in the dataset, other algorithms have been shown to work better. In the extreme case where p predictors $\geq$ n data rows, multivariate linear regression no longer functions, without reducing the number of predictors or increasing the number of data rows [5, pp. 116-118]. One such group of algorithms include Elastic Net and LASSO regression, which are able to conduct automatic feature selection by setting coefficients to zero during the regression calculation. A penalty term (ridge regression component) of Elastic Net is also designed to reduce the risk of overfitting a model based on the dataset [5, pp. 116-118].

Our experience with using the multivariate regression analysis in practice as a level setting method was successful, but we do note a few concerns. Although the approach is mathematically transparent, many stakeholders will not have a background that includes the use of these methods. Especially so, the direct regression output is not easily interpretable without relevant background, and often a good regression or statistical reference manual is needed to translate the information to more familiar metrics. Items like the AIC in stepwise feature selection and regression coefficients and p values of regression terms are often too technical to be taken at face value by a majority of interested parties, and should be translated to a more approachable explanation of their impact on the results. We found that graphically displaying the adders and base allowances in the stacked bar charts led to a better discussion of the results, as the estimated energy consumption by the base versus adders (features) could be interpreted much more comfortably in this context. Stakeholders responded well to seeing the values of the multiple variables overlaid, which improved their understanding and comfort with the multivariate regression calculations. We found that one useful starting point for multivariate regression was to begin with a version depicting a simple linear regression (1 variable), which many more stakeholders were familiar with, and expand that idea conceptually to additional features and variables.

Acknowledgment

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Labelling for "Smartness": Problems for energy labelling and standards schemes

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Abstract

Energy labelling and minimum energy performance standards (MEPS) for appliances have been among the great successes of energy efficiency policy. About 90 economies now have standards and labelling programs, mostly backed by legislation. "Smartness" is emerging as a new parameter in appliance design and marketing, and (like energy efficiency) is claimed to offer material benefits to the appliance owner, as well as social and environmental benefits. Prospective appliance buyers may therefore wish to choose products which offer these capabilities. The energy label may be a convenient way to convey this information. Like MEPS, there may also be a case for mandating certain smart capabilities in all appliances, to smooth the transition to a future "internet of things."

However, several problems have to be solved before we can move in this direction: the lack of standard definitions of "smartness, the contingency of benefits on external conditions which may not be present and the lack of congruity between smartness and energy efficiency.

This paper reviews three national examples where aspects of smartness have been defined - Echonet in Japan, the US EnergyStar "connected appliance" criteria and the AS/NZS 4755 standard in Australia. It examines how these concepts have been communicated through those countries' energy labelling schemes, and considers proposals for incorporating "smartness'' in the European Union (EU) energy labelling scheme.

The conclusion is that ''smartness'' is difficult to communicate to appliance buyers in a simple and actionable way. In the light of these challenges, the paper proposes some basic rules for considering the incorporation of smart capabilities in energy labelling and MEPS programs.

Smart Capabilities of Appliances

"Smart'' is a marketing term. There are no widely accepted definitions of what makes an appliance "smart", although there have been some attempts to define and classify the product capabilities that are generally described as smart.[1] Tellingly, the more rigorous classifications use terms such as "connected" (Energy Star) or "demand response capable" (AS/NZS 4755) rather than "smart."

In general, these capabilities involve some or all of the following:

- Some means for the device to interact with its external environment, beyond the traditional user interfaces (on-board controls, line-of-sight remote controls and thermostats);
- Automated changes in function in response to changes in conditions during operation, both within the appliance and outside the immediate premises;
- Ability to receive and respond to information about the state of the electricity supply system (e.g. voltage, frequency, load constraints etc.), either signaled or sensed directly.

Table 1 presents one possible typology of smart capabilities. These are independent and not hierarchical: any of them may be present without the others. The fourth aspect, interoperability and standardisation, is in some ways the key to the inclusion of smartness in energy labelling and

Minimum Energy Performance Standards (MEPS) programs, which are based on the principles that product performance can be specified in technical standards and objectively measured using reproducible and repeatable tests.

Table1 – Capabilities and functions typically described as ‘smart’

Primary Capability	Example
1. Remote user interaction	a. User control via smartphone app
	b. Communication of energy use, settings etc. to user or authorised external agent
2. Auto-adjust in response to user-origin information	c. User enters electricity tariff details and preferences for operation in high- and low-price periods
	d. Appliance monitors usage, loading or occupancy patterns to modify current or future operation
3. Auto-adjust in response to external-origin information	e. Appliance downloads tariff details from user’s electricity supplier, or monitors dynamic prices
	f. Appliance responds to signals from an external agent (authorised by the user)
4. Interoperability and standardisation	g. Inputs standardised (communications pathways, protocols or commands)
	h. Responses standardised

Source: Adapted from [1]

Until standardisation in performance testing and reporting was introduced in the 1970s and 1980s, “energy-efficiency” was just as loose a marketing term as “smart” is today. To the extent that energy efficiency had any value in product marketing prior to the global oil shocks of 1973 and 1979, which made energy cost a top-of-mind consumer issue for the first time, manufacturers were free to make whatever statements they wished about the efficiency of their products (provided they could substantiate them in accordance with consumer protection laws). Competing suppliers could choose the metric most favourable to their own products, and comparisons were impossible until governments legislated to impose uniform test standards and labelling formats. This is essentially the position with promoting smartness today.

Smartness is not the same as energy-efficiency. The presence of smart capabilities *may* result in some increase in the energy-efficiency with which a product performs its main function (e.g. heating, cooling, lighting) but in most cases the main benefit will be enhanced user convenience, or more economic utilisation of the electricity supply system as a whole through better management of peak load, renewable electricity generation or energy storage. In fact, the deployment of smart capabilities is as likely to increase total electricity consumption as to reduce it, because the supporting communications infrastructure uses some energy, and because delay or interruption of product operating cycles may involve (generally small) energy penalties.

However, the potential economic and environmental benefits of smart capabilities can be substantial, if they lead to more efficient utilisation of the electricity network and an increase in the level of renewable generation it is able to absorb. These benefits mostly accrue to the electricity suppliers and network owners, and it is their decision – moderated by utility regulators – whether and how to pass the benefits on to the owners of the smart appliance.[2]

How Existing Labelling Systems Approach Smartness

Energy labelling and minimum energy performance standards (MEPS) for appliances have been among the great successes of energy efficiency policy. About 90 economies now have MEPS and labelling programs, mostly backed by legislation.[3] The most effective programs have retained a clear focus on measuring and communicating product energy consumption, efficiency or efficacy (using various numerical and graphic devices) without confusing it with vague parameters such as "environmental footprint" or "lifecycle cost" which are hard to quantify and nearly impossible to verify.

"Smartness" is emerging as a new parameter in appliance design and marketing, and (like energy efficiency) is claimed to offer material benefits to the appliance owner, as well as social and environmental benefits. Prospective appliance buyers may therefore wish to choose products which offer these capabilities. A modified energy label may be a convenient way to convey this information. Like MEPS, there may also be a case for mandating certain smart capabilities in all appliances, to smooth the transition to a future "internet of things."

However, several problems have to be solved before we can move in this direction. The first is the lack of standard definitions of "smartness." The basis of all MEPS and energy labelling programs is the statement (implicit or explicit) that "this appliance consumes X kWh per year when tested in accordance with Standard Y". It is not yet possible to make such specific and verifiable statements about "smartness" in appliances, apart from a few cases (Echonet in Japan, the US EnergyStar "connected appliance" criteria, the AS/NZS 4755 standard in Australia).

The second problem is that the benefits are not assured. Buying a more energy-efficient appliance brings immediate benefits, because buyers start to save electricity and thereby money (compared with the less-efficient alternative) as soon they take the product home and plug it in. By contrast, the benefits of smart appliances are usually contingent on the presence of other factors – typically a communications platform, a smart meter or a home gateway – and economic drivers such as a time-variable electricity prices or cash payments. If these are not present, buying a smart appliance may be a cost without a benefit.

The third problem is the distinction between end-use energy efficiency and the overall economic efficiency of the energy supply system. Smart appliances do not necessarily lead to greater energy efficiency. They usually have convenience value (such as the ability to substitute a single smartphone for every remote control in the home and interrogate and operate appliances remotely) and – if appropriately connected and set up – economic value for the energy system. However, the presence of smart capabilities and the communications systems that support them may actually increase primary energy consumption, although the increase in economic value through better utilisation of capital infrastructure will usually exceed the higher energy costs.

Some of these issues have already been addressed in the USA, Australia and Japan – the only countries so far where products have standardised smart capabilities certified under uniform nation-wide government or industry-led schemes.[15] Table 2 summarises the products covered in each country.

USA

In the USA the Energy Star program enables product suppliers to use the Energy Star logo and label for products which meet specified levels of energy efficiency.[16] The program has published "connected appliance" criteria for the products indicated in Table 2, starting with refrigerators in 2014

[15] There are several industry-led groups promoting the 'smartness' and interoperability of the products of consortium members, some using open standards, but only programs with national coverage and/or regulator backing are considered here.

[16] The Energy Star endorsement symbol may also be displayed on the mandatory energy rating label (Figure 2) to reduce the number of labels on products.

[4] Models which meet the criteria can qualify for the Energy Star endorsement label even if their measured energy consumption is higher than would normally be required to meet the efficiency criteria. Connected and non-connected products have identical labels (Figure 1) but consumers can identify “connected” products by selecting that search criterion on the Energy Star website (except for Connected Thermostats, where *only* connected products qualify, and only after their impact on heating and cooling energy use has been demonstrated in the field).

The connected criteria applying to different products are slightly different, but in general they cover the combination of the appliance “plus all elements (hardware, software) required to enable communication in response to consumer-authorized energy related commands…These elements may be resident inside or outside of the base appliance…”[4]

The communications protocol must comply with a list of open standards published by recognised standards bodies, and the minimum functions of the appliance when connected include energy use and status reporting to the customer and customer-authorized agents, and the ability to receive and respond to basic requests to modify settings, defer or reduce load. As these criteria can be satisfied in many different ways, the supplier must make available any add-on components, firmware or software and document how the system should be connected and activated. There is also a test method to validate demand response, at least for refrigerators.[5]

There are no assured benefits form the presence of these capabilities, but there are measurable costs. Energy Star is awarded to refrigerators and freezers which use at least 10% less energy than required to meet the MEPS levels specified by the US Department of Energy. Products claiming compliance with the ‘connected’ criteria need only use 5% less energy than the standard. In fact, the 41 refrigerators and freezer modes registered as “connected” under Energy Star claim an average of 6.8% less energy than the benchmark, compared with 11.8% less for the non-connected products.

For consumers who seek out connected products, and who are able to realise and monetise their potential, the advantages could more than compensate for the 5% (on average) higher energy use. They might value the added convenience (e.g. interaction via smartphone) or benefit from variable tariffs or demand response programs. However, the process of identifying models with and without these capabilities is complex. The question is how well this approach to labelling (or rather, non-labelling) of connectedness informs consumers and clarifies their choices.

Australia

The Australian system takes a different approach. Smartness, in this case more narrowly defined as “demand response capability”, is kept completely separate from energy-efficiency. Air conditioners have carried mandatory energy rating labels since 1987 and have been subject to MEPS since 2004. Following a number of electricity supply problems due to air conditioner peak load in the early 2000s, regulators sponsored the development of standards specifying demand response capabilities for air conditioners and the other products which contribute to electricity load peaks on extreme hot and cold days.[6]

Australian and New Zealand Standard AS/NZS 4755.3.1 covering demand response for air conditioners was published in 2008 and revised in 2012 and again in 2014, on the basis of experience gained with the operation of complying products. In 2010, when the air conditioner energy rating label was revised to re-scale the star ratings, the opportunity was taken to allow suppliers to indicate demand response mode (DRM) capability on the label.

In DRM1 compressor operation ceases, in DRM2 the air conditioner continues to cool (or heat) but power is limited to 50% of a reference level (the calculation of which is specified in the standard) and in DRM3 power is limited to 75% of the reference level. The command to enter the required DRM is sent to the air conditioner via a plug-in communications module called a Demand Response Enabling

Device (DRED). The same approach has now been extended to other products (see Table 2), with the same three basic DRMs (with minimum-load operation and reference power levels defined according to each appliance type's specific functions). The other products may also have DRM4 (switch load on) and DRM8 (for batteries: discharge to grid). A utility or load aggregator will get a predictable and uniform response to each DRM command, irrespective of the type of product that receives it (i.e. the capability matches examples f, g, and h in Table 1). All DRM performance claims can be verified using specified test procedures.

An AS/NZS 4755-compliant appliance must be capable of being electrically connected to an external DRED via an RJ45 connector[17], and recognise and respond to the limited set of instructions that can be sent from the DRED to the appliance via the connector. The method by which the DRED receives instructions (e.g. via internet, mesh radio, mobile phone, Zigbee, powerline carrier or other means) is irrelevant to the appliance. Communications protocols for the DRED are covered in a separate part of the standard, AS/NZS 4755.1. Although the national costs and benefits of mandating compliance with AS/NZS 4755 were considered by regulators, it was in the end left optional [7]. Compliance with MEPS and energy efficiency labelling requirements, however, continues to be mandatory.

Figure 3 illustrates an energy label for a reverse cycle air conditioner. It shows cooling energy efficiency (the stars in the blue band) and heating energy efficiency (the red band) determined in accordance with AS/NZS 3823. The three check boxes at lower right indicate whether the unit is capable of DRM 1, 2 or 3 in accordance with AS/NZS 4755.3.1 At present 828 of the 3,571 models listed on the Australian compliance register (www.energyrating.gov.au) have demand response capability (mostly all three DRMs). These can be identified by a selective search function, as is the case with the Energy Star database. The number of other product types with AS/NZS 4755 demand response capabilities is harder to determine – as they are not subject to energy labelling and registration, there is no ready means of identifying them, so the number of complying models in Table 2 is an estimate only.

The DRM information is of limited salience to consumers, although its presence prompts interest in demand response, just as the introduction of the energy label itself alerted consumers to the importance of energy efficiency. One Australian electricity utility offers cash incentives for consumers to purchase AS/NZS 4755-compliant air conditioners and have them connected to a utility-supplied DRED, and publishes its own list of compliant models.[8] Over 70,000 consumers have enrolled in the scheme, and so have benefited financially from purchasing demand response-capable products, whether or not they used the energy label to identify them. Using the energy label for this purpose will not be possible for much longer, There are now plans to introduce a new air conditioner label design, showing energy efficiency in three climate zones. The new label does not have the space to indicate demand response capability, so the information will only be available on websites.

Japan

The Japanese approach is different again. Echonet (Energy Conservation and Home Care Network), established in 1997, was probably the first large-scale smart appliance initiative in the world.[18] The first Echonet specification was published in 2000, and has been revised several times since, most recently in 2017. An Echonet Lite specification, published in 2011, defines an Echonet Lite Device as:

> "a node that has communications interfaces and system support functions compliant with the Echonet Lite Standards for home devices, home electric products, or building/store devices such as lighting, air conditioning, refrigeration, power equipment, ordinary home appliances, sensors, actuators, etc. This node is also equipped with a centralized system for monitoring,

[17] The common name for the 8PC8 modular connector specified in ISO/IEC 8877:1992, widely used for Ethernet connections.

[18] http://www.echonet.gr.jp/english/index.htm The appliance manufacturers supporting Echonet include Toshiba, Panasonic, Hitachi, Mitsubishi Electric, Sharp, Fujitsu and Daikin.

controlling and operating facilities and equipment, and also such controller functions as operating units (remote controller, etc.)."[9]

The interest in using the Echonet standard to enable inter-operation between products from different appliance, home area networks systems and smart meter manufacturers increased significantly after the earthquake and tsunami of March 2011 created long term disruptions in energy supply. A new Echonet Certification Centre was opened in November 2012. There has been no use of Echonet outside Japan so far, although as a result of participation in Echonet many Japanese appliance manufacturers have included basic demand response capabilities in some globally traded products, notably air conditioners. Table 2 indicates some of the devices for which Echonet-certified models are currently available.[19]

Echonet is in effect an entire smart ecosystem, ensuring consistency and interoperability of end use devices, intermediate devices, communications protocols, hardware and software. The Echonet specification has been adopted and published in various IEC standards. [10].

Manufacturers self-certify products which comply, and for those products "the logo mark for ECHONET Lite or ECHONET Ready devices may be displayed on each certified device or software upon signing a trademark license agreement" (see Figure 4).[11] Other industry-led "smart'" product consortia also use self-certification and licensed logos, but Echonet is more like a regulated national scheme, in that there is no competing standard in Japan and Japanese companies have historically worked with each other and with the Ministry of Economy Trade and Industry (METI) towards consensual national objectives, with a high level of compliance even in the absence of actual legislation.

Japan also has a mandatory energy labelling system, rating the product's energy efficiency on a scale 1 to 5 stars (Figure 5). The label also has an "e" logo to indicate whether the product meets or fails the "Top Runner" criteria. "Top Runner" is an endorsement level, like Energy Star, except that it is made more stringent each year as product efficiencies increase, and it is mandatory to indicate products that fall below the level, not just products that meet or exceed it. There is no provision to include the Echonet logo on the mandatory energy label, so there is no link between the labelling of smart capabilities and the labelling of energy efficiency, as there is with Energy Star (implicitly) and the Australian air conditioner energy label (explicitly).

[19] Echonet-certified sensors, meters, fans, storm windows, shutters, televisions and switches are also available.

Table 2 – Product types covered by published standards for 'connected' or 'smart' products

Product category	US EPA Energy Star "connected" criteria	Australia/New Zealand Standard AS/NZS 4755	Japan Echonet Lite
Air conditioner – window-wall	✓ 7	✓ 0	✓
Air conditioner – split unit		✓ 784	✓
Air conditioner – central/ducted		✓ 44	✓
Electric resistance heating			✓
Pool pump controller		✓ 0	
Water heater – heat pump		✓ 0	✓
Water heater – resistance		✓ 0	
Refrigerator & freezer	✓ 41		✓
Clothes washer & washer-dryer	✓ 0		✓
Clothes dryer	✓ 2		✓
Dishwasher	✓ 0		
Light fixtures	✓ 241		✓
Connected thermostat	✓ 1		✓
Energy/battery storage system		✓ 5	✓
Electric vehicle charger (EVSE)	✓ 0	✓ (a)	✓
Photovoltaic/battery inverter		✓ (b)	✓
Controller for other devices		✓ 0	✓

✓ indicates that there are standards or rules published for these products. Shading indicates there is energy labelling for that product (voluntary endorsement label for Energy Star, mandatory comparative label for Australia and Japan). Numbers indicate distinct models listed as compliant (February 2017). Echonet listings cover model families, so number of models is not shown. (a) Standard/rule under development. (b) Via cross-reference in AS/NZS 4777.

European Union

The European Commission's *Preparatory Study on Smart Appliances*, which commenced in September 2014 under the Commission's Ecodesign Directive, has the objective "…to analyse the technical, economic, market and societal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches".[12] (The study generally uses the term "Demand Side Flexibility" (DSF) rather than "smartness").

The final phase of the study – Task 7 on Policy Options – was not yet complete at the time of writing, but a presentation in May 2016 gave a preview of the findings, which could have an impact on energy labelling in the EU:

- “Various forms of positive rewarding are possible:
  -Visualise DSF functionality on the energy label by means of an icon: horizontal for all appliances or vertical, incl/excl frequency control
  -Attribute higher class in energy label? Upgrading measures e.g. by awarding a better energy efficiency class?

- Impacts:
  - Give visibility to DSF capable appliances
  - Help consumers make an informed purchasing decision
  - Incentivise manufacturers to develop/off DSF capable appliances
  - However, financial reward for consumer investment into DSF functionalities will depend on use of it and availability of remuneration schemes” [13]

Some of these concepts have already been implemented. Energy Star in the USA implicitly attributes a higher energy efficiency score to connected products, but without clearly identifying those products or clarifying the potential benefits (or costs) of purchasing them. Australia currently uses a special graphic element (or ‘’icon”) on the energy label for air conditioners with DSF functionality. However there are plans to discontinue this because interested consumers generally identify the complying products through websites, which are better able than labels to detail the conditions necessary to realise the DSF potential (in this case, the connection of a DRED), state the financial incentives available and enable consumers to enroll in demand response programs.

Figure 1 United States Energy Star label (connected and non-connected appliances)

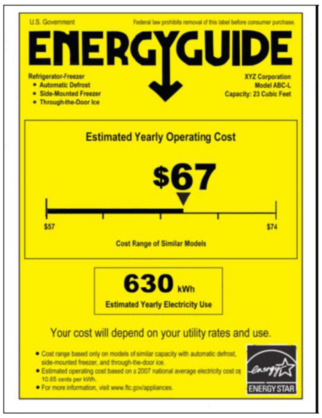

Figure 2 United States EnergyGuide label (Energy Star-compliant product)

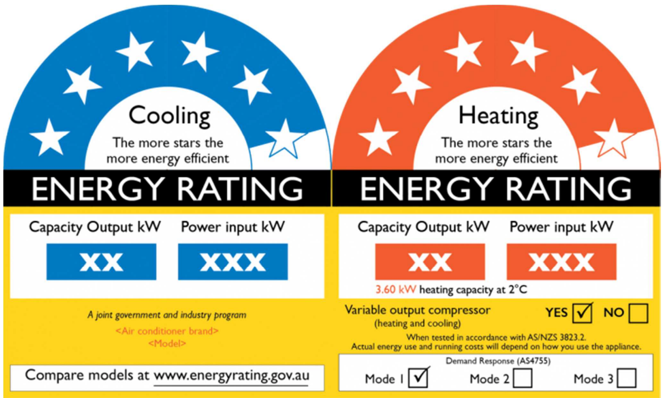

Figure 3 Australian air conditioner energy rating label (with AS/NZS 4755-compliance status)

Figure 4 Japan Echonet Logo

Figure 5 Japan refrigerator energy rating label (with Top Runner status)

Conclusions

The three national approaches examined above differ with regard to both the information they convey about product smartness and how they use labels to convey it.

Energy Star gives no information about product connectedness on the label, so it leaves it up to consumers to make themselves aware of the relevant criteria. Those who seek out connected products can decide how to make best use of them. However, consumers who purchase connected products unknowingly will incur higher energy consumption and costs than they might be led to expect. for no benefit. On the other hand, one advantage of combining energy and smartness criteria is that all products types covered by Energy Star are automatically reachable by connectedness criteria.

The Australian system gives precise information about whether air conditioner models meet a specific demand response standard irrespective of their energy efficiency, but in a way that is not particularly salient for consumers who do not know what the standard means. Furthermore there is no vehicle to convey this information for those demand responsive products that do not have to carry an energy label (those with ticks but no shading in Table 2).[20]

The Japanese Echonet system uses a common logo to identify all elements needed to realise smart capabilities – not just the appliances, as is the case with Energy Star and AS/NZS 4755. However, the logo is not integrated with the Japanese energy efficiency labelling system, so it leaves it up to consumers to make themselves aware of the relevant criteria and seek out the complying products.

Despite these major differences there are also some common factors:

- All three systems refer to published standards covering aspects of "smart" performance (although each country's standards approach is different, and each covers a different range of products);
- None actually use the word "smart", so this term is still left to the mercy of the market; and
- All rely on having products with the smart capabilities listed on websites (but only the Australian label actually refers to the website address).

Given the rapidly evolving nature of smart technology, and of public understanding (and misunderstanding) of the potential, there is a historic opportunity to establish "smartness'" labelling systems which maximise public benefit, in the way that energy labelling has been able to do. The analysis in this paper suggests some useful principles for including "smartness" in energy labelling programs in the future – assuming there is a policy will to do so:

(a) If the benefit is expected to be lower energy use, do not quantify this until there is some evidence (as is the case with the Energy Star "Connected Thermostat" criteria);

(b) If it is expected that there could be monetary benefits other than those related to lower energy use – e.g. through shifting operation to lower energy tariff periods or from using or assigning demand response capability – then state this explicitly (i.e. do not confuse a type (a) and a type (b) benefit);

(c) Do not offset a type (b) benefit against an energy consumption value or energy-efficiency rating;

(d) Develop a consistent mark or logo for all elements and components which a consumer will need to purchase to realise the "smart" capabilities of the appliance (within national markets);

(e) The regulator of the energy efficiency labelling system should own and control use of the mark or logo (even if it authorizes its use to industry groups or other responsible agents);

(f) Use of the logo should depend on verifiable compliance with a published standard or specification (or at the least, with one of a short list of specified alternatives);

(g) Existing energy labelling systems should permit (voluntary and optional) addition of the logo to the labels (whether the label is of the endorsement type – e.g. Energy Star – or the comparative type – e.g. the Australian/New Zealand and the Japanese energy labels);

[20] The parts of AS/NZS 4755 covering other products provide for voluntary point-of-sale labels indicating a product's compliance, but these would be outside the mandatory energy labelling system.

(h) Regulators should permit use of the logo on appliances which are not required to have energy labels or do not qualify for endorsement labels (e.g. because no category exists for them or they do not meet the energy-related endorsement criteria);

(i) The lists of products bearing the logo should appear either on the website of the label regulator (as is the case with Energy Star and the Australian label) or an industry group (as with Echonet);

(j) Third party service providers (e.g. electricity utilities or demand response aggregators) should be encouraged to refer to the relevant websites to identify appliances and other components eligible for incentives such as special tariffs or cash incentives.

None of the existing approaches meets all of these principles.

Solving these problems with regard to smartness labelling will make it easier to develop minimum smartness standards later. The process of adopting performance criteria, registering and listing complying products and enabling consumers to identify them will itself create an interest in and appetite for products with smart capabilities. It will also yield information about the market on which more market-constraining policies can be based. It is of course conceivable to go straight to mandatory standards – as was proposed in Australia – but policy-makers must be confident of the public benefit and cost-effectiveness. This may be easier to achieve after a labelling phase.

The alternative to action is to leave things as they are. This will see a continuation of competing claims from various manufacturers and consortia, no doubt supported by various logos and labels, all of which confuse rather than engage consumers and inhibit rather than promote the development of truly smart appliances and smart girds. Some may think this is premature and the market should be left to sort itself out for a while, but it should be remembered that the first self-declared "smart'' appliance (the LG "Internet Digital DIOS" refrigerator) was launched over 17 years ago, and the market still remains fragmented and confused.[2]

Finally, the question of international consistency might arise, as it regularly does with regard to energy performance testing standards (it has largely been abandoned with regard to energy labelling – countries and trade blocs are too heavily invested in their existing labelling systems and designs to change). It would be very difficult to harmonise the three smart product labelling systems covered in this paper, although it might be possible to manufacture products – especially air conditioners – that comply with all three.[21] This would assist international suppliers, and potentially act as a catalyst for increasing consumer awareness globally.

Perhaps the one realistic potential for international harmonisation is in the development and common ownership by regulators of a logo or symbol denoting 'smartness', that could be used in the energy labelling systems of different countries, although attached to different standards and meanings in each case.

[21] Many of the AS/NZS 4755.3.1 compliant air conditioner models sold in Australia have software and firmware capabilities originally developed for Echonet compliance, with the addition of the physical interfaces and DRED-connectability required by AS/NZS 4755.

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Relationship between Appliance Prices and Energy-Efficiency Standards and Labeling Policies: Empirical Evidence from Residential Air Conditioners

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Abstract

While minimum energy performance standards (MEPS) are commonly used for government policy interventions to enhance appliance energy efficiency, potential increases in appliance prices and loss of economic efficiency are typical criticisms of appliance standards as a policy instrument. We review the long-term relationship between appliance efficiency and prices with a focus on residential air-conditioners (ACs) in selected major economies, including emerging markets such as China and India. As robust historical price data were not available for some regions, we use country- and product-specific price indices (index of wholesale or retail price relative to a baseline year). We find that, in all the economies we studied, energy efficiency of residential ACs have improved over time while their prices decrease or remain stable in real terms over the same period. These price decreases are potentially explained by several factors including strategic pricing decisions by manufacturers, economies-of-scale and learning rates, design innovations, and resource substitution. These trends generally suggest that aggressive tightening of appliance standards does not correlate with price increases in the long run.

1. Introduction

Globally, the demand for air conditioners (ACs) in the residential and commercial sectors has been increasing rapidly in recent years, driven mostly by sales in developing countries such as China, India, and Brazil. For example, China is currently the largest room AC[22] market in the world with demand of over 30 million units every year ([1]). The saturation of ACs in terms of number per 100 households in China's urban areas increases from nearly zero in 1992 to about 100% by 2007, within 15 years ([2]). In India, room AC sales have been constantly growing at 15-20% every year for the past 10 years; although the AC saturation in India is currently low, the combination of increasing incomes and urbanization, falling AC prices and a hot climate is expected to rapidly increase AC demand by nearly eight-fold by 2030 ([2]-[3]). Globally, in the 10 years between 2010 and 2020, a conservative estimate is that nearly 1 billion rooms ACs will be sold, which translates into additional electricity consumption of more than 1,200 terawatt hours [TWh] equivalent to 700 gigawatts [GW] of sola photovoltaic penetration ([4]). Several studies have shown that there is significant potential, as high as 40%, for room AC efficiency improvement especially in emerging economies such as China, India, and Brazil ([2]-[7]).

However, there are significant barriers for adoption of energy-efficient AC technologies. Numerous studies have already analyzed the barriers to adoption of energy efficiency and the appropriate government intervention to correct for this market failure ([8]-[13]). Minimum energy performance standards (MEPS) and labels are common government policy interventions to enhance appliance energy efficiency. Potential increase in appliance prices and loss of economic efficiency are typical criticisms of appliance standards as a policy instrument. One would intuitively predict that increasing appliance efficiency would entail additional manufacturing costs in the short run (for employing

[22] Room ACs generally refer to window and ductless split (known in the U.S. as mini-split) ACs. Central ACs are typically U.S. style ducted ACs, packaged or split.

improved efficient components, materials, and controls, for example) which could, in turn, result in higher AC prices. However, several studies have demonstrated that raising appliance standards has, in fact, always results in a net welfare gain or increase in economic efficiency ([14]-[18]). Exiting literature also provides evidence of stable or declining appliance prices in the long run despite significant efficiency improvements ([14], [19], [20]). However, most of these studies have primarily focused on the United States (U.S.) and European markets. There has been little research on emerging markets like China and India which will account for the majority of new residential and commercial AC demand in the near future. The objective of this study is to review the long-term relationship between appliance efficiency and prices with a focus on residential ACs in selected major economies, including emerging markets such as China and India.

The remainder of this paper is organized as follows: Section 2 reviews the literature on regional appliance prices, Section 3 describes our data and methodology, Section 4 describes key results organized by country, and Section 5 summarizes our conclusions.

2. Literature Review

There is substantial literature on appliance prices and efficiency trends, focused mostly on the U.S. and European markets. The subsections below summarize that literature.

2.1. United States

Previous studies analyzed actual U.S. appliance prices (refrigerators, ACs, and clothes washers) since energy-efficiency standards took effect and concluded that real prices were falling over time despite increases in efficiency ([14]-[15]). Those studies documented the following declines in appliance prices: 2%-3% per year (1974-1987) to 0.5%-1.5% per year (1987-1993) for room ACs, approximately 2.7% (1967-1988) for central ACs, 5.3% (prior to 1990) and 2.3% (after 1990) for refrigerators, and 4.1% (1980-2001) for clothes washers. Another study found that studies of learning rates (defined as the rate of cost decline with each doubling of cumulative production) in ACs reported an average learning rate of more than 15% (with a range of 8% to 22%) based on data sets for the U.S. and Japan ([13]). Another study found that as appliances such as refrigerators, clothes washers, and dishwashers have become more energy efficient, performance generally improved or stayed the same, manufacturers offered new features to consumers, and prices declined or stayed the same ([22]). A recent study found that after new efficiency standards were adopted, within a short time frame actual average prices decreased by $12 (in 2011$) but with a wide range of variation by product, e.g., minus $224 (2009-2010) for commercial ACs, minus $162 (1998-2000) for room ACs, and plus $207 (2005-2007) for large size (3 tons) central ACs ([20]). Another study found evidence of an average drop in clothes washer prices at the times when efficiency standards changed in the U.S., both in 2004 and 2007, within selected product categories; i.e., the prices of the three lowest-efficiency groups dropped the most although the overall price distribution did not significantly change ([18]). The study also showed that the average market price for room ACs, deflated using the consumer price index (CPI), dropped once, then was comparatively stable between 2002 and 2008.

2.2. Europe

For the European region, one study identified a long-term decline in both price and energy consumption of large appliances (washing machines, laundry dryers, dish washers, refrigerators, and freezers) ([23]). Another study analyzed price, performance, and efficiency data for 15 consumer electronics, including computers, monitors, network devices, televisions, etc., and found that, in general, price did not relate to product efficiency and that prices of comparably performing electronic products decreased over time, with an average time constant of minus 0.30 per year ([24]). For the three relationships that can be considered among performance, efficiency, and time, the study concluded that the performance of electronic products tends to increase over time (performance and time), higher-performing products tend to be more efficient (performance and efficiency), and products tend to become more efficient over time (efficiency and time).

2.3. International comparison

One study demonstrated that the implementation of regulatory policies in Australia, Europe, Japan, and the U.S. during the 1990s and early 2000s did not increase the price of regulated products such as refrigerators/freezers, ACs, clothes washers and dryers ([19]). The authors of that study concluded that classical engineering analysis alone may overestimate future prices. The study found that price and energy consumption decreased over time, including both periods before/after relevant energy policies were adopted. The study also pointed out that the design of a new product typically incorporates major performance improvements including energy efficiency as long as manufacturers have sufficient prior information about efficiency standards, concluding that the observed decrease in appliance prices over time is mainly a result of increased production volume, design solutions innovation, and decreased production cost. The study demonstrated that the difference between the prices predicted by an engineering analysis of an upcoming standards revision and those actually observed in the market has grown considerably; actual prices are found to be much lower than expected. Another study also reviewed the literature for yearly rates of decline in prices and energy consumption of selected appliances (washing machines and dryers, dishwashers, and refrigerators) in Australia, Japan, the United Kingdom, the Netherlands, and the U.S. ([23]).

Although several studies have assessed the relationships among price, efficiency and/or performance in appliances in some countries, the literature on residential ACs is limited, and none of those studies assessed trends in economies that account for the majority of the residential AC market. ACs are a key end-use and are expected to continue to contribute significantly to electricity consumption. AC ownership is expected to grow rapidly in warm/hot climates. In particular, China and India account for over 40% of global room AC sales ([1]). Our analysis shows that even though AC MEPS are increasingly stringent in some countries, which has been improving AC efficiency over time, AC prices have tended to continue to fall over time.

3. Methodology and data sources

This paper uses AC- or appliances-specific price indices and efficiency data for China, Europe, India, Japan, Korea, and the U.S., which collectively account for about 70% of the global room AC market ([1]). Robust historical price data were not publicly available for most regions. Therefore, we use country- and product-specific price indices (i.e., indices of wholesale or retail price relative to a baseline year). Because the objective of this paper is to assess long-term trends, using price indices serves the same purpose as using retail prices in real terms. Specifically, consumer price indices (CPIs) and producer price indices (PPIs) can be key indicators of price changes in household appliances.

3.1. Price indices

In general, CPIs measure the average changes in the prices of consumer goods and services that households consume. CPIs are mainly used as measures of general inflation or retail sales deflation; governments also use CPIs to track price and wage adjustments ([25]). Although the statistical methodologies used to determine the CPI in many countries are largely consistent with international guidelines, international comparisons depend on the approach used by individual countries – for example, the weighting and aggregation methodologies, the treatment of quality differences, the selection of replacement items, the treatment of new/seasonal items ([26]).

Whereas CPIs measure changes over time in average retail prices of a set of goods and services that represent household consumption habits, PPIs do not consider commercial mark-ups. In fact, the term “PPI” is mostly used to refer to output PPIs that represent changes in ex-factory gate prices, i.e., the prices received by the producer at the first stage of commercialization ([25]). Wholesale price indices (WPIs) reflect changes in the prices paid at various stages of distribution of a product, e.g., for raw materials, intermediate or unfinished goods, and finished goods. In some countries, e.g., the U.S., the term "PPI" replaced the term "WPI" during the 1970s or 1980s. In other countries, WPIs follow the same or a similar methodology as is used for PPIs elsewhere ([25], [27]).

CPI and PPI differ in purpose, use, scope and coverage, categorization (e.g., composition of the set of goods and services), and other technical definitions (e.g., types of prices collected for the included goods and services) ([26]). However, because both CPI and PPI in principle measure price change over time for a fixed set of goods and services, observing the direction and magnitude of price changes in both of these indices for the same or similar items is helpful in assessing long-term price trends. For this reason, researchers sometimes use both price indices in combination. For example, if one is interested only in changes in producer prices, rather than in absolute prices, inflation-adjusted PPIs could be appropriate for the analysis, e.g., using PPI divided by CPI ([28]).

3.2. Regional price indices for air conditioners and appliances

In this paper, we analyze price trends using regional price indices (depending on the availability of data specific to residential ACs), but we do not compare price indices among the selected regions. Table 1 summarizes regional price indices associated with residential ACs or appliances in general. Details of the regional data sources follow.

Table 1. AC- and appliance-related categories in regional price indices

	PPI/WPI	**CPI**
Japan	CGPI (PPI): Room ACs	Room ACs
South Korea	PPI: Room ACs	Room ACs
United States	PPI: Room ACs	No appliance specific category
India	WPI: ACs	No appliance specific category
China	PPI: Electrical Machinery and Equipment; Communication Equipment, Computers and Other Electronic Equipment	Household Durable Goods
Europe	PPI: Manufacturer of electrical machinery and apparatus; radio, television and communication equipment and apparatus	HICP: Household Appliances

1. PPI (producer price index); CPI (consumer price index); RPI (retail price index); HICP (harmonized index of consumer prices); CGPI (corporate goods price index)
2. CGPI is Japan's version of PPI. Japanese CGPI consists of PPI (renamed from domestic corporate good price index in June 2014), export price index (EPI), and import price index (IPI).

Japan

The Statistics Bureau of Japan has been publishing monthly and annual price indices that include room ACs (http://www.stat.go.jp/). In Japan, the corporate goods price index (CGPI) has replaced the former WPI and measures the price developments of goods traded in the corporate sector ([29]-[30]). The CGPI is divided into PPI (formerly domestic corporate goods price index), the export price index (EPI), and the import price index (IPI). In this paper, we use both CPI and PPI (excluding consumption tax), both of which has been tracking room ACs.

South Korea

The Korean Statistical Information Service (KOSIS, http://kosis.kr/) has been providing both a CPI (by commodities & services and by expenditure category) and a PPI that specifically track room ACs in the country. In this paper we use both the CPI and PPI for room ACs in the country.

United States

The U.S. Bureau of Labor Statistics (http://www.bls.gov/) has been publishing both CPI and PPI, but only the PPI tracks ACs. As discussed above, we are interested only in changes in producer prices rather than absolute prices, so we use CPI-adjusted PPI for our analysis, i.e., the PPI for room ACs divided by the CPI for all items.

India

India's Ministry of Statistics & Programme Implementation releases CPIs based on data collected from 1,114 markets in 310 towns in the country (http://mospi.nic.in/, https://data.gov.in/). However, India's CPI does not specify room ACs or household appliances, and the data on the website are available only from 2011 on. The Office of the Economic Adviser (OEA) of the Ministry of Commerce and Industry publishes a WPI for appliances and electrical and industrial equipment. India's WPI is different from PPIs used in other countries; for example, the WPI includes taxes and tracks transactions for goods only at the wholesale level whereas PPIs generally track average change over time in sales prices that producers receive for goods and services, reflecting inflation. The OEA has already initiated the process of constructing PPIs for India, and an experimental price index is in place for selected services such as railways, banking, postal, and telecom ([31]-[32]). In this paper, we use an inflation-adjusted WPI for ACs.

China

The National Bureau of Statistics of China (http://www.stats.gov.cn/) publishes annual price indices, including CPI, retail price index (RPI), and PPI for industrial products. The Chinese CPI consists of 10 primary components covering food, clothing, home facilities, services, health care, transportation, communications, entertainment, education, and housing. The weights for calculating the RPI and CPI are determined according to the total retail sales of commodities and the composition of the consumption expenditures of more than 90,000 urban and rural households, respectively (NBS, 1996-2014). However, it appears that there is no AC-specific price index in China. In this paper, we go over the CPI for household durable consumer goods, the RPI for household appliances, which includes residential AC systems, and identified recent AC price information in China.

Europe

The harmonized index of consumer prices (HICP) is a set of consumer price indices used in the euro area. Although HICP and CPI both measure the inflation faced by consumers and are mostly based on the same data sources, they differ in how they measure inflation, and the HICP is mainly used for monetary policy purposes ([33]). Eurostat (http://ec.europa.eu/eurostat) has also been providing specific statistics on manufactured goods, including AC systems (Eurostat, 2002-2013). Purchasing power parities are used as indicators of price differences across countries, reflecting fluctuations in currency exchange rates. However, it appears that there is no AC-specific price index in Europe. In this paper, we go over the HICP for household appliances and actual AC prices in Spain, which accounts for about 10-11% of the room AC market in Europe.

3.3. Residential air-conditioner efficiency trends

For historical residential AC efficiency trends, we relied on literature, governmental data, and various reports. Efficiency of commercially available ACs is typically reported in a region-specific metric which is of limited value to other regions given the difference in performance of the same model due to differences across region in test procedure, energy efficiency metric, and climate condition. In this paper, we do not compare efficiency in a region with those in other regions. Table 2 lists the AC efficiency data sources use for this analysis.

Table 2. AC efficiency data for selected regions

Region	Efficiency data	Years covered	Data sources
Japan	Product-weighted or sales-weighted efficiency in COP or APF	1970-2015	[34]-[37]
Korea	Product-weighted average EER and CSPF	1996-2013	[38]-[40]
United States	Shipment-weighted SEER of central ACs and room ACs	1990-2009	[41]-[42]
India	Sales-weighted average EER for room ACs	2008-2013	[43]-[47]
China	Product-weighted and sales-weighted average EER or SEER for room ACs	2005-2013	[48]-[53]
Europe	Product-weighted average EER	2002-2009	[54]-[55]

EER (energy efficiency ratio); SEER (seasonal energy efficiency ratio); COP (coefficient of performance); CSPF (cooling seasonal performance factor); APF (annual performance factor)

4. Results

In this section, we present the AC price indices and efficiency trends for the past several years in the AC markets studied.

4.1. Japan

Figure 1 shows trends in room AC efficiency reported as COP and APF, and room AC prices represented by CPI and PPI of room ACs. Since 1970, the efficiency of room ACs in Japan has improved nearly threefold ([35]). In particular, efficiency in coefficient of performance for cooling (COP cooling) improved by over 60% between 1997 and 2004, primarily because of the introduction of the Top Runner Program, a policy to improve the energy efficiency of end-use products by setting mandatory energy-efficiency standards based on the most efficient products on the market ([35]). Efficiency in its revised efficiency metric called annual performance factor (APF) also improved by about 15%% from 2005 to 2010, between the 1st (2004) and 2nd (2010) target years ([36]-[37]). During the same time period (1997-2010), room AC prices in CPI dropped by 65%. Another study also showed a relationship between AC efficiency and price for units sold in Japan from 2001 to 2005. Prices of ACs meeting the 100% energy-efficiency level were estimated to have decreased or stayed constant ([34]).

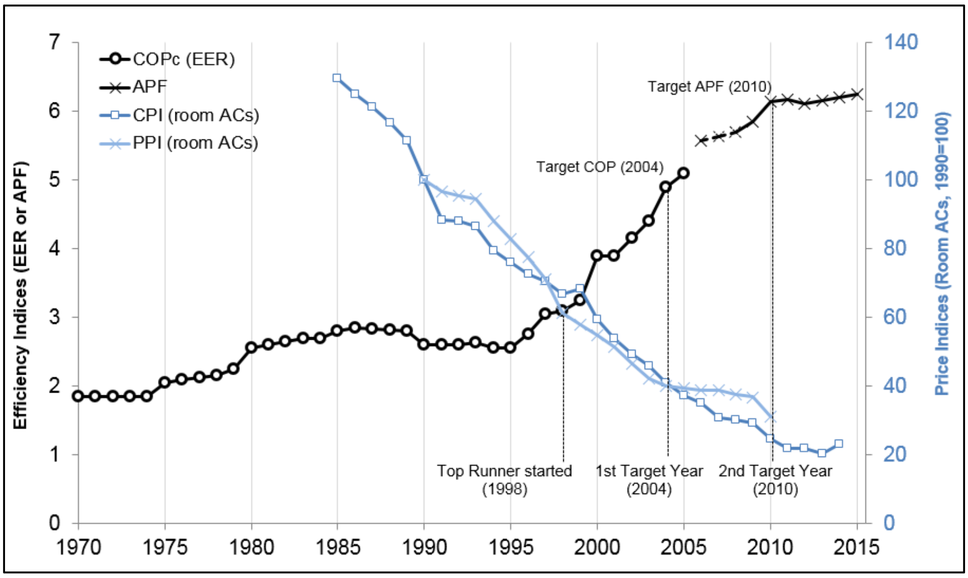


Figure 1. Room AC efficiency and price trends in Japan

Authors' work based on data from [34]-[37], the Statistics Bureau of Japan, and the database of products registered in the Top Runner Program. For AC energy-efficiency metrics, Japan used COPs for cooling and heating; however, for the second target year (2010), modified test methods and replaced the COP metric with an annual performance factor (called APF) that reflects actual outdoor temperature changes and corresponding indoor thermal loads.

4.2. South Korea

The Korean government has been running the Energy-Efficiency Label and Standard Program since 1992 with the aim of improving the energy efficiency of key products, including appliances and vehicles that account for majority of energy consumption ([56]). Mandatory MEPS were published in 2002 and took effect in 2004 for window and split ACs up to 23 kilowatts (kW) cooling capacity ([49]). In September 2011, the governmenet announced the Energy Frontier program, which sets mid-term energy-efficiency goals in key appliances at 30-50% more efficient than grade 1 (most efficient). The first phase of the program inlcuded four major appliances: TVs, refrigerators, ACs, and clothes washers ([56]). The efficiency of room ACs in Korea improved by more than 20% between 1996 and 2010 ([38]-[39]). Since 1990, the CPI for room ACs has been comparatively stable, except between 1998 and 2001 when Korean experienced a financial crisis; the CPI for all items more than doubled during the same period, resulting in decreased AC prices in real terms, i.e., room AC specific CPI over CPI for all commodities.

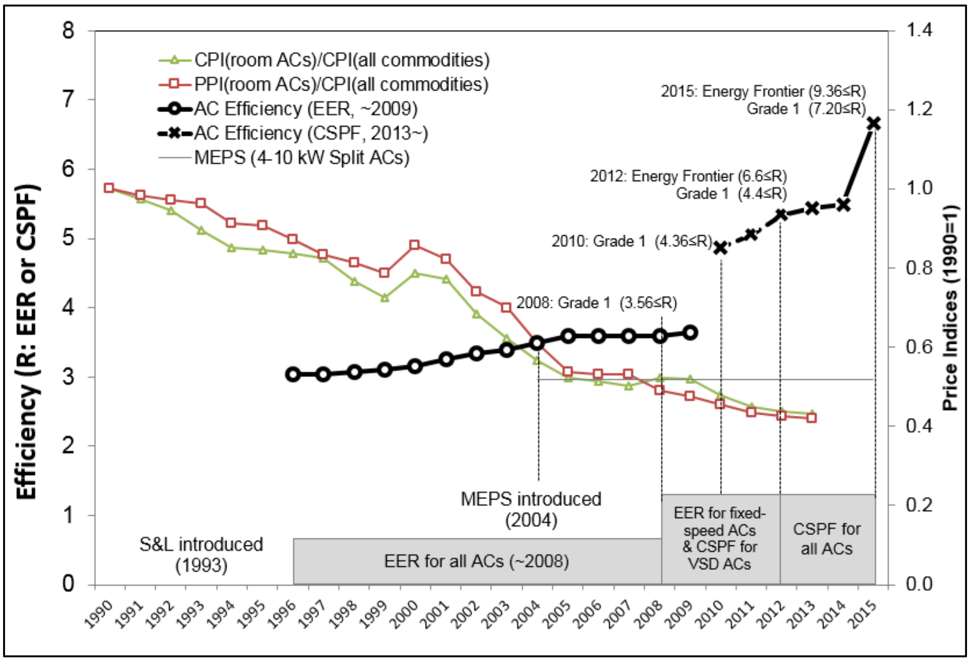


Figure 2. Room AC efficiency and price trends in South Korea

Authors' work based on data from [38]-[40], the Korean Statistical Information Service and the Korea Energy Agency. According to interviews with industrial experts, the share of inverter ACs in Korea is estimated to have rapidly increased from less than 10% in 2008 to more than 80% in 2015.

4.3. United States

Residential ACs in the U.S. fall into two broad categories: room ACs and central ACs ([49]). Central ACs in the U.S. includes split and multi-split packaged non-ducted ACs, which are classified as "room ACs" in other countries ([3], [49]). A room AC in the U.S. is defined as a consumer product powered by a single-phase electric current and sold as an encased unit for mounting in a window or through the wall ([41]). Unlike in Japan, large ducted air-to-air whole house AC systems dominate in the U.S. ACs with capacity of 7.2 to 10.5 kW account for about 60% of all central ACs in the U.S. ([49]). In addition, approximately 70% of U.S. ACs are cooling only whereas most room ACs in Japan are reversible for both heating and cooling ([49]).

AC prices in the U.S. declined or fluctuated around a flat or slightly declining trend during the period of 1995 and 2005 ([15]). Although the real price of central ACs increased from 2001 to 2010, e.g. by approx. 35% for three-ton (36,000 British thermal unit [Btu] central ACs, the increase is attributed to a significant increase in copper prices, which, were more than three times higher in 2010 than they were in 2001. AC manufacturers have been replacing copper tubing with aluminum because of the increased copper price ([22]). Although the CPI for all items and PPIs for metal products have significantly increased or fluctuated since the 1970s, the PPIs for appliances, including ACs, have been comparatively stable since the early 1980s in spite of the implementation of and revisions in energy-efficiency standards since the late 1980s.

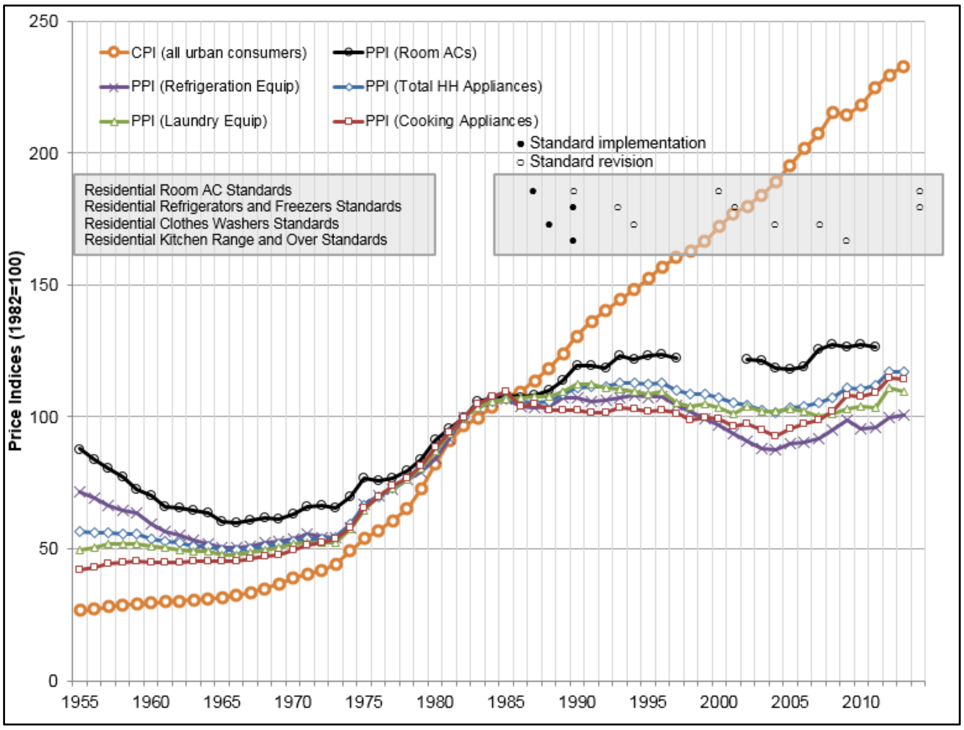


Figure 3. Price Indices and Appliances Standards Implementation in the U.S.

Authors' work based on data from the Bureau of Labor Statistics

Between 1970 and 2000, as MEPS became increasingly stringent, the efficiency of room ACs and central ACs improved in the U.S. For example, in 2001, more than 80% of central AC models had efficiency levels below a SEER of 13 (Btu/Wh) whereas in 2012 nearly 80% of models achieved SEER 14 (Btu/Wh) or higher ([22]). Specifically, the efficiency of split ACs improved by approximately 1 SEER point primarily as a result of the first set of standards (MEPS=SEER 10) in 1992, and by approximately 2 SEER points as a result of the second set of standards (MEPS=SEER 13) in 2006 ([42]). The shipment-weighted average efficiency of room ACs also increased by about 16% from 1990 to 2009 and by about 43% from 1981 to 2009.

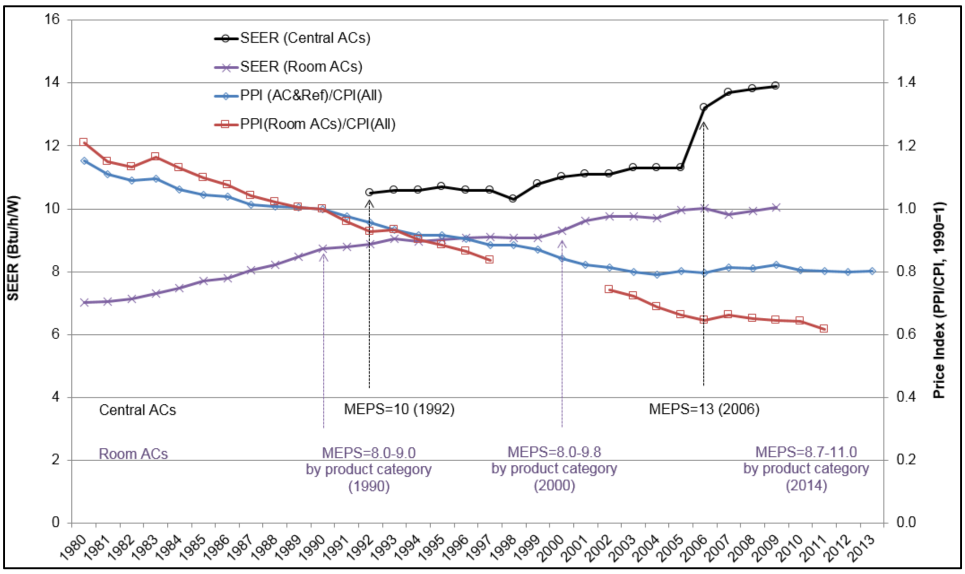


Figure 4. Residential AC efficiency and price trends in the U.S.

Authors' work based on data from [41]-[42], the U.S. Bureau of Labor Statistics. Note that AC efficiency in the U.S. is based on Btu/h/W, while other markets on W/W.

4.4. India

The Energy Conservation (EC) Act 2001 provides the legal and institutional framework for the Government of India to promote energy efficiency across all sectors of the economy. The Standards and Labeling (S&L) Program was launched by the Bureau of Energy Efficiency (BEE) in May 2006 as a voluntary scheme with an overarching agenda to reduce the energy intensity of electrical appliances used in the country. The label provides a comparative 5-star rating system based on annual or daily energy consumption. BEE typically revises the rating criteria every few years. Since 2010, mandatory labeling was introduced for room ACs (split and window) under this scheme.

In India, the average price for room ACs has fallen since 2000 by 60% in real terms, i.e., compared to average inflation in all commodities (see Figure 5). Even after the introduction of voluntary (2006) and mandatory (2010) labeling, including MEPS, prices appear to have continued falling in real terms (see Figure 6). Although it is possible that the price reduction could be partially a result of inferior materials being used in AC production, which would reduce appliance life, if this were the case. However, given the highly globalized AC supply chain, it would have affected all countries considered in this analysis, if at all, but this is not the case.

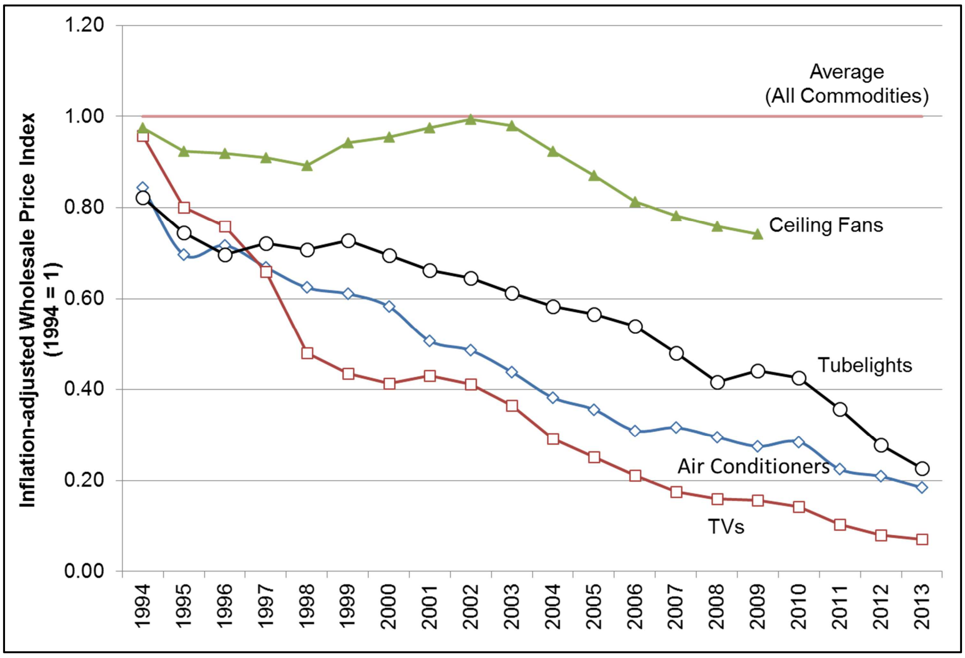


Figure 5. Inflation-adjusted WPI of selected appliances relative to all commodities in India

Authors' work based on OEA WPI Data. Department of Industrial Policy and Promotion, Ministry of Commerce and Industry. http://www.eaindustry.nic.in/.

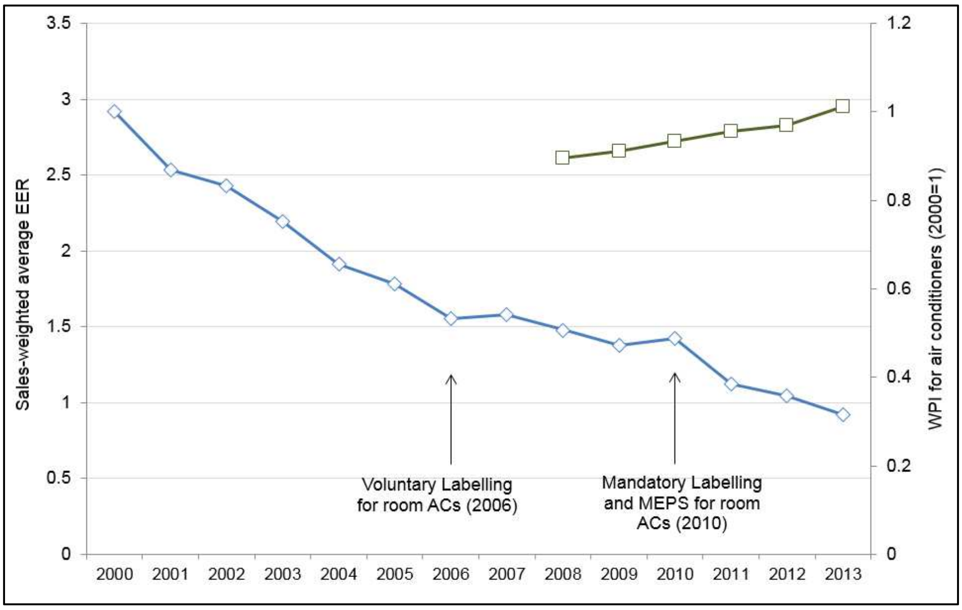


Figure 6. Room AC efficiency and AC price trends in India

Authors' work based on OEA WPI Data.

4.5. China

China has the largest AC market in the world, accounting for about 40% of the global room AC market, e.g., demand of about 30 million units in 2015 ([1]). China's AC market had an estimated value of about US$7.9 billion in 2011 and growing ([57]). According to the 2010 national electricity consumption survey, 21 energy-consuming products including various types of ACs consumed about 2.9 trillion kilowatt-hours (kWh), which represents about 70% of the country's total electricity consumption (4.2 trillion kWh) of which room ACs accounted for about 6% ([51]). As a product group, all types of ACs together represent an estimated 30% (2.27 billion kWh) of total electricity savings potential (7.7 billion kWh) in this category of 21 energy-using products ([51]).

In China, MEPS were introduced for fixed-speed room ACs in 1989 and revised in 2004 (effective from 2005 on) and 2009 (effective from 2010 on). MEPS and labeling requirements for variable-speed units were introduced separately in 2008 and revised in 2013 ([49]; [58]). Low-energy-efficiency products (grades 3 to 5) had been dominating China's room AC market, accounting for more than 85% of the market in 2009 ([48]). As seen in Figure 7, the majority of room AC products in China only met MEPS implemented in 2005 although the best available efficiency was much higher than the market average efficiency.

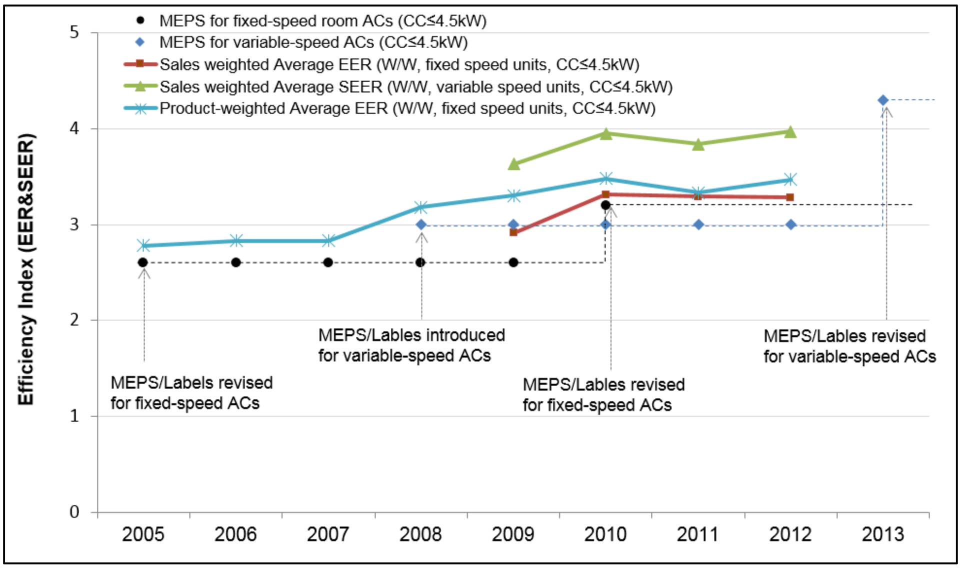


Figure 7. Energy efficiency of room ACs in China

Authors' work based on data from [49], [50]-[52], and [58]. According to [50]-[52], the sales-weighted average efficiency is estimated to be 1-22% less than the product-weighted average efficiency, depending on product category by cooling capacity. Since the 2013 standard revision, China has adopted CSPF for cooling-only products and APF for reversible products for efficiency metric.

Actual retail prices of white appliances (ACs, refrigerators, and clothes washers) in China decreased from 2001 to 2004 by about 6-7% year by year, but increased from 2005 to 2007 by 8.3% (ACs), 11.4% (refrigerators), and 9.2% (clothes washers). These increases were mainly a result of a significant increase in prices of key raw materials such as copper and steel ([63]). In addition, in the years 2001-2004, the number of AC manufacturers in China was about 300, resulting in a highly competitive market. Even though prices of raw materials significantly increased, e.g., 15% for aluminum, 44% for copper and 10-15% for compressors in 2003, the AC prices were reported to be falling by 10-20% ([59]). Among many different metals that ACs contain, copper (or aluminum) and steel are important for ensuring thermal properties, energy efficiency, and environmental safety. The average hourly compensation cost for manufacturing employees in China increased from US$0.6 in 2002 to US$1.74 in 2009 ([64]).

As the number of manufacturers in the market decreased and only about 20 manufacturers were left in 2006, the AC price increased, e.g., 12% on average between 2005 and 2006 ([53], [60]). From 2009 to 2012, the Chinese government provided subsidies and trade-in discounts to promote energy-efficient home appliances, leading to an increase in room AC sales. Since then, major vendors have stopped selling low-energy-efficiency products, which has increased the market share of energy-efficient (grade 1 and 2) products; as of 2010, these products represented more than 40% of the market ([48], [57]). According to a report, the overall energy efficiency level in ACs increased by 24%; financial subsidies, coupled with economies of scale, significantly reduced the selling prices of high efficiency energy saving products, e.g., the lowest selling price of Grade 1 qualified model in the market around RMB 1000 (~USD 100) ([61]).

In 2011, the Chinese AC market experienced price increases in ACs due to the increased costs of raw materials ([68]). In 2013, non-inverter 1-1.5 horsepower (HP) (2.6-3.5kW capacity) ACs sold at RMB 2,000-3,500 (USD 280-490) seemed to be still most popular, although high-end inverter ACs were getting increase the share ([62]). The average price in the AC industry was reported to be dropped by 3.6% compared to the previous year in 2015, but increased by more than 1.5% in 2016

([67]). Figure 8 shows that from 1994 to 2012, household-related price indices were decreasing or stable while those for all commodities were stable or increased.

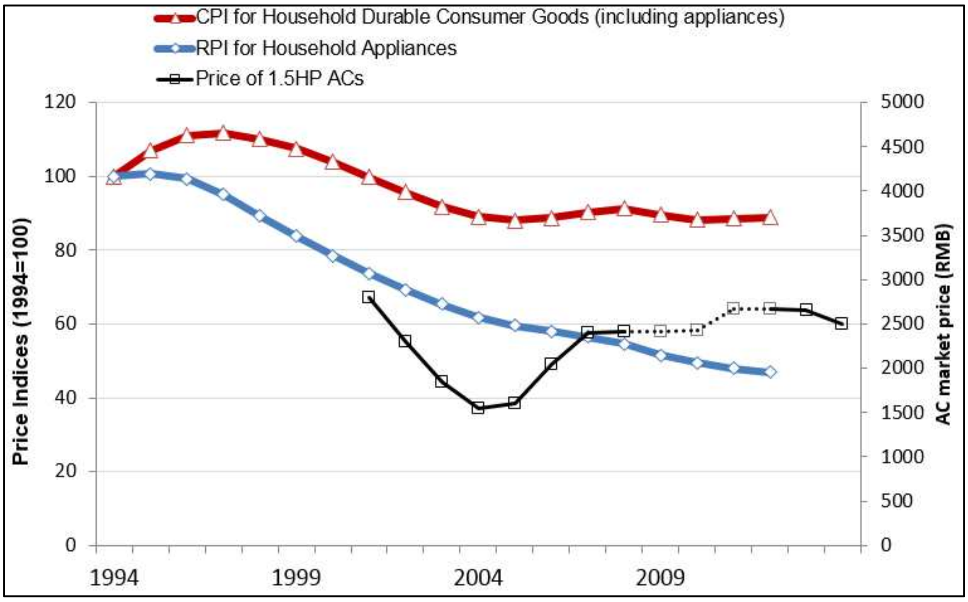


Figure 8. Chines Price Indices (1994=100) for Home Appliances and Household Consumer Goods from 1994 to 2012 and AC market prices

Authors' work based on data from [53], [62] and National Bureau of Statistics of China. The average market price of ACs represent non-inverter 1.5 HP (3.5kW capacity) fixed-speed AC units. The dotted-line is authors' estimates based on data from [53], [62], [67] and [68].

4.6. Europe

Since the European efficiency labeling scheme was implemented in 2002, efficiency of new ACs has improved – by 20-30% in 2009 in the EU region. This is partly a result of the market share of variable-speed ACs increasing from 4% to 50% ([55]). Specifically, it was reported that the product-weighted average energy-efficiency ratio (EER) increased from 2.61 in 2002 to 3.18 in 2009 (and the sales-weighted average EER increased from 2.72 in 2006 to 3.28 in 2009). In addition, the share of Class A products in the residential room AC market increased from 41% in 2007 to 57% in 2010 across Europe ([54]-[55]). In addition to improvements in room AC efficiency, the energy efficiency of eight other end uses or appliances (heating, water heating, cooking, refrigerators, freezers, washing machine, dishwashers, and TVs) was improved by 30% from 1990 to 2011in the EU region ([55]).

While the average efficiency of room ACs in the European region has improved since the EU energy labeling scheme implementation, the average AC price has been decreasing or stable. For example, the AC Unit Value (defined as the value of AC production sold in thousands of Euro over the volume of AC production sold in thousands of units) significantly decreased from 820 EUR ($US 779) in 2002 to 248 EUR ($US275) in 2015. The HICP for household appliances decreased from 103 in 2002 to 95 in 2015, where 2005=100 (see Figure 9).

We also went over actual AC prices normalized for Spain, which accounts for about 10-11% of the room AC market in Europe. The Spanish, Italian, and Portuguese markets are assessed to be price sensitive with large share of low- and middle-end products, while energy-saving and environmentally-sustainable features are popular in the French, German, UK, and Scandinavian markets ([65]). The AC price without inflation adjusted in Spain has been decreasing or stable, depending on product category.

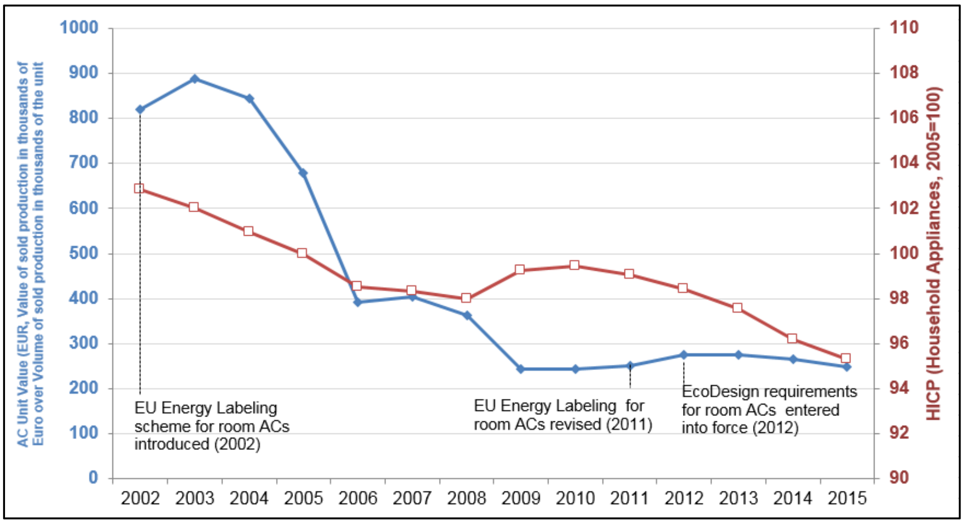
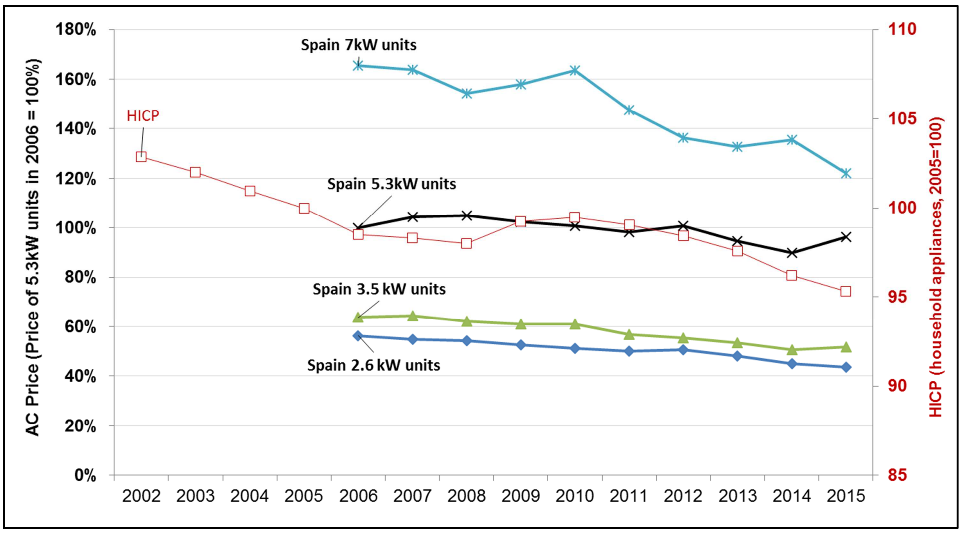


Figure 9. AC unit values and HICP for household appliances in the EU region

Authors' work based on data from Eurostat Harmonized Index of Consumer Prices (HICP): Household Appliances for European Union (27 countries), retrieved from FRED, Federal Reserve Bank of St. Louis, and statistics on the production of manufactured goods: window or wall air-conditioning systems, self-contained or split systems (Prodcom Code 28251220, EU27 for 2003-2013, EU15 for 2002).



Authors' work based on data from the industry and Eurostat Harmonized Index of Consumer Prices (HICP): Household Appliances for European Union (27 countries), retrieved from FRED, Federal Reserve Bank of St. Louis.

5. Summary and Discussion

Our analysis shows that, in most of key markets, AC prices (in real terms, reflecting inflation) have been consistently dropping over several years despite significant increases in product efficiency. In Japan, room AC prices in CPI dropped by 70% between 1990 and 2008 while product efficiency more than doubled. In Korea, room AC prices were nearly stable between 1990 and 2010, and average efficiency increased by more than 20% between 1996 and 2010. In India, the average room AC price fell by more than 60% between 2000 and 2012 while the market average AC efficiency increased by about 13% from 2008 to 2013. In the U.S., between 1990 and 2010, the overall AC price dropped by 20%-36% while product efficiency increased by 32-43% between 1992 and 2009. In China, the average efficiency of room ACs increased by 25% since 2005 as a result of MEPS and subsidies provided from 2009 to 2012; during the same time frame (2004-2012), the prices of household appliances represented by the RPI decreased by 20%. In Europe, while the average efficiency of room ACs in the region has improved since the EU energy labeling scheme implementation, the average AC price seems to have been decreasing or stable.

Our analysis agrees with the existing literature, showing that during the past several years AC prices have been consistently falling in real terms in all key countries while energy efficiency has been increasing significantly. This phenomenon might be explained by increasingly rapid learning rates, pricing policies, economies-of-scale, and technology and design innovation in the appliance industry as well as factor substitution in manufacturing ([23]). In addition, there could be other firm- or industry-specific factors (e.g., top-management's commitment, market competitiveness, supply & demand structure, etc.) that can lead to technological improvement, including energy-efficiency improvement and cost reduction, within an appliance industry ([66]). Although there are many potential explanations for the price trends, the bottom line is that evidence shows that introduction of energy-efficiency technologies does not increase the market price of products in the long term.

As aforementioned, some might argue that increases in costs of raw materials, labor, and marketing are bound to increase the cost of finished products, and that therefore, when prices decrease, this suggests that manufacturers might be compromising quality to achieve lower cost. However, regional market standards for performance, energy, and environmental safety have become more stringent over time and non-compliance is not reported to be a problem.

Energy-efficiency policies, such as standards, potentially explain the rising efficiency levels of ACs, and falling prices are potentially explained by increases in learning rates as well as by pricing policies, economies-of-scale, technology and design innovation in the appliance industry, and factor substitution in appliance manufacturing. Our analysis shows that, in general, introduction of energy-efficiency technologies may be expensive initially, but it does not increase the market price of products in the long term.

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A consumer oriented digital label to improve energy labelling impact

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Abstract

It is widely accepted that informed consumers make better purchasing decisions. This principle is applied through the European energy label to promote more energy-efficient appliances. The energy label has been quite a success story, with over 80% of consumers recognising it. Many consumers also say that they understand the energy label and use it for their purchase decisions.

Despite the positive results, data show that the absolute energy consumption in households have increased in recent years and that despite improvements in overall product efficiency, absolute power consumption of some products has increased due to bigger product sizes and more features. Furthermore, studies have shown that consumers do not understand all elements of the various energy labels. Thus, better media are needed to improve communication and positively influence these important consumer choices. Digital labelling tools are one of the best solutions for overcoming these problems.

This paper presents research into the development of a digital energy label called *PocketWatt* as an add-on to the EU energy label. Besides offering more information, one major advantage of the digital concept is that it's designed as a point of sale tool. Thus consumers would be able to access relevant information during the actual purchase decision. In the paper the tool is described and its features are outlined. Furthermore the objectives, methodology and detailed findings of spontaneous consumer reactions to *PocketWatt* from two consumer focus groups conducted in summer 2016 in Germany and Spain are reported. Currently, the tool is tested in pilot stores in Spain and the UK.

Introduction: A new approach to energy labelling

We know that the residential sector in the EU accounts for 29.7% of final electricity consumption in 2010; with electrical consumption from appliances accounting for nearly 62% of that[23]. Estimation of efficiency potential come to the conclusion that every European household could save 454 Euro a year starting 2020 by choosing top class products compared to a scenario without product policy for efficiency [1]. Thus, increasing energy efficiency at constant service levels are a powerful means to reduce energy consumption levels at low impact levels in daily life.

The challenge remains that a lack of information is one of the barriers to consumers saving energy. This barrier, whilst known for many years, is still present and relevant. It is widely assumed that informed consumers make better purchasing decisions. This principle is applied by the European energy label to promote more energy-efficient appliances. The label was introduced in 1992 to contribute to the overall goal of reaching the climate targets of the Council of Communities (Directive 92/75/EEC). The label intends to target consumers' decisions at the point of sale by providing information about energy efficiency in order to support product choice in terms of energy efficiency but also running costs. Additionally, the label is supposed to contribute to encouraging manufacturers to invest in the development of energy efficient products if consumer interest in those products is rising.

The energy label has been quite a success story, with over 80% of consumers recognising it [2] [3]. Consumers also claim that the energy label is overall comprehensive and that they use it for their purchase decisions. Further studies have shown that the energy label is seen as a sign for quality and that consumers are willing to pay more for the products in concern [4] [5]. Generally, product policy has been proven to be quite effective at reducing the energy consumption of households. Between

[23] http://iet.jrc.ec.europa.eu/energyefficiency/sites/energyefficiency/files/energy-efficiency-status-report-2012.pdf

2005 and 2011 the average annual consumption of labeled products decreased by 9% in total [6]. In 2015, 50% of the sold washing machines, tumble dryers, dishwashers, coolers/refrigerators and freezers were class A++ and A+++ [7]. For these product groups A+ is the least efficient class right now allowed to enter the market.

Thus it is questionable whether the label really still gives the right incentives and information. Statistics point out that the absolute energy consumption in households increased in recent years and that while the general efficiency of products increased, the absolute consumption of the products continued to rise as well [8] [9]. This is due to the fact that due to increases in size e.g. for TVs or fridges or additional features. Several studies have shown that the energy label in its current form does not seem to be enough to increase energy efficiency in the expected way [10] [11]. The reasons for this can be manifold but besides unforeseen market developments they most likely also include shortcomings of the current energy label: consumers do not always understand the efficiency scale, the variety of best classes, the average annual consumption, the fiche and the pictograms as it lacks language for further explanation, information on individual running costs and a connection to individual behaviours and needs. Furthermore, in this age of instant messages, real-time streaming and readily accessible information, passive paper stickers like the energy label are most likely not that engaging (anymore). We therefore postulate that catching the attention of consumers when they are making purchasing decisions – and promoting energy-efficiency – requires a different approach.

Against this background this paper wants to present a proposition for such a different approach to support consumers on energy efficiency issues during the purchase of appliances. We give a summary on the outcomes from the *Digi-Label* project which seeks to develop an active internet-based solution for the energy label that provides easy to understand product information, accessed in a format suitable for the Information Generation. *Digi-Label* will create a comprehensive information hub accessible to consumers at point of sale, in store and online, across five EU countries, and is recently piloting a first version at retail stores in Spain and UK. Links to the information hub will be offered via website, mobile app or scanable technology. Consumers will be offered easy to understand product information, annual running cost, and comparison options. This solution is called *PocketWatt.* An earlier version of it has been evaluated by two consumer workshops which took place in Spain and Germany. Details from these discussions which informed the further development within the project are reported in detail in this paper.

***PocketWatt*: a digital consumer tool**

PocketWatt is a digital tool for consumers which will be available as an online resource, mobile app and via retailer websites. The aim of the tool is to provide consumers across Europe with the impartial information they need to make informed choices when purchasing electrical appliances. *PocketWatt* achieves this by giving tailored, high quality information about energy performance to consumers at the point of sale via a simple scan-and-learn in-store smart phone experience or a single click for those shopping online.

PocketWatt runs on QR Codes which can be found in conjunction with the existing energy label and a dedicated Java applet embedded within retailer websites. Both QR codes and the applet have encoded URLs acting as instant access gateways to the Digi-Label products database; this implies that consumers have a consistent experience and flow of information independent of where they look for an appliance. *PocketWatt* is part of the wider Digi-Label online resource, an enterprise level end-to-end solution where product data is securely managed, product performance calculated and all QR Codes and Java applet inserts generated. The following figure gives an overview on the Digi-Label resources, whose heart is the central database which interacts with the *PocketWatt* tool including data managers with the ability to submit products manually, via automated feed or bulk upload and secure retailer access where QR codes can be downloaded and Java applets managed.

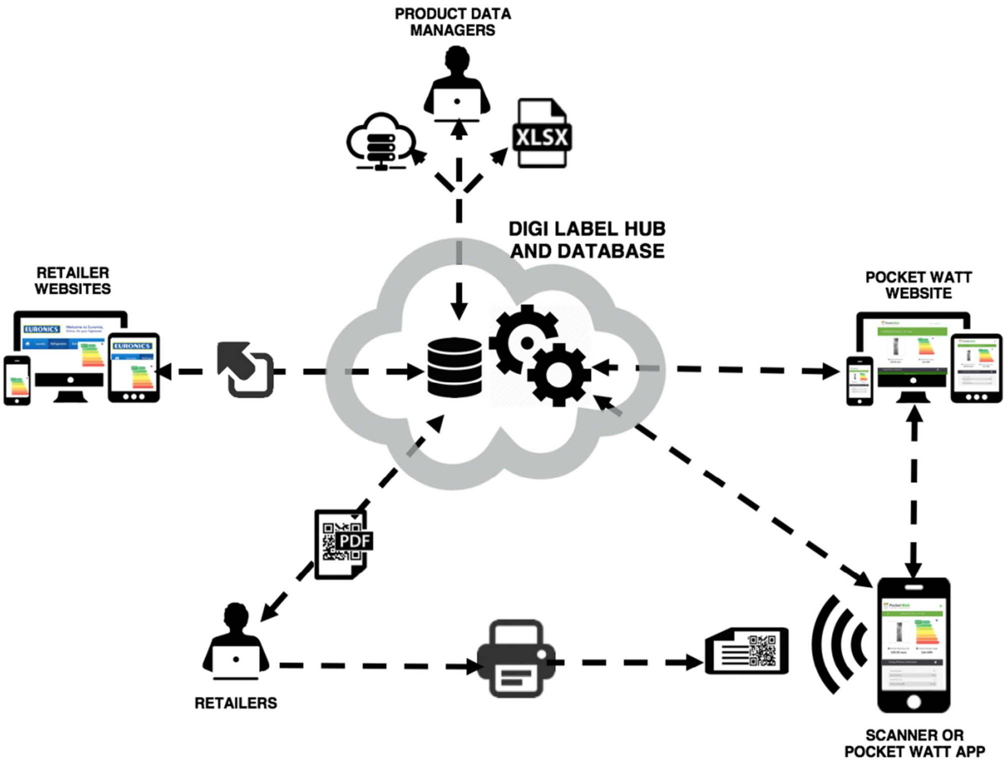

Figure 1. Overview on the Digi-label resource, including the central database and interactions around the *PocketWatt* tool

As *PocketWatt* is made for consumers across Europe it has full multi-language functionality built-in with language selectors presented on the web tool, mobile app and Java applet to accommodate user needs. This is implemented by driving all content including menus, navigation, tips and product details from the central database with all consumer views being dynamically generated with appropriate language, content and data each time they are accessed. This approach has been adopted to ensure consistency without compromising the flexibility of *PocketWatt* to accommodate change and updates.

If *PocketWatt* is used in store it is characterised by a simple scan-and-learn process drawing on QR codes scanned through the *PocketWatt* App or any general QR scanner. Thus, the consumer scans a code and is directed to an at-a-glance information page providing summary performance data of the product the QR code is attached to which includes an efficiency ranking of the product compared to similar products within the database. Additional details are also provided to expand upon the summary and for categories of products such as washing machines where number of uses is an important factor consumers are able to adjust to instantly recalculate annual running costs. To help inform consumer choices, products can be added to a compare list, shared with others via email or social media and saved for later review. The entire products database can also be searched and reviewed. The following images summarise the in-store experience.

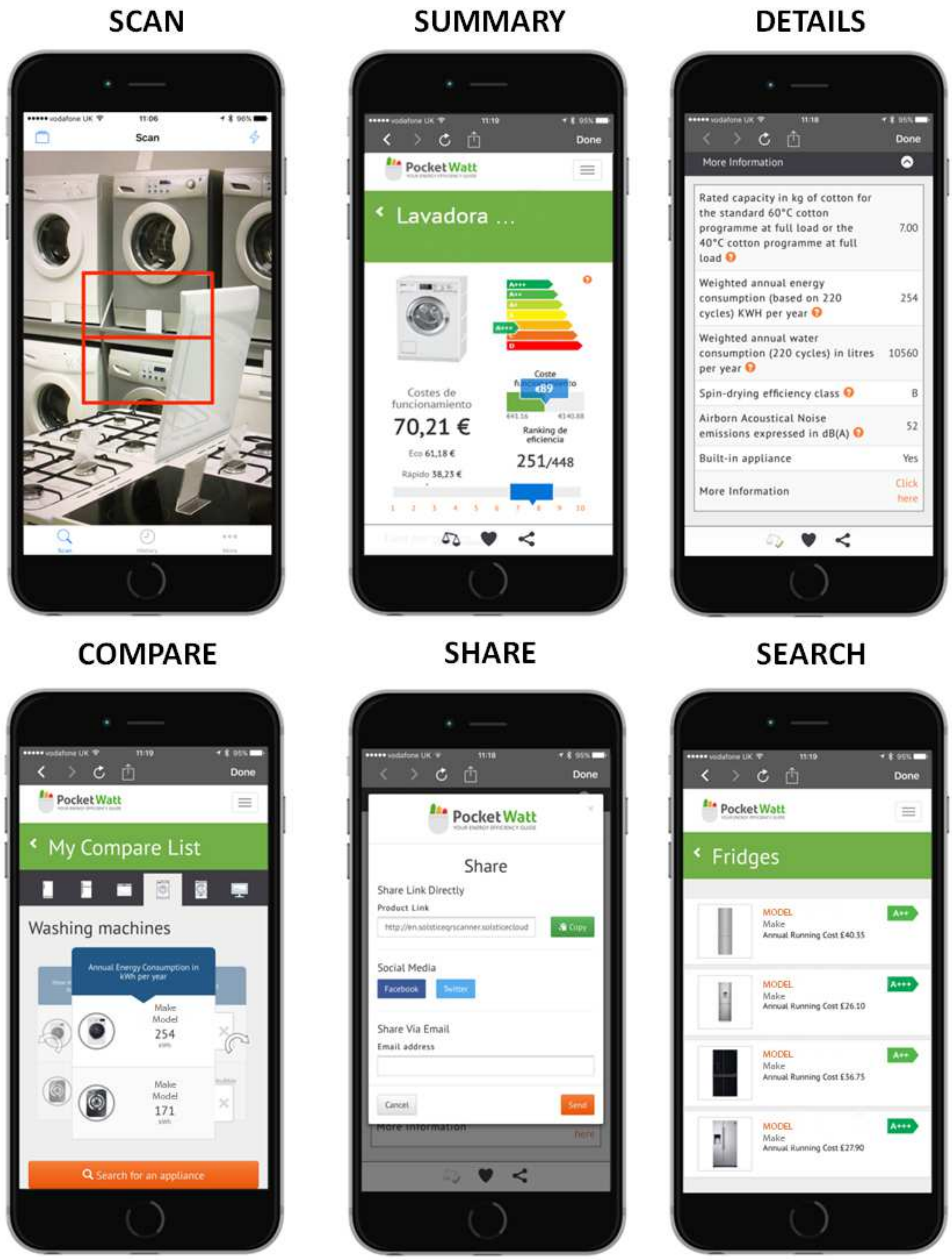

Figure 2. Illustrations for the in-store experience with *PocketWatt*.

For online retail the embedded Java applet provides access to the same functionality and information as the in-store experience, accessed via clicking on a *PocketWatt* smart link displayed on the retailer website alongside product details. A 'pop-up' modal window then presents all information and functionality to the consumer. The following images show an example retail page with embedded *PocketWatt* logo and *PocketWatt* window displayed.

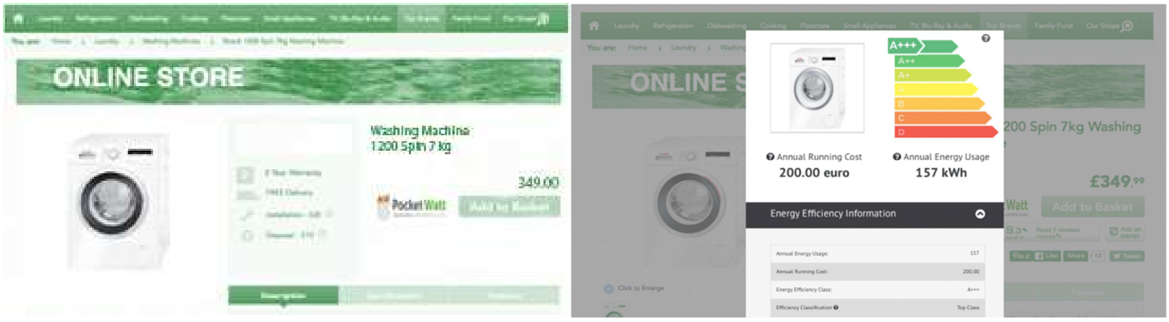

Figure 3. Possible implementation of *PocketWatt* into an online retail store.

Consumer involvement during *PocketWatt* development

In this chapter we report on an empirical study which gathered consumer feedback on an earlier version of *PocketWatt* tool. A detailed report on this consumer study has been published as well [12].

Research question and methods

To assemble consumer feedback a qualitative approach was chosen, more specifically structured group discussions were conducted in two of the participating countries, Germany and Spain. A workshop approach is especially suitable if the subject of interest is new, as in this case, because the group process supports participants in forming an opinion and giving ideas to each other [13] [14]. Another advantage is that the researchers also have the possibility to react flexibly to feedback and, e.g. expand explanations if issues are not well understood. It is important to note that this approach has its strength in collecting broad and informative feedback but its weaknesses in quantitative terms and representativeness, i.e. it is not possible to derive shares of potential tool users or non-users etc.

Procedure and analysis

The main aim of the workshops was to receive feedback and recommendations from the participants about the draft (alpha) version of the *PocketWatt* tool. This was done by combining questionnaires with group discussions. The questionnaire had the goal of ensuring that feedback from every participant was collected, while the group discussions served as an open format in which participants could openly exchange and develop views by interacting with each other. The following figure gives an overview of the procedure.

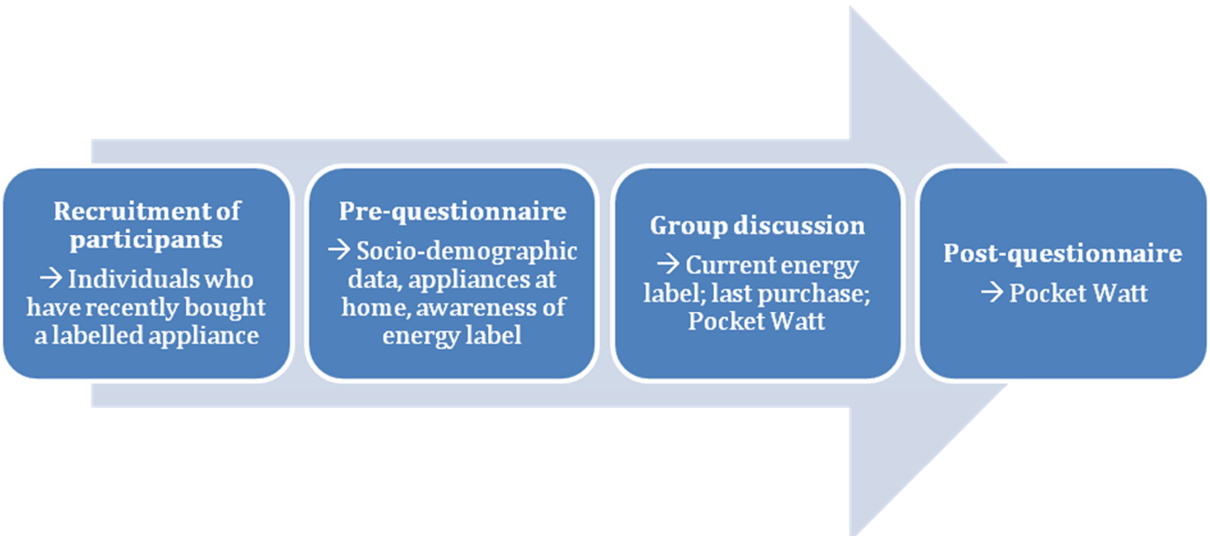

Figure 3. Procedure for empirical study.

The German workshop took place in July 2016, the Spanish in September 2016; the workshops lasted 2.5-3.5 hours. The group discussions were recorded and verbally transcribed afterwards. The transcripts were analysed using content analysis software. The qualitative data were coded with the software ATLAS.ti. Some of the codes were pre-determined, i.e. derived from the topics in the discussion guideline. However, new codes arising from the data were also developed [15] [16].

Sample

Choosing the appropriate target group is a major concern of qualitative research. In our case, we were interested in how consumers deal with the issue of energy efficiency when purchasing an appliance, and how the *PocketWatt* tool can support them in taking energy efficiency into account when making such choices. Therefore, the target group for the consumer workshop should comprise preferably individuals who have recently purchased one or more of the relevant appliances. It is assumed that the process of decision making is more salient to them so they are able to give more valid feedback. Besides this criterion, another aim was to recruit a heterogeneous group of participants. For the German group, finding suitable participants was outsourced to a market research institute, which recruited participants using the screening questionnaires from their contact directory to ensure heterogeneity. In Spain, participants were identified by consumer organisations.

In total, 22 individuals participated in the two workshops (ten in Germany, twelve in Spain). Women accounted for half the participants in each group. Ages in the German group ranged from 29 to 63, and from 36 to 68 in the Spanish group. The majority of the German group had completed a professional training and only one person had a university degree, while in Spain all the participants had completed tertiary education, i.e. the level of education was higher in the Spanish group. Overall, the sample represented a broad range of professions, but also included some individuals who are not working. Several of the Spanish participants worked in fields related to energy and / or consumer issues. The sample of participants included a few people who live on their own as well as some families. Overall, the distributions regarding different characteristics indicate that a heterogeneous sample has been compiled. Participants also provided information about what kinds of appliance they have. While all have a fridge and/or freezer, a TV and a washing machine, there is some variation for other appliances; on average, seven of the nine appliances listed were present. From the German participants all had recently bought one or more appliances (range 1-6 months, mean 2.7 months ago). In Spain, eight of the twelve participants had bought an appliance about one year ago and four of them more than one year ago.

Results of the consumer workshops

This chapter presents the workshop results on awareness, knowledge and evaluation of the energy label as well as feedback on PocketWatt. While presenting the findings it is also pointed out in how far the consumer feedback led to adaptations in the tool.

Awareness, knowledge and evaluation of current energy label

The questionnaire handed out before the group discussion suggested a high level of knowledge about the European energy label – all but one participant from Germany stated they had seen the label before. This was confirmed in the group discussion. Almost all the consumers – in Germany and Spain – are aware of the energy label and have seen it several times before, mostly while shopping

After showing two example energy labels it turned out that while the main messages about the energy efficiency class is well understood, several details about the label are less clear, e.g. several participants wondered about the meaning of the decibel value and the symbols for load capacity on the label for washing machines or the meaning of “kWh/annum”. Nevertheless, the majority of participants regarded the energy label as useful but demanded more information e.g. about the meaning of the energy efficiency classes. Thus, discussions around the energy label replicated earlier findings from the literature as summarized in the introductory section of this paper.

Evaluation of *PocketWatt*

This initial discussion about the current energy label was followed by a discussion around the draft version of the *PocketWatt* tool which was introduced step by step.

Accessing the tool and initial product page

The proposed digital tool is intended to be accessed using a QR-code at a retail store or an internet link. Participants were asked about their relevant habits. It turns out that, with a few exceptions, most own a smartphone, but only a few of them have installed a QR-code reader *and* regularly use it. This confirmed the discussion within the *Digi-Label* project team that the implementation of a QR-code reader into the tool is crucial to avoid an unnecessary barrier for users.

Especially the Spanish and some of the German participants liked the easy access via the QR-code while shopping. These participants suggested placing the *PocketWatt* symbol next to the product information or next to the energy label. Several participants also appreciated the idea of scanning the products in the shop and using this as a source of information at the point of sale:

> *German participant: 'In this case it can even be helpful, for example, my iPhone is broken, I can go to a shop, access the tool, compare appliances with each other, then it tells me, this is the best one, ok, fine, I'll take it, I'll buy it. Thus, it can be advantageous.'*

However, a few German participants were not enthusiastic about studying the information provided on the smartphone screen as they consider it too small to do so. Others were reluctant as they do not want to spend that much time in shops. These participants preferred to access the tool at home via a website prior to the purchase – a possibility that will be available as well.

In addition, several participants from Germany and Spain proposed retailers should provide access to *PocketWatt*, e.g. by providing small screens in stores where consumers can access the tool. This idea will be taken to the discussions with retailers to check feasibility.

If users scan the QR-code in a shop they will see information on the energy efficiency of a specific appliance. A screen shot was discussed in the groups. The majority of the participants in Germany and Spain considered the information on the annual running costs to be especially useful – a piece of information that is not included in the current energy label. Several consumers said it would be good to customize them to individual household sizes and/or usage patterns, which has now been implemented in the recent version of the *PocketWatt* tool.

Additional features of the PocketWatt tool

The tool can add products to a *comparison list* and then rate them simultaneously. The use case behind this is that consumers scan, e.g. all the washing machines they are interested in, and then compare models on relevant features. When presented with two appliances in the comparison list during the group discussion, the participants wondered about the differences in annual energy consumption and annual running costs within the same energy efficiency class.[24] They wanted more information on how the annual running costs are calculated. They proposed to include this behind the question mark which offers a possibility to access additional information. In general, the comparison list was seen as useful by both the German and Spanish groups. This function makes it possible to compare appliances.

> *German participant: 'The compare list, this is actually crucial for me, because I can compare; I have for example two appliances, this [make A] and [make B]. The [make A] costs 800 euros, the [make B] costs 1,000 euros.'*

The participants suggested including a sorting function, for example with regard to the running costs of the appliances. They also suggested including pictures of the appliances in the compare list, so that it is easier to recognize them. The model name did not seem to be sufficient and not really helpful, thus, this has been implemented in the recent version.

However, many participants also stated that there should not be too much information in the comparison list. The idea behind it is that consumers can process the information at a glance. Thus, they opted to not include mandatory pictures but only when clicking on the appliance name.

In the Spanish group, some considered the information about possible energy savings more important than the information on energy costs. Potential savings are believed to be more appealing to consumers than costs.

[24] An example of different freezers in the 'my compare' list was presented to the group. In this example, the two freezers with the energy efficiency class A+++ showed differences with regard to the annual energy consumption (156 and 132 kWh) and the annual running costs (43.68 and 36.96 euro).

Spanish participant: 'It is important to focus on the savings and not on the cost to promote the purchase of energy efficient appliances.'

Other participants suggested including information about the payback time. However, as this depends strongly on usage patterns and local electricity prices the project consortium decided to not include this at this stage.

To make *PocketWatt* suitable for a broad range of shopping situations it also allows its users to manually search for products or to browse through product categories, e.g. washing machines. It includes several filter functions to limit search results. The participants in the consumer workshops rated this feature as useful. They appreciated that it allows appliances to be ranked with regard to certain product characteristics. For the German participants, the product search function is useful prior to visiting shops to make a first selection of appliances. For example, appliances can be compared with regard to household size, volume and size of appliance. The participants liked the filter function as part of the product search. The filter option is useful for them to become aware of all the potential different characteristics of an appliance that might be important for the individual household. The German consumers especially opted for filters with regard to household size, volume and size of appliance:

German participant: 'Exactly, to choose a two-person household as the reference and find out what the best appliances are here. There are also different volumes; there are slim washing machines, there are big washing machines. If I live in a two-person-household, I do not really need [...] an industrial washing machine.'

Others suggested also including the brand, the date of its market introduction, the purchase price and differences in purchase prices at different retailers. However, as prices are changing quickly and wrong numbers would hamper trust into the tool, it was agreed that customers will have the possibility to enter the price themselves, but that it will not be provided by the tool.

The German participants wanted a sorting function as well: The user should be able to sort the results of the product search according to specific aspects. For some participants, it would be sufficient to have a sorting function with regard to running costs, energy consumption and energy efficiency class. Others also want to be able to sort the results by purchase price.

In sum, the participants visualized the product search supporting purchasing decisions in a quick and easy manner:

German participant: 'Exactly, bing, bing, bing, bing, what do I want and then it tells me, okay, buy this and this and this. Fine.'

The participants were asked what they thought about the possibility to give feedback in the tool – on the appliances or the tool itself. Giving feedback with regard to the appliances was not considered necessary by the German group. Commonly cited reasons were that consumer feedback on appliances can be found elsewhere, that this is often very subjective and that integrating this in the tool would be too extensive to use comfortably on the smartphone screen. Others evaluated the option to give feedback as useful, provided that it is objective and there were no requests that annoy users. The Spanish group shared this opinion.

Feedback with regard to the tool itself was considered not necessary by some participants, because they are not interested in giving feedback and find the invitations of certain websites to give feedback annoying. Others evaluated this option as useful, but emphasized that it should be voluntary.

The possibility to save and download the results of the product search or the compare list, to print them and to send them via email to users was assessed positively. This could be especially useful if there is poor internet connection in the shops – with this option the results are available offline:

Spanish participant: 'I think it would be very useful to download the information in the smartphone.'

It was discussed whether the tool should also propose highly efficient products to consumers, e.g. point out the most efficient model if someone searches for a washing machine. However, the German group did not like the idea of including this. They perceived this as annoying and like an advertisement.

Further information required

Some participants agreed that energy efficiency has only minor relevance for the purchase decision. Consequently, it should not be the only information in *PocketWatt*:

> *German participant: '[…] energy efficiency is one criterion amongst maybe ten which I have with regard to a product. Thus, I think I wouldn't do it (access and use the tool) for the energy label alone. To compare different appliances, I would like to have the main functions which are important for me, like for example the installation dimensions of a refrigerator, how much storage volume I have or for a TV, the size.'*

The majority of German and Spanish participants proposed including the size and – where applicable – the volume and weight of the appliance. These additional product details should be selected depending on the type of appliance. Some asked for the inclusion of other product characteristics, e.g. specific washing programs for washing machines. One participant suggested including product ratings of consumers. Others suggested including the design or different variations of the appliance. They want the *PocketWatt* tool to compare different appliances with regard to all or the most important characteristics. One possible solution to this could be the inclusion of a link to dedicated websites with product comparisons.

Several participants in both countries asked for the purchase price of the appliance to be included, because they consider it very important for the purchase decision. Because prices vary at different retailers, some Spanish participants suggested consumers could add the purchase price themselves.

> *Spanish participant: 'About the purchase price, maybe the app could include a "favourite section" where the consumer could include the price.'*

In the Spanish group, some suggested inserting information on the efficient use of an appliance. In general, many participants of the Spanish group thought that the tool should be kept simple so that consumers understand it better.

Overall evaluation and behavioural intentions

In the German group, several participants evaluated *PocketWatt* as a useful tool for comparing the most important characteristics of appliances. The tool can give them an initial impression of the range of products available in a certain category and provide some orientation. However, *PocketWatt* is not considered as providing real support with regard to the purchasing decision, because it cannot provide the information on all the product's characteristics (e.g. specific washing programs) like dedicated product comparison platforms:

> *German participant: 'For me this is no price- or product comparison platform like there are in the internet, e.g. "Idealo", where I can say, the appliance has this function, this function, this function, this function. I think the tool is just not able to provide this. But I find it really good to compare the key facts, because it does so simply.'*

Consequently, the tool was evaluated as not essential, but as "nice to have" by the German group. Thus, those who do not consider energy efficiency a decisive criterion in the purchase decision did not evaluate the tool as useful. Some stated that the tool is not needed, because all the information it contains can be found elsewhere, e.g. in the internet. Others prefer to seek advice from sales staff instead of using the tool. The Spanish participants were more positive about the tool and evaluated it as useful, e.g. because it provides additional information to the energy label. Whereas some assessed the tool as useful for all kinds of appliances, others perceived it as more useful for white appliances than for brown ones.

With regard to the features of *PocketWatt*, several German participants suggested keeping it simple, i.e. it should focus on the information on energy efficiency and not attempt to give recommendations for appliance purchases.

Some German and some Spanish participants appreciated that the tool provides immediate and up-to-date information on appliances – this is especially important with regard to the rapid development of technologies.

Spanish participant: 'I think that this app provides very immediate information.'

Several participants from both countries said that the tool needs to be trustworthy. If it were provided by manufacturers, it would not be trustworthy. Providers considered trustworthy include research institutions, government ministries or consumer organizations like in the *Digi-Label* consortium. Some said the providers of *PocketWatt* should collect the data for the tool themselves to ensure trustworthiness, others considered this too time-consuming. Related to this is the importance of the completeness of the database which was emphasized as crucial by the participants.

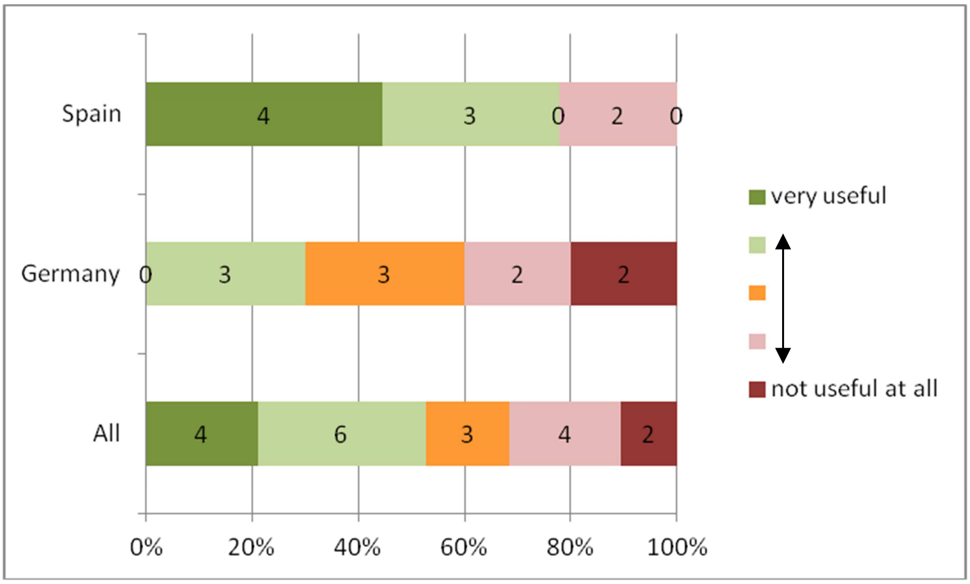

Figure 4. Overall evaluation of the *PocketWatt* tool.

The questionnaire handed out after the group discussion also asked for an overall evaluation of the usefulness of the information provided by the *PocketWatt* tool (Figure 4). It turns out that the feedback from the participants ranges from very useful to not useful at all, with around half of all participants rating the tool positively. A closer look shows that the German group is much more critical – a difference that is also statistically significant (using the Mann-Whitney U test[25]).

Furthermore, the majority of participants expected that using the *PocketWatt* tool would influence their purchase decision (Figure 5). The most likely influence concerns paying more attention to energy issues, but a significant group states the *PocketWatt*'s influence would probably depend on the respective appliance (e.g. TV vs. washing machine).

[25] The Mann–Whitney U test is applied to test whether the distribution of one variable is stochastically greater than another; in our case, we wanted to find out whether the ratings of the Spanish participants are different from those of the Germans, or whether the observed difference is due to chance. The Mann–Whitney U test is suitable for non-parametric variables, i.e. where ratings signify a ranked order.

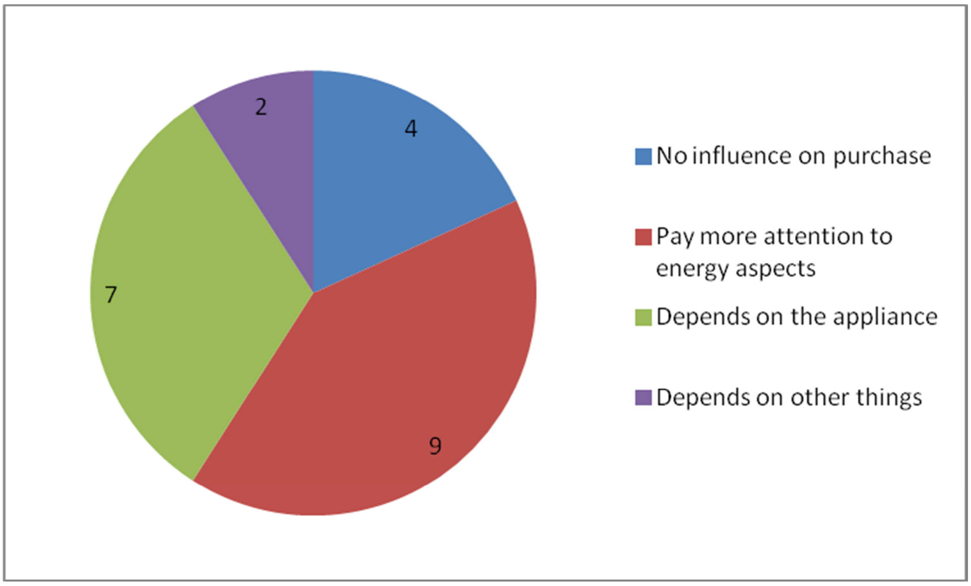

Figure 5: Influence of *PocketWatt* tool on purchase decision.

Responses on behavioural intention also paint a differentiated picture: In the German group, the majority (8 out of 10) said they do not think they will use it, while the reverse was true in Spain, where all but one participant said they were likely to use it. This difference is also significant in a statistical sense (Mann-Whitney-U-test).

This pattern had already become apparent during the group discussion when many German participants said they had no intention of using the *PocketWatt* tool. One reason given is the expected complexity of using the tool, the technical focus and the fact that it provides too much information. Some expected the tool to be too difficult to use and instead prefer personal advice in the store:

> *German participant: 'This is way too technical for me, maybe because I am old already, not part of the younger generation. I wouldn't enjoy it. I am someone who looks at brochures now and then and then just strolls through shops and gets advice from nice people, so that I can see right away whether I like it or not.'*

Subsequently, participants thinking along these lines suggested that the tool might be interesting for younger people:

> *German participant: 'I think, all this searching etc. – this was, I think, mentioned before – a problem of generations. I wouldn't do it, but when I see how my granddaughter or in general my grandchildren handle it, for them this is a piece of cake.'*

It is assumed that younger people will learn easily how to handle the tool, because they are more used to information and communication technologies. Furthermore, they might prefer online shopping and searching for product information online.

Others believed that using the tool will take a lot of time – in many cases purchase decisions are taken very quickly, especially when white appliances break down. One participant explained that as energy efficiency is not such a relevant purchase criterion for these products – the tool would only be used if it provided information on all the relevant product characteristics similar to product comparison platforms. Moreover, the information about energy efficiency is already included in the energy label. Others argued that the information in *PocketWatt* could also be retrieved elsewhere on the internet and – contrary to what was stated earlier about interactive features - one participant stated that he would like consumer feedback on the products.

Others expressed an intention to use the tool as an additional source of information, e.g. in addition to advice from sales staff – on the condition that it is not provided by manufacturers:

> *German participant: 'I would use it as an additional source of information if I could be sure, well in quotation marks can be sure, that it is not supplied by a certain provider or controlled by advertising and that I really have reliable and trustworthy information […]'*

However, the tool cannot be used as the single source of information and purchase decisions cannot be entirely based on the information provided by the tool. Instead, it is seen as an additional information source. One participant stated intending to recommend the tool to friends and relatives.

In the Spanish group, all the participants were interested in the *PocketWatt* tool and satisfied with the information provided. Most of them say they would use the app once it is available and agreed that it would help them in their future selection of appliances.

> *Spanish participant: 'I can use it at home and I have more time to consider the purchase and to compare different appliances.'*

The questionnaire also asked those intending to use the tool when they thought they would access it (Figure 6). It turns out that more people expect to use it at home to get information than while shopping.

Accessing the *PocketWatt* tool via the QR-code was nevertheless confirmed as the preferred access point (14 of 22 participants); some interest was also shown in accessing it directly via an internet link (8 of 22 participants).

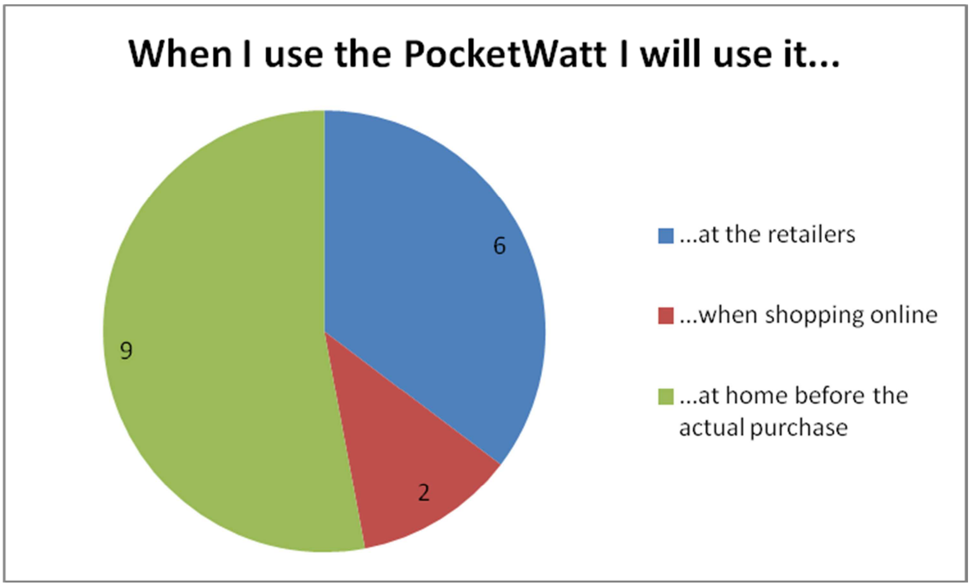

Figure 6: Behavioural intentions when and where to use the *PocketWatt*.

Discussion and outlook

The aim of the Digi-Label project is to provide support to consumers to choose the most energy efficient appliance according to their needs by reducing lack of information. This is motivated by the fact that while technological progress towards efficiency has increased, household consumption is not decreasing. The existing energy efficiency label is already aiming at the same problem, however, studies have repeatedly pointed out that consumers feel that the current label does not completely fulfil their needs. Furthermore a more innovative and interactive approach seems to be more suitable for the digital age.

Thus, the project team has developed and started to realise *PocketWatt* as an innovative solution that is adaptive to consumer needs and accessible 'everywhere' – in store during shopping but also at home when gathering information or shopping online. An analysis of consumer evaluations gathered in two consumer workshops revealed that consumers appreciated many features of the proposed tool, e.g. the possibility to compare relevant attributes like running costs for several appliances; they also provided further ideas for refinement, e.g. for customising the information, of which many were implemented. The flexibility of easily accessing the tool while shopping was confirmed as valuable.

Thus, while several issues are identified that can be tackled by a further refinement of the tool two major challenges remain: *PocketWatt* is only able to unfold its potential to support an increase in energy efficient choices if (1) it is implemented by retailers in their stores and if (2) consumers use it and transfer what they learn from it to the appliance choice.

Currently, in early 2017, a pilot phase with stores in Spain and UK is under preparation. The first meetings and activities with retailers did took place by the end of 2016. The Spanish Retailers Association did engage DigiLabel and invited all their members in a Meeting of Board of Directors. Three companies of this Association and one independent retailer are participating in the pilot phase. In the UK two retailers of a big appliance retailer company are participating. These five will be the first to test PocketWatt in store, use ad benefit; Escan (Spanish partners) did create some materials - posters and leaflet for retailers that are used in the pilot shops; EST (UK) with other partners created leaflets for consumers. The roll out phase of other retailers from Czech Republic, Italy and Germany that will use the Digital tool is foreseen for summer 2017

During the pilot phase the evaluation process will also be ongoing, including the collection of data on actual changes in purchasing behaviour but also interviews with shop employees and a survey with customers to collect feedback on the tool. The learnings from this will be used for a further refinement of the tool itself but also of its implementation in the shops. In a later project phase *PocketWatt* will be trialled at a larger scale in more shops and countries.

Nevertheless, as known from earlier research, but also confirmed in our study, not all consumers are interested in energy issues and willing to take them into account. And also for those that are interested the energy efficiency of a product is usually only one attribute amongst others [17]. On the one hand, these findings have to be accepted to some degree which means that expectations what information based measure are able to achieve have to be reduced to a realistic level. From our participants, around half of the sample stated they intend to use the tool and a majority expected that using it would influence their purchase decision. As the study does not draw on a representative sample it does not make sense to use these numbers for estimating interest in the tool in larger populations, but it confirms that a relevant share of consumers might be interested in using it and applying the knowledge while it obviously will not involve everybody. On the other hand this points to the necessity that creating the tool is not an end in itself but it will be necessary to accompany the introduction of the tool by additional measures which e.g. direct consumer attention to it or motivate to use it. Retailers and their staff may play an important role in this.

Finally, lack of information is of course not the only barrier to buying energy efficient appliances and as outlined before increases in consumption are not necessarily due to a lack of efficient appliances in households but to an increase in sizes and features of appliances as well as increasing use as well as rebound effects. Nevertheless, the informational barrier is a relevant one in the purchase process and the success of the energy label in terms of being well known points out that there is a gap to be filled. A report in 2012 assessed current levels of consumer usage of QR codes in Europe and the U.S. around 15% of consumers.[26] Based on the impact assessment with regard to labelling of energy-related products, we found an estimation that around every second consumer takes the energy label information into account.[27] Thus, our target group is around a maximum of 7.5% of consumers who might be influenced by the *PocketWatt* tool. During the rollout phase the project team will closely monitor the actual impact of the tool also in energy terms by closely monitoring shifts in product sales following the implementation of the tool and also collect consumer experiences.

[26] http://pressroom.pitneybowes.co.uk/download/1917/
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10 APPLIANCES

The quest for Energy Efficiency in Ceiling Fans for a mass market

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Abstract

Ceiling fans are widely used in tropical countries. An overwhelming majority of these fans use inefficient single-phase induction motors. In India alone there are more than 350 million fans which consume 95000 Megawatt hours every day and pose a demand of 13650 MW to the grid. A cost-effective innovation enhancing energy efficiency in ceiling fans targeting mass markets would be welcome.

This paper puts forward the technology transformations needed to improve the efficiency of the ceiling fan and the issues faced therein.

The first of these transformations is the use of sensor-less Brushless Direct Current (BLDC) motors, a type of permanent magnet synchronous motors, in place of induction motors. This can enhance the efficiency of the fans by at least a factor of two. However, BLDC motors are electronically commutated and cause current harmonics in the supply grid which compromises power quality. The paper outlines the impact of the harmonics and the measures to minimise them. Two configurations of the motor and electronics with power factor correction, a low voltage motor configuration and a high voltage motor configuration, are compared with respect to safety, cost and efficiency.

To further increase the fan efficiency aerodynamic blades can be used. Blades with optimum aerofoil shape are made of industrial plastics. These blades incur expensive tooling and are expensive to manufacture. This paper looks at a sub-optimal design which can still enhance fan efficiency by 12% to 13% and which costs less to make.

To conclude the paper looks at the possible use of alternate topologies and new power devices in the electronics to enhance the fan efficiency.

Introduction

Ceiling fans are used in very large numbers in countries with humid climates in the tropical zone. In India alone according to an estimate in 2010 about 350 million fans were in use (Ref. [1]). Almost all these fans use single phase induction motors and range in size (measured in blade sweep) from 900mm to 1400mm (36 inches to 56 inches) (Ref. [1], [5]).

Estimating in a very conservative way, the number of fans in India can now be put at 400 million (December 2016). The power consumption of these fans is around 75W when run at top speed (Ref. [5]) and is around 39W when run at a medium speed (3^{rd} speed in a 5-speed setting) (Ref. [1]). When run at medium speed this amounts to a demand of 15600 MW. There is a vast scope for saving energy here by using more energy efficient ceiling fans. According to Ref. [2], if the energy consumption for all fans in the world could be reduced by 50%, the savings per year could be 70 terra-watt hours per year by 2020 AD.

Highly efficient fans have been available in the developed markets such as USA for a long time (Ref. [3], [4], [7]). However, these fans have wider sweep and they are expensive for mass markets in the developing countries as they cost several hundred dollars.

Fans which consume less power have been available in India (Ref. [6]) but they deliver about 10% less air as compared to the higher power fans and hence are not very popular.

This paper looks at the technology transformations which can be made to improve the efficiency by at least 50% while delivering the same amount of air, and also looks at the issues faced in the quest for higher efficiency. Most of the data presented is collected from the work done in the author's organisation while developing more efficient ceiling fans. Data of fans made by other companies is also used in some comparisons.

Using Electronically Commutated Brushless DC motor to enhance the efficiency

The first of the changes which can be done is the replacement of the inefficient single-phase induction motor with an efficient 3-phase permanent magnet ac motor (also known as BLDC motors). This leads to more than doubling of the efficiency at the top speed and even higher gains at the lower speeds as shown in the table below.

Table 1 A comparison of power consumption of ceiling fans based on different motor technologies at various speeds (Ref. [8])

Speed	**Power consumption (W)**	
	Standard fan based on Single-phase Induction motor	**Fan based on PM BLDC motor**
Low	12	4
Medium	39	14
High	75	35

The most common use case for the fan is to run it at the medium speed. As can be seen even if 10% of the induction motor fans in India are replaced with the BLDC motor fans the demand can come down by 1000MW and there can be a saving of 10000MWh per day assuming the fans run for 10 hours a day.

BLDC motors are synchronous motors and hence are not self-starting. An electronic motor drive comprising of a power supply and an inverter is required to start and run these motors at variable speed. The addition of the motor drive electronics is an added cost.

Modern motor drives are made of switching circuits. These drives draw a non-sinusoidal current from the mains supply. In any electrical appliance, the useful work is done by the fundamental frequency current component drawn by the appliance from the mains supply i.e. the 50/60 Hz component. For linear loads i.e. loads in which the load current is not distorted, this is the only current component and hence there are no higher frequency current components. However, in case of nonlinear loads such as switched mode power supplies, the current drawn from the ac supply is not a pure sinusoid but is distorted. Due to this distortion, higher frequency components called harmonics are present in the input current. These harmonics do not contribute to any useful work. On the contrary, they cause losses in the distribution network and increase the volt-ampere demand from the electric supply.

The distortion of the load current due to the harmonics is measured by a number which is called Total Harmonic Distortion or THD in short. THD is defined as the ratio of the distortion component of the current to the fundamental frequency component (Ref. [9]). In terms of root-mean square (rms) values

$$I_{dis} = (I^2 - I_1^2)^{1/2}$$

$$\% \text{ THD} = 100 \times (I_{dis} / I)$$

$$\% \text{ THD} = 100 \times ((I^2 - I_1^2)^{1/2} / I)$$

Where I is the rms value of load current

I_1 is the rms value of the fundamental frequency component of the load current

Obviously the THD % should be as low as possible for a given electrical system.

Table 2 gives the THD % measured for various common electronic loads found in an office. The measurements have been taken using a Fluke 43B power analyser (Ref. [10]).

Table 2 Power, Power factor and THD values for common electronic loads

Load	Active power (W)	Power factor	Total demand (VA)	Current (A)	Current THD %	THD amps for 500 loads (A)
20W CFL HPF	21.0	0.96	21.9	0.096	25.0	12.0
35W tube light with electronic ballast	32.5	0.95	34.2	0.15	29.0	21.75
Laptop adapter	25.0	0.46	60.0	0.25	88.0	110.0
Assembled PC SMPS	48.0	0.61	78.7	0.35	78.0	136.5
Monitor 14-inch model	52.0	0.65	80.0	0.35	75.0	131.3

Table 3 gives the power factor and THD values for BLDC fans with power factor correction circuit (Ref. [10]). As can be seen from the above table a 48-inch BLDC fan (Super X1) running at 4th speed will cause distortion somewhat less than a 20W CFL with a good power factor. A 56-inch fan (Super V1) running at top speed will still cause less distortion than a 35W tube light with electronic ballast.

Tables 2 and 3 compare the power profiles of commonly used electronic devices with and without built-in power factor correction. As can be seen from the data switching electronic loads with built-in power factor correction produce much less current THD as compared to the loads without it.

Table 3 Power, Power factor and THD values for BLDC fans with power factor correction

Load	Active power (W)	Power factor	Total demand (VA)	Current (A)	Current THD %	THD amps for 500 loads (A)
Super X1 at 3rd speed	13.3	0.88	15.1	0.066	19.1	6.3
Super V1 at 3rd speed	14.6	0.88	16.6	0.069	19.5	6.7
Super X1 at 4th speed	21.7	0.94	23.1	0.103	21.7	11.1
Super V1 at 4th speed	22.8	0.94	24.3	0.103	21.2	10.9
Super X1 at 5th speed	34.0	0.96	35.4	0.158	21.7	17.1
Super V1 at 5th speed	36.2	0.96	37.7	0.166	23.4	19.4

From the above data and arguments, it is evident that BLDC fans have to have power factor correction built in in order to avoid polluting the electrical supply grid. However, for a fan targeted at a mass market it is imperative that the cost of the electronics including the motor drive, power supply, and the power factor corrector be kept as low as possible.

There are two basic topologies for the motor drive with power factor correction. The block diagrams for the two topologies are given below in Fig 1 and Fig 2. Based on the DC bus voltage magnitude one can be termed as a high voltage drive and the other a low voltage drive. Typically, the bus voltage is 24V in the low voltage drive and 380V in the high voltage drive.

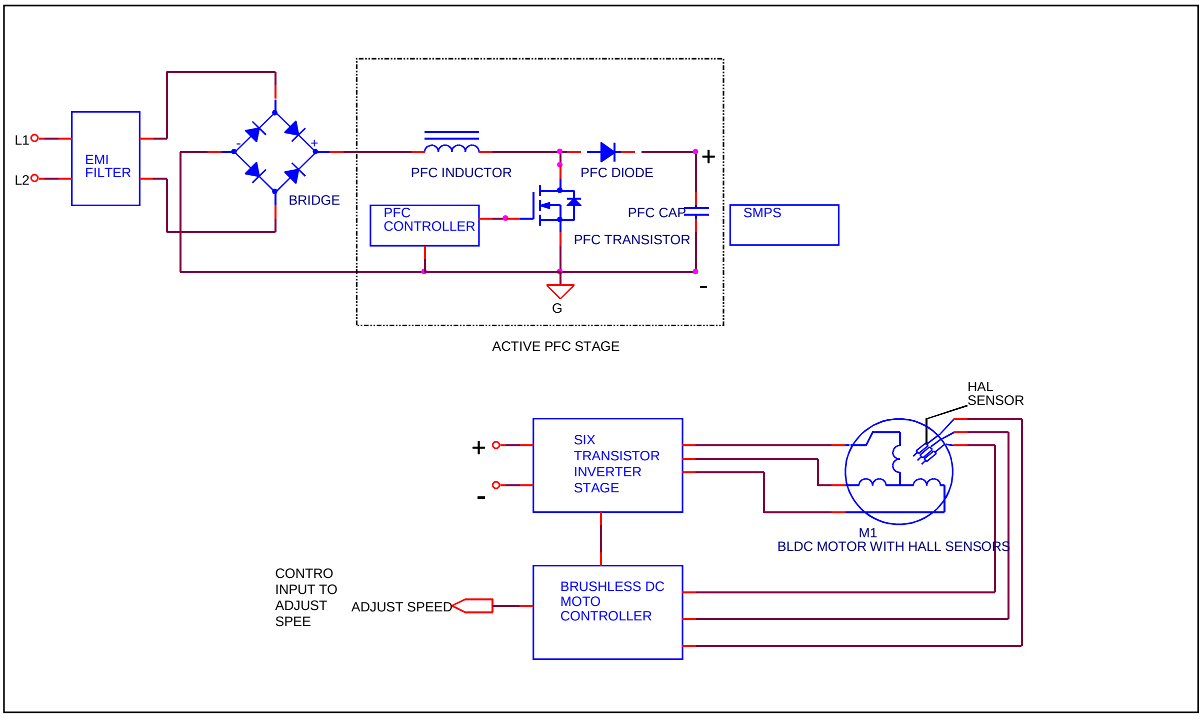

Fig 1 High voltage circuit block diagram for the BLDC motor drive with power factor

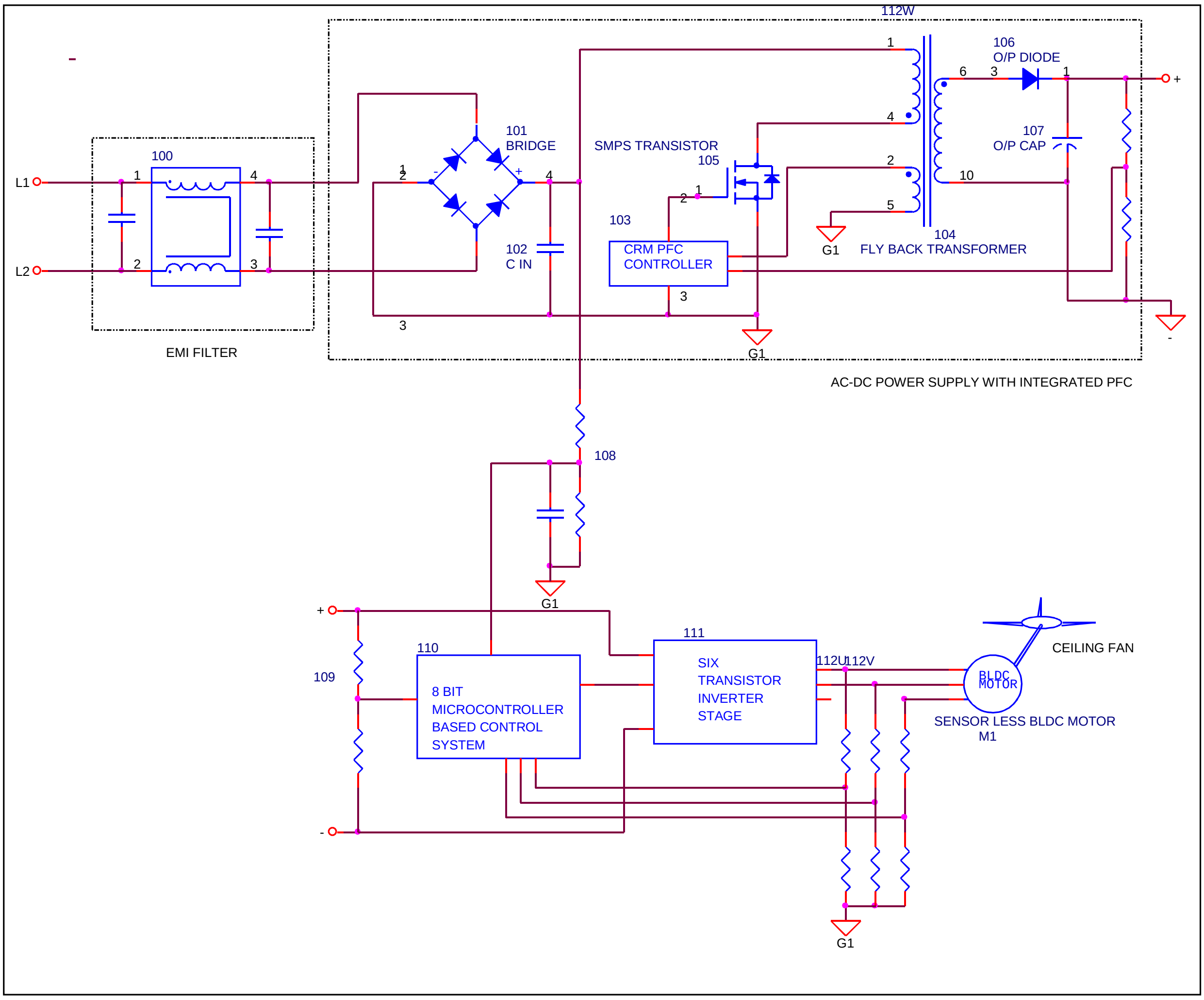

Fig 2 Low voltage circuit block diagram for the BLDC motor drive with power factor

Table 4 below has a comparison of the typical costs of the power components of the two drives.

Table 4 Comparison of the costs of power components of low voltage and high voltage drives

Low voltage drive		**High voltage drive**	
Component	**Unit cost in USD**[1]	**Component**	**Unit cost in USD**[1]
SMPS Transformer	0.3	PFC Inductor	0.3
Transition mode PFC Controller	0.3	Transition mode PFC Controller	0.3
SMPS MOSFET; 800V, 3A	0.5	PFC MOSFET; 650V, 3A	0.25
Output diode; 200V, 6A, ultrafast rectifier	0.22	PFC diode; 600V, 2A, ultrafast rectifier	0.12
Bulk capacitor; 2200uF, 35V, 105°C	0.36	Bulk capacitor; 47uF, 450V, 105°C	1.03
Low voltage MOSFET inverter	1.1	High voltage IGBT inverter	2.5
24V - 5V linear regulator	0.15	AC-DC auxiliary SMPS (transformer + SMPS IC)	0.57
Sum	2.93	Sum	5.07

All costs are unit costs taken www.mouser.com or www.digikey.com and for at least 1000 numbers order quantity

It can be seen that the power stage for the high voltage drive is 70% more expensive as compared to that of the low voltage drive.

The choice of circuit topology affects the motor costs too. Table 5 gives the weights of the various components of the low voltage motor and high voltage motor corresponding to the low voltage drive and high voltage drive respectively.

Table 5 Comparison of the material inputs of low voltage and high voltage motors

Description	**Low voltage motor**	**High voltage motor**	**Units**
Total weight of motor excluding drive	2.105	3.44	kg
Stator details			
Number of slots	18	12	
Shaft length	120	148	mm
Stator weight	1.03	1.862	kg
Total copper weight	0.2064	0.31	kg
Wire gauge	22 SWG	34 SWG	
Rotor details			
Number of poles	16	14	
Back iron weight	0.152	0.337	kg
Magnet dimensions	25 x 22 x 7	28 x 26.55 x 8	mm
Total magnet weight	0.2879	0.4	kg

As can be deduced from table 5, the high voltage motor employs 80% more in stator metal, 50% more copper, 120% more back iron, 38% more magnet. Thus, on the whole the high voltage configuration (motor + drive) would cost at least 50% more compared to the low voltage configuration.

Let us now compare the performance of the low voltage motor fan with that of the high voltage motor fan.

Table 6 Comparison of the power, air delivery, and service value of high voltage and low voltage fans

Fan type	Power (W)	Speed (RPM)	PF	AD (CMM) Single moving vane anemometer (1300170); 8 sample moving average method	Service Value (CMM/W)
High voltage	24.3	364	0.93	197	8.1
Low voltage	25.2	344	0.98	198	7.86

For comparing fans a figure of merit termed service value is used. This is defined as the air delivered in cubic metres per minute per watt of power consumption. Table 6 shows that the high voltage fan is about 3% better in terms of service value.

Leakage current is an important safety parameter when it comes to electrically powered appliances in the context of protection against electrical shock. The safety standard which applies to household appliances, IS 302-1:2008, states that the leakage current for a stationary class I motor driven appliance cannot exceed 3.5 milliamps (Ref. [11]).

Table 7 Leakage currents of high voltage fan and low voltage fan

Leakage current measured as per IS 302-1:2008, clause 13	
High voltage fan	Low voltage fan
6.8 milliamps	0.96 milliamps

The leakage current from high voltage fan is much higher than the mandated limit. This is due to the high dv/dt resulting from the fast switching of the high bus voltage as the leakage current from the motor is given by C * dv/dt where C is the parasitic capacitance between the motor windings and the motor body. The dv/dt is much lower in the low voltage configuration. To reduce the leakage current in the high voltage motor, the parasitic capacitance would have to be reduced and this would increase the cost of the motor further as the construction and materials would have to be changed. It is not apparent whether the leakage current can be brought within limits in a cost-effective way.

Even though the high voltage circuit block diagram shows hall sensors as a part of the motor, advances in BLDC motor control have made it possible to eliminate these sensors. This reduces the cost of the motor in both configurations and makes it more reliable.

Considering all the above it is concluded that the low voltage motor is more cost effective for a mass market fan.

Improving the efficiency further using aerodynamically better blades

Changing the motor technology from single phase induction motor to PM BLDC motor is the first and the most impactful step in improving the ceiling fan efficiency. The next step is to improve the fan blade design and thereby the fan's efficiency.

There is no step by step design methodology readily available for the design of ceiling fan blades. Ceiling fans fall into the broad class of open turbomachines akin to propellers and wind turbines (Ref. [20]). There has been a lot work done in Aerodynamics on the design of propeller blades ([Ref. [12],

[13], [14]). However, ceiling fan blades rotate at very low speeds as compared to the speeds in propellers and the design methodology cannot be applied without modifications.

A modified methodology has been invented and used by Danny Parker and his associates to design ceiling fan blades of very high efficiency (Ref. [16]). These have been commercialised as Gossamer wind fans (Ref. [7]). A fascinating account of the journey by which these designs were arrived at in given in the article in Ref. [15].

The aerodynamically efficient blades must have an aerofoil cross section suitable for the low speeds (Ref. [16]) and continually twisting blade angle in order to maintain an angle of attack such that optimum lift (for a ceiling fan this translates to thrust downwards) is generated (Ref. [17]). This entails the use of plastic blades. For longevity and stiffness industrial plastics have to be used. Such blades would cost at least twice more than aluminium blades. Also, the plastic moulds to produce the blades cost upwards of INR 4.4 million (roughly USD 63000). The blades are 100% more heavy than aluminium blades and hence cost more in usage of material. All these factors lead to less than satisfactory blade when targeting a cost sensitive mass market.

To make cost-effective blades our organisation decided to work on an aluminium blade of 1mm thickness that would have a width similar to that of the conventional aluminium blades used in various fans depicted in Ref. [5] and Ref. [8]. We started with a flat trapezoidal shaped blade which was 140mm wide near the hub (the edge near the motor) and 90mm wide near the tip to be used for a 48-inch fan. There is no particular reasoning for the widths other than that they are found in commonly used blades.

A tool consisting of two sections (Fig. 3 and Fig. 4) was made to form the flat blade into a blade with a continuously twisting angle. The blade twist angles, which were used to arrive at the coordinates for the forming tool, were calculated using the Betz condition (Ref. [12]) for uniform loading of the blade.

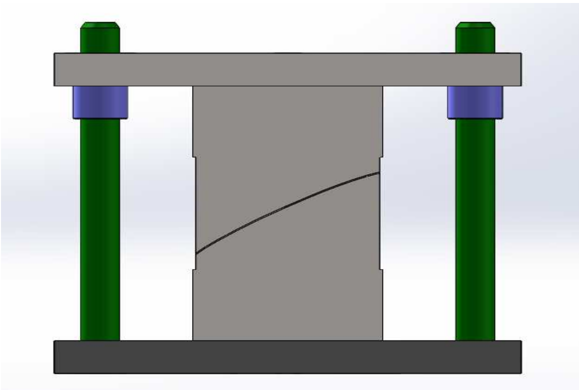

Fig. 3 Forming tool front view drawing (Ref. [18])

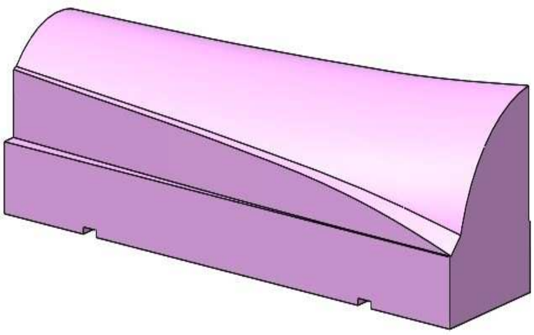

Fig. 4a Bottom section of forming tool

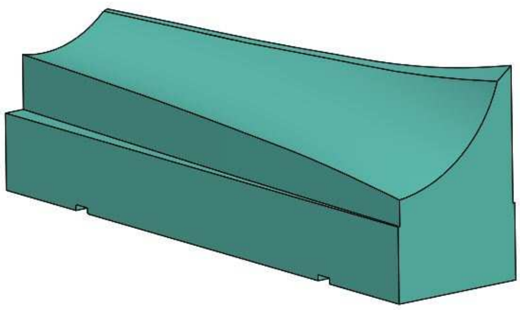

Fig. 4b Bottom section of forming tool (Ref. [18])

The Betz condition is given by the equation

$$r * \tan \Phi = \text{constant}$$

Where Φ is the blade section angle with horizontal (Ref. [12]). The tool was divided into six sections and the angles in the various sections of the tool are given in table 8 below.

Table 8 Twist angles in sections from hub to tip in the forming tool (Ref. [18])

Section	Radial distance from centre (inches)	Blade twist angle (degrees)
1 (Hub)	6	33
2	7	29.06
3	11	19.48
4	15	14.53
5	19	11.57
6 (Tip)	23	9.6

The tool went through six iterations. These iterations were primarily necessitated by the need to compensate for the spring back in the formed blade. The tool radii in different sections were changed by trial and error.

Nine blades were formed and three blades were further formed by hand tools to get angles close to that given in table 8. The air delivery was then measured and the result was 226 cmm with a power consumption of 34.5W. This yields a service value of 6.544. This is not very different from 218 cmm obtained at 34W from a regular blade fan with both the configurations employing the same low voltage BLDC motor.

Then another set of the three formed blades from iteration 6 were taken. The twist along the entire length was changed by placing an 8.5mm spacer under one of the two mounting screws of each blade. The air delivery measurement results were good: 256 cmm @ 33.5W yielding a service value of 7.633 cmm/W. The improvement in service value is more than 18% at the top speed as compared to that obtained with BLDC motor fans with relatively flat blades. We named the twisted blade as R1 blade.

The air delivery figure is important as more air delivered is always welcome in humid climates.

To compare with the BLDC fans with regular blades the fan with R1 blades was run at a lower speed matching the power consumption in an approximate way. The results are below in table 9.

The blade efficiencies of the regular (relatively flat) blades improve at lower speeds. Even then there is an improvement of more than 12% with the R1 blades. Thus, the R1 blades give the user the option of running at top speed and getting quite a lot of air with smallish 48 inch blades or run the fan at lower speeds consuming more than 10W less and getting the same air as a 35W fan.

We note that in comparison with the induction motor fan (table 1) and a fan with BLDC motor and R1 blades there is an improvement of 150% in terms of service value (standard fans have a typical service value of 3).

An added benefit of the new blades is that the fan runs at a much lower speed. The speed of the fan made with R1 blades is more than 100 rpm less as compared to that of fans made with regular (relatively flat) blades. This reduces the noise made by the blades as they cut through the air considerably. Cursory measurements made in office room show a reduction of 7-9 Dba in the noise level. More rigorous measurements have to be made.

Table 9 Comparison of the power, air delivery, and service value of high voltage and low voltage fans with regular blades and low voltage fans with R1 blades

Fan type	Power (W)	Speed (RPM)	PF	AD (CMM) Single moving vane anemometer (1300170); 8 sample moving average method	Service Value (CMM/W)
High voltage	24.3	364	0.93	197	8.1
Low voltage	25.2	344	0.98	198	7.86
Low voltage with R1 blades	24.0	229	0.98	212	8.83

The R1 blades weight is in the same range as other aluminium blades. The process cost of making the R1 blades is the same as that for making other aluminium blades. The tool costs are expected to be around 300,000 INR (4285 USD) which is about the same as for other aluminium blades. Taken as a whole the per piece cost of R1 blade is expected to be 120 INR (1.71 USD) which is about the same as that of the regular aluminium blades (INR 100 i.e. 1.43 USD). Thus, the improved energy efficiency comes at a marginally higher cost.

Summary and Conclusion

There is enormous scope for energy savings through the wide spread usage of energy efficient ceiling fans in mass markets of countries with tropical climates. This paper looked at some of the technological transformations taking place in this space.

The change having the maximal impact is that of replacing the single-phase induction motor with the Permanent Magnet BLDC motor. This can result in savings of more than 50% in energy consumed. Using PM BLDC motors requires switching electronics and power factor correction to be built in. Two motor configurations, a low voltage motor and a high voltage motor, are compared with respect to performance, cost, and safety factors. The low voltage motor is more cost-effective and has much less leakage current.

Further efficiency enhancement results from using aerodynamically designed blades. Optimally designed blades require true aerofoil cross sections and continually twisting blades. These have to use industrial plastics, expensive tools and cost more per piece as compared to regular aluminium blades found in mass markets. It has been found experimentally that twisted aluminium blades of 1mm thickness can yield 12-13% more savings as compared to aluminium blades used in common fans and the savings come at no extra cost in tooling or process or material. An added benefit of these blades is that the fan runs at a much lower speed resulting in a reduction in the noise produced by the fan. More measurements need to made to quantify the reduction in noise.

Now a look at what lies ahead in getting more out of the fan. We can get more savings in energy by enhancing the efficiency of the motor drive. Low voltage MOSFETs are continually improving their current conduction capability (the on resistance is reducing) while keeping the component costs the same. There are available new MOSFETs with half the on resistance (ex. DMC4040SSD) as compared to older MOSFETs used in our design. This can lead to a saving of more than 0.7W (2%).

A type of AC-DC power supply promising an efficiency of 90% or more as compared to 87% of the current AC-DC SMPS in the low voltage configuration is described in Ref. [19]. This has to be evaluated with the same considerations of cost, performance, and safety.

Fans with WIFI connectivity can be incorporated into a building energy management system offering good energy saving potential. However, this use case applies only in contexts where large number of fans are used. Equipping all fans with connectivity may not be wise as pointed out in Ref. [21].

Looking even further, availability of new cost-effective and light-weight materials can lead to even more efficient blades with optimal aerofoil cross-sections. This can lead to an increase of more than 40% more efficiency as compared to the BLDC fans with regular blades. However, as always in the context of targeting a mass market cost is the key.

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Fighting Food Waste and Saving Energy by improving Household Refrigeration

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Abstract

This paper discusses the main outcomes of a recent study on the possible contribution of household refrigeration appliances in combatting food waste.

The EU food system, from ‘farm to fork’ and beyond, takes up around 17-26% of the EU’s material, energy and water resources and causes 23-24% of greenhouse gas emissions.

Food waste at the end-use level, i.e. private households and food services, amounts to 84 Mt or 18% of annual food purchases. On aggregate, food waste is 25% of the organic and mixed waste fraction at end-use level. Of this, almost two-thirds or 11% of purchases is avoidable, i.e. caused by food spoilage because of bad planning.

Roughly two-thirds of food purchases, including most of the food that is eventually wasted, passes through the refrigerator. The study revealed that 85% of household refrigerators feature only one compartment and basically one storage temperature for non-frozen foodstuffs (4°C), which is suboptimal for a large share of foodstuffs, i.e. too warm or too cold. By creating multiple non-frozen food compartments, including chillers (-1°C to +2°C) and cellar (+8-14°C), the average shelf life of perishable foodstuffs can be increased safely by on average a factor three or more.

Suitable metrics in policy measures for setting minimum requirements and energy labelling of refrigerators could promote, or at least not hinder, this improved practice. On the longer term, a thorough examination of the current practice on setting expiry dates could make a valuable contribution.

Keywords: food waste, refrigeration, households, food storage conditions, food spoilage, sustainability, circular economy, resource efficiency, Ecodesign, European Union, EU

Introduction

Food waste is a recognised problem that has gained political and social importance in recent years. The phenomenon occurs all along the food chain, from 'farm to fork' and many studies have stated that, at global level, around one third of the food produced for human consumption is wasted or lost.

As such, fighting food waste is an important part of the European Union's Circular Economy package [1] and, according to the European Court of Auditors [2], should be integrated in existing policies where appropriate.

The EU policy framework of Ecodesign and Energy Labelling is no exception, especially where it is dealing with food related products such as household refrigeration appliances. A 2016 preparatory review study of these appliances [3], addressing the Ecodesign and Energy Label (delegated) regulations for household refrigerators [4, 5], identified opportunities where longer food preservation could be helpful in reducing the considerable volume of food spoilage and -spills at end-user level.[28]

A recently concluded complementary study [6] explores the size of the problem, optimal storage conditions for prolonged food shelf life, the quantitative balance between avoiding food waste through better refrigeration and the possible increase of energy use of the refrigeration appliances, and

[28] Notice: The information and views set out in this study and the complementary study mentioned thereafter are those of the author(s) and do not necessarily reflect the official opinion of the European Commission.

possible policy measures to reach the appropriate balance between the two.[29] This paper discusses the main results of this complementary study (hereafter 'the study').

An important problem in the quantitative assessment of food waste is that it can be defined in many different ways and there is no unique methodology for measuring it. Apart from definition questions on what is 'waste', 'losses', 'avoidable' or 'unavoidable', there is the matter of picking the right accounting unit (real mass or raw mass equivalent, mass or nutrient value e.g. of proteins), choosing appropriate system boundaries, solving partitioning problems and harmonising conventions on water content of foodstuffs. On top of that, the quantitative data is poor and fragmented [6, 7].

There are numerous sources looking at the food system: the FAO Food Balance Sheets [8], Eurostat [9, 10, 11, 12, 13, 14], EFSA and national nutrition surveys [15], surveys of food industry associations [16, 17], national waste statistics [18, 19] and field research, like the UK WRAP studies [20] and many others, where food waste is actually measured in a (usually limited) sample of households. Each source has its own methods and is looking only at a part of the whole picture. Within the EU food system, the results from all these sources, within plausible margins of uncertainty, should be interrelated and coherent, but no evidence was found that this has been put to the test before.

As regards solutions for reducing food waste, most studies recommend a 'change in behaviour' of all actors, a strategy that is notoriously difficult to implement successfully in a policy context. In industrialised countries, the end-user has been identified as the main source of food waste through food spoilage of ingredients and leftovers not used in time and –especially in food services– meals prepared but not eaten. Basically these are all planning issues, stemming from not always predictable items like the number of people at the dinner table or in a restaurant, the preferences and appetites of these people. A good planner may decrease the uncertainty by buying and preparing food 'just-in-time', but daily shopping trips –apart from having their resources repercussions when using a car– are not an option for everyone. The alternative is to increase flexibility, i.e. increase the probability of food being eaten by prolonging the period in which it can be safely preserved. The latter is the focus of the study: the possible contribution of technical solutions in reducing food waste, i.e. notably of refrigeration appliances.

To that end, it should be known how much the 'shelf life', the period of safe food preservation, can be prolonged. Also, it should be assessed if such longer preservation periods can be taken into account within the present practice of expiry dates. It should be determined what the possible consequences would be for the design of the refrigerator in terms of volumes, temperatures and its energy use. Finally, if indeed the balance of benefits and costs is positive, it can be considered what policy measures could bring about the necessary change.

The EU food system

The study aimed to increase reliability of quantitative data on the food system by creating a complete and consistent picture of the food system, where data from the various sources are compared and checked for consistency. In a 'closed' accounting system, using Sankey-type flow analysis, an extensive analysis of food processes was undertaken, where inputs match outputs and recycling loops across sectors are properly taken into account.

This paper only discusses the main output of the 180-page study. For full details see the study-report [6]. In that sense, figure 1 gives a simplified representation of the full EU food flow diagram in the study.

[29] Ibid. 1.

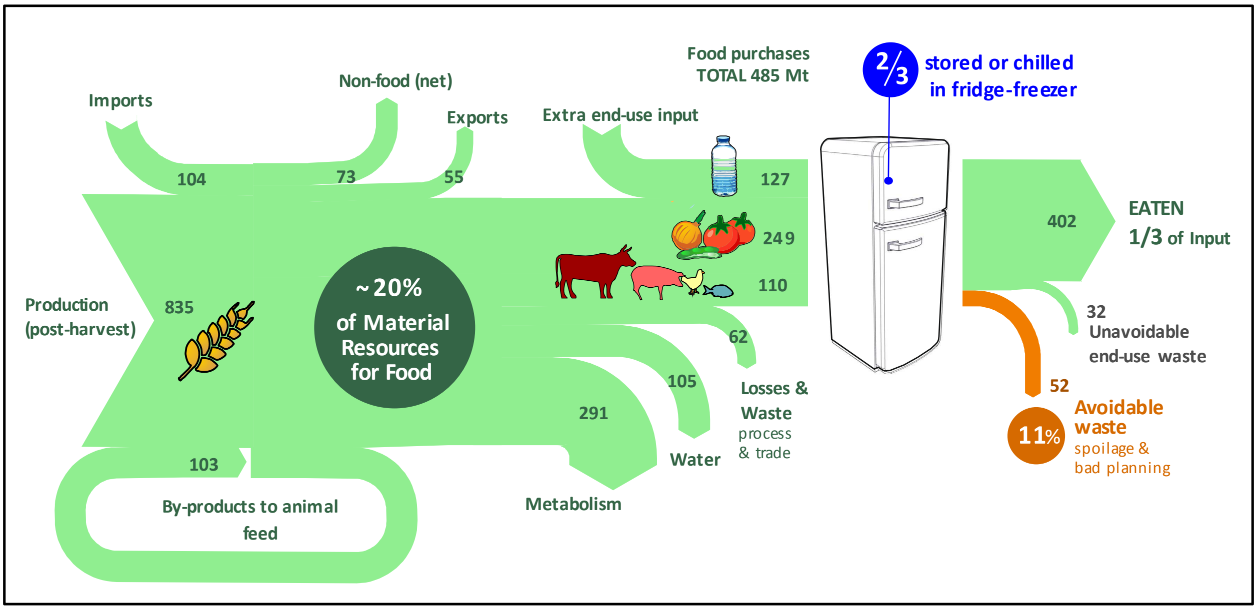

Figure 1. Simplified EU food flow diagram (source [6])

The system relates to the EU 2011/2012 data, including extra-EU trade. All figures are in million metric tonnes (Mt). The food system starts, as do the FAO Food Balance sheets, with the raw material equivalent (RME) mass of the crop imports (104 Mt), exports (55 Mt) and production (835 Mt) after the harvest, i.e. excluding (pre-) harvest losses[30]. For crop imports and -exports the 'Rücksack' of material resources spent/saved in the country of origin/destination is taken into account. For forage feed (grass, green fodder, etc.), original source data are given in 'dry hay equivalent' (humidity 20%) and this is maintained. Nonetheless, where appropriate e.g. to compare with Eurostat data, also the real forage mass (estimated at close to 65% humidity) is given. The production of seed material and on-farm use was identified but excluded from the initial figure.

There is one recycling flow, i.e. by-products from downstream processes that are (re)used as input for animal feed (103 Mt). In studies with a more restricted scope, this considerable recycling flow is often ignored or classified as 'waste'. The recycling of by-products adds to the gross material input of the system, but is excluded from the net material input.

The non-food industry constitutes a system boundary, consuming crop and products that could potentially be used for human consumption, but also supplying –along with actual waste– significant quantities of animal feed, like oilcake and milling residue, back into the food system. The 73 Mt for non-food is thus a balance between the two.

The farm animal products (meat, milk, eggs) are not separate inputs, but are modelled as the result of the animal feed input. For accounting purposes –not necessarily biologically correct– the difference between feed inputs and animal product outputs, in net carcass weight mostly, is defined as 'metabolism' (faeces, urine, gas, body heat, growth/maintenance, movement, etc., totalling 291 Mt). Fish & seafood, predominantly caught in the wild, is treated as a separate input.

At the later stages of food industry, the RME start to deviate from actual mass. At the latest from that stage onwards, all flows relate to real mass using data from economical and technical sources for a dozen main food flows. Apart from bread making, the actually avoidable waste from the food industry is relatively low (1-2%). Most of the waste streams are losses that are inherently linked to the processing technology and the product format desired. In total, losses and waste are estimated at 62 Mt, including losses in retail and trade.

Various processes influence the water content of the foodstuffs. In most cases, these are small quantities and are implicitly included in the waste streams. Only where there is a very large water extraction (i.e. in producing raw sugar, in cheese and milk powder) or large addition of tap water (i.e.

[30] Figures relate to the simplified diagram. In the full accounting the imports are split between primary (crops) imports/exports and secondary (product) imports/exports

for beer making) these flows are modelled explicitly. In balance, there is 105 Mt of water loss in food processing.

Figure 1 summarizes the end-use products into two flows of respectively vegetal products (249 Mt, including vegetables, fruits, oil crops, sugar, potatoes and cereals) and products of animal origin (110 Mt, including meat, fish, dairy products and eggs). In the end-use phase the main food flows are complemented by some small flows (21 Mt) and less resource intensive food flows such as soft drinks and bottled water (106 Mt). These give an extra input of 127 Mt.

In total 486 Mt of foodstuffs are being purchased by end-users, i.e. private households (~80%) and food services (~20%). Of this, 402 Mt is actually eaten or drunk and 84 Mt or 18% is wasted by private households (~70%) and food services (~30%). Following the definitions of food waste field studies, 32 Mt or 7% of purchases is unavoidable waste (peels, bones, etc.) and 52 Mt or 11% is avoidable, i.e. spoiled or spilled after purchase because ‘not consumed in time’, leftovers (‘prepared too much’) and meals prepared but not eaten (e.g. in buffet-type canteens and restaurants).

European Union impacts

This section shows the impact of the European food system regarding material, energy, water resources, emissions, monetary expenditure and waste. It compares the outcomes of the study with other sources and it compares the impact of the food sector with the impact of Energy-using Products (ErP) in general, and –where possible— household refrigeration appliances.

Material resources

Domestic Material Consumption (DMC) measures the total amount of materials directly used by an economy and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports. Eurostat’s DMC indicator provides an assessment of the absolute level of the use of resources. For the year 2011, Eurostat [10] estimates the EU-28 DMC at 7.3 billion metric tonnes (7.3 Gt).

According to the study, the net materials input into the food system, counting 223 Mt of forage at dry hay equivalent and excluding the animal feed recycling loop, is around 1100 Mt (1.1 Gt). When counting the real weight of forage feed, the outcome is close (±10%) to the Eurostat figure for EU Domestic Material Consumption (DMC) of 1.44 Gt for biomass minus wood (see figure 2). This constitutes almost 20% of all DMC and implies that roughly only one-third of the net material input ends up being actually consumed by EU citizens.

In comparison, the non-energy materials used in production and use of all ErP regulated thus far amounts to 43.8 Mt or 0.6% of DMC, of which 0.4% for metals, 0.1% fuel feedstock for plastics and synthetic rubber, and in total 0.1% for minerals (e.g. glass) and biomass (wood for paper manuals and cardboard packaging, natural rubber) [21, 22].

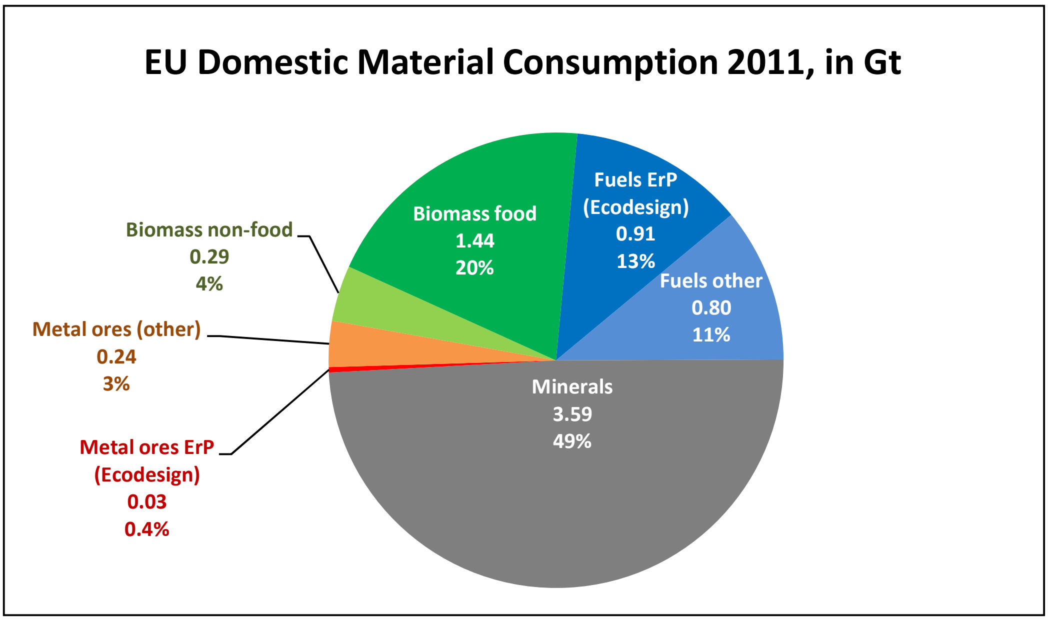

Figure 2. EU Domestic Materials Consumption 2011, indicating shares of food and of Energy-related Products. ***(Rounding may give deviation in the sum. Note that the smaller ErP fractions of 0.1% fuel feedstock for plastics and in total 0.1% for minerals and biomass are not shown)***

Energy

JRC [23] estimates the overall amount of energy embedded in the food consumed in the EU in 2013 at 283 million tonnes of oil equivalent (Mtoe). This is equivalent to 17 % of the EU's gross energy consumption (1667 Mtoe) and 25.7 % of its final energy consumption (1107 Mtoe), i.e. after energy production and feedstock use [11].

The equipment and vehicles involved in food production and handling are responsible for 17% of the EU energy consumption. According to Ecodesign Impact Accounting [24], roughly 40-50% of the energy use of that equipment is regulated by Ecodesign, like irrigation pumps, industrial fans, process chillers, professional and commercial refrigerated stores and all sorts domestic appliances. (see figure 3). Refrigeration appliances in private households and restaurants take up 7% of that number, i.e. 20 Mtoe.

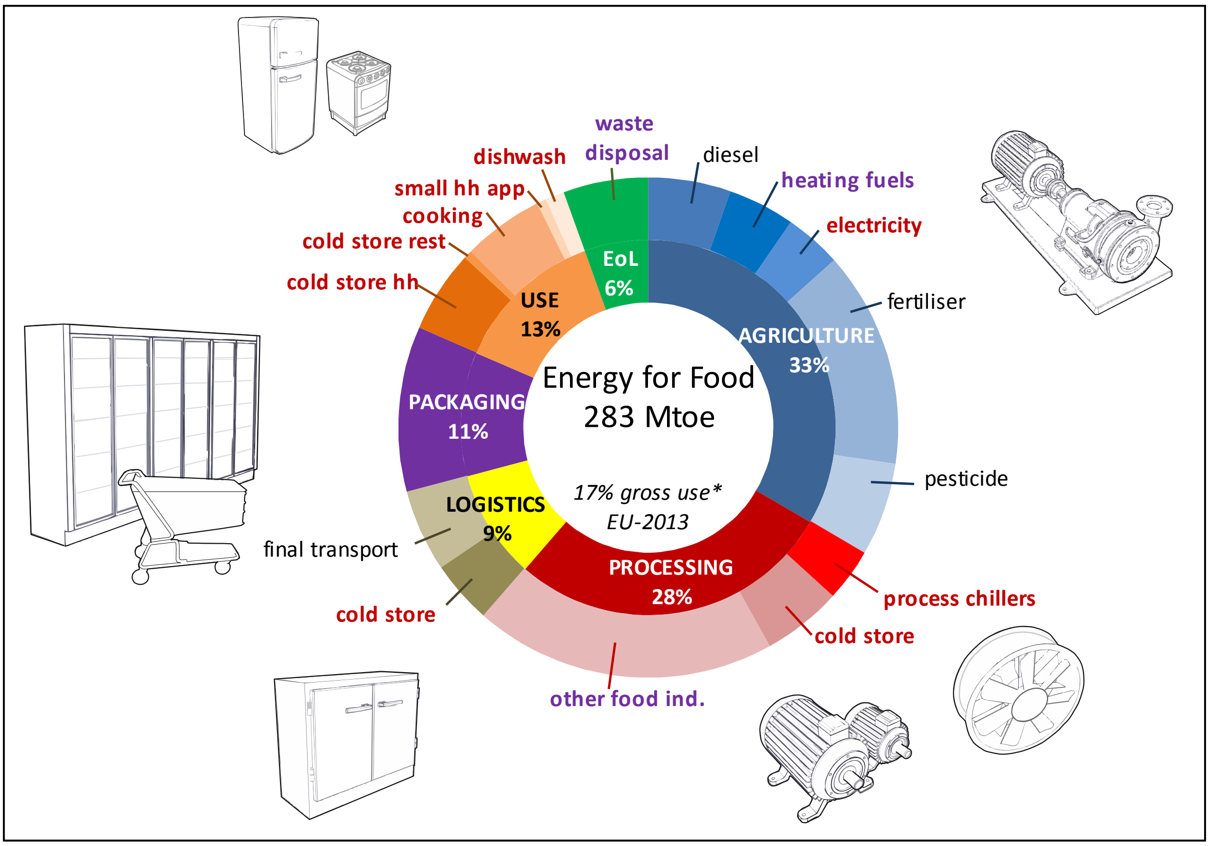

Figure 3. Energy consumption for the EU food chain. (ind. = industry, sources [21, 24])

Water

In 2007, the EU abstracted 237 billion m³ ground- and surface water for cooling, irrigation and consumption. The EU's agriculture used 64 billion m³ or 27%, of which 62 billion m³ for irrigation and 2 billion m³ as sanitary water. In comparison, in the same year, all private households consumed 27 billion m³ from the public grid [25].

Note that within the concept of 'water footprint' the above refers strictly to 'blue water'. Globally, blue water is only 12% of the water footprint [26]. The 'water footprint' also includes green water (rain, 78% of total) and grey water (virtual water that would be required to dilute polluted water to acceptable levels, 10% of total).

Greenhouse gas emissions

The EU's 2012 Greenhouse Gas emissions (GHG) amounted to 4548 Mt CO_2 equivalent (Mt CO_2 eq.)[31] [12]. Food production is responsible for 1070 Mt or 24%, consisting of 10.35 % for methane and nitrous dioxide emissions from manure, enteric fermentation, soils, etc. and more than 13% of CO2 emissions from the direct or indirect (for electricity) combustion of solid fuels [27]. In total, the EU food sector causes more than 1 Gt (1000 million metric tonnes) CO_2 eq.

In comparison, the energy consumption of the regulated ErP per 1.1.2017, including F-gas emissions of refrigerants, is responsible for approximately 2 Gt CO_2 eq. of GHG-emissions, of which 268 Mt are overlapping with the food sector. The share of household refrigerators therein is 34 Mt CO_2 eq of GHG [24].

[31] Excluding LULUCF (Land use, land use change and forestry). From 2012 data extracted by Eurostat 2013. The current official data for 2012 –extracted from EEA Feb. 2017– are slightly higher, i.e. 4558 Mt CO_2 eq.

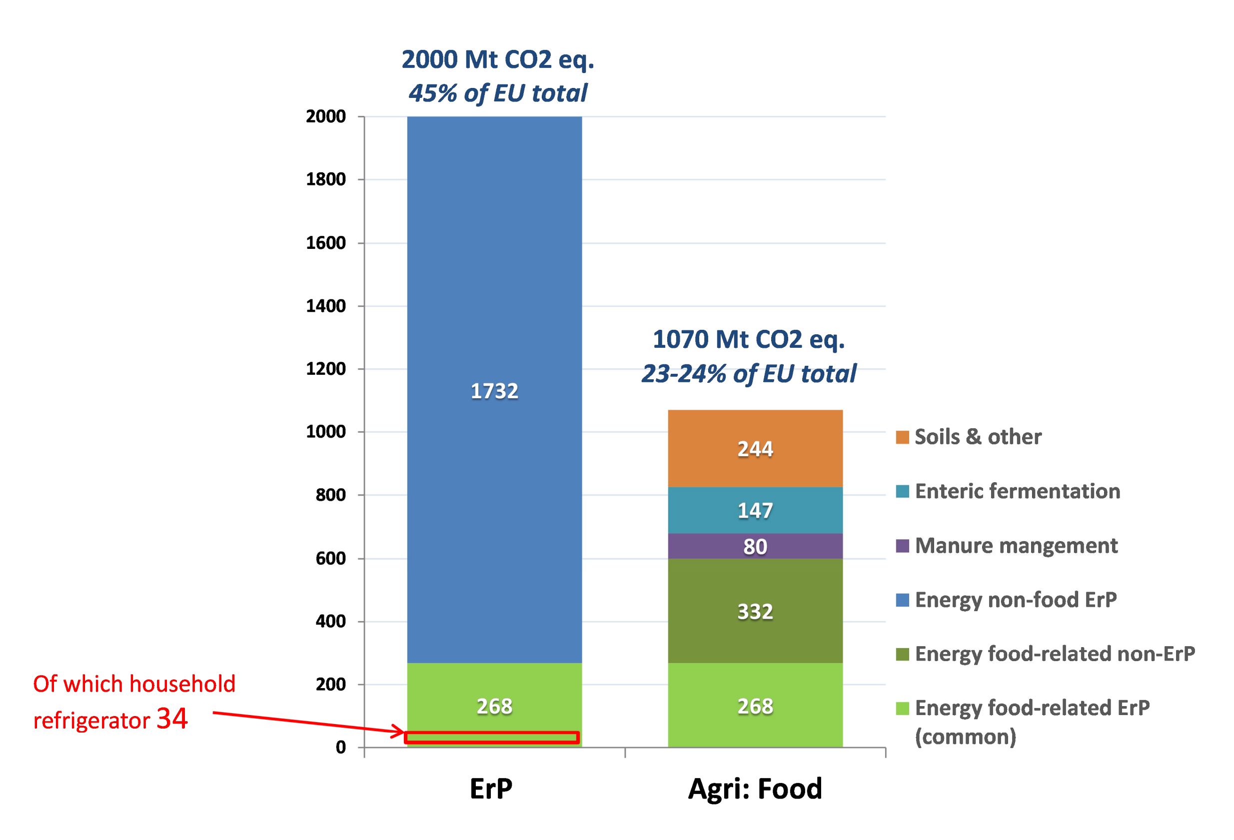

Figure 4. Greenhouse gas emissions by regulated Energy-related Products (ErP) and from the EU food sector.

Money

The monetary impact of food on the household budget is considerable. Although the focus of the study was not on monetary parameters, the streamlined Eurostat expenditure data for private households show that in 2011 an average 2.3 person household spends 6900 euros/yr on food and beverages, both at home (2/3) and outdoors (1/3) [13]. This is almost 21% of the total household budget. Taking just food and drinks expenditure at home, an avoidable waste of 11% constitutes an expenditure of 759 euros per year. In comparison, the 1.4 refrigeration appliances installed per average household have a write-off of around 46 euros and the operating costs are around 77 euros, resulting in total costs of 123 euros annually. These figures are generic and specific investment calculations are required to calculate the situation for an individual household, but they illustrate the economic potential of investing in refrigeration appliances if it results in lower food waste.

Waste

On a total of 213.4 Mt household waste collected in the EU in 2012, Eurostat finds 137.6 Mt mixed waste and 28.6 Mt of organic waste [14]. For the food service sector (excluding "wholesale of waste and scrap" [14]) the totals are 36.1 Mt of mixed ordinary waste and 12.6 Mt of organic waste on an overall sector-total of 113.5 Mt. In total this gives 215 Mt of collected organic and mixed waste at the end-users.

The study estimates a food waste fraction in the mixed waste of 22% and a food waste fraction in organic waste of 35% (65% being garden waste and other). The aggregate food waste for households is thus approximately 40 Mt and for food services 12.4 Mt. This comes down to a food waste fraction of 24% of the total EU organic and mixed fractions for households and 25% for services.

Taking into account also separate collection of used cooking oil as 'mixed waste' from mainly the food service sector, the study estimated the total collected food waste at 56 Mt (15 Mt organic and 41 Mt mixed waste). Apart from that, it is estimated that some 12 Mt of (semi-) liquid food waste is flushed down the sewer, 7 Mt ends up on the private compost or was illegal dumped/incinerated and 9 Mt evaporates as unavoidably as vapour during cooking.[32] These figures are roughly in line with estimates of the FUSIONS project [7] and give the total end-use food waste of 84 Mt. Note that this is only end-use food waste and thus not include the waste and losses from food processing and trade.

Overview

Table 1 gives an overview of the main impacts of the EU food sector. Total EU figures match official sources. The margin of error in the food and waste figures is estimated at ± 10%. Note that impacts of fertiliser and pesticides are not elaborated. The EU food production takes up 19 Mt of fertiliser, 12 Mt manure and 0.2 Mt of pesticides, which have an important impact both in terms of resources and emissions.

Table 1. Overview of main EU food impacts (reference years 2011-2013 unless indicated otherwise)

Impact category	***Unit***	**EU**	**Food**		**Avoidable end-use food waste**	
		unit	unit	*% of EU*	unit	*% of EU*
Domestic Material Consumption	*Mt*	7 300	1 440	*20%*	158	*2.2%*
Energy, Gross Inland Consumption	*Mtoe*	1 667	283	*17%*	31	*1.9%*
Greenhouse gas emissions	*Mt CO_2 eq.*	4 548	1 070	*24%*	118	*2.6%*
Water abstracted for cooling, irrigation and consumption (2007)	*bn m^3*	237	64	*27%*	7	*3.0%*
Mixed and organic waste collected from private households and food services, excl. sewer, private compost and cooking losses.	*Mt*	215	56	*14%*	37	*17%*
Private households budget total EU	*bn euros*	7 337	1 517	*21%*	167	*2.3%*
Budget per private household	*euros*	33 350	6 900	*21%*	759	*2.3%*

Refrigerators and food waste

Figure 5 gives the estimate of end-use food storage practices in the EU, based on anecdotal data. The numbers represent the aggregated total EU mass of end-use food purchases in Mt per year.

There are items always stored in freezer (36 Mt), refrigerator (115 Mt) and at room temperature (161 Mt). Then there is a group of 175 Mt of long-life beverages which passes at some point in their use

[32] This estimate is the balance of some foodstuffs like rice and pasta taking up water during cooking and other foodstuffs like most vegetables, meat, fish, etc. losing water during cooking.

through the refrigerator, at the latest after being opened and/or served chilled. All in all, this means that 326 Mt or two-thirds of the 486 Mt purchased passes through the refrigerator before being consumed.

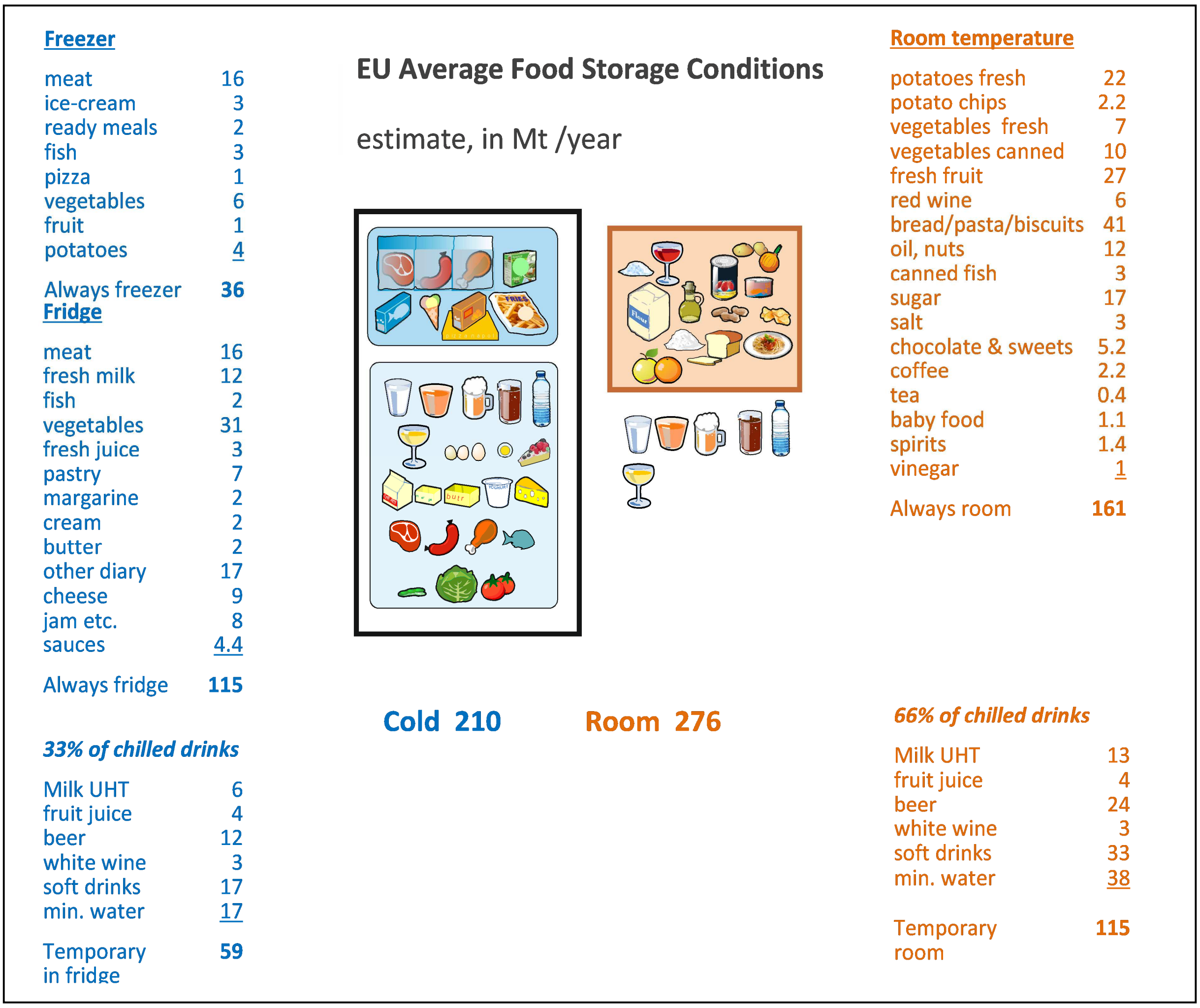

Figure 5. Estimated EU storage-practice for food & drinks. (VHK estimate)

In terms of the average volume of the refrigerator occupied, it is assumed that long-life beverages spend two-thirds of the time (or for two-thirds of the total volume) at room temperature outside the refrigerator and one-third inside. On average over time, 115 Mt is thus stored at room temperature and 60 Mt is stored in the refrigerator. This brings the average volume of foodstuffs stored in the refrigerator at 210 Mt.

Consumers are estimated to consume 80% of food at home and 20% through food services. The waste of food services per meal is substantially higher than at home, mainly because not all food prepared is actually ordered (especially in self-service restaurants). There are few surveys [18, 19], but they all indicate that total food loss is 50% higher per meal than at home. This means that also the ingredients purchased by food services will be not 20% but 30% of the total food purchased.

To estimate the actual annual purchases per capita and private household, excluding food services, the numbers have thus to be multiplied by 70%. This means 679 kg/capita/year (13 kg/cap/week) and 1593 kg/household/year (30.6 kg/hh/week).

Assuming that the estimate in figure 5 is correct, 43% (210/485 Mt) of these mass values should end up in the refrigerator. For the average household this means a mass of ~13 kg of refrigerated foodstuffs per week. This is in line with the findings of Geppert [28], who found in field research a median value of 4 to 4.4 shopping trips for households in Germany, UK, Spain and France. The average weight of foodstuffs put in the refrigerator after each shopping trip is 3.2 kg.

For comparison, Table 2 gives end-use purchases, total and avoidable waste, including the fraction that was wasted because –according to respondents— not used in time. These are again aggregated data of private households and food services combined.

Table 2. Annual food purchases and waste EU 2011, by food group

	Purchase	**Waste in % of purchase**			**Waste in Mt**				**Intake**
		Total	Avoi-dable	Not in time	Total	Unavoi-dable	Avoi-dable	Not in time	
	Mt	*%*	*%*	*%*	*Mt*	*Mt*	*Mt*	*Mt*	*Mt*
Sugar	17	6%	5%	1.9%	1.0	0.2	0.9	0.3	16
Veg. Oils & nuts	14	35%	6%	1.8%	4.9	4.1	0.8	0.3	9
Potatoes	28	39%	18%	8.0%	10.8	5.7	5.1	2.2	17
Vegetables	54	35%	18%	15.7%	19.1	9.1	9.9	8.5	35
Fruit	52	24%	12%	6.5%	12.3	6.2	6.1	3.4	40
Cereals	84	12%	12%	6.3%	10.1	0.0	10.1	5.3	74
Meat	32	22%	11%	3.3%	6.9	3.3	3.6	1.1	25
Fish	7	7%	6%	1.8%	0.5	0.1	0.4	0.1	6
Dairy	67	8%	8%	3.4%	5.5	0.5	5.1	2.3	61
Eggs	4	17%	6%	2.3%	0.7	0.4	0.2	0.1	3
Soft drinks	106	7%	7%	0.3%	7.9	0.0	7.9	0.3	98
Small flows	20	19%	8%	0.2%	3.9	2.4	1.5	0.0	16
Total EU	485 *100%*				84 *17%*	32 *7%*	52 *11%*	23 *5%*	402 *83%*
Kg per capita	*962*				*167*	*63*	*103*	*46*	*795*

These figures show that, in absolute terms, cereal products (mainly bread and pastry), vegetables and fruits cause the highest avoidable solid waste at around half of the total. These are also the top three of products wasted because they are not used in time. Overall, the avoidable waste due to food spoiled because 'not in time' is almost half of the avoidable waste. The avoidable waste from the resources-intensive animal products (meat, fish, dairy, eggs) is relatively smaller but still significant at 18% of avoidable waste. Considering that fresh fruit, vegetables and animal products are the main occupants, the refrigerator seems well placed to make a contribution to reduce food waste.

Prolonging the preservation period

Currently, over 85% of refrigeration appliances offer –apart from a freezer compartment– only a single fresh food compartment at a temperature of +4°C [3]. For about half of the fresh food (and drinks) this is either too warm or too cold for best fresh food preservation, according to various food storage guidelines. The presence of chillers (-1°C for meat/fish and +2°C for leafy vegetables) and a 'cellar' compartment (8-14°C) could increase the shelf life, in days, with on average a factor 2 or 3. For certain foodstuffs like fresh meat the shelf life could be prolonged from 3 to 20 days by using a chiller instead of the usual fresh food temperature. In 'Dairy', storage conditions for fresh milk and other dairy products the current conditions are optimal, but storage conditions for cheese can be considerably improved.

Figure 6 gives an overview of the minimum days without spoilage for the current refrigerator ('NOW'), an improved food-optimised refrigerator ('BETTER', see also table 3) and a theoretically 'BEST' refrigerator that also optimises the safe preservation of fruit and vegetables that already have a long shelf life (e.g. apples, carrots, potatoes). Note that 'leftovers' are not included because, although also the preservation of leftovers could benefit from food-optimised refrigeration, there are no average data.

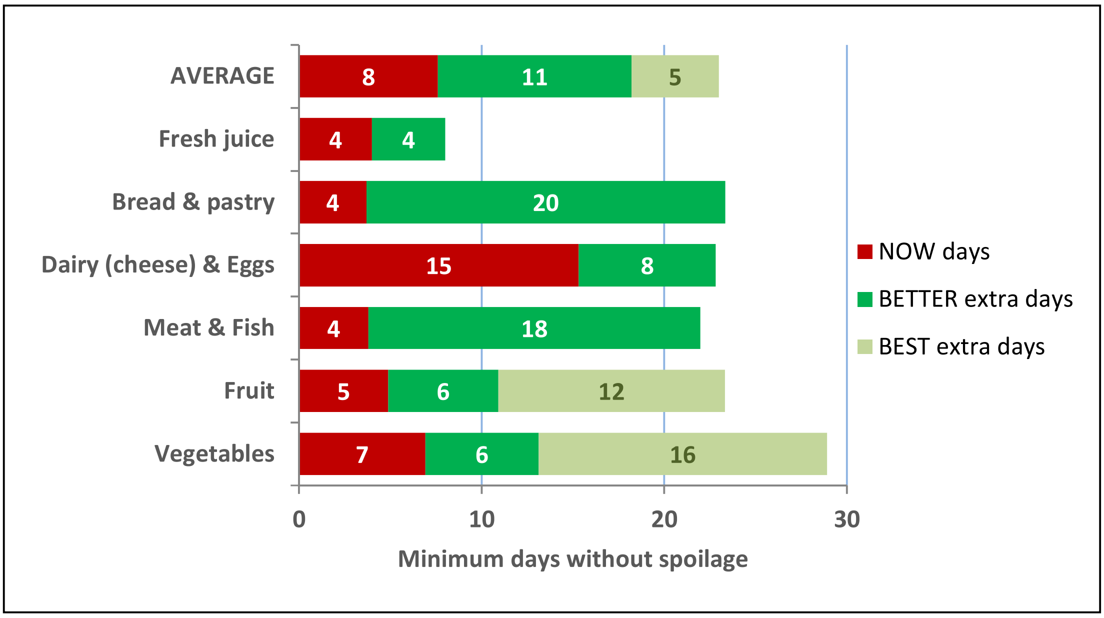

Figure 6. Prolongation of shelf life BETTER and BEST versus NOW.

An appropriately designed refrigeration appliance is an important condition to realise much longer shelf life, but it is not the only condition for end-users to change their behaviour. The current food labelling practice of suppliers setting 'use-by' dates based on a worst-case scenario is the reported reason of large part of the avoidable food waste, at least for some (animal-origin) foodstuffs. If a strategy of less food waste through better refrigerated preservation is to be successful for these products, appropriate lateral measures are needed.

Food-optimised refrigeration

Refrigerator-design will always be differentiated by a mix of consumer preferences and company product policies, but this section looks more in general how the archetype average refrigerator may change as a result of a larger emphasis on longer and better food-preservation.

Preliminary calculations from EU food flows and findings on optimised storage conditions resulted in the following data presented in table 3. Purely based on the occupied storage space (in litres), including sufficient surrounding space for convection cooling, and 'all other factors being equal', the ideal food-conserving refrigerator ('BETTER' design) would have an average temperature slightly lower and the total volume slightly bigger than a conventional refrigerator ('NOW' design). The equivalent volume V_{eq}, calculated according to the expected Ecodesign Commission Regulations for household refrigeration, would increase from 41.6 to 50.1 litres.

Table 3. Comparison volume and equivalent volume of refrigerator NOW and BETTER

	NOW					BETTER								
T_c	***20°C***	***4°C***	***-18°C***			***20°C***	***17°C***	***12°C***	***4°C***	***2°C***	***-1°C***	***-18°C***		
r_c		*1*	*2.1*				*0.35*	*0.60*	*1*	*1.1*	*1.25*	*2.1*		
	ltr	*ltr*	*ltr*	***Total***	*avg rc*	*ltr*	*ltr*	*ltr*	*ltr*	*ltr*	*ltr*	*ltr*	***Total***	*avg rc*
Vegetables	2.4	12.1		**14.5**	*0.84*		3.9	1.5		9.1			**14.5**	*0.85*
Potatoes	2.8			**2.8**	*0.00*	3.0							**3.0**	*0.00*
Fruit	7.3			**7.3**	*0.00*		3.7	1.5	1.4	0.8	0.0		**7.3**	*0.61*
Meat & fish		4.4	2.3	**6.6**	*1.38*						5.5	1.1	**6.6**	*1.40*
Dairy & eggs		9.7		**9.7**	*1.00*				6.8	0.8	2.1		**9.7**	*1.06*
Bread & pastry	3.6	1.7		**5.3**	*0.32*	1.8			1.7			1.8	**5.3**	*1.03*
Beverages	19.1	9.0		**28.1**	*0.32*	17.7		5.4	3.9	1.1	0.0		**28.1**	*0.30*
TOTAL	**35.2**	**36.8**	**2.3**	**74.3**	*0.56*	**22.5**	**7.5**	**8.4**	**13.9**	**11.8**	**7.6**	**2.9**	**74.5**	*0.67*
o/w refrigerated		*39.1*					*52.0*							
V_{eq}		41.6		**41.6**			50.1						**50.1**	

*T_c is the temperature of compartment c in °C; r_c is the compartment c temperature coefficient with r_c=(24−T_c)/20; V_{eq} is equivalent volume in litres where V_{eq} is the sum of V_c * r_c for all compartments, with V_c being the compartment c volume. Note that in this case the 'compartment volume' is in fact the estimated volume of the foodstuffs, including a specific factor to guarantee sufficient convective heat transfer. This represents the minimum compartment volume needed; the actual compartment volume is (much) higher as discussed hereafter.*

Ignoring the 0.6 litres of difference in freezer space, figure 7 gives a comparison of the occupied food space in the refrigerator NOW as well as the BETTER and BEST alternatives.

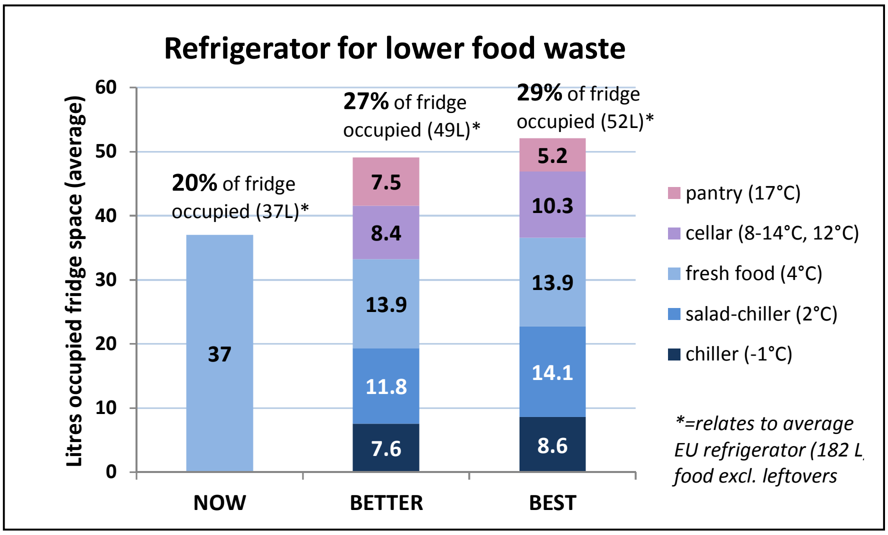

Figure 7. Comparison of occupied space (in L) and storage temperatures for current, 'better' and 'best' refrigerator in terms of food storage

In theory, the increase of equivalent volume indicates that the BETTER refrigerator would consume at least 20% more electricity than today's reference, with all other factors being equal. Having said that, 'all other factors' need not be equal:

- At the moment, the average refrigeration appliance is –even when taking into account peak usage twice as high as average– at least a factor two oversized with respect to the peak load. On average, the foodstuffs -including sufficient extra space for effective cooling-- occupy only one fifth of the refrigerated space available [6, 28].
- The preparatory study [3] showed that for household refrigerators there is still a significant technical saving potential of up to 30-40% and an economic saving potential of 18-20%. This means that a future food-saving appliance would not use more in an absolute sense, but it would save less.

- The existence of several different temperature compartments ranging from -1°C to +17°C creates new energy saving possibilities, e.g. from cascading and re-use of 'waste cold' from defrosting.[3]

Nonetheless, even when not considering these factors, the section on European Union impacts (e.g. table 1) shows that it would be enough to save 1-2 percentage points on end-use food waste, i.e. 9-10% instead of 11% avoidable waste, to compensate for a 20% higher energy use of the refrigerator.

Conclusion

Outcomes of the study highlight the need for an improved refrigerator design expanding the temperature compartments with a 17^{0}C, 8-12^{0}C, 2^{0}C, and -1^{0}C compartment additional to the standard 4^{0}C and -18^{0}C freezer. This has the potential to increase the average shelf life of fresh food with a factor 2 to 3. The amount of food that can be saved with these refrigerator modifications is difficult to estimate at this stage. Further research in the form of, amongst others, a field study is required.

The study confirms that there is a solid basis for policy makers to allow multi-door correction factor for refrigeration appliances in Ecodesign and Energy Labelling. At least this would no longer penalize the multi-door appliances, with e.g. inherently larger door-leakage energy losses than a single-door refrigerator, in Ecodesign and Energy Label rating.

Secondly, harmonisation at EU-level of (parts of) setting 'use-by' dates is recommended. For instance, comparable to today's food labelling for frozen products, the use-by dates for meat and fish could differentiate between storage at +4°C (normal refrigerator) and -1°C (meat chiller).

Information campaigns raising consumer-awareness can gain in effectiveness when linked to proper storage with benefits of not only less food waste but also healthier and tastier food.

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Heat Pump Clothes Dryers in the Pacific Northwest

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Abstract

This study presents a summary of lab and field research conducted by the Northwest Energy Efficiency Alliance (NEEA) from 2013 through 2016 on heat pump clothes dryers for the North American Market. NEEA developed a modified lab test protocol that adds four test cycles using real clothing in a variety of load sizes and cycle settings to the US DOE dryer test protocol. The resulting metric has proven to be a better indicator of actual field performance. Lab testing of heat pump equipped clothes dryers are compared to three field studies of clothes washer and dryer pairs in 27 homes. The outcome of these lab and field tests are 1) a multi-tiered dryer efficiency specification that is the basis of utility energy savings estimates 2) a qualified products list used to promote high efficiency dryers sold in the Pacific Northwest and 3) recommendations on how future test protocols can be improved.

Background

Conventional dryer technology and efficiency have not improved since 1981. The small drop in dryer energy use shown in the NRDC graph in figure 1 is actually due to more efficient washers, which extract more water, so that the dryer does not have to work as hard. Northwest consumers own six million electric clothes dryers, more than 80% of which use electric resistance heating to remove moisture. NEEA is interested in advancing the adoption of “Super-Efficient Dryers” (SEDs) because of the potential (180aMW) of energy savings if the 6.6 million conventional electric clothes dryers in the region were replaced with super-efficient models.

Conventional dryers blow heated air into a rotating tumbler of clothing; moist air is then exhausted from the drum to the outdoors. This approach is effective, but very energy intensive, commonly using over 900 kWh per year for an average home, making it the highest energy use appliance. In a conventional electric dryer, only half of the energy is used to vaporize the water from the clothing, and virtually all of the expended energy is exhausted from the home. A conventional electric dryer is rarely capable of drying more than about three pounds of real clothing per kWh expended. By comparison, a heat pump clothes dryer is capable drying more than six pounds of real clothing per kWh expended.

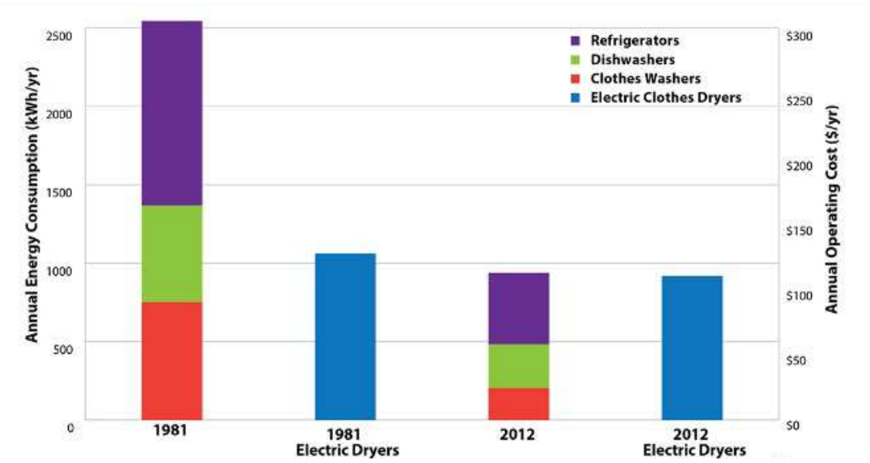

Figure 1 – annual energy consumption of electric clothes dryers vs. other major appliances (Courtesy of the NRDC [1])

Initial Field Study

In 2011 NEEA used fifty homes from its Residential Building Stock Assessment to provide a representative household sample for a field study of laundry energy use. The age of the laundry equipment in the sample homes was less than five years old and included 30% front loading washers. Researchers installed data loggers capable of monitoring the energy use of both the washer and dryer in the homes, and the homeowners were paid to record the setting, load weight, and completion time for each wash and dry cycle. The results [2] provide the following significant insights into dryer operation and usage:

- Average annual clothing weight dried in the Pacific Northwest is 2,342 lbs in 311 loads.
- Cycle settings and load sizes have significant impacts on dryer performance.
- Annual average dryer energy use is 915 kWh/yr, which translates to 2.56 lbs dried per kWh, 43% more energy per pound than is determined using the DOE D1 test procedure.
- About 40% of all loads weigh less than 4 pounds; these loads use nearly twice the energy per pound than loads greater than 12 pounds.
- The average initial moisture content from the washing machines was 62%. Many cycles begin much wetter than the average – the result of an incomplete or unbalanced spin cycle.

Supplemental Test Procedure

From 2012-2014 NEEA and Pacific Gas & Electric (PG&E) contracted the services of Ecova's appliance laboratory in Durango, Colorado to test various dryers, examine test procedure issues and ultimately develop a Supplemental Test Procedure [3] designed to increase the accuracy of energy consumption estimates of clothes dryers. The procedure generated a new metric based on the average performance of 5 different tests: one using the DOE test procedure cloths and setting, and four additional tests using real clothing in a variety of cycle settings and load sizes (see table 1 and figure 2). While the individual tests are not quite as repeatable or precise as the DOE test procedure, the lab results show better accuracy and predictive value than the DOE test procedure. The metric generated was deemed the "Utility Combined Energy Factor" (UCEF) with units of pounds dried per kWh. The UCEF value is a weighted average the "Combined Energy Factor" (CEF) of each of the five different tests.

Table 1 – Supplemental test procedure cycles and settings

Test	Common Test Name	Load Type	Cycle Setting	Cycle Temp	Nominal Load Weight (lbs)	Start Moisture	Max End Moisture
DOE Test (3.3.1.1)	D2	Standard DOE Test Load (4ft3 and larger drum)	Default	High	8.45	57.5%± 0.33%	2%
One (3.3.1.2)	Small	Small Supplemental Test Load	Normal	Medium	4.22	62%± 2%	4%
Two (3.3.1.3)	Large	Large Supplemental Test Load	Normal	Medium	16.9	62%± 2%	4%
Three (3.3.1.4)	Eco	Medium Supplemental Test Load	Mfr Defined	Mfr Defined	8.45	62%± 2%	4%
Four (3.3.1.5)	Fastest	Medium Supplemental Test Load	Heavy Duty	High	8.45	62%± 2%	4%

Figure 2 – Dryer test procedure clothing items

In 2015, NEEA and PG&E used the STP to evaluate 12 conventional (non-ENERGYSTAR) dryers and six other dryers of various performance levels. With the closure of the Ecova test lab in 2015, NEEA transferred testing of laundry equipment to a nationally recognized test laboratory and conducted several validation tests to compare laboratory to laboratory results. As new super-efficient dryers entered the market, NEEA provided supplemental testing and feedback to participating manufacturers about how their products performed.

As of December 2016, 11 "super-efficient" dryer models have been tested. Table 2 provides a summary of the results of all testing to date. These dryers have distinctly different operating behaviors but can be generally classified as either a hybrid dryer or a heat pump dryer. The hybrid dryer has both the electric resistance heating elements of a conventional dryer and the vapor-compression cycle used to dehumidify the air and recapture heat of a heat pump dryer. Both vented and ventless dryers were among those tested. Ventless dryers located inside homes in heating climates provided additional energy savings benefits contributing to heat that offsets space conditioning needs. The amount of this offset depends on the home heating system, but in an average Pacific Northwest home this provides a 29-48 kWh/yr increase in annual total energy savings in a home.

Table 1 – Summary comparison of dryer performance supplemental test procedure testing

Test Machine	Model	Tech	Type	Vol	D2 cycle Time minutes	D2 lb/kWh	Small lb/kWh	Large lb/kWh	Eco lb/kWh	Fast lb/kWh	UCEF lb/kWh
Conventional 1	NED4600YQ	Conv	Vented	0.0	71	3.49	1.53	3.23	2.48	2.08	**2.3**
Conventional 2	MEDC300BW	Conv	Vented	0.0	59	3.08	1.50	2.05	3.13	3.16	**2.4**
Conventional 3	AED4675YQ	Conv	Vented	0.0	45	3.27	1.77	3.15	2.64	2.31	**2.5**
Conventional 4	WED4800	Conv	Vented	0.0	42	3.86	2.23	3.01	2.36	2.12	**2.5**
Conventional 5	DV45H7000EW	Conv	Vented	0.0	59	3.32	2.05	3.60	3.04	2.44	**2.7**
Conventional 6	GTDP220	Conv	Vented	0.0	45	3.52	1.84	3.59	3.10	2.65	**2.8**
Conventional 7	HTDX100EDWW	Conv	Vented	0.0	45	3.49	2.23	3.59	2.50	3.15	**2.9**
Conventional 8	MED3100DW	Conv	Vented	0.0	32	4.06	2.32	3.55	2.56	2.49	**2.8**
Conventional 9	FARE1011MW	Conv	Vented	0.0	55	3.19	2.16	3.49	3.61	2.50	**2.8**
Conventional 10	81382.00	Conv	Vented	0.0	48	3.57	2.39	3.64	3.23	2.87	**3.0**
Conventional 11	WED4800BQ1	Conv	Vented	0.0	56	2.99	1.94	3.19	2.80	2.61	**2.6**
Conventional 12	NED4600YQ1	Conv	Vented	0.0	75	2.87	1.26	2.91	2.42	2.31	**2.2**
ENERGYSTAR 1	WGD94HEXW0	Conv	Vented	0.0	57	4.02	2.20	3.82	3.00	2.40	**2.8**
ENERGYSTAR 1	WED87HEDW0	Conv	Vented	0.0	68	4.07	1.96	4.50	3.08	2.03	**2.7**
SED 1	DLHX4072	Hybrid	Vented	7.3	59	4.39	2.09	3.73	3.86	2.91	**3.3**
SED 2	WED99HED##	Hybrid	Ventless	7.3	62	5.43	2.20	4.38	3.64	2.89	**3.3**
SED 3	DHP244012W	HP	Ventless	4.1	76	10.25	5.62	7.78	7.45	7.16	**7.3**
SED 4	WED7990F#	Hybrid	Ventless	7.4	76	5.09	2.12	4.35	3.86	3.56	**3.6**
SED 5	WED9290F#	Hybrid	Ventless	7.4	67	5.43	2.63	4.84	3.87	3.38	**3.7**
SED 6	WHD3090##	HP	Ventless	4.3	99	7.48	3.59	5.53	6.07	5.80	**5.4**
SED 7	WHD5090##	HP	Ventless	4.3	98	7.41	3.25	5.42	4.36	5.53	**4.8**

EF and CEF values are in pounds dried based on bone dry weight starting at 62% remaining moisture content

Field Testing

NEEA completed three field tests of clothes washers and "super-efficient" dryers (see table 3). Field work was performed by staff of Ecotope Inc., while data processing and initial analysis was performed by staff of Ecova Inc. Final analysis and evaluation of the results was performed by NEEA.

The objectives of these field studies were as follows:

- Evaluate the effectiveness of the dryer supplemental test procedure
- Validate the savings difference between conventional and heat pump dryers
- Obtain initial consumer response and experience feedback on heat pump dryers
- Gather data useful in federal rulemaking procedures for washers and dryers

The field studies were performed according to the SEDI Field Test Protocol [4] developed by NEEA and the Super-Efficient Dryer Initiative (SEDI) The data collection included continuous metering of washer and dryer energy use during the study period. The test protocol required considerable effort by participants as they were asked to accurately record data for each load that included: time, weight before the cycle, weight after the cycle, settings used and observation notes on a laundry logging form.

Each field test started with ten households which recorded washer and dryer settings and clothing weights while a data logger recorded the energy consumption of both the washer and the dryer. Participant selection varied by each test, and was not done using a random sampling method, as time and access to willing participants was limited. Compensation was provided for participants in the form of either a discount for the purchase of their machine once the test period was completed, or financial compensation in the form of a gift card.

Each household washed and dried at least five loads using their pre-existing machines to establish a reference performance of conventional washers and dryers. Each household then washed and dried ten or more loads using a new matched pair of efficient machines provided by NEEA and the Manufacturers.

Table 3 – Field Tests

Field Test	SED Manufacturer	Location	PreExisting Machines	Date	General Notes
1	Whirlpool	Portland Metro	Various	Jan-15	*9 households completed*
2	Blomberg	Renton	Stacked Combo	May-15	*8 appartments completed*
3	LG	Boise Metro	Various	Jul-16	*10 households completed*

Data Logger System

The data logger used was the Onset U30. A Continental Control Systems WattNode collected energy pulse information. Collection of energy use data occurred in a custom enclosure located between the washer and dryer plugs and the wall receptacles. One-minute interval data logging allowed for fine resolution characterization of washer and dryer cycles. Temperature and relative humidity were collected in a few homes to capture the impact of the machine on the room air. Each site venting system was checked prior to the installation of the monitoring equipment to ensure it was not blocked and a reasonable venting system was present.

Each participant was provided with a digital scale accurate to +/- 0.1 lbs with which to weigh the clothes before and after each cycle. The participants were asked to subtract the tare weight of the basket before entering data in the logbook.

Data Sets

Each site generated at least two data sets. The first data set is the raw metering data collected by the data logger. This data set consists of minute level recording of the washer watt-hours, dryer watt-hours and time stamp. The second data set includes the logbook recordings from the participant. These data are hand written paper forms. A third data set was generated in a few homes where temperature and relative humidity recorded using an Onset Hobo MX temp/RH logger.

Ecova staff digitized the customer log book data and double checked entries for reasonableness and missing entries. When analyzing each participant’s logbook entries, it was necessary at times to interpret or make assumptions for some specific entries. The Whirlpool logbook gathered the most information from the participants, however it was also the hardest to interpret and analyze.

Customer data and metered data sets were combined and aligned. Each entry in the logbook was identified in the metered data. Because of participant errors or skipped entries not all laundry cycles could be properly identified and aligned between the two data sets. In a few cases the alignment was difficult with less than 50% of entries being accurately identified. For most sites however, more than 90% of all entries were clearly identified and aligned.

The process of aligning the two data sets required matching the start and end timestamps of the logger data to determine a “cycle time”. This was not always possible due to participant errors. In some cases, the date and time that the participant recorded did not exist in the logger data. In other scenarios the participant may have written a single date and time when the logger data would show two separate cycles. These separate cycles could be within an hour of each other or some instances showed the cycles being over 5 hours apart from each other. Care was taken to only accept data where cycles could be clearly aligned.

Data Scrubbing

Consistent with the work done in the in NEEA laundry field study [2] of 50 homes, data was screened for reasonableness. Entries where the logbook entries resulted in nonsensical results the data was discarded. For example, when starting weight of wet clothing in the dryer was less than ending weight of dry clothing.

The primary data scrubbing criteria discarded any wash cycle that ended with moisture content above 100% or below 33%. Lab testing NEEA had conducted of both cotton polyester blends and 100% cotton loads did not produce remaining moisture contents below 36% under any circumstance. Cycles above 100% are suspect as participant logbook failures because this would be indicative of a washing machine malfunction. Data scrubbing also removed cycles where the energy factor (pounds dried per kWh) exceeded the theoretical performance limits of the dryer.

Additional data scrubbing was applied when the logbook did not provide enough information to explain minor gaps within logger interval data within a single cycle. For example, a participant may record a single date and time of a cycle with no other information whereas the logger data shows a dryer cycle of 40 minutes with a 15-minute gap of power consumption and a final 20 minutes of power consumption. When analyzing this data, one would either assume two separate cycles or a single cycle with a gap (possibly participant caused). Assumptions were made throughout the data to best correlate power consumption data to participant transcribed entries. In some cases, data could not be correlated accurately to participant entries and were removed from the final results. Care was taken during analysis to infer that any removed or bad data found from the power logger and information transcribed by the participant were beyond a reasonable doubt to alter the results.

Reasons for Data Removal:

- Customer did not record weight or other relevant information (participant left entry blank).
- Participant removed clothing during the cycle but did not record the weight of clothes removed.
- More cycles recorded by data logger than what they recorded in the logbook.
- Unreasonable values recorded by participant (5.6 lb start weight to 21.2 lb wet weight) lead to high remaining moisture content (RMC) values that skew data.
- Participant logged more cycles than were recorded on data logger for the specified date by participant.
- Participant did not record vital information (time or weight).
- Participant recorded cycles and no logger data was found for that day/time.
- Participant recorded date could not be correlated to logger data.

Field Test Details

Whirlpool Field Study

The study tested the Whirlpool WED99HED “HybridCare™” with the companion Whirlpool WFW87HEDW Duet® washer. The HybridCare dryer was the first full-sized dryer to enter the US market using a heat pump. (Note – US models are based on volume, and do not provide rated capacity by load weight). The study began in late 2014 as part of Whirlpool’s customer use field testing just prior to market introduction. The Whirlpool WED99HED “Hybrid Care™” clothes dryer is a

7.3 cubic foot dryer that has both a 1300W electric resistance heating element and a roughly 900W heat pump compressor cycle. The unit is ventless, meaning it continuously circulates air through the drum rather than venting air to the outdoors. Each time air is cycled, the cold evaporator coil removes moisture and the hot condenser coil re-injects heat. The electric heating element adds additional heat during both startup and when a cycle setting requires additional heat. All condensation is pumped to the same drain location as the washing machine.

Whirlpool generously provided both washer and dryer sets at no cost to the participants in exchange for data collection. The participants were selected by Whirlpool from a group of Energy Trust of Oregon and NEEA staff. The participants in this group tended to have smaller families with above average household incomes. Whirlpool acknowledged that the product was initially targeted at households where energy savings were important and with incomes that could support premium product pricing.

Blomberg Field Study

The second study began in the fall of 2015 soon after the Blomberg DHP24412W became available in retail stores in Washington. The preexisting machines were Whirlpool LTE5243DQ9 units (compact washer/dryer unit). The efficient machines were a Blomberg WM98400SX washer and the DHP24412W heat pump dryer. The Blomberg unit is the 5th generation heat pump compact (24” wide) clothes dryer built by Blomberg. Blomberg is owned by Arçelik A.S., which is based in Turkey, and is a major manufacturer of appliances for Europe and Africa. The Blomberg dryer has no supplemental electric resistance heater. The dryer and matching washer are only sold as a pair because the washer plugs into the dryer and both operate on 240AC. The North American version is based on the European product with component changes needed to achieve UL listing. Blomberg positioned these products for the apartment and condo markets to take advantage of their compact size and ventless characteristics.

The participant households were selected by the property manager of an apartment building from a limited number of respondents. Participating households had family incomes considerably lower than the other field studies. This study was challenged by the indirect nature of working through a property manager rather than directly with the apartment occupants, language barriers, and scheduling visits. The laundry equipment was located in the hallway or spaces adjacent to bathrooms. In many sites, the washer/dryer pair were located behind louvered doors, which limited the air circulation near the equipment.

LG Field Study

The third study began in the spring of 2016 in Boise, Idaho. The energy efficient machines were an LG WM3670HVA washer and the DLHX4072 EcoHybrid heat pump clothes dryer The LG DLHX4072 dryer that was used had been in the market for some time, but with minimal sales. This unit is nearly mechanically identical to the Kenmore hybrid heat pump dryer. Both are vented machines, exhausting air through the same ductwork that a conventional dryer uses and dumping condensed water into the same drain location as the clothes washer. Unlike the Whirlpool hybrid dryer, the LG unit has a larger (2500W) electric resistance heater element, making it capable of operating more quickly when both the heat pump and electric resistance element are on.

Idaho Power selected ten single-family households to participate based on general criteria provided by NEEA. All participants completed the study. All pre-existing washers were top loaders, and many of the pre-existing dryers were very old. Households selected by Idaho Power provided a good representation of size and income levels, with a mixture of largely indoor and some garage laundry locations.

Field Test Results

Laundry Use

Table 3 provides a high level summary of laundry use in the three tests. Cycle temperature settings were not available on the Blomberg and Whirlpool units as these units fully automated that element of the dryer cycle. Total laundry use if extrapolated to an annual amount varied between the different tests, likely because they were taken at different times of the year when clothing weights and the amount of clothing washed may vary.

Table 3 - SED Field Test Laundry Use

	Blomberg	Whirlpool	LG	PreExisting	
Number of Cycles	151	104	275	242	cycles
Valid Cycles	58	79	138	177	cycles
% Valid	38%	76%	50%	73%	%
Total Lbs Clothing	389	712	1158	1440	lbs
Average Load Size	6.70	9.01	8.39	8.13	lbs/cycle

Figure 3 shows the distribution of load sizes bins (pounds) for each machine. While the Blomberg unit specifications indicate it can handle full sized loads, users infrequently loaded the dryer with more than 10 pounds of clothes. No instruction was given to participants on how full they should fill their machines. The size of the washing machine is likely a strong influence in how full the dryer was filled. Thus the larger the washer to drum volume ratio, the more likely the dryer had a fuller load, possibly enhancing drying efficiency. The washer to dryer volume for both the Blomberg and LG machines was 61%, and the Whirlpool machine was 56%.

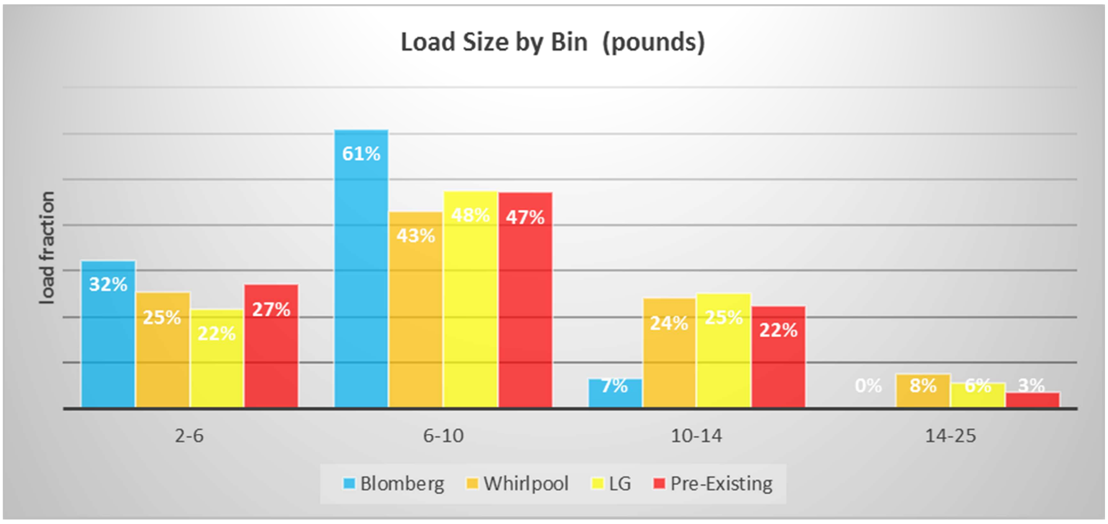

Figure 3 - Load Size by bin

Figure 4 shows cycle time by the same 4lb bins used in figure 3. It is surprising how much longer small loads take on a per pound basis than large loads. This data suggests that it is best to load the washer and dryer full for the fastest overall laundry washing and drying. Breaking the drying into multiple cycles results in a total drying time that is roughly 1.5-2.0 times longer.

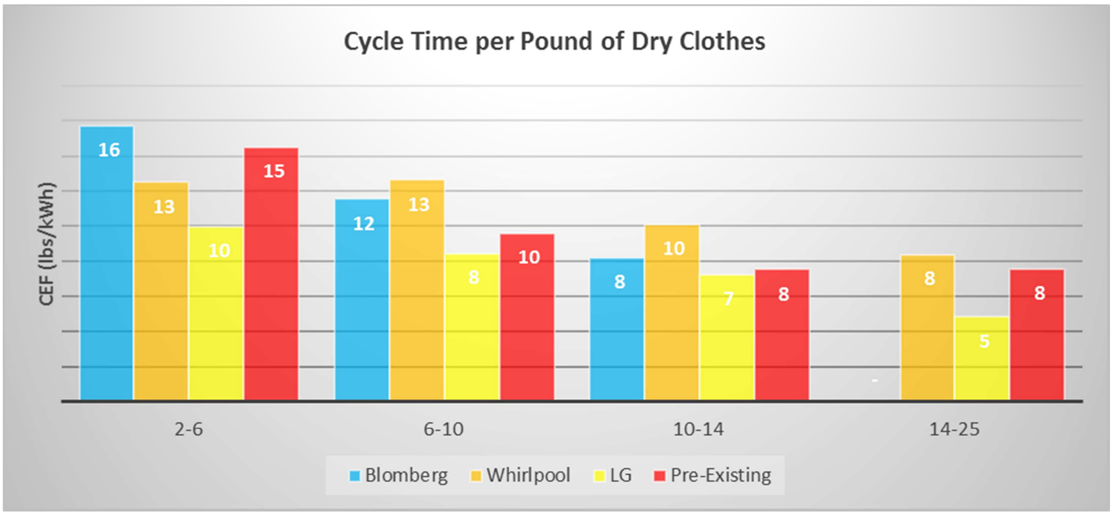

Figure 4 – Cycle Time by load size bin

The time it takes a clothes dryer to complete a drying cycle depends mostly on the start of the load and the amount of water in the clothing. Figure 5 presents the drying speed per pound of water removed. This provides a ranking that is independent of what kind of washing machine was used. A typical laundry load for a compact (24" wide) dryer contains about 3lbs of water, whereas a full sized (27" wide) dryer load contains about 4 lbs of water at the start of the cycle.

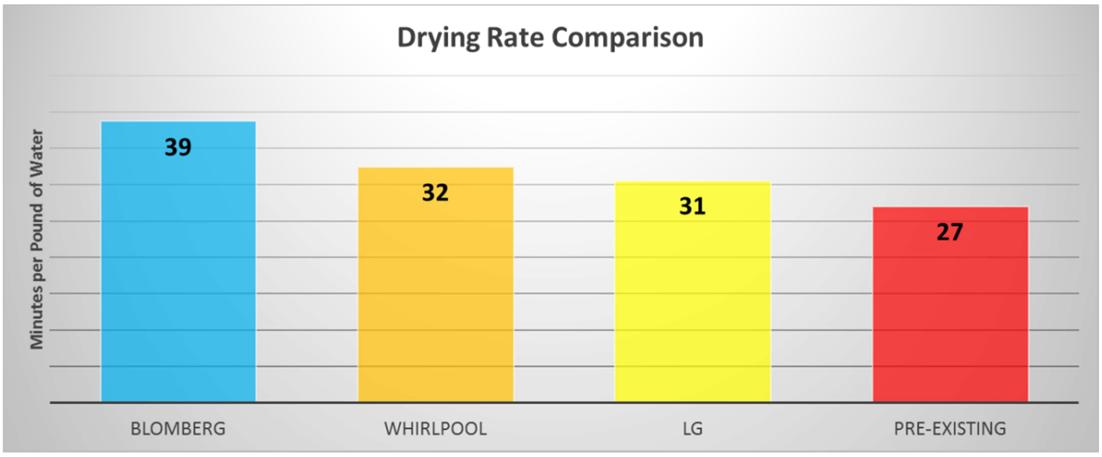

Figure 5 – Drying rate per pound of water

Figure 5 shows hybrid dryers take 16-18% longer and the tested heat pump dryer (Blomberg) took 44% longer per pound of initial moisture. This is not surprizing, given that the heat pump-equipped dryers had 20%-50% less heat injected into circulated area. The true consumer experience is best presented in figure 6 which shows the additional time each machine type took to dry an average load of laundry compared to the pre-existing machines. The difference is not as significant under real world conditions because of the size of the drum and starting moisture the paired washing machines.

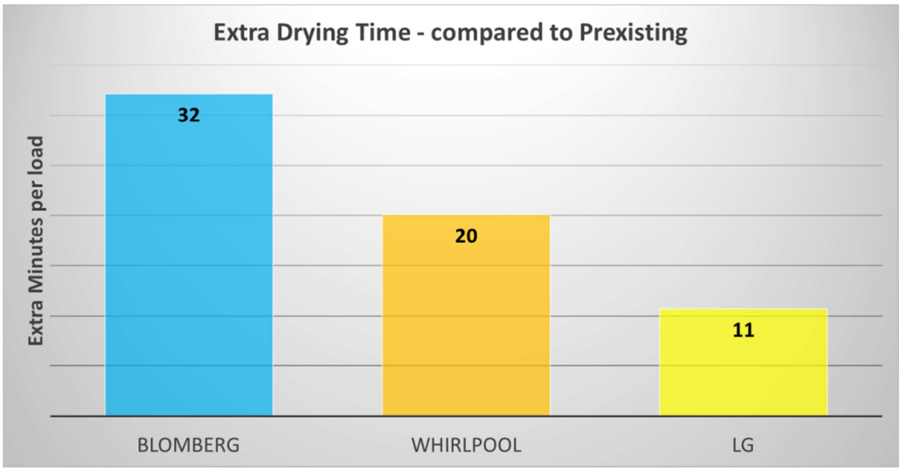

Figure 6 – Extra drying time for typical load compared to pre-existing

Participant Perception

Participants completed a survey about their perception of the dryer in comparison to their expectations and previous experience with other dryers. The survey was used to determine if there were any underlying product problems inherent in hybrid heat pump or heat pump clothes dryers that were different from conventional dryers. While each survey varied slightly, the core questions remained the same. Overall, customers were satisfied with the experience of all heat pump dryers. No significant problems with hybrid or heat pump dryers were identified.

Whirlpool Perceptions

The Whirlpool field study survey asked for participant impressions both at the conclusion of the field study and six months later via a separate questionnaire, but responses remained did not change significantly. A few participant notes on the surveys indicated that the hybrid dryer took longer than desired when drying large loads. Condensate drains on a few of the Whirlpool participants' systems were not properly attached when installed. This resulted in initial complaints because water ran onto the floor under the dryer. This is not a machine failure, but rather likely because the installing crew for these systems were untrained and unfamiliar with condensing dryers.

Blomberg Perceptions

The Blomberg survey indicated that participants were satisfied with overall performance but provided valuable insights on potential concerns. The first insight is the importance of having properly trained installation crews ensure the condensate drain line is connected from the dryer to the washer drain standpipe. The condensed water poured on the floor and the participants assumed the washer had failed. Once the condensate drains were properly connected, there were no further complaints.

A second insight is that drying took longer than expected by some of the participants. The highest fraction of participants that chose "fair/acceptable" related to the drying time of the dryer. Written comments and notes that indicated that a small sample of participants needed to run additional and different dry cycles in order for clothes to become completely dry.

LG Perceptions

Overall those using the LG washer and dryer pair had very high satisfaction levels. All ten participants chose "Very Satisfied". As with both the Blomberg and Whirlpool field tests, installation of the condensate drain was identified as a potential issue. Extra care was taken to ensure the condensate drain was attached and participants understood the purpose of the drain line from the dryer.

Performance

Clothes dryer performance can be investigated using a variety of metrics. The common North American dryer efficiency metric is how many pounds of clothes can be dried per kWh of expended energy (lbs/kWh) assuming the same starting moisture content. This metric is generically referred to as the "energy factor" (EF). Adding in additional energy used in standby mode for over a year generates a "combined energy factor" (CEF). The standby energy is small (typically less than 50 Wh/cycle), and therefore has minimal impact on the energy factor values. The "utility combined energy factor (UCEF) that uses the supplemental test procedure is a lab test metric and more accurately estimates real world energy use the current DOE test procedures (D1 or D2) generate.

Field studies cannot collect data needed to precisely determine the remaining moisture content because the bone dry weight of any load is unknown. We do not know if the clothing placed in the washer was wet or if the clothing removed from the dryer was truly dry. Field study CEF calculations are based on an assumption that both the moisture content of clothing before it went into the washing machines was 4%, and the ending moisture content is the average of how the machines performed in the lab, or 4% when that data was not available.

To compare field CEF values to lab UCEF values requires normalizing the CEF values to the same starting moisture level as the lab tests. For example, if one cycle started at 62% RMC and another started at 41% RMC the results would not be comparable because the two cycles removed different amounts of water from the clothing. CEF values in this study were adjusted to common staring moisture of 62% to be consistent with lab test conditions. This adjustment introduces some error into the CEF values because drying efficiency is not constant during laundry cycle. Lab tests show that the final 10-20 minutes of a drying cycle are less efficient than the bulk drying phase of the drying cycle. To account for this non-linearity, CEF values were adjusted to a common initial moisture content using a two-step approximation for drying that assumes a different drying rate during the "finishing" part of the. We assumed the average finishing efficiency of all dryers to be 0.63 kWh/lb of water during once the clothing achieved 13% remaining moisture content.

While the pre-existing machines are not a market average representation of older machines they do provide a reasonable reference baseline because the both pre-existing and new laundry equipment were conducted in same household, with the same laundry habits, and desired outcomes. For evaluation simplicity, all pre-existing machine performance data was combined into a single data set.

Error cause by data entry mistakes, tare weight errors, logger error, scale accuracy, and possible data scrubbing and filtering mistakes, is estimated at ±0.1 lb/kWh. This is not the same as the uncertainty of the metric however, as it does not include the larger impact of clothing type, cycle type, load size and setting selection. The average CEF of all the pre-existing machines was 2.45 lb/kWh. By comparison, the fifty homes sampled in 2012 had an average CEF value of 2.66 lb/kWh.

The scrubbed performance data is presented in Table 4. The Raw Field CEF values are based on the remaining moisture from the clothes washer, which varies considerably from load to load. The Adjusted CEF values have been normalized using a two-step adjustment to a common remaining moisture content of 62%.

Table 4 – performance summary of field results

	lb/kWh Calibrated Lab UCEF	lb/kWh Raw Field CEF	Ave Field RMC	lb/kWh Nomalized Field CEF	Energy Savings
Blomberg 24412	7.3	8.3	52%	7.1	65%
Whirlpool WED99HED	3.3	3.8	52%	3.3	25%
LG HPDLHX4072	3.3	4.2	49%	3.2	22%
Pre-Existing Dryers	2.6	2.5	59%	2.4	0%

Normalization adjusts field data to same 62% starting RMC (consistent with Lab Test)

Figure 7 presents the performance of the machines as a function of load size. Heat pump-equipped dryers are more efficient with larger loads, whereas conventional dryers appear to perform less efficiently with larger loads.

Figure 7 – Performance by load size

Figure 8 presents annual dryer energy consumption assuming 2342 pounds of clothing were dried[33]. "Lab Results with Ave Washer" columns show lab test results with staring remaining moisture of 62%. "Field Results with Ave Washer" are based on field data with the starting remaining moisture of 62%. The shaded bars show the energy use of the dryer as it actually performed in the field with the clothes washer with which it was paired. Field results of Whirlpool and LG are essentially the same with an estimated annual energy consumption of 717 kWh/yr and 742 kWh/yr respectively. The Blomberg dryer however would use an estimated 330 kWh/yr to dry the same amount of clothes.

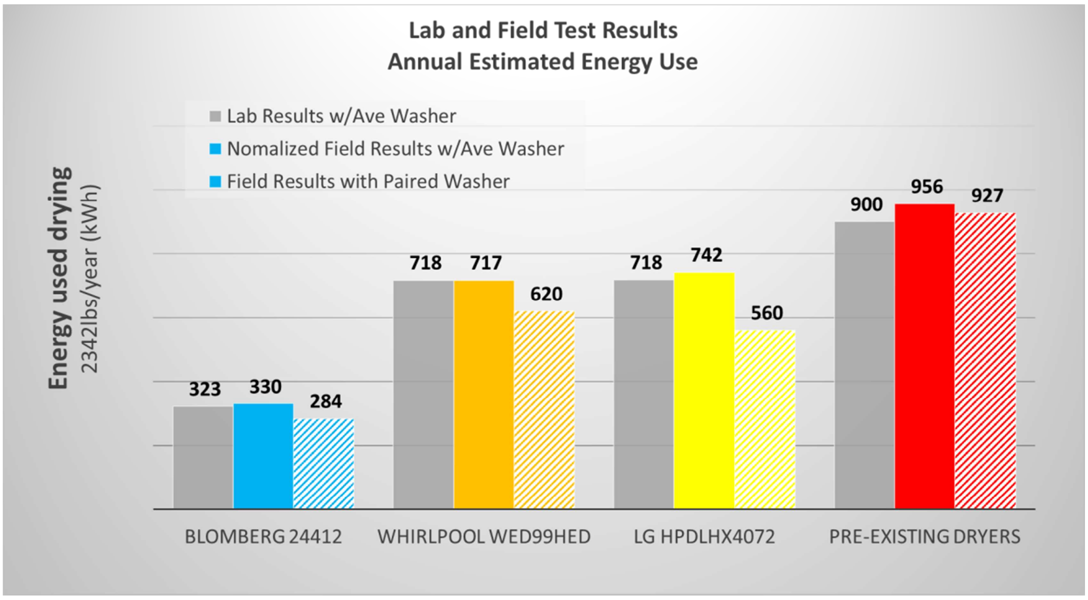

Figure 8 – comparison of lab to field results

Figure 8 also shows the difference between energy a dryer would use if paired with a typical washer that leaves the clothing at 62% remaining moisture content, and the actual remaining moisture content of the paired washer. The bright color columns illustrate the energy use if paired with typical washing machines and the stripped color columns illustrate estimated annual energy when paired with the more energy efficient clothes washer. The LG washing machine was able to spin-dry the clothes to a lower average RMC of 45% helping it achieve an annual energy consumption estimate of

[33] The NEEA field study [2] established that an average household dried of 2342lbs of clothes each year

560 kWh/yr. The Whirlpool washing machine was able to achieve an average RMC of 47% helping it achieve an annual energy consumption estimate of 620kWh/yr. The Blomberg washing machine was able to achieve an average RMC of 50% helping it achieve an annual energy consumption estimate of 284 kWh/yr.

Figure 9 shows the remaining moisture content from the clothes washers for different load sizes. The washing machines are able to extract a consistent amount of moisture in all but the small loads bin. This is consistent with lab testing of washing machines conducted for NEEA in 2015 that revealed that loads of 4 pounds or less had a higher likelihood of incomplete spin cycle resulting in higher RMC values for low weight loads. It should be noted that the data was scrubbed for incomplete cycles by removing load sizes than 2lb load sizes and RMC values greater than 100%.

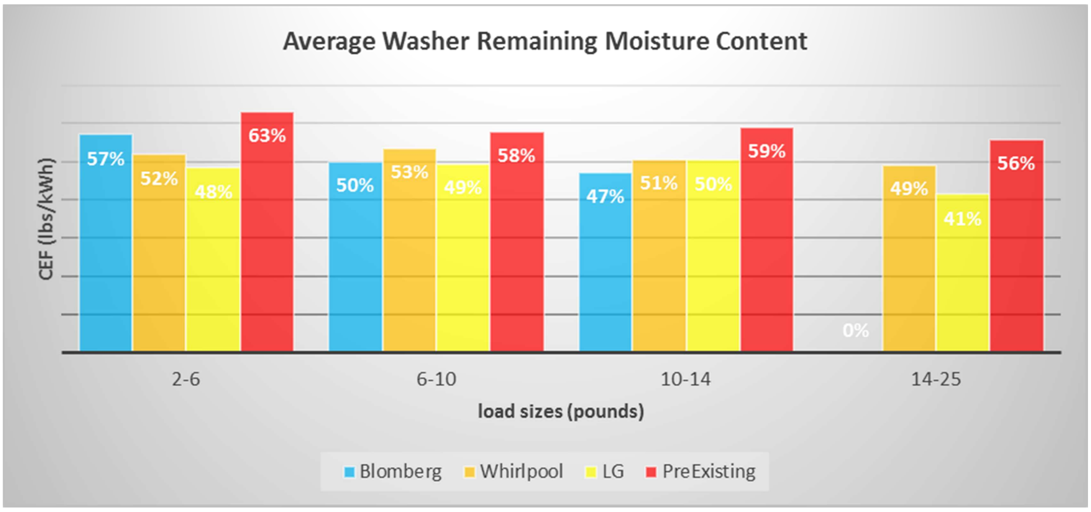

Figure 9 – Average RMC of clothing before being dried by load size bin

Figure 10 breaks out the energy savings resulting from the clothes washer and clothes dryer compared to the pre-existing dryers and washing and the baseline washing machine that leaves clothing with a 62% remaining moisture content. The graph illustrates the interdependence of the washer and dryer on overall performance. The Whirlpool dryer for example is more efficient, but the LG washer does a better job of removing moisture, resulting the paired performance being better with the LG than the Whirlpool. The washer savings of the pre-existing machines is slightly positive (29kWh) because the average RMC of the pre-existing machines in the field test was slightly lower (56%). This is because several of the homes in the field set had more efficient ENERGYSTAR front load washers.

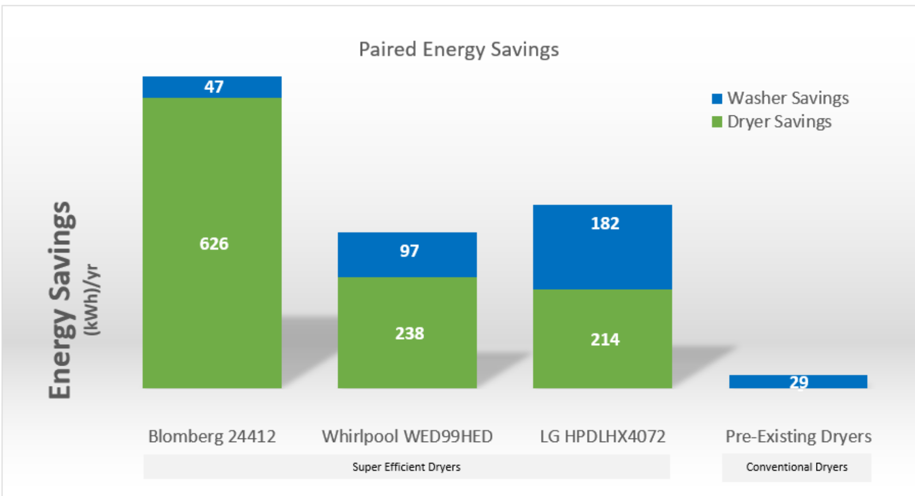

Figure 10 – Energy Savings from washer and dryer

Dryer savings of the three tested machines is consistent with savings estimates generated by lab testing and approved by the Northwest Regional Technical Forum (RTF) prior to the field tests. The RTF savings were estimated at 484 kWh/yr for the Blomberg 183 kWh/yr for the Whirlpool and LG machines.

Laundry Cycle Comparisons

Figure 11 shows dryer energy use versus the weight of the water removed. This provides a clean comparison of dryer performance independent of how well the washing machine spun-dry the clothing before it was placed in the dryer. The LG and Whirlpool machines are more efficient than the pre-existing machines, especially for larger load sizes. For small amounts of water removal, the difference between the hybrid dryers and pre-existing machines is small, whereas the pure heat pump technology used by the Blomberg dryer however is consistently more energy efficient.

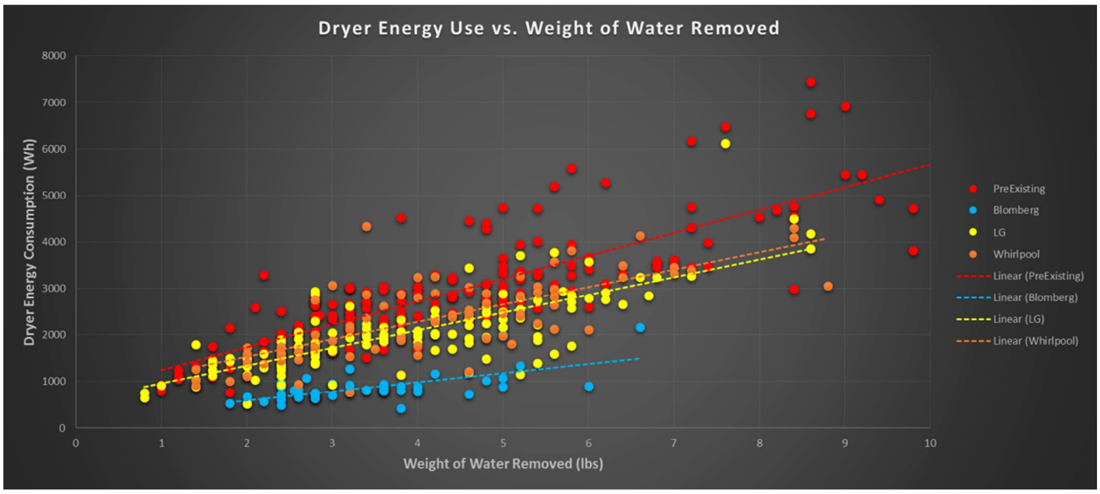

Figure 11– Wash and Dry Energy

Figure 12 shows the total energy consumed by both the clothes washer and clothes dryer compared to the cycle time of the clothes dryer. The Pre-Existing machine data his has greater variability and clearly shows very high energy for some wash and dry cycles, consuming as three times as much energy as the Blomberg pair is used for the same amount of clothing. Closer investigation of the Blomberg paired energy use revealed that the Blomberg's onboard water heater added an average 336 Wh to the wash cycle, which was not present in the LG and Whirlpool machines.

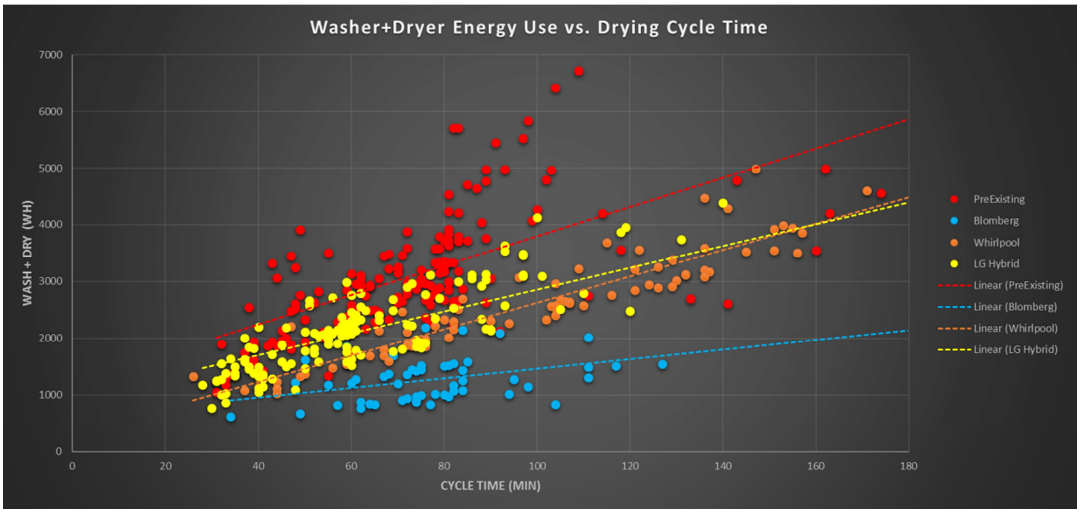

Figure 12 – Washer and Dryer Energy Use Cycle Time

UCEF Metric Calibration

Data gathered in the field was used to calibrate the weighting factors applied to each of the five supplemental test procedure CEF values. Figure 13 shows the proportion of loads used for each machine in the four field tests. Prior to this analysis the weighting factors of the five tests was assumed to be 20% on all cycles. The revised weighting factors of 10%, 30%, 10%, 20% and 30% applied to the test cycles of D2, Small, Large, Eco and Fast respectively

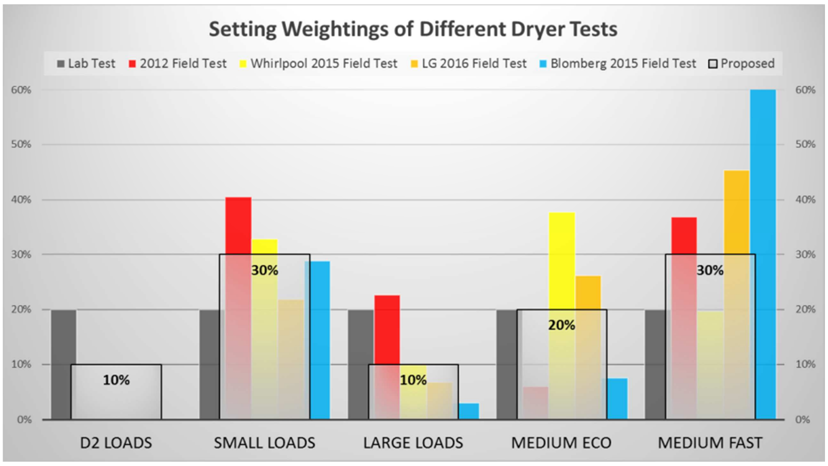

Figure 13 – Revised Weighting Factors based on real world use

Using the DOE D2 test results in an underestimation of annual energy consumption. In addition, the relative performance of different settings are not reflected in the overall dryer performance. *On average*, the D2 metric underestimate energy consumption by 33%. By comparison the energy use estimates based on the supplemental test procedure are on average within 5% real world conditions. Using the supplemental test procedure, while not perfect, is much better at characterizing the dryer energy use by not solely relying on the “as shipped” default cycle setting and testing with dimensionally simple, thin 50% polyester momie cloths as the basis for testing the dryer performance.

Summary

The field studies successfully achieved the study objectives.

First, the supplemental test procedure appears to provide an effective metric for estimating energy use of clothes dryers under real world conditions. The data enabled a change in the weighting factors applied to the five different tests of the supplemental test procedure.

Second, the savings between conventional dryers and SEDs met real world expectations, though just barely. The incremental savings of the hybrid dryers was expected to be approximately 30% better than conventional dryers. The field data however, reveals that the percentage savings was 20-25% for the first generation of US market hybrid models and 65% for the tested compact heat pump model. Recent testing of the second generation US market hybrid dryers will reveals savings in excess of 30% (see table 2).

Third, consumer response was favorable, with no major faults identified. The one issue consistently identified is the need for installation crews to reliably connect the condensate drain to the washer drain. While no long term evaluation was conducted it is reasonable to speculate that training should also be provided to instruct consumers to properly vacuum out the secondary lint filter on machines that have them (e.g. Whirlpool and Blomberg). Recent anecdotal evidence supports this assertion. Drying time may also be a factor that should be explained to consumers. When paired with a good high speed washing machine, SEDs provide drying times that are typically 10-30 minutes longer than conventional machines.

Fourth, considerable data was collected to support improvements in US federal dryer test procedures. Data collected will allow stakeholders to consider the benefit of increasing the number of tests conducted to improve the overall accuracy of energy consumption measurements and the impact of user-selected cycle settings, and user-chosen load sizes and fabric types.

Discussion

Determining how much energy a clothes dryer will use is not simple, especially in hybrid machines that employ two methods of reducing humidity in the air circulated. A performance metric is difficult to validate because of the interaction between the washer and dryer, user cycle settings and fabrics being washed and dried. Developing an absolutely accurate metric is neither necessary nor affordable. This study has confirmed the limitations of the US DOE clothes dryer test procedure. At a minimum, the following minor changes would enhance clothes dryer test procedures:

1. The normal load load sizes should be based on drum volume. 1.0 lb/ft^3 of drum volume would provide a reasonable average of the weight of clothing typically placed in a clothes dryer.
2. A small load size (e.g. 0.3 lbs/ft^3 of drum volume) should be added to capture the inherent inefficiency of under-capacity dryer cycles.
3. Testing should include at least one additional alternative cycle setting. The most logical choice is a high energy consumptive setting. This would avoid the risk of machines being shipped with default settings that are rarely used by consumers and capture a broader range of operating conditions.

A combined washer and dryer pair performance metric is worth serious consideration for two reasons. First, laundry equipment manufacturers commonly design and sell matched washer and dryer pairs for both aesthetic and customer satisfaction reasons. Second, it would simplify the overall performance estimation of laundry equipment and avoid the energy use overlap currently present in the two metrics. The current US DOE Washer metric includes dryer energy that results in both an overestimation of washer energy use, and underestimates the benefit of a pairing a highly efficient clothes dryer with a clothes washer that does an excellent job of spinning out moisture prior to drying.

Although Hybrid clothes dryers are intended to improve customer satisfaction by allowing quicker drying times, the data suggests that this benefit is only moderate. Development of full sized heat pump dryers for the US market should be possible with only moderate impact to drying time.

Data collected on laundry room relative humidity and temperature (while not presented in this report) suggests that unvented machines need to be evaluated for condensation efficiency and the amount of heat being added to the space. Further study is warranted to determine if unvented hybrid machines risk adding too much heat and moisture to laundry rooms in climates where such heat would be a disadvantage.

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Additional Relevant Resources

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Replacing HFC refrigerant with HC refrigerant resulting in 7-10% higher energy efficiency.

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Affiliation: BSH Home Appliances Corp.

Abstract

This paper presents the results of laboratory tests comparing a residential refrigerator/freezer using two different refrigerants. The results support energy efficiency advantages of R600a refrigerants compared to R134a.

Background

The two commonly used refrigerants in today's household refrigerators/freezers are R134a (HFC, Hydrofluorocarbon) and R600a (HC, Hydrocarbon). R134a is mainly used in the United States and Canada, whereas nearly all the rest of the world uses R600a. This division is mainly driven by very different safety and design standards in North America. The IEC standard does limit the charge size of R600a to 150g, whereas in the UL standard the charge size limit was only 57g.

R134a = Tetrafluoroethane[1] is a non-flammable gas used primarily as a refrigerant for domestic refrigeration. It has a GWP (Global Warming Potential) of 1,300. Because of its environmental impact there is an EPA (US Environmental Protection Agency) proposal on the table to ban it as a refrigerant by 2021.

R600a = Isobutene[2] is a flammable gas and used as a refrigerant in domestic refrigeration and as propellant in spray cans. Due to its very low environmental impact it is an ideal replacement for R134a in the US and Canada.

The main focus of this paper is to show the energy efficiency advantages of R600a in direct comparison to R134a used in one and the same product.

Besides regulatory differences between the IEC standard (International Electrotechnical Commission) and the UL standard (Underwriters Laboratories), there are also some basic differences in the properties and use of R134a vs. R600a. In the UL White Paper "Revisiting Flammable Refrigerants" you can find additional details[3].

Advantages of R600a compared to R134a

- With R600a we reach approximately 7% higher energy efficiency
- Close to zero environmental impact (ODP=0 and GWP=3)
- No need to collect and recycle, R600a can be vented into atmosphere
- No issues with illegal venting
- No negative environmental impact at end of life/ product recycling
- Lower cost (factor 25)
- Lower system pressure (up to factor 3),

Challenges of R600a

- Flammable
- Lower and Upper Flammability Limit in % by volume of air: LFL=1.8 and UFL=9.6
- Product design has to fulfill more stringent safety standards with explosion proof electrical components.

- Current UL and CSA safety standards do limit the charge size per cooling system to 57g due to its flammability. This charge amount is not enough for most of the cooling systems used in the US (using standard parts and components, like refrigerant tubing, condenser coils, etc.) and therefore it is not widely used yet. History of the standard development on natural refrigerants can be found at the UL Standards Update on Natural Refrigerants[4].

DOE Rule making

We used this direct comparison test with one and the same product to be awarded by ENERGY STAR with the 2016 Emerging Technology Award. But still there had a lot to be done to make this technology broadly available in the United States. In 2014 EPA excluded R600a from the Venting Prohibition[5], but the biggest hurdle was the charge size limit of 57 g in the UL Appliance Safety Standard (UL 250). Industry started to work together through AHAM (Association of Home Appliance Manufacturers) with UL, CSA (Canadian Standard Association) and CPSC (US Consumer Product Safety Commission) to address the charge size and harmonize with IEC for a charge size limit of 150g. This happened finally when Edition 2 of UL60335-2-24 was published on April 18, 2017.

There is still one issue in the way of implementing the 150g R600a charge for HC refrigerants in the US: EPA's SNAP (Significant New Alternatives Policy Program) is still referencing the previous UL 50g max limit. AHAM and Industry is working together with EPA to get this resolved as soon as possible.

There are four main areas the US home appliance manufacturing industry has to consider: First, the product design and layout of household refrigerator/freezers has to fulfill the UL Safety Standard requirements for flammable refrigerants. Second, suppliers for refrigeration components like compressors and valves for R600a need to be able to provide these components in 115V and with relevant UL approval for the US. Third, the manufacturing facilities and test labs have to be able and approved to handle flammable refrigerants. Fourth, Service Technician training is an important task, especially during the transition phase. Service Technicians have to be aware how to handle HFC and HC refrigerants.

Study design

The study compared the performance of a single refrigerator/freezer that met the ENERGY STAR 2016 Emerging Technology Award criteria when operating with R600a and R134a refrigerants. The test unit purchased was designed to operate using R600a refrigerant. Once the initial energy efficiency test with this unit was completed, the unit was converted to operate on R134a. This required replacing the compressor and refrigerant matched in capacity to the original unit.

The test unit was a B11CB50SSS refrigerator/freezer built by BSH Home Appliances Corp. with a refrigerator capacity of 7.7 cu.ft, and a freezer capacity of 3.3 cu.ft (see figure 1). This unit is highly energy efficient with an ENERGY GUIDE label estimated annual energy consumption of 357 kWh/a

Table	Refrigerant R134a	Refrigerant R600a
Compressor	Embraco VEMY 5 H; variable speed	Embraco VEMZ 9 C; variable speed
Compressor rpm	2000	2000
Charge amount	104 g	48 g
Stop valve	no	no
Capillary flow rate	180 l/h	180 l/h

Table 1

Test description

The appliances were tested in a test chamber and equipped with thermocouples according to the cooling performance standard AHAM HRF 1-2008: Refrigerator fitted with 3 thermocouples, freezer fitted with 3 thermocouples. They are evenly distributed between the center, top and bottom of the cooling/freezer compartment to be able to calculate an average compartment temperature, compensating for the temperature difference between top and bottom of a compartment. The power consumption and the compartment temperatures were recorded in the thermostat setting medium/medium. The energy consumption was evaluated when the unit reached steady state condition; this is an intended deviation from energy consumption determination according to AHAM HRF 1-2008. The target was to evaluate the sole impact of the refrigerant to the energy consumption. Also the energy consumption target temperature (3.9°C for refrigerator and -17.9°C for freezer) was not considered, the aim here was to achieve in both tests the same compartment temperatures.

The data logging system fulfills the requirements of the AHAM HRF1-2008 and the IEC 62552/1,2,3-2015.
The assessment of steady state was done according to the requirements defined in IEC 62552-3/2015 (evaluation time > 7 hours)

Appliance energy consumption (compressor):

Compressor	Refrigerant	Charge amount	Energy consumption	Temperature refrigerator	Temperature freezer	Compressor run time
VEMZ 7C	R600a	48 g	1,047 kWh/d	+1.9°C	-19.1°C	83.3 %
VEMY 5H	R134a	104 g	1,298 kWh/d	+1.9°C	-18.9°C	85.1 %
Appliance energy difference			23.9%			

Table 3

Compressor data:

Compressor	Refrigerant	Cooling capacity	Power consumption	COP (Coefficient of Performance)
VEMZ 7C 115V/60Hz	**R600a**			
CECOMAF [(1)] (catalogue data) (-25°C/+55°C) @ 2000 rpm		77 W	43 W	1.81 W/W
Calorimeter data (-25°C/+45°C) @ 2000 rpm		80.9 W	42.1 W	1.92 W/W
VEMY 5H 115V/60Hz	**R134a**			
CECOMAF (catalogue data) (-25°C/+55°C) @ 2000 rpm		88 W	51 W	1.72 W/W
Calorimeter data (-25°C/+45°C) @ 2000 rpm		92.8 W	52.7 W	1.76 W/W

Table 4

[(1)] CECOMAF Comite Europeen des Constructeurs de Materiel Frigorifique

Equivalent to the US organization ASHRAE (American Society of Heating Refrigerating and Air-conditioning Engineers)

Analysis

In order to get the impact on energy consumption contributed solely to the refrigerant, all other factors influencing energy consumption have to be excluded. To eliminate product to product tolerances (due to tolerances between different components), the compressor was the only component changed. This change was necessary due to the higher pressure needed for the R134a refrigerant. I want to add here a special remark about the compressors for R600a:

> In Europe nearly 100% of the market is R600a and the EU energy efficiency requirements are more severe than in the US. ENERGY STAR Most Efficient requirements are approximately 25% less stringent than the European EEC A+++. In order to reach this, appliance manufacturers had to implement product and component enhancement like the use of vacuum panels and more efficient compressors. The compressor manufacturers were able develop today's high energy efficient compressors for R600a with a better COP than the current R134a compressors.
>
> We also have to consider the impact of the condenser temperature on energy consumption: +1K results in 2% higher energy consumption. The corrections for compressor COP and condenser temperature differences are lined out in table 5.

	R134a	**R600a**	**delta**
Energy consumption test result	1.298 kWh/d	1.047 kWh/d	23.9%
Condenser temperature	40°C	36.5°C	-7%
Compressor COP	1.76 W/W	1.92 W/W	-9%
Final difference based solely on refrigerant			7.9%

Table 5

Conclusion

This test shows that there is an energy efficiency advantage of R600a compared to R134a of 7.9% and confirms general statements in literature claiming a 5% - 9% advantage.

Discussion

In this paper I wanted to show the complex interactions and different aspects that have to be considered when introducing a new technology to the market.

1.) The safety standards as well as energy and environmental regulations have to be ready and in place to be able to introduce this new technology to the market.
2.) Manufacturers have to adapt their products and their manufacturing processes.
3.) Certification and Verification bodies have to be able to certify and test the new technology.
4.) Customer Service has to be trained and ready to give every customer the product service they need.
5.) End of Life and handling of the products in the recycling chain has to be considered.

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11 DRYERS

Thinking Outside the Box: The clothes drying process is more than the dryer

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Abstract

Energy efficiency efforts typically focus on reducing the energy consumed by a single piece of equipment such as a clothes dryer. However, to the consumer, laundry is a process which produces clean, dry items ready to wear or put away.

Dryers are installed and used in about 80% of US households. European dryer installation is around 50%; conversely, iron use for wrinkle removal is much higher. Dryer penetration in Asian countries is lower still. While use of a clothes washer is common, the drying process includes more variation even when the household has access to a dryer. For example, laundry from the washer may be separated, with delicate items going on a drying rack and the remainder into the dryer.

The laundering process generally adds heat and humidity to the immediate area, possibly impacting occupants and building. Individuals may use clotheslines or drying racks, heated racks such as towel bars, clothes dryers, irons or clothes presses, depending on weather, fabric type(s), available time or space, sanitization need, urgency, convenience or a preference for a certain smell or feel.

Observations from a prior field study and informal interviews were used to capture residential environment, dryers and behavior, creating a holistic view of the laundry process in multiple countries. The variations recorded suggest that further research may be needed to guide residential laundry energy efficiency efforts; aggregate savings depends upon both the energy efficiency individual measure and the percentage of drying process choices actually using it.

Overview

Energy efficiency efforts typically focus on reducing the energy consumed by a large appliance such as a clothes dryer. However, from the consumer point of view, laundry is a process which produces clean, dry items ready to wear or put away. More detailed knowledge of the actual consumer process can lead to more insight into adoption of energy efficient appliances and other behavioral aspects. This paper presents the laundry drying process as observed in situ and as described by respondents.

Creating a holistic view of the drying portion of the laundry process is not a laboratory subject. Individuals choose to use an outdoor clothesline or drying rack, the indoor equivalents, a heated rack such as a towel bar, a clothes dryer, an iron, or a clothes press – often a combination thereof. The selection for a given load depends on the weather, the type of fabric, available time or space, the need to sanitize laundry, urgency, convenience or a personal preference for a certain smell or feel.

According to US Energy Information Administration (EIA) figures, dryers are installed and used in about 80% of US households. 1 Many US households own an iron, but during their field study and interviews, the authors did not observe regular iron use at any US site. Dryer installation in Europe is often around 50%; conversely, iron use for wrinkle removal is much higher. 2 Anecdotal accounts suggest that dryer penetration in Asian countries is lower still, with a larger dependence on clotheslines.

The data reported here was obtained from observations during a prior field study of dryers 3, and informal interviews with others who live or have lived in N America, Europe, the UK, Asia and Africa. It is not intended to be a large-scale, statistically valid collection of data, but enough to indicate the variety in laundry processes as actually practiced.[34]

[34] South and Central America, India and Australia are omitted from this discussion because the authors have no direct information from these areas.

Methodology

During in situ testing of dryers 4, the authors recorded their observations, and asked the hosts about laundry practices. In addition, informal interviews were conducted with other individuals who live or have lived in N America, Western Europe, the UK, Africa, and Asia. Questions were deliberately open ended, to avoid introducing survey bias. When possible, information was obtained through conversation rather than specific questions.

The information sought includes:

1. What types of loads or items do not go in the dryer? How is that decision made?
2. For those loads or items which do not go in the dryer, how are they dried? How is that decision made?
3. Does your household iron laundry? What percentage? How is that decision made?
4. What % of year or loads is done with each combination of methods?
5. Have the household laundry practices changed over time?
6. From your own observations, do your parents or extended family make different laundry decisions? Why?

Questions were independent of dryer fuel to the extent possible, focusing primarily on the laundry processes.

Respondents' locations are indicated on the map in 0.

Locations of respondents

Note: Locations in Asia and Africa not shown.

No attempt was made to match the collective socio-economic characteristics of the respondents with those of the populations as a whole. Other research, such as the DoE scoping study on dryers, have done statistical surveys covering individual appliances. 5 The purpose of this data was to document the variety of drying processes used, rather than to create a statistically valid model with closed questions.

Drying systems

Energy efficiency and household demand studies don't always include drying processes other than clothes dryers. For example, REMODECE 6 assessed select appliances in European homes with at-the-plug measurements; dryers were measured, but not irons. RECS 1 and RBSA 7 also measured dryer energy consumption, but not that of irons, in US residences. Indirect laundry costs of dehumidifiers, fans or air conditioning were not identified in either study, although some of these devices were included as miscellaneous electric loads (MELs).

Drying system may be any, combinations or all of:

- Outdoor Clothesline
- Dryer (fully dry)
- Dryer (damp dry)
- Indoor line or rack
- Drying cabinet or room
- Dehumidifier
- House or room air conditioner[35]
- Iron or clothes press
- Fan

Hosts of dryer testing sites and others interviewed were asked about their use of combinations of these items.

The laundry work flow may also include any or all of transferring laundry into or out of the machine(s), hanging it on a clothesline or hanger, ironing it or folding it. The laundering process generally adds heat and humidity to the immediate area, possibly impacting the occupants and the building. While use of a clothes washer is common, the drying processes includes variety even when the household has access to a clothes dryer. For example, a load from the washer may be separated, with delicate items going on a drying rack and the remainder into the clothes dryer.

Europeans interviewed by the authors hung most garments to dry, even if they owned a dryer. In fact, 40% of those approached for an interview did not even own a dryer.

How much goes into the dryer?

We observed that most of the household laundry is done at the residence; however, there were some exceptions. Several respondents in the US and Japan used laundry services for business attire which needs pressing; they did not iron at home. Others in rented housing without convenient laundry facilities also sent their laundry out to a service.

How much of the household laundry is put in a tumble dryer? The answers ranged from everything ("my wife doesn't have time for clotheslines" 8), to partial loads ("I don't put hand knits or sweaters in the dryer" 9), to nothing ("you do realize that we don't own a dryer" 10). In Western Europe and the US, not owning a dryer is usually a matter of choice, but in Zambia and other nations without always-on electricity, there is no point, and there are a large number for whom a dryer is simply not affordable.

Observations

Energy consumption was rarely mentioned by respondents. It was primarily a factor in the initial purchase, not in the ongoing use. Two respondents, one in the US and one in Europe, stated that they chose their dryer based on energy consumption ratings. 1112

[35] Air conditioners remove humidity from the air as they cool it; the moisture condenses along the cooling coils and is typically collected in a tray or dropped directly into a drain.

Fabrics

Fabric differences contribute to difference in the laundering process. A check of the racks in several US clothing chains revealed that most garments can be both machine washed and machine dried. In contrast, the racks in a similar number of Austrian and German apparel stores[36] revealed that most adult clothing is marked as either hang-dry or dry-flat. The notable exceptions were denim jeans, which were typically marked "tumble dry". However, care labels in children's apparel in those stores instruct the purchaser to tumble dry the garments.

European clothing is often not intended to go in the dryer. An examination of care tags in several German clothing stores showed that only about 1 garment in 15 is intended to go in a dryer. Children's clothes, much like those in the US, were labelled "machine dry".

Fabric differences contribute to differences in the laundering process. European garments often do not have a permanent press finish; this initially was avoidance of patented processes. Later however, it became a part of the "less chemicals" aspect of culture, especially in Germany.

Pre-shrinking of fabrics also has an effect; fabrics which are not pre-shrunk have a greater risk of shrinkage in the dryer. A check of the racks in several US clothing chains revealed that most garments can be both machine washed and machine dried. In contrast, the racks in a similar number of German apparel stores revealed that most adult clothing is marked as either hang-dry or dry-flat. However, German children's apparel is intended to be machine dried just as it is in the US.

Several US respondents mentioned that hand-knit garments were not put in the dryer, but instead laid flat to dry. Others mentioned "performance fabrics", such as the wicking under layer garments worn for sports, as items which did not go in the dryer.

Perceived fabric wear is also a reason not to put items in the dryer; delicate fabrics such as loosely woven gauze, trims such as lace, hand-made buttons, and elastic used in lingerie were all cited.

Outdoor drying

Clotheslines, and railings were the two methods mentioned most often. Respondents who had lived in Japan reported that laundry, especially bedding, was hung on balcony railings whenever weather permitted. 1314

However, some respondents did not hang outside. One cited privacy in a small town, "I couldn't do that to my family." 15

Indoor drying racks, clotheslines, and substitutes

When weather or location does not permit outdoor drying, European respondents hung most garments indoors to dry. Most of the respondents hung laundry inside the dwelling, in conditioned space.

If clotheslines were available in the laundry area, these were often used, although in one apartment building in Lubeck, Germany, the laundry area was so damp that the windows were left open for air circulation. The laundry area with the open windows became too cold in winter for anything to dry, so clothes were dried inside the individual apartments during that season.

US respondents who hang dry followed the same seasonal patterns as European respondents, except for those in cold dry climates such as Montana. Laundry was often hung outdoors even in winter; the low humidity caused clothes to dry even at freezing temperatures.

In inclement weather, respondents in Japan was hung laundry indoors on drying racks or furniture.

[36] In a 30-day period in 2016 the authors visited apparel and white goods stores in Vienna, Moers, Munich, Portsmouth, Chicago and Seattle, examining garment care labels and noting dryer features and Energy Star and EnerG labels.

Interestingly, some US respondents who had lived in Europe or Japan reported continuing to hang dry garments even after their return to the US. 1116

Convenience and drying time

There is a seasonal variation in dryer use. Both respondents in these data and the REMODECE indicated that clothes dryers were more likely to be used in the winter. 2

There is also variation between dryers. Average drying times for sample loads of bath towels, as measured by the authors, is shown in Table 1 below for several dryers tested in situ. The heat pump and the compact dryers take longer than standard models.

Table 1. Average drying time for a load of bath towels

Drying process	Dryer volume (l)	# of towels	Location	Average drying time[37] (minutes)
Electric dryer, basic model	170	6	Montana, USA	98
Gas dryer	198	6	Washington, USA	64
Heat pump dryer	118	6	Nordrhein-Westfalen, Germany	188
Electric dryer, basic model	115	4	Hampshire, England	49
Electric dryer, mid-range model	200	6	New York, USA	55
Compact electric dryer	102	4	British Columbia, Canada	124

Source: Authors' unpublished data.

Residents in older houses or apartments with steam radiators reported laying laundry on those radiators for faster drying, both in Germany and in the US.

A respondent in Zambia, who did not have access to either a washer or a dryer, did laundry in the evening and hanging outdoors. The exception to this practice involved hanging laundry indoors in front of a fan "if I needed a shirt dry for the next morning." 17

Accuracy (or inaccuracy) of dryer termination

Although automatic cycle termination is advertised by dryer manufacturers, many respondents were not using it. "The automatic cycle never works. I've just learned how long to run the dryer for different types of loads," was a typical comment. 18

Load size affects the operation of auto-termination; at most test sites, neither very large nor small loads are handled well. Heavy fabrics or multilayer items such as bath towels, quilts, jackets, or duvets also are not handled well; the outer layers are dry while the inner layers still contain moisture.

Ironing

While casual business attire is becoming more common in the US, outside of North America ironed shirts are viewed as professional dress. Growth of the steam iron market in 2016-2024 is estimated at 5% CAGR worldwide 19. Electrification increases the possibility of irons. Iron penetration in the EU is 98% 2. Although nearly as many US households have an iron 1, few use it regularly, due to the prevalence of permanent-press fabrics and the acceptance of the casual look at work.

[37] Because these times are for cotton terry bath towels, ironing is not included.

One German respondent uses the “damp dry” cycle on her dryer, which intentionally leaves the load damp so that it is ready to be ironed immediately. When asked if ironing was a waste of time because she could be doing something else, she replied, “But when else would I watch TV?” 12

Although pressed clothing is an indicator of professionalism, long-term, unpredictable rolling blackouts in Zambia and other developing countries have increased acceptance of un-ironed clothing. Zambians often revert to using charcoal-powered irons during blackouts. 17

Several respondents in the US and Japan used laundry services for business attire which needs pressing. “I take my shirts to the cleaners so they come back pressed. But if I forget, I throw one in the dryer on the steam cycle and the wrinkles come right out.” 8

Yet despite worldwide use, irons are very rarely included in studies of household energy use. One explanation is irons’ very familiarity. “The electric iron has been around so long and is so ubiquitous (11 million are sold each year in the U.S.) that many users never give it a second thought. Irons just ‘are’.” 20

Building considerations

Dryers add significant heat to their surroundings, which can be very noticeable if the dryer is located inside conditioned space. While it may be obvious that this additional heat is undesirable in hot climates, the effect in heating climates is not as clear. Respondents in both Washington State and Idaho described uncomfortable heating from dryer operation during the warmer half of the year even though these are both considered to be heating climates.

In urban Japan, respondents indicated that the extreme small size of apartments generally precludes owning a dryer.

Standalone dehumidifiers[38] in the laundry area were observed in 11% of the sites visited, and air conditioning in 12%. The drying process is driven by the difference in partial pressure of the water vapor between the surface of the laundry items and the air surrounding them, typically the air in the dryer drum. Anything which increases this pressure difference, such as dehumidifiers or air conditioners, improves the overall efficiency of the process, but may also increase the household energy consumption because it is removed laundry-related moisture as well as ambient moisture.

Local Ordinances or Codes

Although the lowest-energy drying process is outdoor clotheslines followed by minimal ironing, hanging laundry is prohibited in some locations. For example, respondents living in homeowner or neighborhood associations near Chicago, IL, Phoenix, AZ, and Lubeck, Germany, reported that covenants prohibit the hanging of laundry outside. The Glasgow study 36 also reported that condominium associations prohibited hanging laundry on balconies.

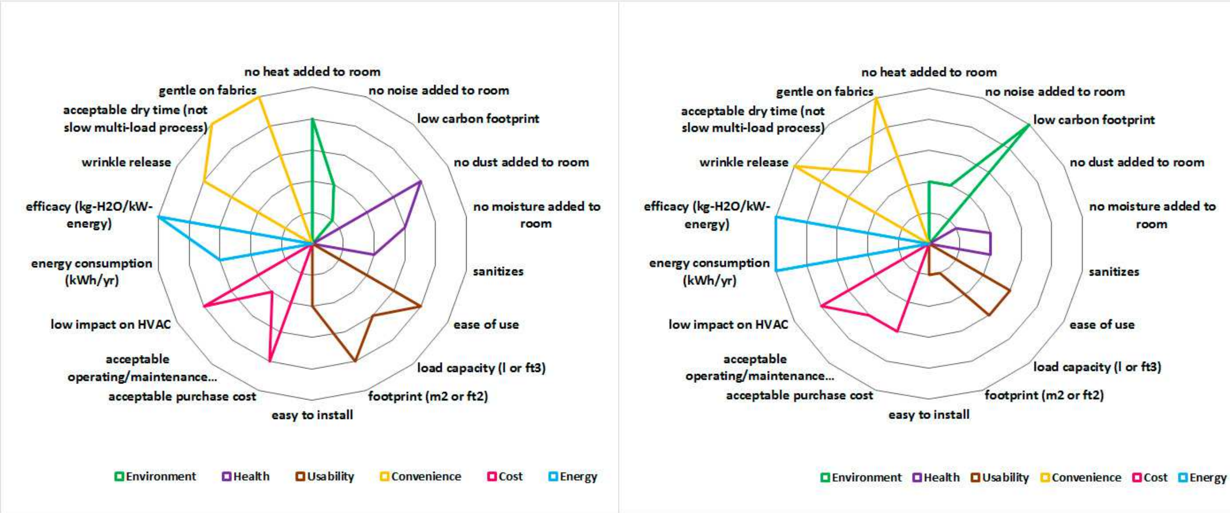
Interestingly, there is one area near Lubeck in which hanging laundry along the river banks is strongly encouraged because the practice has a history of several hundred years in that location.

Respondents’ preferences

As a qualitative summary of preferences, respondents’ responses were mapped onto radar charts such as those in 0. On an arbitrary scale of 1 (innermost ring) for not very important, to 5 (outermost ring) for very important, attributes are grouped into general categories for Environment, Health, Usability, Convenience, Cost and Energy. Each category of preferences is shown with a thick line, using different colors so that the categories can be easily distinguished.

[38] Whole-house dehumidification associated with the HVAC system was not included in this calculation; hosts at the 11% (sites with standalone dehumidifiers) had added dehumidifiers in the laundry area specifically to deal with moisture from the laundering process.

On the left is the radar chart for one respondent who values convenience and usability highly; on the right is a different respondent who places higher values on Environment and Energy. Note that these radar charts are not an evaluation of whether or not the authors agree with the respondent's preferences, but rather a way of visualizing those preferences.



Preferences for drying system attributes. Left: Site 01, Right: Site 36.

Source: Interviews by authors.

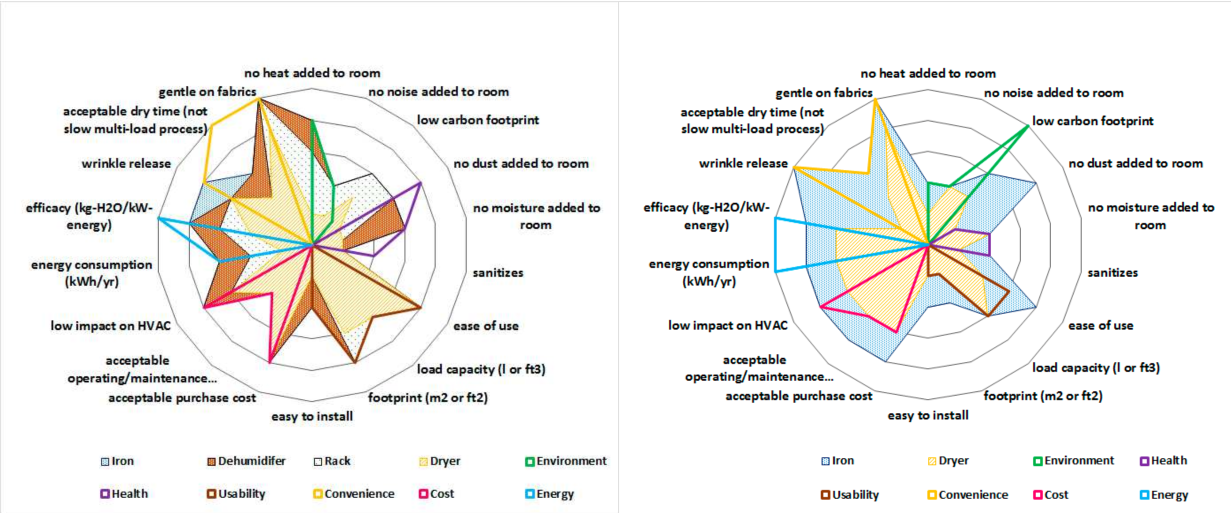
After a respondent's preferences were mapped, the diagram was shaded in with the elements of their drying system, to illustrate that the desired result (clean, dry, ready to use items) is accomplished by a combination of methods. In 0, on the left, the diagram shows that at Site 01 laundry may be but in the dryer or hung on a rack. A dehumidifier is used to remove moisture from the basement which contains the laundry area. At Site 36, on the right, laundry is often damp-dried in the dryer (yellow shaded area), then removed and ironed (blue shaded area).

These diagrams are deliberately done on an arbitrary scale, to avoid implying that they are quantitative. They are subjective, because the respondents' preferences are inherently subjective.

Respondents' memories

Many respondents recounted childhood memories hanging wash outside, followed by ironing nearly all items, from handkerchiefs to bedsheets, shirts and pants.

Several reported helping their grandmothers do laundry using wringer-washers – open tubs with motorized agitators and wringers (tightly spaced rollers, either hand cranked or motorized) for removing water from the clean, saturated laundry.



Drying system elements as compared to preferences. Left: Site 01, Right: Site 36.

Source: Interviews by authors.

One recalled his mother doing laundry in an outdoor tub of boiling water during and after WWII in Denmark. The boiling water, heated by an open fire, minimized the spread of disease, a very real risk in their situation at that time. An unvarnished wooden rod was used to remove laundry from tub, protecting hands from the boiling water. 21 The authors recall similar experiences in the 1950s in rural America.

It is worth remembering that although outdoor hang drying and irons are more than 2000 years old, the powered washing machine is only 100 years old and the tumble dryer even younger. The laundry process has changed much in one lifetime.

Discussion

History and changes

Drying processes are not static; there is a strong temporal component as technology develops, community norms change and people age. The first powered washing machines were introduced approximately in 1910; they achieved wide installation in the 1940s. Irons (heated surfaces) were used during the Roman Empire, BCE. Metal irons heated externally by fire or stove were used by many respondents' grandmothers. Charcoal-powered irons are still in use in some parts of the world. 15 Household electric irons were introduced in the US in 1915, and steam irons in 1926, but ownership in rural areas lagged due to the slow spread of electrification. 22

The rise of eco-consciousness has driven additional changes in laundry practice. As an example, in a German online survey about washing machines, 51% said low energy consumption was important, and 43% said low water consumption was important. 23

Efficiency of time (dryer cycle time, eliminating ironing)

In the US, one manufacturer advertises its extra-large 9-cubic-foot dryer as "the fastest", emphasizing the convenience of saved time. Some new models from another manufacturer have a "super speed" mode.

The German washing machine survey indicated that the two “special functions” (modifiers to the chosen cycle) which used most frequently are “express washing” and “energy saving”, in that order. 23

An early USDA report cited a time-and-motion study which concluded that the use of tumble dryers saved 10 minutes per load as compared to hang-drying indoors, and 13 minutes per load as compared to hang-drying outdoors. 22

Other factors

Noise or quietness of the dryer wasn’t mentioned by any respondent. This may be because, unlike other appliances such as dishwashers, the laundry is not usually in a frequently occupied room. US Energy Star labels for dryers do not list sound levels. European EnerG labels do list the sound level; however no one mentioned this as a key determination of which model to purchase.

While noise perception is very individual, it can become a factor. In a Florida field study of heat pump dryers, noise was cited as a reason for disliking the dryer. 24

If price is an issue, first cost (purchase and installation) appears to be more important than operating cost (energy use). When US respondents were asked why they purchased the particular model of dryer, typical responses were, “It was on sale.” 25 and “I chose the washer I wanted and it was cheaper to buy the pair together.” 26

Wrinkle release

Many fabrics, especially those used in North America, include chemical wrinkle-resisting treatments or crease-setting treatments. These have an activation temperature of approximately 50^{o} C (122^{o} F) 27; drying processes which do not reach this temperature do not achieve the expected less-wrinkled condition, creating customer dissatisfaction. Wrinkle release temperatures are typically achieved via dryer cycle temperature setting.

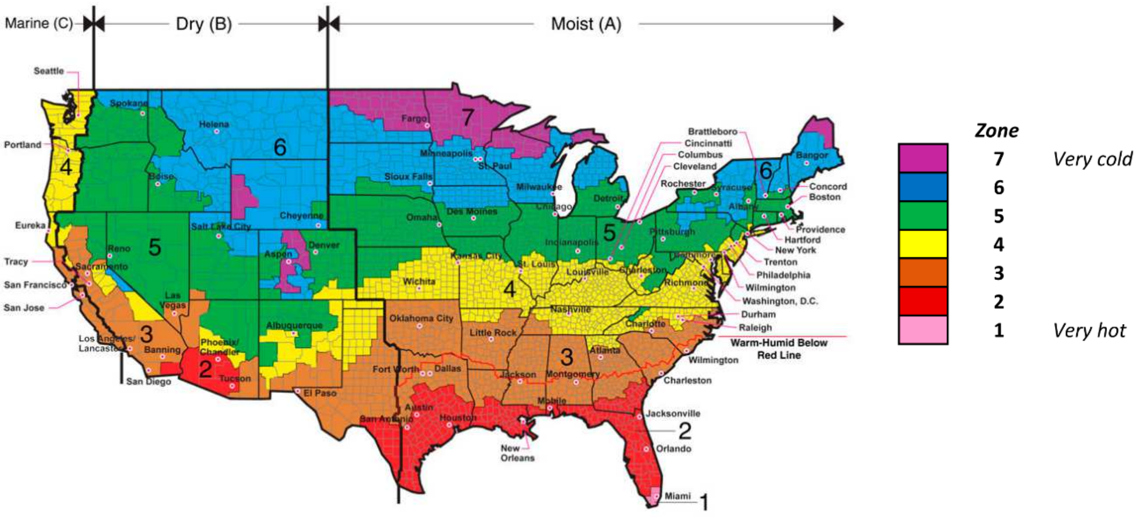
Since the early 2000s, dryers with a “steam cycle”, high-temperature steam injection into the drum, have been on the market. These cycles are expected to provide wrinkle release; it is up to the consumer to decide if they are efficacious because no objective test is published by the manufacturers. Consumer Reports’ (CR) analysis of the steam cycles indicated that dryer steam cycles were effective at reducing wrinkles and odors in small- to medium-size loads. 28 However, CR indicated that when run on maximum size loads, the steam cycles were often not as effective at wrinkle release as an iron. 29

Climate

The drying process is driven by the vapor pressure difference between a fabric and its surrounding environment. Tumble dryers increase this difference by either raising the temperature in the drum (thus lowering the relative humidity) or by purposely dehumidifying in the drum. Outdoors, fabrics will dry rapidly if the ambient temperature is above 0^{o} C (32 ^{o} F), has low relative humidity (< 30%) and sufficient air movement to ensure that the boundary layer of air (the thin layer just over the surface of the fabric which contains the moisture just released from the fabric) is replaced with dry air.

At moderate humidity levels, less than 45%, laundry will dry albeit taking longer. Climate zones for the US are shown in 0.

As the outdoor humidity increases above 60% the speed at which the fabric dries slows significantly while risk of molds increases. However for many areas of the northern hemisphere those conditions favorable for outdoor drying exist for nearly half of the year.



Climate Zones in the US.

Source: Original chart from ASHRAE 30. Colored version from www.iaqsource.com. Zone criteria may also be found in IECC 31.

It might be expected that the warmer weather in the southern US would encourage outdoor hang-drying. However, in the arid Southwest, wind frequently brings dust storms which coat everything in a layer of dirt. Cold weather does not preclude hanging laundry outdoors. One study reports that Canadians hang laundry outside for approximately 3.5 months per year. 32 Several Montana respondents report hanging laundry outdoors for 5 months per year. 2518 Clothes dryers that the authors observed in situ were designed to work in an indoor conditioned space. This creates broad market applicability but does not take advantage of favorable outdoor conditions when they exist.

Ventilation

Both dryer exhaust and dwelling ventilation are covered by the International Mechanical Code (IMC) or locally adopted codes.

There are no explicit requirements for ventilation of residential laundry areas. Section 401 of the IMC declares that “Every occupied space shall be ventilated by natural means … or by mechanical means… Ventilation shall be provided during the periods that the room or space is occupied.” 33 Rooms, including laundry rooms, which have neither openings to the outdoors nor mechanical ventilation, are permitted to ventilate through an adjoining room providing that the access meets minimum size criteria, and ventilation for the entire residential is adequate for the total floor area, including the interior room(s).

Neither the IECC nor the IMC specify ventilation needs for indoor hang-drying. However, the Glasgow study found that indoor hang-drying is often accompanied significant increase in humidity and by opening windows for ventilation 36. Comments from our respondents are consistent with this conclusion.

Energy efficiency studies

“Other” drying is not always included (unless whole-residence metering is used). For example, in the US, an electric towel bar in the bathroom would probably be counted as a MEL (Miscellaneous Electric Load) along with mobile phone chargers, display cabinet lighting, etc., while in Europe it might be heated from the hot water boiler, thus being included with water heating or space heating.

Irons or clothes presses are rarely seen in audits of residential energy use. European households do laundry 3-5 times per week 2. The Europeans who were interviewed iron many of their clothes, and irons range from 750W to 2000W. Using a typical 1000W iron for 15 minutes four times per week adds up to 52 kWh/yr. While this is less than the 400 kWh average annual energy consumption of a European household's dryer 5, it is by no means insignificant. While US households seem to iron less frequently, 95% own an iron. 34

Another factor is presented in the results of the Glasgow study: "The trend of opening windows and/or boosting heat while drying [hanging indoors] has been calculated to more than double a space heating load in January in a naturally ventilated home." 36 This additional HVAC burden due to indoor hang-drying of laundry is rarely identified separately. Instead, these effects are hidden in total HVAC usage tied to winter weather.

Energy Labeling

Labeling is done differently in the EU than in the US and Canada. The European EnerG labels, as shown in 0 give the appliance a rating from A+++ to G in addition to a standardized energy consumption estimate. The plusses were added as standards tightened, so that a model with an A rating still had that rating when newer, more efficient models were introduced. The US has two separate processes; the Federal Trade Commission (FTC) determines which appliances must have an EnergyGuide label showing a standardized energy consumption estimate, while the Department of Energy (DoE) sets the pass/fail criteria for appliances to be awarded Energy Star rating.

Unlike the EU approach of adding plusses to ratings, the US DoE has taken a different tack; when the standards are tightened, older models still on the market may no longer qualify for the Energy Star label. While Energy Star ratings for dryers became effective in 2016, there is still no defined EnergyGuide label for dryers. At this writing, the situation does not seem likely to change in the near future.

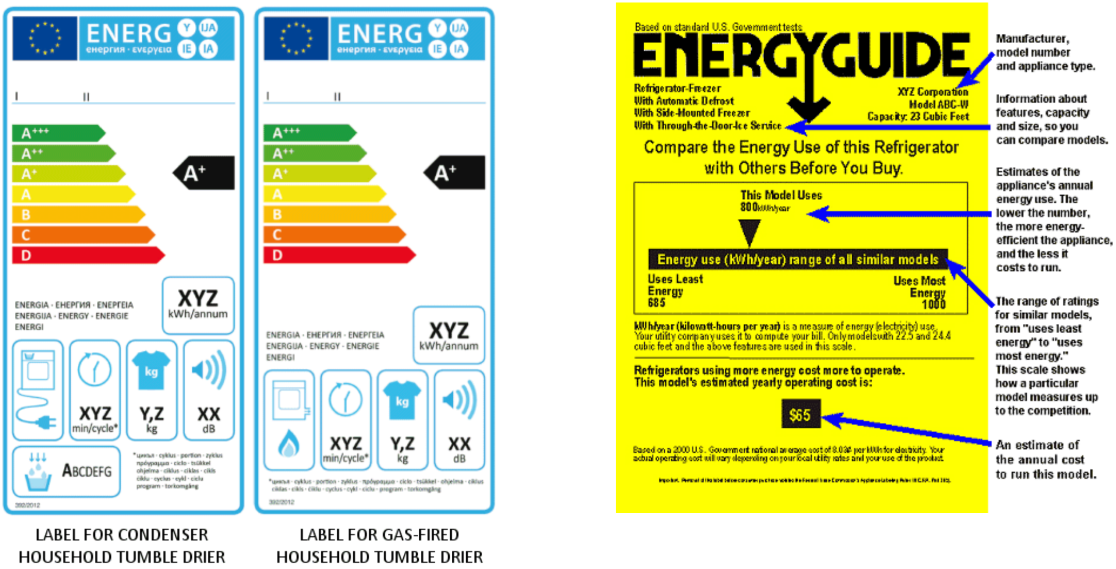
European dryer labels contain more than just the calculated annual energy use. There is also the definition of the load capacity for a standard cotton load, and the cycle time for that load. The EU EnerG label also shows the sound level of the dryer in operation. For condensing dryers only, a rating from A to G of the dryer's water removal efficiency is required. EnerG labels allow consumers to match their preferences (the "spider diagrams" in 0) to appliance features. Two German respondents with newer dryers indicated that they considered the moisture removal rating to be more important than the energy rating. 12 35

Standard loads are for generating Energy Star, EnerG, and other ratings, thereby comparing machines against each other. Standard loads represent the mode (mathematically) – the most common type(s) of loads, not necessarily the ones which consume the largest fraction of energy, nor the ones which would be easiest to improve. In fact, dryer performance for the standard loads may be the most difficult to improve; because the results are very public in the form of Energy Star certification and EnerG ratings, dryer manufacturers have an incentive optimize performance for those loads.

Although the load size is specified on the EnerG label, this is not the recommended load size for most types of loads. A Siemens dryer user manual shown to the authors by one testing site host had a dense two-page table of load definitions and recommended load sizes. 12 11 Although the dryer's label showed it to have an 8.0 kg capacity, that specification only applied to standard cotton loads. Load sizes for all other load types were smaller; some were as small as 1.0 kg. Of the 11 load types lists, the median capacity was only 2.0 kg. When asked how to determine load size, all but one appliance salesperson could not explain. The one stated that he recommend customers buy a scale and weigh each load. None of the respondents actually did so; instead they used heuristics such as "If I can just stick my arm into the dryer above the wet load, that's the right load size." 1235

The manuals of dryers at our US test sites did not indicate measurable load size. In general it is assumed that the user already knows how large a "small" or "large" load is.

Estimates of dryer energy use are based on the energy required to dry the standard loads, multiplied by an assumed number of loads per year. Actual consumption of a dryer installed in a consumer's residence depends on all the other factors discussed here, plus the effect of the number of persons in the household. The Glasgow study found that energy ratings on laundry appliances did not correspond well to the energy consumption measured in situ. 36



How to read energy labels: Samples of EU EnerG (left) and US EnergyGuide (right).

Sources: EU: http://www.newenergylabel.com/uk/labelcontent/tumble_driers. FTC: www.consumer.ftc.gov.

CO_2 production

Eco-consciousness is part of some respondents' concerns, as previously discussed. The choice of dryer to purchase is based on its perceived earth-friendliness. Sometimes reality and perception do not precisely align.

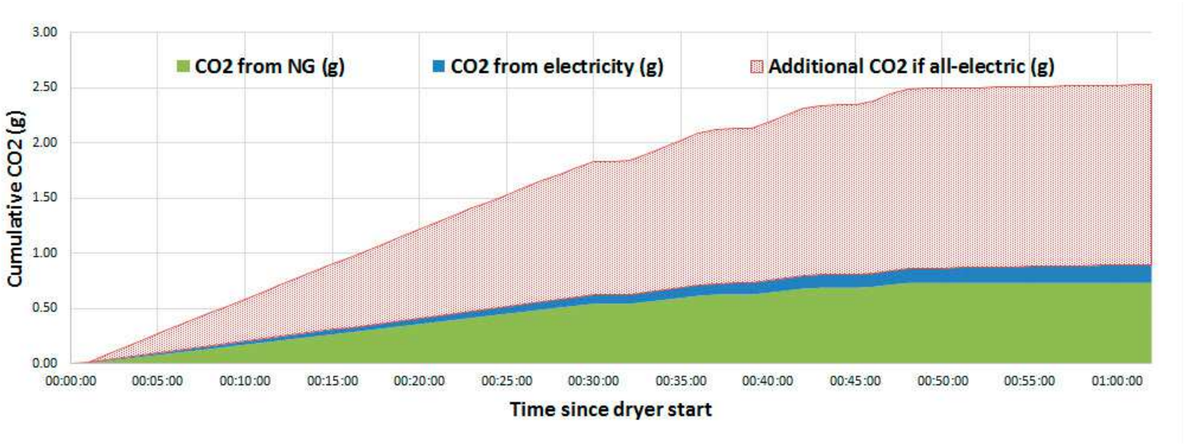
The CO_2 production of an electric dryer is directly proportional to the carbon footprint of the electrical grid. This varies by location and is generally improving every few years. The world's electrical grids may become carbon free at some point in the future; however, they are not carbon free at present. EIA figures indicate that electrical generation in the US releases 0.52 tonnes of CO_2/MWh; approximately 40% of electrical generation in the Pacific Northwest region comes from hydroelectric dams, so this region releases 0.30 tonnes-CO_2/MWh. 37 European numbers from the EEA show 0.39 tonnes-CO_2/MWh for the EU-27. 38

While the same applies to the electricity consumed by the motor, blower and controller of a natural gas dryer, this was measured to be a much smaller fraction (approximately 7% for dryers tested by the authors) of the energy consumption of the dryer. The carbon footprint of the gas consumed can be calculated from stoichiometric equation of combustion of the average natural gas stream and the average heat content of natural gas[39]. 39

0 shows the cumulative CO_2 production for a load of 6 bath towels in a low-end natural gas dryer in N America. Electric consumption was measured directly; gas consumption was calculated from measured burner-on time. Measurements were taken approximately once per second.

The CO_2 generated from natural gas combustion totaled 0.73 g of CO_2, shown in green; electric consumption generated a total 0.16 g of CO_2, shown in blue. The production is not linear, due to on/off cycling of the burner.

[39] Heat content of natural gas varies slightly by season due to temperature affecting density. An average heat content of 3810 MJ/m^3 (1.02 Thm/ft^3) is used for these calculations.



Cumulative CO_2 production for six-towel load in low-end gas dryer in US

Source: Authors' unpublished data.

As a reference comparison, if the natural gas had been replaced by the same number of (heat-equivalent) kWh of electrical heat, additional CO_2 would have been produced, due to the carbon footprint of electrical generation. The additional 1.63 g of CO_2 produced is shown in the red crosshatch. The fact that a natural gas dryer produces less CO_2 may not seem obvious; it is largely due to the inefficient transfer of heat from electrically heated wires to air.[40]

Other studies have reached similar conclusions; given current dryers and the current electrical generation mix, a natural gas dryer produces less CO_2 than a comparable electric one does for the same load. A NRDC study concluded that with the current electrical grid, converting to gas dryers would immediately reduce US residential CO_2 emissions 40. The Glasgow study states "A comparison of CO_2 emissions shows gas dryers more favourably than any electric dryer. Given that electricity is more expensive than gas, a gas dryer is also significantly cheaper to run than an electrical alternative." 36 Their conclusion even accounted for heat pump dryers which consume, on average, only 42% of the energy of an electric vented dryer.

Health impacts and sanitization

Many energy efficiency efforts focus on reducing energy consumption by decreasing temperature of wash water, and dryer heat. These simultaneously reduce the sanitizing possibilities of both machines. This may create negative effects on health, especially in the washers and dryers shared between multiple families,

The trend toward washing in cold water, whether for energy efficiency (saving water heating energy) or convenience (water heating inside European washers is very slow), reduces sanitizing in the washer. For example, in a shared laundry facility, the first load in the washer should probably be washed in hot water, which will sanitize the washer for following loads.

Without active control, bacteria and viruses survive surprisingly long. *Salmonella spp*. can survive up to 24 weeks. *E. coli*, *P. aeruginosa* and coliform bacteria can also be found in residences. 41

Dust mites, which live on human skin scales, are found in fabric in every occupied space. Per the US National Institute of Health NIH), "water must be hotter than 130º F [55º C] to kill the mites. Cold or warm water used with detergent and bleach can also be effective." Bedding should be washed each week in hot water. NIH also recommends "Reduce indoor humidity to below 60 percent (ideally between 30—50 percent). Dehumidifiers or central air conditioners can do this." 42 A New Zealand study indicates that, even if cold water is used for washing, mites can be effectively killed by drying at temperatures of at least 55º C. 43

[40] Unlike electric resistance dryers, electric water heaters are much more efficient because the heat transfer from resistance to water is very high.

Drying in cooler temperatures reduces the sanitizing effects of the dryer. Steam cycles in newer dryers may be certified to kill bacteria using NSF Protocol P154 44, but there is no standard method of evaluating dryer performance against nits and other biological hazards.

Although sunlight is widely viewed as sanitizing, UV does not penetrate densely woven or multi-layer fabrics, nor garments designed to limit UV exposure of the wearer. Natural fibers swell when wet, limiting UV penetration during outdoor drying. 45 UV can also cause fabric damage, including fading. 46 Despite multiple searches, authors were unable to find conclusive research defining a method of predicting the length of outdoor exposure time for effective sanitization. UV exposure should be regarded as a surface disinfectant for the surfaces facing the sun.

Hang-drying indoors has a health penalty as well. The Glasgow study states that "over 75% of households had average absolute moisture levels above the recognized upper threshold for dust mite growth linked to asthma" during the heating season. 36 It also said that also no visible mold was traced to indoor hang-drying, "a strong relationship was found between [mould] spore concentration in the air and presence of passive drying – average 300% more than Finnish health standards." For tumbling drying, outdoor drying and indoor hang-drying, the average concentration of Aspergillus fumigatus spores was measured at 644, 680 and 1398 colony-forming units (CFU)/m^3. Readings above 1000 CFU/m^3 are considered a health risk.

Hotels and hospitals use a combination of hot water washing, bleach and high-temperature drying to minimize the risks of transmission of disease or allergens. 43

Per the respondent in Zambia, sanitizing was not discussed there. Most wash was done in tap water, hand wrung and hung outdoors. 15

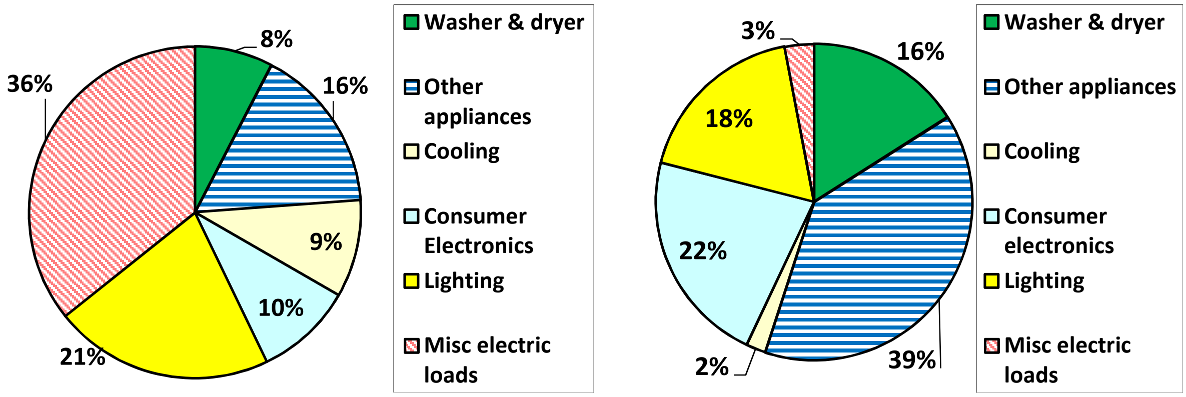
Laundry as a share of residential energy consumption

Energy consumed by the dryer is only one slice of the total energy required for the residential laundry processes. Two views of average residential energy consumption are shown in 0. These charts omit space heating, water heating, pools and spas because the REMODECE data does not separate water heating for hydronic spacing heating from water heating for domestic water use. Pools and spas are not included in a large enough percentage of residences in either dataset.

Pie charts such as those in 0 only address the major appliances, e.g., the washer and the dryer, not any of the ancillary energy-consuming aspects such as laundry-area dehumidifiers or irons. They are also difficult to compare across studies because of differing definitions of the categories. To create the closest possible comparison between the studies, space heating and water heating were omitted because these are done with a variety of fuels, including sources such as wood stoves or district heat. Data for pools and spas was removed from the RBSA data because it was not present in the REMODECE data. Washer and dryer data from RBSA were combined to match the category in the REMODECE data. Likewise, because the REMODECE data did not separate office electronics from entertainment electronics, these two categories were combined from the RBSA data.

As an example of the difficulty of using consumption data from different studies, one can look at the relative sizes of the miscellaneous electric loads (MELs). It seems likely that there are some electronic items which are included in MELs in the RBSA study but categorized as consumer electronics in the EEA study. MELs in the RBSA were calculated by subtracting all measured loads from the metered whole-residence consumption. MELs in REMODECE data were calculated by adjusting the average consumption for each metered category by its penetration, summing those, and subtracting the total from the average consumption. These differences in methodology also lead to difficulty in making comparisons.

To guide tradeoffs of various laundry strategies and equipment, energy consumption pie charts would be better if the laundry-related MELs (irons, clothes presses, dehumidifiers, etc.) were a separate slice from other MELs. This arrangement would better reflect that the laundry process is more than just a washer and dryer. The washer efficiency affects the dryer efficiency which in turn affects the iron and the air conditioner.



Residential Electricity Consumption, excluding space heating, water heating, pools and spas. Left: US Pacific Northwest, Right: Europe.

Sources: RBSA 7, REMODECE 5, EEA 38 data.

Hang-drying indoors has an energy penalty as well. If the energy required to evaporate the moisture is not supplied by the dryer, it must come from the HVAC system, a heated drying rack or elsewhere.

Conclusions

The variety of drying process solutions found in the collected observations suggests that further research may be needed to guide residential laundry energy efficiency efforts; aggregate savings from any given energy efficiency measure depends upon both the individual measure and the percentage of drying process choices which actually use the measure.

Several important aspects of the observed clothes drying processes emerged from the collected information:

1) There are reduced possibilities of hanging laundry outdoors. Energy efficiency advocates should work to eliminate these barriers to consumer choice.
2) Widespread education of consumers, appliance salespersons, and energy efficiency professionals about the health impacts of laundry choices, including reduced temperatures of wash water and dryer heat, along with mitigation strategies, is needed.
3) Definition of a US EnergyGuide label for dryers, including moisture removal and sound (noise) level information such as that on the EU EnerG label, would inform consumers and assist the adoption of more efficient machines.
4) Manufacturers' instructions for dryers should contain more information about appropriate load sizes and cycles for fabric types, and sanitization capabilities.
5) Consumer education regarding energy-efficient drying solution combinations could help reduce energy consumption. For example, running permanent press clothing in the dryer at or above its activation temperature for a minimum time followed by hanging the garments to finish drying.
6) Reducing the energy consumed by the laundry process should consider the entire process so that unintended consequences (e.g., increasing the use of MELs such as irons or laundry-area dehumidifiers while decreasing the use of clothes dryers) neither derail overall efficiency improvement nor distort load profiles used for planning.
7) To avoid long-term damage to air-tightened residences, mitigation strategies are needed for the humidity added by indoor hang-drying. One such strategy is locating the laundry area outside of the core conditioned living space.

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Affordable Hybrid Heat Pump Clothes Dryer for the U.S. Residential Market

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Abstract

A novel hybrid heat pump clothes dryer has been developed that can potentially save 50% or more of the energy used by conventional electric dryers at comparable drying times. The hybrid concept combines an electric element and a vapor compression heat pump to overcome two primary hurdles of introducing heat pump dryers to the U.S. residential market, high cost and longer drying times. Drying times can be comparable to conventional electric dryers, because the drying air is heated to the same operating temperatures as conventional electric or gas dryers. A detailed model of the clothes drying process is presented that was validated using data from a commercial electric vented dryer. The model was then used to design a hybrid heat pump clothes dryer using conventional components that is projected to save greater than 50% of energy with comparable drying times. A prototype was built by modifying a commercial electric clothes dryer and tested in an environmental chamber using the standard DOE test procedure. Results show greater than 50% energy savings but with longer than expected drying times. Payback is projected to be less than 3.5 to 9 years for 25% of the U.S. residential market. The demonstration system showed significantly greater energy savings than heat pump dryers currently on the U.S. market. A significant step-change reduction in energy used for residential clothes drying is on the horizon, and reasonable payback for a sizeable fraction of the U.S. market is within reach with additional technology development and volume manufacturing.

Introduction

The total number residential tumble clothes dryers in the U.S. is expected to increase from 92.5 million units in 2015 to 105.8 million by 2025 [1]. In 2015, dryers consumed 4% of the total U.S. residential building electricity [1]. Higher clothes washer spin speeds have contributed significantly toward reducing clothes dryer energy consumption by reducing residual moisture content (RMC) [2], because the latent heat associated with evaporating the moisture from the wet load dominates dryer energy consumption. Significant future energy savings will likely require energy recycling such as through energy recovery heat exchangers or heat pumps [3, 4]. The challenges with these concepts include higher first cost that can lead to long payback periods for most consumers and longer cycle times [5].

Discerning how energy is used during clothes drying is beneficial for developing approaches for reducing energy consumption. Figure 1 shows power and drum exhaust temperature profiles from a commercial standard electric clothes dryer [6]. A significant fraction of energy is used to heat up the wet load, the heating elements, and the rest of the dryer during the first warm-up phase of the cycle, although some drying occurs from the start. Once temperatures stabilize, most of the heating goes to latent duty to evaporate water during the constant rate drying process (CRDP) [7]. The latent duty decreases as the load becomes dry, causing the load and exhaust to increase in temperature during the falling rate drying process (FRDP) [7]. Often the heaters are modulated during the FRDP to prevent overheating of the load while maintaining temperature of the load to ensure dryness. Typically, the heaters are turned off for a period at the end to allow the clothes to cool before ending the cycle.

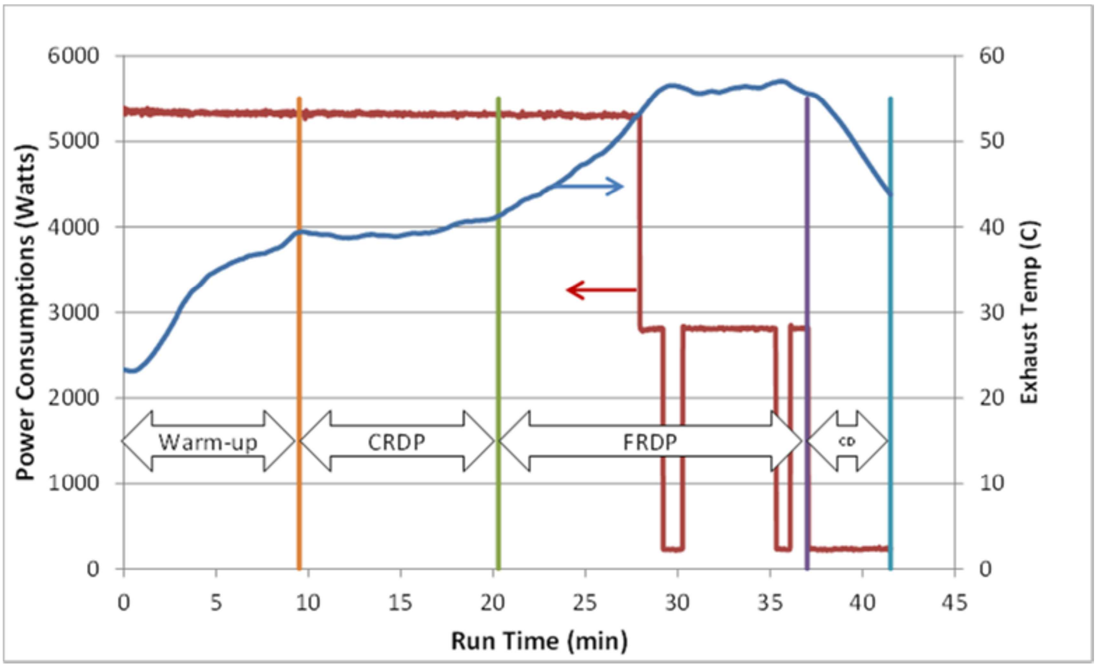

Figure 1. Power and drum exhaust profiles for a standard vented electric clothes dryer divided into the four phases, warm-up, CRDP, FRDP, and cooldown (CD).

Overall, the latent heat to evaporate all of the water out of the load is the minimum energy that must be supplied to the drum, which occurs primarily during the CRDP. The high sensible duties of the warm-up and FRDP phases are not 'productive' but are necessary to expedite the drying process and to ensure thorough and consistent dryness of loads of varying sizes and clothe types. While a variety of efforts have been made to reduce energy use [3, 8-12], recovering and recycling energy is necessary to make significant reductions in energy use [3].

The simplest approach for improving energy efficiency is to add a recuperative heat exchanger to recover energy from the drum exhaust to preheat the incoming air. However, recuperation is limited by the exhaust temperature, so it is most effective later in the cycle when the exhaust temperature is high. Heat pumps overcome this limitation by raising the temperature of recovered heat as it is recycled.

Heat pump clothes dryers are able to use 50% less energy than electric dryers but higher cost and longer drying times deter adoption by consumers, particularly in the U.S [3]. The hybrid concept shown in Figure 1 is able to shorten the drying time by continuing to use an electric heater, albeit at lower power, to heat the air to the same temperature as conventional electric dryers [13, 14]. The large arrows in Figure 1 indicate air flow and thin arrows indicate the heat pump circuit or condensate flow. A recuperative heat exchanger is also included that is particularly effective at saving energy at the end of the cycle by allowing active heating to be turned off earlier.

The proposed concept is open-cycle, drawing ambient air into the recuperator and venting the exhaust from the evaporator. Recirculating the drying air in closed-loop cycles is more typical, but the energy added to the system by the compressor, fan, and electric element must be rejected to maintain an overall energy balance after the warm-up phase. The open-loop approach avoids the added cost and size of an additional air-to-air heat exchanger and blower to reject heat. Venting dryer exhaust outside the living environment is common in the U.S. and Kenmore and LG are currently selling vented heat pump dyers in the U.S. consumer market. The HyHPCD significantly cools and dehumidifies the exhaust, making it more feasible to exhaust within living spaces.

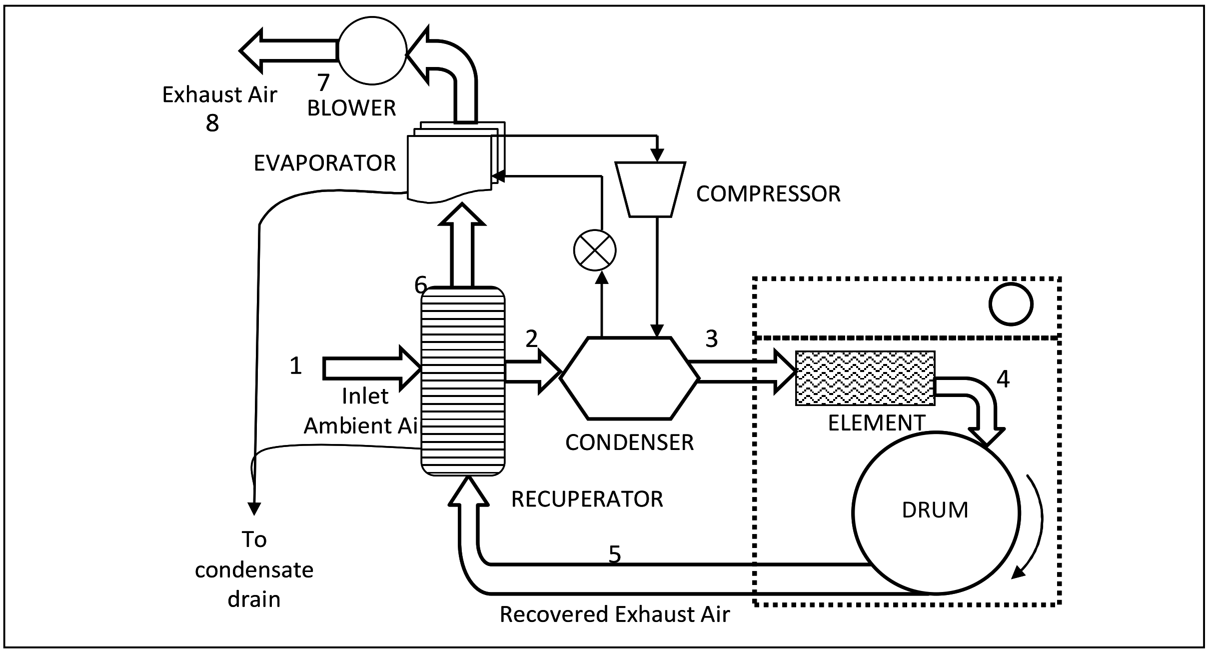

Figure 2. Schematic of the Hybrid Heat Pump Clothes Dryer.

A hybrid heat pump clothes dryer (HyHPCD) has been designed, constructed, and tested. The design was accomplished through detailed modeling of the drying cycle and the design was projected to save over 50% of the energy at comparable drying times. A demonstration system was then constructed based on the design using off-the-shelf and customized conventional components. Testing using the standardized DOE Test Procedure [15] achieved the desired energy savings but at considerably longer drying times.

Clothes Dryer Model

The first step in developing a process model for the HyHPCD was to develop a model for a conventional electric dryer that accurately reflects the drying process occurring in the drum during the various phases of a drying cycle. Subsequently, the heat pump system is added to the conventional dryer model which is used to design a HyHPCD capable of saving 50% of the energy.

Conventional Electric Clothes Dryer Model

The clothes dryer model consisted of an Excel model for simulating process dynamics coupled to a steady-state process model for calculating heat and mass balances at a given point in time during the cycle. The process model uses ChemCAD, a Chemstations™ commercial process simulation software package. The drying process in the drum was modeled as simple adiabatic mixing of a liquid water stream and hot air to produce humidified exhaust. The varying drying rate was represented by varying the water flow rate, using correlations derived from test data from a commercial standard vented electric clothes dryer [13]. The data were obtained from testing that followed the DOE D2 Test Procedure [15] with the exception of the test load which followed AHAM 2009 specifications [16]. Other parameters of the steady-state drying model including the heater power, thermal mass heat duties, and air flow were also determined from test data [13]. The model divided the cycle into the four phases described above with different correlations for drying rate that were dependent on drum exhaust temperature or residual moisture content of the load.

Figure 3 shows the agreement in exhaust temperature and relative humidity between the model and the original test data. The energy factor of 3.03 lb/kWh and cycle time of 40 minutes were also in good agreement, indicating the electric dryer model is a valid representation of the process and performance of commercial electric clothes dryers.

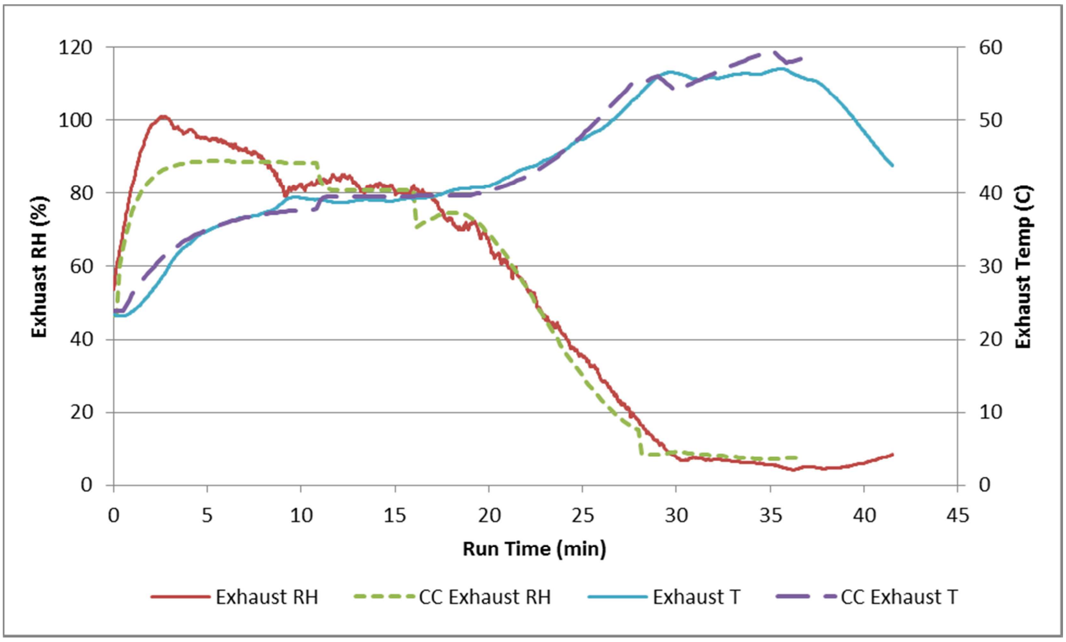

Figure 3. Comparison of exhaust RH and temperatures between the ChemCAD simulation (CC) and the experimental measurements.

Hybrid Heat Pump Clothes Dryer Model

Next, a vapor compression heat pump system was added to the electric dryer model in order to design a HyHPCD capable of 50% energy savings, which is equivalent to an energy factor of 6.06 lb/kWh. This approach preserved the drying process dynamics of the original electric dryer. Component specifications were constrained to be compatible with off-the-shelf or customized conventional components.

The compressor was the critical component for meeting the design objectives. Commercial compressors are difficult to find that are rated above 65°C condensing temperature, but modeling indicated 50% energy savings would require at least 70°C. Embraco granted that their Model FFI12HBX-EJ compressor operating with R-134a refrigerant could be operated at 70°C, which was stipulated in the design. Embraco supplied rating correlations for refrigerant flow and power [17] that were used in the model. The superheat from the evaporator was set to a constant 8.3°C. The evaporator was modeled as co-flow and the condenser as a two-stage heat exchanger with a desuperheater section and a condensing section, with fixed heat transfer coefficients and areas. The heat exchanger effectiveness was low enough to be compatible with multi-pass tube-fin designs. The recuperative heat exchanger was modeled as counter-flow with fixed heat transfer coefficient and area, but the effectiveness was held low enough to be implemented in a cross-flow design.

The drying cycle of the HyHPCD emulated the drying cycle of the original dryer with a warm-up phase, a CRDP phase at high exhaust humidity and nearly constant exhaust temperature, an FRDP phase with a similar exhaust temperature profile, and a similar cooldown phase. This is to argue that the HyHPCD design performs comparably to the original electric dryer in terms of the drying process and final dryness of the load, and justifies an apples-to-apples comparison of energy usage.

Model results for the HyHPCD design are summarized in Figure 4 showing energy factor versus drying time with the heater being turned off either when the exhaust temperature reaches 40°C or later when it reaches 50°C. The curves show the effect of varying heater power (fixed for a given cycle simulation) with lower heating power saving more energy but requiring longer drying times. Performance follows the same trade-off curve when the heater is turned off earlier or later in the cycle.

The average performance of the original electric dryer [6] and the target for achieving 50% energy savings are also included in Figure 4. The original blower power of 235 Watts was assumed despite the added pressure drop of the heat pump. The model predicts that the HyHPCD design is capable of saving 50% of energy use at close to the same drying time. Significantly greater energy savings, up to 56%, is also possible if the consumer is willing to be patient. There are diminishing returns as the motor becomes a bigger fraction of the energy use with longer cycles.

Combined energy factors (CEF) and drying times are included in Figure 4 for three commercial heat pump dryers currently on the U.S. market. Data for the Kenmore Model 8759, the LG Model DLHX4072, and the Whirlpool Model WED99HED were obtained from the Energy Star website [18]. The model predicts the HyHPCD can potentially save 30% more energy with up to 1/3 shorter drying times. Although, the comparison isn't quite equitable because CEF includes standby and off-mode energy use that are not included in the EF, and the DOE load was used in testing instead of the AHAM 2009 load.

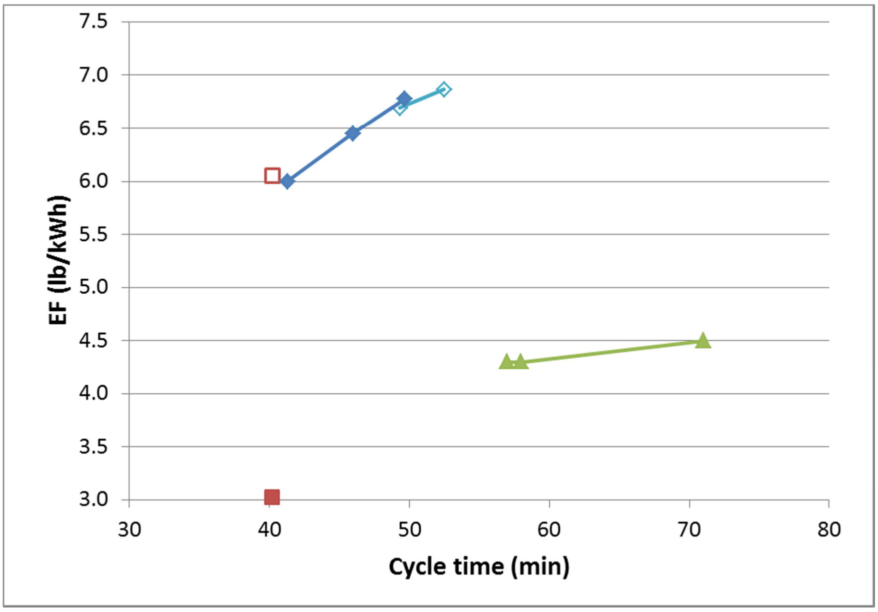

Figure 4. Energy factors for the original electric dryer (■), the target for 50% energy savings (□), and commercial heat pump dryers (▲). Hybrid HPCD results with heater turned off at 40°C (◆) and 50°C (◇).

Hybrid Heat Pump Dryer Demonstration System

The HyHPCD design was tested by constructing a demonstration system starting from a GE Model GTDN550ED standard vented electric dryer that was modified and augmented with a heat pump. Previous testing of the same dryer [6] provided a baseline for calculating energy savings. The existing electric elements were used, but at reduced power. The heat pump was designed to fit inside a pedestal under the dryer. The cabinet was modified to accommodate air flow between the dryer and the heat pump. The original blower and motor were used but were supplemented with two Tjernlund Model LB1 booster blowers to overcome the added pressure drop of the heat pump and maintain similar air flow. Components for the heat pump system were selected based on HyHPCD design specifications. The refrigerant was R-134a, the compressor was the Embraco model FFI12HBX-EJ, and thermostatic expansion valve was a Parker/Sporlan EFJ-1/2.

The Heat pump heat exchangers were obtained by providing performance specifications to vendors, who responded by providing customized designs. Super Radiator Coils provided designs for conventional copper-tube, aluminum-fin coils for the evaporator and condenser. The evaporator tube-fin design had 3 rows of 9.53 mm diameter tubes with 9 passes per row. The coil face was 22.8 cm by 22.8 cm and the depth was 7.6 cm. The condenser tube-fin design had 10 rows of 5 mm diameter tubes with 8 passes per row. The coil face was 15.2 cm by 25.4 cm and the depth was 12.7 cm, and the condenser was oriented horizontally with air flowing upwards, as specified. Heatex provided a stacked-plate design for the recuperator with dimensions of 20 cm by 20 cm by 28 cm tall. The heat pump was constructed as shown in the schematic in Figure 5 with plenums constructed from sheet metal to direct air flow.

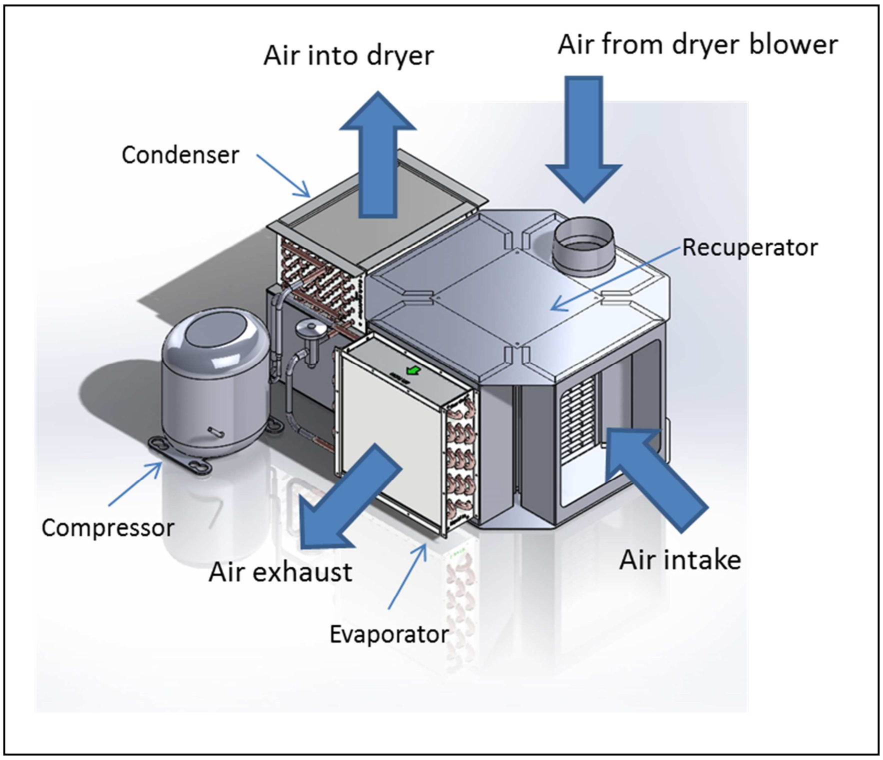

Figure 5. Heat pump design and air flow path.

The electric power supplied to one of the original heating elements was reduced to either 145 VAC or 120 VAC which corresponded to 1000 Watts or 700 Watts, respectively. The power to the second heater was 640 Watts at 120 VAC at 100% and could be modulated to lower power. The system was equipped with a data acquisition and control system (DACS) for manual control and data logging at 1 Hz. Energy use was determined by monitoring power consumption using 2 power meters accurate to ±1% and integrated over the entire cycle to calculate total power use. Thermocouples were located in the drying air stream at the inlet to the recuperator, the inlet and outlet of the condenser, and the inlet and outlet of the evaporator. The drum exhaust and environmental chamber were equipped with combined probes for measuring RH and temperature. Thermocouples in contact with the outer wall of the refrigerant piping were used to obtain refrigerant temperature measurements. The assembled HyHPCD demonstration system is shown in Figure 6, with the environment chamber used to control ambient temperature and humidity shown in the background.

The DOE D2 Test Procedure [3] for measuring energy factors of residential clothes dryers was followed as closely as possible [1]. Tests were performed using the standard DOE test load defined in the DOE D2 Test Procedure [15]. At the end of the cycle, the load was removed and weighed to determine if the final RMC was below 2%, as prescribed by the procedure. Some cycles were operated in EXPRESS mode with an electric heater on during most of the cycle, while in ECO mode, heaters were only used during the initial warm-up phase.

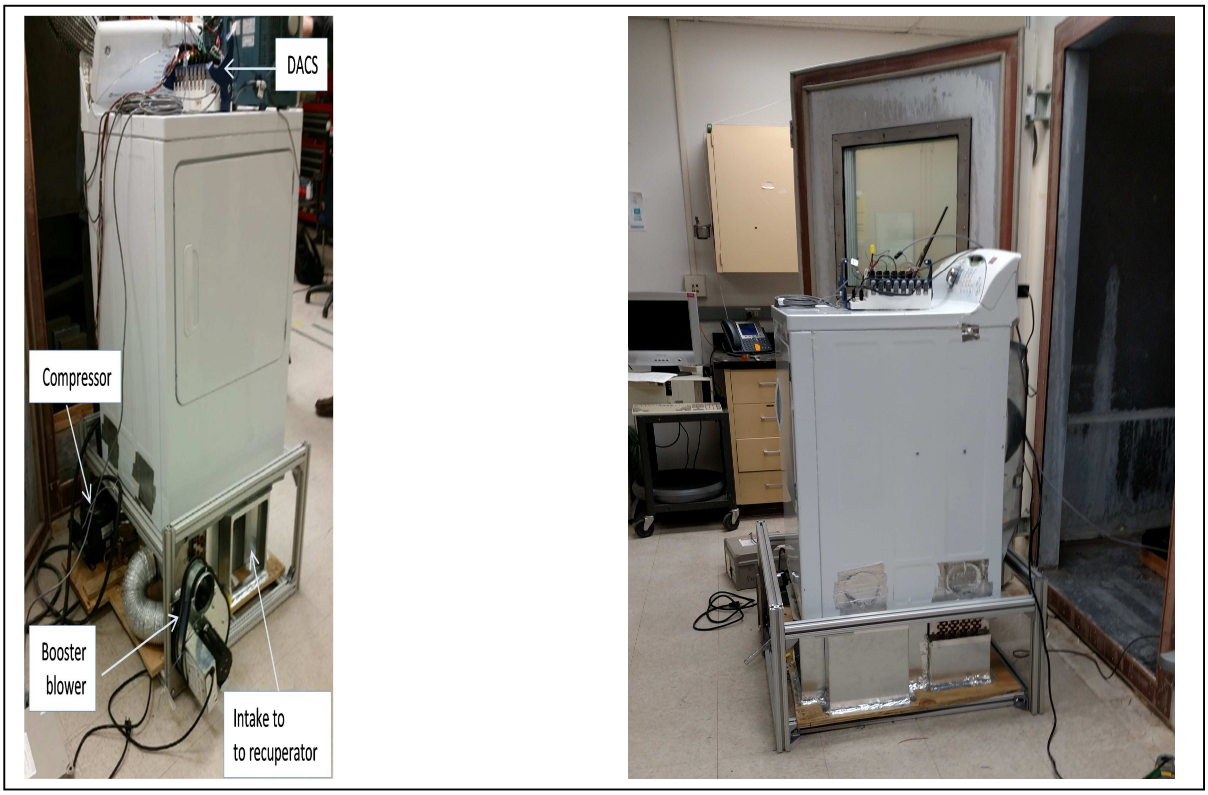

Figure 6. The HyHPCD system next to the environmental chamber used for testing.

Figure 7 shows temperature readings for one of the EXPRESS tests where a 700-Watt electric heater was used for 39.4 minutes out of the total cycle time of 51.5 minutes, and the heat pump compressor was turned off after 43.8 minutes. These temperatures are only indicative of temperature trends in the drying air, because the heat exchangers are all cross-flow. A single thermocouple placed in a plenum is not adequate for obtaining a stream temperature that varies across the face of a panel. Nevertheless, the temperature profiles in Figure 7 illustrate the drying phases and successful heat recuperation, particularly at the end of the cycle when both heater and heat pump are turned off. It should be noted that significant water condensation occurs from the exhaust from both the recuperator and evaporator during the middle of the cycle when exhaust humidity is high. The recuperator and heat pump continued supplying enough heat to the air after the heater was turned off for the exhaust temperature to continue rising. Heater cycling that often occurs with conventional electric dryers during the final stage [13] is not necessary because the recuperator continued recycling sufficient heat to maintain load temperature, which contributes significantly to energy savings.

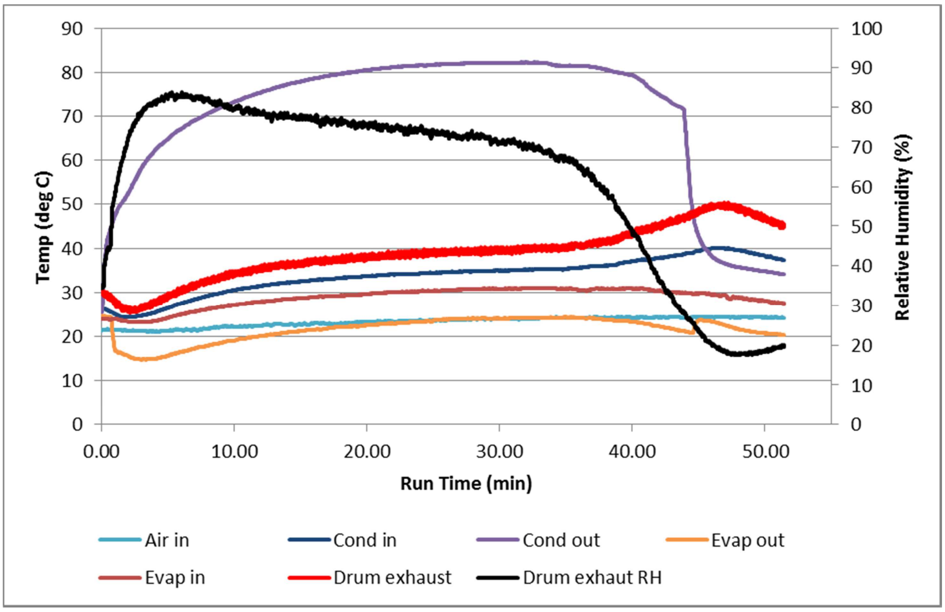

Figure 7. Example drying air temperature profiles for an EXPRESS test using a 700 Watt electric heater.

Test results presented in Figure 8 show the trade-off between energy use and cycle time for ECO and EXPRESS mode tests, with the ECO tests showed higher energy factors and longer drying times, as expected. Figure 8 also shows the importance of final load dryness. The average energy factor from 3 tests with the original electric dryer is also included [13], as well as the target value to achieve 50% energy savings at the same cycle time. The goal of 50% energy savings was achieved in ECO mode but required 50% longer drying times. The demonstration system did outperform other heat pump clothes dryers currently on the market, which are also represented in Figure 8.

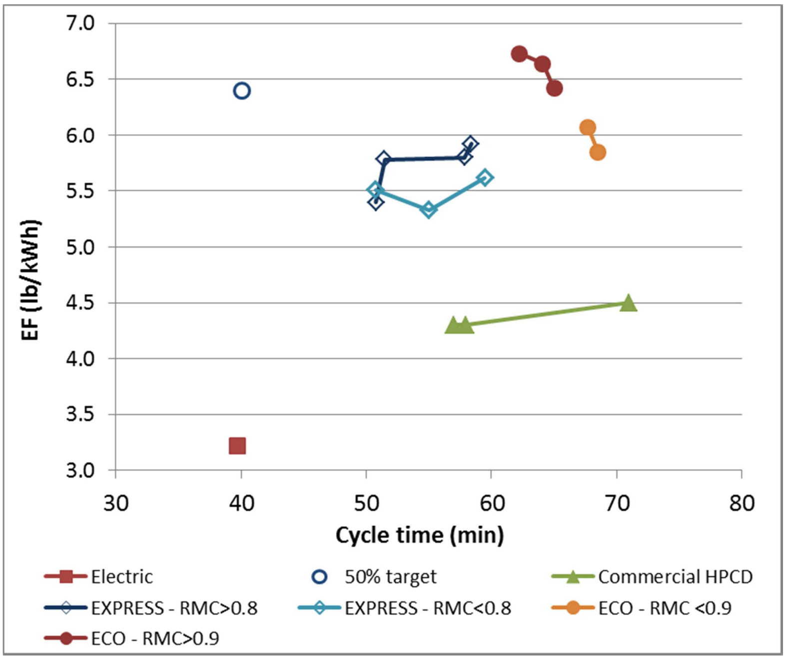

Figure 8. Comparison of results with the DOE test load to the original electric dryer, the 50% savings target, and commercial standard-size heat pump dryers; data are divided between higher and lower final RMC for the ECO and EXPRESS modes.

Energy savings were lower and drying times longer than projected by the HyHPCD model. Lower air flow through the drum due to increased pressure drop despite adding booster blowers is the most likely cause. Poorer temperature and flow distribution of air entering the drum due to modifications of the air flow pathway is another possibility. Internal baffling around the drum to direct air flow and the added load on the blower may have slowed the drum speed, reducing mixing and drying efficiency. Internal air leakage causing air bypass within the system would also reduce performance, as well as leakage to the outside, such as around the door seal. These types of issues are not unusual with a first-of-a-kind system, and can be easily rectified. The biggest potential impact for improving the technology would an improved recuperator—one with similar performance but a fraction of the pressure drop.

Payback Analysis

A bottoms-up analysis using vendor quotes at a volume of 10,000 units per year for component costs gives a payback of 8.8 years or less for 25% of the heaviest users—households with the most drying cycles per year—at the average U.S. residential electricity rates. This analysis compiled major component costs at $759, which with $225 of assembly labor and a 1.3 markup factor, totals $1279. Assuming 54% energy savings from 400 cycles per year saves 489 kWh/yr, which corresponds to the breakpoint for the 25% heaviest users in the U.S. [5]. With these energy savings, average payback is 8.8 years using a population weighted price of 12.35 ¢/kWh for the U.S.[41] and an incremental purchase cost of $530.

Reducing payback to 5 years is believed to be achievable with further development of the design and with volumes exceeding 10,000 units per year. A reasonable expectation is for the incremental price to eventually be closer to the price of today's window air conditioners (~$150 - $200) that use similar heat pump components. The Frigidaire 8,000 BTU 9.8 EER window air conditioner has a capacity comparable to the HyHPCD duty. Using the Internet price of $210 as the incremental cost lowers average payback to 3.5 years or less for the top 25% heaviest users.

Conclusions

A computational model has been used to establish the feasibility of saving 50% of energy use in residential clothes dryers with comparable drying times. The proposed hybrid heat pump dryer can be constructed from off-the-shelf or customized conventional components with a projected payback of less than 3.5 to 8.8 years for 25% of the heaviest users in the U.S. The model was first developed for electric dryers using measured data from a commercial standard vented dryer. The model was able to accurately predict drying time and energy usage. When a heat pump that included a recuperative heat exchanger was added to the model, a design was invented that increased energy factor from 3.0 lbs/kWh to between 5.4 to 6.0 lbs/kWh with the same drying time and similar exhaust temperature, humidity, and RMC profiles. The use of a passive recuperative heat exchanger to recover and recycle heat is a key to attaining 50% energy savings.

The hybrid heat pump dryer design was implemented in a demonstration system, and tested using the standard DOE Test Procedure to measure energy savings. A commercial electric dryer was modified and previous measurements of energy use provided a baseline for calculating energy savings. An off-the-shelf compressor was selected, and vendors provided heat exchangers designed to meet performance specifications created from the design. The demonstration heat pump dryer was operated manually and tested at varying heater powers. The desired 50% energy savings was successful achieved, albeit with longer drying times. Energy savings and drying time were sensitive to the heater power level and the duration the heater was on, as well as the final dryness of the load. The most important need for further development is the recuperative heat exchanger that contributes substantially to the energy savings but has a pressure drop that is too high.

The demonstration system showed significantly greater energy savings than heat pump dryers currently on the U.S. market. A significant step-change reduction in energy used for residential clothes drying is on the horizon if model projections can be realized in practice. Furthermore, reasonable payback for a sizeable fraction of the U.S. market is within reach with additional technology development and volume manufacturing.

Acknowledgements

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Gauging Consumer Appetite for Super Efficient (Heat Pump) Dryers

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Evergreen Economics

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Abstract

The fundamental technology and efficiency levels of residential clothes dryers in North America have remained largely unchanged for decades while other energy-intensive appliances in homes have seen substantial efficiency improvements. Heat pump technology offers a way to substantially reduce the energy use of dryers. However, it is unclear how interested consumers will be to purchase heat pump-based dryers, as they cost substantially more than mainstream dryers (unless heavily rebated), require longer drying times, and present a somewhat different drying experience. Hybrid dryers offer a compromise on drying time with a loss of some of the energy efficiency benefits associated with heat pump-based dryers.

This paper presents results of a United States-based consumer study completed in 2016 to inform an anticipated program initiative to promote heat pump-only or hybrid dryers. Consumer research explored household considerations and practices when shopping for dryers, their response to heat pump-only and hybrid dryer technology, and how they would weigh trade-offs in purchase cost, drying time, and energy consumption between mainstream, heat pump-only, and hybrid dryers. The authors also discuss how the study results informed the initiative program strategy and applicability of the study results on a more global scale.

Introduction

The Northwest Energy Efficiency Alliance is a regional collaborative serving over 140 utilities and energy efficiency organizations in the northwestern United States to drive market adoption of energy efficiency products, services, and practices for the benefit of utilities, consumers, and the region. NEEA does this by conducting research, designing and implementing energy efficiency programs, and tracking their progress toward key performance indicators through market progress studies.

In 2010, NEEA began exploring opportunities to advance the market for clothes dryers that use heat pump technology to reduce laundry-related electricity use by residential consumers. NEEA collaborated with like-minded organizations serving other regions in the United States to form the Super Efficient Dryer Initiative and began conducting technical and consumer research to better understand whether and how to support adoption of this technology to consumers most effectively in the region NEEA serves.

One component of this research was a market characterization to investigate both the supply and demand components of the dryer market and their potential adoption of heat pump-based dryers [1]. Evergreen Economics conducted that study for NEEA. This paper focuses on the consumer (demand) components of this research and the manner in which these insights were applied by NEEA's initiative planners and managers.

Research questions addressed in this paper include:

- What is consumer awareness and understanding of dryer technology types?
- What are consumers' dryer preferences and purchasing behavior?
- What are consumers' willingness to pay for more efficient dryers?

- Which non-energy benefits and attributes of heat pump-based dryers would attract purchasers?
- Are heat pump-based dryers suited for the mainstream market or more promising for a niche market?
- What opportunities and barriers exist to changing consumer purchases?
- Can a NEEA initiative for dryers focus on just clothes dryers, or does it need to address clothes washer purchases too?

This component of the research drew from a series of focus groups, a web survey of consumers, and a stated preference analysis.

In parallel (but not addressed in this paper), the study examined manufacturer and retailer practices concerning heat pump-based dryers, regulatory standards, technology research, and market penetration. The broader study also examined the role of natural gas dryers in the market.

Technology and Market Background

Clothes dryers are a pervasive, albeit not universal, home appliance. In the United States, 81 percent of homes have a clothes dryer, while 79 percent of those appliances are electric dryers and 19 percent use natural gas [2]. Penetration rates outside North America are likely lower due to the greater prevalence of air drying in other developed countries and a lower level of appliance penetration in developing countries.

Heat pump technology in clothes dryers takes one of two forms. Some dryers rely solely on heat pumps to generate heat and remove moisture from wet clothes while they tumble in a drum, while others (so-called hybrid models) combine heat pumps and traditional electric resistance heaters to achieve the greater efficiency of heat pumps but with faster drying speeds.

Internal field testing conducted by NEEA and US efficiency standards for conventional dryers indicate that heat pump-only dryers provide efficiency gains over conventional dryers. They dry 2.7 kilograms (6 imperial pounds) or more of laundry per kilowatt-hour, compared to about 1.1 kilograms (2.5 pounds) for conventional dryers. Hybrid dryer performance depends on operator choices, but hybrid dryers generally dry about 1.6 kilograms (3.5 pounds) of laundry per kilowatt-hour.

Heat pump-based dryers have been available in Europe since the mid-2000s, but have been introduced more slowly and have not achieved any significant market share in North America. A handful of appliance manufacturers introduced hybrid models in North America in 2015, and only two are offering a heat pump-only model. These appliances cost more than basic dryers that are available for as little as US$400, but tend to be comparable in retail prices with high-end traditional dryers – sometimes costing US$1,400 to US$1,600 without any rebate. Members of the broader Super Efficient Dryer Initiative and NEEA program staff have worked with manufacturers to roll out their heat pump-only and hybrid dryers and assist them with marketing support and cost reductions for consumers.

One of the potential concerns about heat pump-based dryers is the amount of time they require to dry a load of laundry. Heat pump-only dryers operate at a lower temperature—which offers efficiency advantages and may be gentler on clothes—but drying time could be a deterrent to potential customers. As noted, hybrid dryers compromise some of the efficiency gains and give consumers the choice to operate at comparatively faster or more efficient modes, although their efficiency falls between conventional and heat pump-only dryers regardless of mode. According to the Natural Resources Defense Council, cycle times for heat pump-based dryers tend to range from 75 to 120 minutes, while conventional electric and natural gas dryers have cycle times of 30 to 60 minutes [3].

Consumer Practices

Consumer research for NEEA's study of the heat pump dryer market concentrated on the four northwestern states that the alliance serves: Washington, Oregon, Idaho, and Montana. Research activities comprised six focus groups involving a total of 50 participants and a web panel survey of 620 households in this geographic area. The focus groups explored prevalent laundry habits, the dryer shopping process, what drives consumer dryer purchase choices, and how heat pump-based dryers would fare in a shopping process. The web survey investigated similar topics as the focus groups, but in a more closed-ended fashion. The web survey also included a series of questions that explored trade-offs that respondents would make with varying dryer characteristics and offers; responses to these questions provided data for a stated preference analysis. Focus group and survey questions were informed by extensive background research and involvement of NEEA staff. Participants and respondents were screened to ensure that they owned a dryer and were (or could soon be) in the market for one, so that questions about dryer purchases were relevant and real. All of the consumer research was completed in the winter and spring of 2016 by Evergreen Economics.

General Practices and Priorities

The study's focus groups explored broader issues about household laundry practices and likely dryer purchase processes before obtaining more direct reactions to heat pump-based dryers. This broader context provided insights about features and equipment attributes that are important to households, as well as the likely contexts and information sources that would influence their purchase decisions.

Among participating households, we found that there is no typical person in charge of doing laundry. Both men and women take care of laundry – sometimes for the entire household and sometimes only for themselves. As a result, purchases of new laundry appliances have multiple stakeholders in many households.

The timing and sequencing of laundry varies as well. Some households do laundry on specific days of the week and others wait until hampers are full or particular clothes are needed. Those with fixed laundry days seemed more interested in being able to complete multiple loads back-to-back, for which alignment of washer and dryer cycle times was valued. For these households, dryer cycle times would likely be more relatively important.

The degree to which households separate clothes by color and isolate specific articles of clothing for more gentle drying (such as air drying) varies as well. A small number of participants indicated that they take great care to remove certain items from dryers or do not dry them mechanically at all in order to protect the fabric or keep them from shrinking. These households may find dryers appealing that operate at lower temperatures or that are convincingly gentler on clothes.

Dryer Purchase Scenarios and Considerations

Focus group participants indicated that they would be most likely to purchase a new dryer when a prior one breaks or stops functioning properly, but may also replace a dryer as part of a paired purchase with a new washing machine. In both of these scenarios, the dryer purchase may not receive extensive consideration. In an "emergency replacement" scenario, households would want a replacement within a few days. In a paired purchase, the washer receives the majority of the attention because washers are perceived to be the appliance with more features, choices, and importance. For a share of purchasers, the dryer paired with their selected washer becomes the default choice. This default selection appears to be particularly prevalent for those who place value on the aesthetics of paired laundry equipment and matching designs for machine controls. Some others are willing to entertain washers and dryers that are not as consistent, however.

Focus group participants identified multiple information sources to educate themselves about dryer choices. Specifically, they mentioned personal contacts (friends and family), repair technicians, ratings from other consumers and independent consumer organizations, and general Internet searches, where they are likely to encounter manufacturer and retailer information. When prompted to discuss energy utility providers, participants indicated trust in their advice, but also stated that they would not think of their utilities when looking into clothes dryers. Dryers appear to be primarily a laundry appliance and not foremost an energy-using device in consumers' eyes.

We recognize that these information sources were provided by consumers in the absence of the time pressure that a failed appliance poses. It is conceivable that consumers would also simply check for retailer offerings and prices, either in stores or on the Internet. Hence, retailer messaging may be more important than focus group responses suggest.

Features the focus group participants would emphasize in their purchase decisions include size and capacity, energy efficiency, reliability, drying time, price, and value. Energy efficiency was seen as a positive and generally associated with the ENERGY STAR label and the Energy Guide. However, few focus group participants had much awareness of how much energy dryers use, how much they pay to operate them, or how much less an ENERGY STAR-certified appliance uses. (In the United States, the ENERGY STAR label is intended to signify that a particular model is among the more energy efficient choices for similar products, while the Energy Guide label estimates annual operating cost for energy used by the model and compares these costs to similar models.)

Reaction to Heat Pump and Hybrid Dryers

The focus groups also explored awareness of heat pump technology, heat pump-based dryers, and potential interest in acquiring one upon the participants' next dryer purchase. Participants were generally unaware of heat pump-only and hybrid dryers, although those closer to the metropolitan areas of Seattle and Portland had some awareness and even experience with heat pump technology for space and water heating. After asking focus group participants general questions about laundry habits, features, and appliance replacement strategies, we described heat pump-only and hybrid dryers to them and presented a full range of conventional and super efficient dryer options available. Our description compared different conventional and heat pump-based dryer types along the dimensions of technology used, purchase cost, operating cost, drying temperature, drying time, requirements for venting and water drains, and the availability of other, optional features. This information led to an exercise in which we had focus group participants identify which dryer types they would consider among their top choices if they were shopping for a clothes dryer. Participants could choose up to two choices they would be likely to consider.

Results show that participants would consider energy efficient conventional and hybrid dryers, as well as high-end conventional dryers. As shown in Table 1, participants were noticeably less inclined to consider basic, low cost dryers and heat pump-only dryers. These results suggest that low purchase cost is not a primary driver, but features do matter. Energy efficiency alone is of interest to consumers (as shown by the greater self-reported interest in modestly more expensive ENERGY STAR-certified models than non-ENERGY STAR-certified conventional dryers in this exercise), but higher cost machines need to provide either the flexibility of hybrids or other features typically available with high-end dryers. (These features can include a steam feature, wrinkle guard, settings for heavier loads, and the availability of matching appliances). In other words, value is more important than price. Energy efficiency is in the mix of features that matter, but not as an isolated feature separate from other considerations. For those who rated hybrid dryers highly, the choice between an eco mode and conventional operation was an important feature. (The eco mode is the setting on hybrid dryers that allows users to select a slower but more efficient drying process that relies on the heat pump technology.)

Table 21: Focus Group Participant Dryer Choices (among those selecting electric dryers)

	Number of Participants Who Selected (Among Top Two)
Conventional Electric	6
Conventional Electric - ENERGY STAR	24
Conventional Electric – High End	17
Hybrid Electric (ENERGY STAR)	14
Heat Pump Electric (ENERGY STAR)	6

Consumer Trade-Offs

We used a stated preference questionnaire within the web panel survey to elicit respondents' preferences for the following dryer features: energy use, drying temperature and time, ENERGY STAR designation, and price. We asked each respondent to choose one of four alternative dryers, each with a different set of attributes available in a conventional or super efficient dryer (a term that comprises both heat pump-only and hybrid dryers). Presenting choices this way removes the influence of actual in-store experiences, brand advertising, and stocking practices, thereby providing insights about what consumers might choose if super efficient dryers were as available and were marketed in a similar way as conventional dryers.

Figure 1 below illustrates how we presented the first of two panels of choices to study participants. In this first panel, we presented respondents with four dryer choices (A, B, C, and D), each with a unique set of four key characteristics: purchase price, energy savings compared to a base case, drying temperature and time, and ENERGY STAR status. We asked respondents to choose one of the dryers and then presented them with a second panel of dryer choices in which the order of the dryers differed and the price of either or both the heat pump-only and hybrid dryer randomly changed within a predefined range based on the respondent's dryer choice from the first panel. We presented purchase costs in dollars, but energy savings in percentage terms relative to a basic, non-ENERGY STAR-certified dryer.

	Choice A	Choice B	Choice C	Choice D
Cost	$600	$1,200	$1,000	$700
Energy Savings (reduced energy consumption compared to basic dryer	0%	50%	25%	10%
Drying temperature and time	Normal temp (with standard drying times of 45-60 minutes)	Lower temp (with drying times that are 50% longer, but safe for a fuller range of clothes)	Normal <u>and</u> lower temp (setting that lets you choose)	Normal temp (with standard drying times of 45-60 minutes)
ENERGY STAR	No	Yes	Yes	Yes
Your Preferred Choice	○	○	○	●

Figure 1: Example of the First Panel of the Stated Preference Questionnaire

It is important to note that stated preference surveys, such as this one, only elicit what respondents say they would choose, which is not the same as revealing what they actually did. Because of this, stated preference surveys, while providing valuable and potentially actionable information, are not as reliable as revealed preference surveys, in which the researcher observes the actual choices made by an individual. Consequently, we cannot be certain that the choices made by respondents in our survey are the same choices they would make when purchasing a dryer. It is also equally important to note that the hybrid and heat pump-only dryers are not widely available and most consumers are unfamiliar and even unaware they exist. Therefore, stated preference is the only practicable means for gathering information on consumer dryer preference.

The primary benefit of this exercise is that it allows us to gauge *potential* interest in hybrid and heat pump-only dryers in the absence of a marketplace where such dryers are widely available and product placement and presentation affect consumer choices. Presenting survey respondents with alternative dryers and asking them to choose the dryer with the preferred set of characteristics allowed us to understand consumer trade-offs and preferences within a controlled environment and to estimate the impact on dryer choice associated with changes in the price of the dryer. This is important information when considering the level of rebate that may be required to induce a consumer to consider a super efficient dryer.

When ENERYGY STAR and non-ENERGY STAR-certified conventional, heat pump-only, and hybrid dryers were presented side-by-side, respondents showed a clear preference for energy efficient dryers of either the conventional type or those that use some form of heat pump technology. As shown in Figure 2, only nine percent of respondents indicated a preference for conventional dryers that are not ENERGY STAR-certified even though these dryers were presented with the lowest purchase price (of US$600). Thirty-seven percent showed a preference for conventional, but ENERGY STAR-certified dryers (at a cost of US$700). The largest share of respondents—54 percent—indicated a preference for super efficient dryers at a price ranging from US$800 to US$1,400.[42]

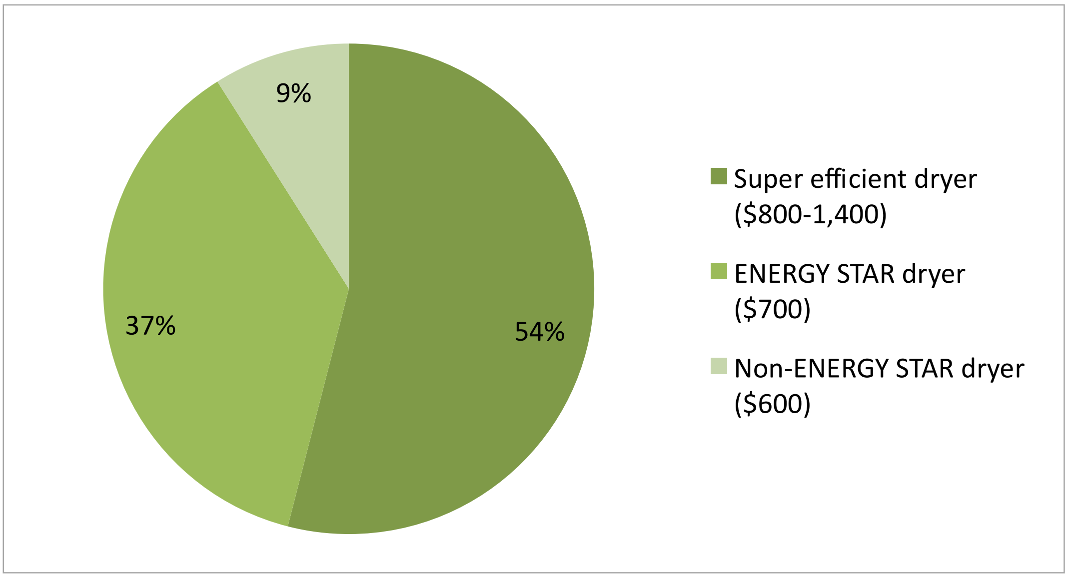

Figure 2: Customer Dryer Efficiency Preferences, from Choice Modeling

Of those survey respondents that chose a super efficient dryer, 43 percent preferred a hybrid model, while 57 percent chose a heat pump-only dryer. We recognize that actual product availability, placement in stores, and messaging about the dryer options would have substantial impacts on actual choices. Hence, these results should be taken as an inclination or predisposition rather than as predictive of future market shares.

[42] These amounts reflect our pre-defined range of potential post-rebate prices for super efficient dryers shown in the second panel of the stated preference questionnaire.

Through stated preference modeling, we were also able to estimate impacts of varying pricing through rebates or other discounts for heat pump-only and hybrid dryers, as well as observe the effect of two different levels of energy savings for conventional ENERGY STAR-certified dryers. Results of six different scenarios are presented in Table 2.

Table 22: Market Share Simulation of Stated Preference Model Results

		Percentage of Respondents			
Scenario	**Description**	**Conven-tional**	**ENERGY STAR (ES)**	**Hybrid**	**Heat Pump**
Base	Price of Hybrid Dryer is US$1,400 Price of Heat Pump-Only Dryer is US$1,400 ES Dryer reduces energy use by 10%	*9%*	*37%*	*23%*	*31%*
1	Price of Hybrid Dryer is US$1,400 Price of Heat Pump-Only Dryer is US$1,400 ES Dryer reduces energy use by 20%	8%	47%	20%	26%
2	Price of Hybrid Dryer is US$800 Price of Heat Pump-Only Dryer is US$800 ES Dryer reduces energy use by 20%	5%	31%	37%	27%
3	Price of Hybrid Dryer is US$800 Price of Heat Pump-Only Dryer is US$1,400 ES Dryer reduces energy use by 10%	7%	26%	47%	20%
4	Price of Hybrid Dryer is US$1,400 Price of Heat Pump-Only Dryer is US$800 ES Dryer reduces energy use by 10%	8%	31%	19%	43%
5	Price of Hybrid Dryer is US$800 Price of Heat Pump-Only Dryer is US$800 ES Dryer reduces energy use by 10%	6%	23%	41%	31%

*Note these percentages represent statistical estimates based on stated preferences of respondents.

As expected, consumer interest in super efficient dryers increased as we dropped their purchase prices, but the detailed results reveal an interesting and important dynamic. At a price of US$800, respondents prefer the super efficient dryers to the conventional, but among super efficient dryers, hybrid dryers are more popular than heat pump-only dryers. This is due to the model predicting that respondents will shift their preference for the conventional ENERGY STAR dryer to the hybrid dryer as the price of the hybrid dryer decreases. In contrast, the share of respondents who prefer a heat pump-only dryer changes comparatively little with the lower price. This suggests that one share of the population is more price sensitive and has a tendency toward the relative conventionality of the hybrid dryer, while another share of the population has an inherent interest in the heat pump-only dryer and shows less price sensitivity.

We inferred from these results that, not surprisingly, energy savings are important to consumers, but are only one factor they consider. Comparatively short dry times are an important consideration, and some attitudinal characteristics matter as well. Respondents who chose a super efficient dryer (of either type) were much more likely to indicate that they “tend to like trying the newest technology” (60 percent versus 39 percent).

Implications for Heat Pump-Based Dryers

These insights about consumer awareness, priorities, and interest have several implications for the promotion of heat pump-based clothes dryers in North America. These include the following:

Consumers have limited information about heat pump-based dryers, so education and consumer information needs to be part of any campaign to encourage their adoption. As noted in the portion of the study that investigated supply chain practices, stocking of heat pump-based dryers in stores appears to lag behind potential consumer interest, so third parties need to be the conveyors of information and help spur demand.

Conventional dryers with energy-efficient features that qualify them for the ENERGY STAR label do not appear to need much, if any, price support. Consumers seem willing to pay the marginal cost of these models for their energy savings and seem to trust the ENERGY STAR label as an indication of energy efficiency. Interestingly, consumers do not know how much they might save with ENERGY STAR models, but that does not appear to serve as a substantial barrier to their preference for these models as they appeared to be interested in ENERGY STAR-qualified models without expressing an innate need for quantified savings.

The full cost of heat pump-based dryers of US$1,400 (or more) does appear to be a deterrent to many consumers. Those interested in heat pump-only dryers seem more willing to pay this price, but lower costs would shift demand from conventional dryers toward hybrid dryers. Price support for hybrid dryers would be more effective for a program, while price support for heat pump-only dryers brings the risk of free ridership due to the seemingly low price elasticity in the demand for the heat pump-only dryers.

Energy efficiency and the use of new technology hold the strongest appeal for heat pump-only and hybrid dryers, while the flexibility to use either an eco mode or dry clothes faster with the use of standard technology is an essential attribute for many who would consider buying a hybrid dryer. Gentleness on clothes and the option to forego external venting are substantially less important to most interested consumers (but could be important in individual cases).

Study Application by Program Initiative

NEEA’s research, program, and marketing staff were all closely involved throughout the study in numerous ways, which strengthened the quality of the study, tailored the research to the key issues any future NEEA initiative will need to consider, and led to more actionable insights for the NEEA team. We discuss this interactive approach and subsequent application of study insights.

NEEA staff helped frame the research questions of interest during the study scoping process and provided feedback to all data collection instruments. In particular, NEEA feedback in framing the questions for the focus groups and web survey proved helpful to ensure that the dryer options were presented as realistically as possible and that potential price discounts were in line with the ranges that a program might actually offer. Interaction between the Evergreen Economics research team and NEEA staff representing research, program, and marketing ensured a sound study that was well rooted in the key questions NEEA needed to address. In-project interaction made the study more actionable than a turnkey study could possibly have been.

Likewise, direct observation of the focus groups by multiple NEEA staff and presentations of interim and final study results by Evergreen Economics to NEEA with interactive discussion of the implications helped communicate results to make them more actionable. These presentations provided an additional avenue for relaying study results, thereby reinforcing and complementing the report. Beyond that, however, the discussions helped NEEA staff and the Evergreen Economics research team better combine research results and program implications into deeper insights.

Subsequent to the market characterization study, NEEA's program team developed a set of three main strategies that were partially based on and confirmed by the market characterization, and further informed by more narrowly constructed marketing research. These strategies involved:

- Developing a consumer value proposition;
- Persuading retailers to floor super efficient dryers; and
- Developing initial market demand for super efficient dryers in the multifamily market.

The first of these strategies—developing a consumer value proposition—is a common approach in determining the nature of consumer-facing messaging and program strategies. The market characterization study provided key input and overall insights about consumer preferences, priorities, and considerations to this process through the findings that:

- The general appeal of energy savings and the ENERGY STAR label translate to clothes dryers and are one driver behind potential interest in super efficient dryers;
- There is a generally positive response to improved technology and features and heat pump technology specifically;
- Some specific non-energy benefits of super efficient dryers, such as possible gentler treatment of clothes, had a more limited appeal or resonated with only subsets of consumers;
- Households' dryer purchase practices and varied in-home approaches to laundry result in somewhat differing needs and preferences across the full range of dryer models available on the market.

NEEA's program team commissioned a follow-on marketing research and prioritization project to explore consumer value propositions and to build on the market characterization findings. This effort concluded that positioning super efficient dryers as a "better dryer" with cutting-edge yet proven technology, emphasizing the dryers' ENERGY STAR labeling, and quantifying their energy savings are likely to appeal to potentially interested consumers.

The second strategy—persuading retailers to floor super efficient dryers—was under consideration prior to the market characterization study and arose as a key strategy based on the findings that potential consumer interest in super efficient dryers appears to be greater than actual adoption of the technology, which is likely held back by the lack of visibility of super efficient dryers as an option during the purchase process.

The third strategy—developing initial market demand for super efficient dryers in the multifamily market—was influenced only minimally by the market characterization study, which had found ambiguous results in a brief exploration of super efficient dryer's application in this sector. The program team's approach is tactically significant as a way to achieve an initial market lift for the technology.

Not all of the market characterization study's results translate into actionable program strategy, however. Program or organizational strategy and competing objectives sometimes dictate a different direction than a focused research study might suggest. For example, NEEA's program team will likely continue offering incentives for heat pump-only dryers in parallel with hybrid dryers for both equity reasons and due to their desire to signal support for both types to the supply chain even if consumer research alone would point to differing responses by purchasers.

Transferability within North America and Globally

Although this study focused on the northwestern region in the United States, the results are likely to apply broadly throughout much of the United States, as suggested by interviews with representatives of the Super Efficient Dryer Initiative that operate and are exploring similar initiatives in Eastern states as those being developed by NEEA. With some adjustments for currency and cost-of-living factors, these results should also be transferable to Canadian consumers, who tend to have similar lifestyles, housing stock, availability of appliances, and energy efficiency programs.[43]

Globally, some of the insights from this study may apply conceptually in developed countries, but differences in consumer preferences, laundry practices, housing stock, and appliance stocks available for purchase need to be taken into account.

Conclusions

North American consumers are open conceptually to the idea of more efficient heat pump-based dryers and find their greater energy efficiency appealing, but numerous barriers need to be addressed before these products would be considered by mainstream consumers.

One of the most prevalent barriers is lack of awareness and visibility. Due to the emergency replacement nature of many dryer replacement purchases, visibility of heat pump-based models among retailers is essential. Because most retailers do not yet offer any floor space or prominence to heat pump-based dryers, energy efficiency programs can play a useful role in promoting awareness, interest, and demand. More prominent consumer exposure to these dryer options is essential so that programs and advocates can better understand consumers' revealed preferences and willingness to pay.

The current retail prices of heat pump-based dryers appear to be a deterrent as well, especially during emergency replacements when there is little time for consumers to conduct research and recognize the benefits of unfamiliar new options. Cost reductions through rebates or cost buy-downs are likely to make these dryers more competitive, but their effectiveness may differ between heat pump-only and hybrid dryers.

Our analysis of stated willingness to pay suggests that there is more fluidity and price sensitivity in consumer interest in hybrid dryers than heat pump-only dryers. Price reductions—either through market forces, scaled up production, or program interventions—are likely to shift interest from conventional energy-efficient dryers toward hybrid dryers. Demand for heat pump-only dryers—which appears to be similar as that for hybrid dryers at full prices—is less price elastic. That is, price reductions are less likely to affect demand for the heat pump-only dryers.

Acknowledgements

We wish to acknowledge and thank the Northwest Energy Efficiency Alliance for sponsoring this research and refer readers to the full market characterization study report available from NEEA [1]. We also refer readers to a related paper published at the International Energy Program Evaluation Conference with a more domestic focus [4].

[43] Transferability to Mexico may be more limited, however.

References

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[2] EIA (Energy Information Association) 2013. *Residential Energy Consumption Survey (RECS)*. Washington, DC: U.S. Department of Energy.

[3] NRDC (National Resources Defense Council) 2014. *A Call to Action for More Efficient Clothes Dryers: U.S. Consumers Missing Out on US$4 Billion in Annual Savings.* New York, NY: National Resources Defense Council. Retrieved from https://www.nrdc.org/sites/default/files/efficient-clothes-dryers-IB.pdf.

[4] Bensch I., Helvoigt T., Webb-Cabrera, A. and Baker, S. Gauging Consumer *Appetite for Super Efficient (Heat Pump) Dryers*. Proc of the 2017 International Energy Program Evaluation Conference (Baltimore, Maryland, USA, 7-10 Aug 2017). Available at www.iepec.org

Dryer usage patterns and energy saving potential during normal use

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Abstract

While there is limited end use metering data for clothes dryers in Australia, most energy measurements suggest that dryer use in an average Australian home is relatively low compared to Europe and North America. However, there appear to be a significant minority of households that are heavy dryer users. This paper examines three main issues.

Australia is looking to adopt IEC61121 as the test method for clothes dryer energy labelling in the medium term. In 2016 the Australian government sponsored a round robin of two dryer appliances (one conventional, one heat pump) across four test laboratories. Additional investigative tests beyond those defined in the standard were conducted in order to better understand dryer performance under a range of usage conditions likely to be encountered in households. These allowed a generalized performance curve to be developed to assess the energy impact of different initial and final moisture contents on energy consumption.

The second element of the paper is the appraisal of end use metering data for 28 dryers in Australia to assess the level of dryer usage and associated energy consumption during normal use. The analytical techniques developed allowed a frequency distribution of dryer load masses to be estimated for each house during normal use. Analysis shows that average load sizes are generally around 1.5 kg (equating to 20% to 30% of dryer rated capacity).

The third element builds on the previous two elements. A targeted replacement program run by Sustainability Victoria monitored the energy consumption and usage patterns for existing older conventional clothes dryers and compared this with a new heat pump dryer in four houses. The heat pump energy savings are impressive at an average of 69% across the retrofit houses.

Introduction

Energy labelling was introduced for clothes dryers in 1989 in the state of Victoria and this became a national energy labelling scheme in 1992. Clothes dryers have traditionally used very basic technology – a fan that blows air, heated by a resistive element, through clothes that are tumbled in a rotating drum. While there are a number of refinements and variants to this basic dryer technology, such as automatic sensing of load dryness, reversing rotation and condensing dryers, until recently there has been little variation in efficiency of most products on the market. Australia has been tracking the sales weighted efficiency of whitegoods since 1993 and dryers are the only appliance that has not shown any significant improvement for over 20 years [1].

While heat pump dryers were developed in the mid-1990s (details were released at the first EEDAL conference in Firenze in 1997) and have been commercially available since 2000, very few units have made it into houses in Australia. This appears to be primarily due to their very high purchase cost. However, heat pump dryers started to appear in significant numbers in the Australian market in 2010 and in 2014 they had a market share of about 4% [1]. Prices for heat pump dryers have been trending down strongly since their appearance on the market in 2010 as sales volumes increase. Most dryers that use conventional resistive elements achieve a star rating of 2 to 3 stars. The dryer energy label shows the energy and capacity and allows for a star rating of up to six stars. In order to recognize the increased prevalence of heat pump dryers with much higher efficiency, the super efficiency rating label, showing up to 10 stars, was introduced into the government determination in 2016, as shown in Figure 1. Most heat pump dryers rate from seven to eight stars under the current algorithm.

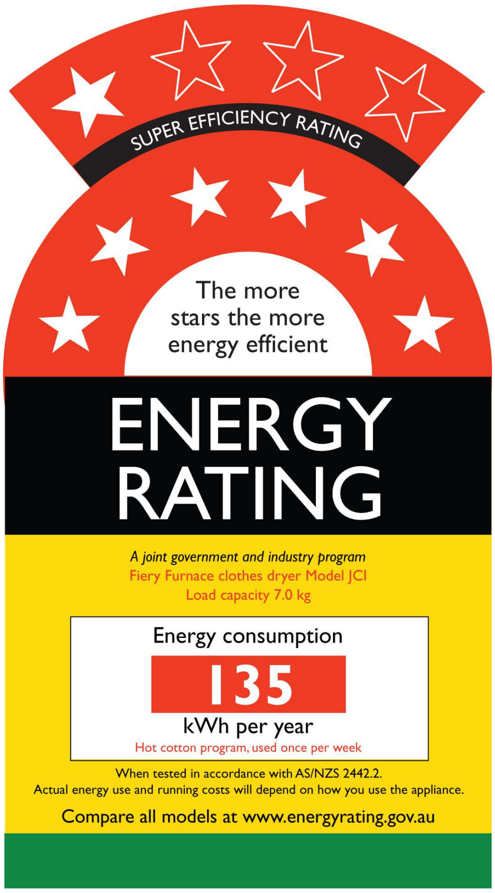

Figure 1: Super efficiency rating energy label for clothes dryers in Australia and New Zealand

In Australia, the ownership of dryers is currently around 55% and this has been fairly steady since around 1980 [2, 3]. The original energy label algorithm assumed 150 uses per year, but data collected in around 100 homes in the 1990s found that usage levels were much lower [4], so the label was revised in 2000 to one load per week at rated capacity. This is significantly lower than dryer usage North America and Europe. End use data for clothes dryers in the field is fairly limited in Australia and there has been anecdotal evidence that usage patterns for dryers vary widely and the average load sizes are relatively small.

Australia is looking to adopt the test method published by the International Electrotechnical Commission (IEC) standard IEC61121 as the national test method in the future. In order to assess the suitability of this standard for local application in energy labelling, a round robin of independent accredited test laboratories was undertaken in 2016 [5]. This testing also allowed some deeper investigations in the behavior of dryers and the development of a more generalized performance curve in terms of initial and final moisture content under a range of different load capacities.

The recent advent of affordable data logging equipment has allowed detailed energy data to be collected in homes on a routine basis. This paper looks at several issues with respect to clothes dryers. Firstly, the headline results from the Australian round robin of dryers is examined. Secondly, data logging data for 28 clothes dryers in homes has been reappraised to assess the frequency of use and to indirectly estimate the average load size dried in a typical home. And lastly, the results of a dryer retrofit trial undertaken by Sustainability Victoria in four homes are reviewed. Conventional dryers were monitored for a period of 6 weeks and these were replaced with heat pump dryers. Actual energy savings during normal use were quantified.

Australian round robin to IEC61121

Australia and New Zealand have a policy to adopt international test methods where possible. Presently, clothes dryers are required to demonstrate compliance with GEMS Level Requirements through test procedures specified by Australian and New Zealand Standard AS/NZS 2442.1, which is based on the Association of Home Appliance Manufacturers (AHAM, USA) test method from the 1980s. At the time of its development, there was no IEC standard for clothes dryers. The Australian government, in conjunction with state authorities undertook round robin testing of IEC61121 Edition 4 in 2016. The objectives of the round robin were to:

- Provide experience for those facilities charged with undertaking verification testing to Australian and New Zealand laws to gain practical testing experience with the relevant IEC test procedure for clothes dryers, which is the proposed testing basis for energy labelling in the future;
- Build testing capacity within local test laboratories;
- Assess the reproducibility and repeatability of the IEC test method and provide expert opinions as to its technical suitability as a basis for future regulation in Australia and New Zealand;
- Generate data and conduct analysis in order to provide technical feedback to the IEC with respect to any specific weaknesses or issues in the IEC test method prior to its adoption in Australia; and
- Give stakeholders confidence that the new test procedure gives sound results suitable for regulatory enforcement.

The round robin yielded substantial information regarding the IEC test method. The data collected also allowed some limited benchmarking back to the Australian and New Zealand test method currently used for local regulation. The results were encouraging in the context of the possible policy goal of using the IEC test method for regulatory purposes in the future. The overall variation in measured energy consumption across test laboratories was 3% at full load and 3.5% at half load (following application of specially developed correction factors for initial and final moisture content), which is in line with expectations for this type of appliance. However, investigation in this report found the IEC correction factor specified in the standard is likely to be flawed, so IEC is encouraged to review the data provided and consider the development of a more robust correction approach [5].

A wide range of recommendations were made regarding the IEC test method and these are currently being considered by the relevant IEC sub-committee (IEC SC59D). The most significant technical issue raised by the report was the current correction factor for variations in initial and final moisture content. The IEC standard assumes a linear correction where the initial or final moisture content are not at the specified target values. However, it is well known that changes in initial and final moisture content are not linear in their impact. In particular, each additional percentage point of moisture to be removed from the dryer at the end of the cycle is increasingly more difficult to remove and the apparent efficiency falls very quickly as the load becomes very dry. At the limit, the efficiency of removing the last bit of moisture to achieve the bone dry state (a residual moisture content (RMC) of around -7%) is close to zero. The performance curve for one of the heat pump dryers is illustrated in Figure 2. Note the different initial and final slopes of the curve.

Preliminary analysis undertaken in the round robin suggests that a compound approach that applies separate corrections for variations in initial and final moisture content would be more accurate, repeatable and reproducible. A set of suggested corrections is illustrated in Figure 3. Note that the primary objective of the round was not to develop improvements to the IEC correction and these proposals are based on limited tests. But the natural variations in final moisture content across different laboratories on the same machines show that an improved correction is warranted.

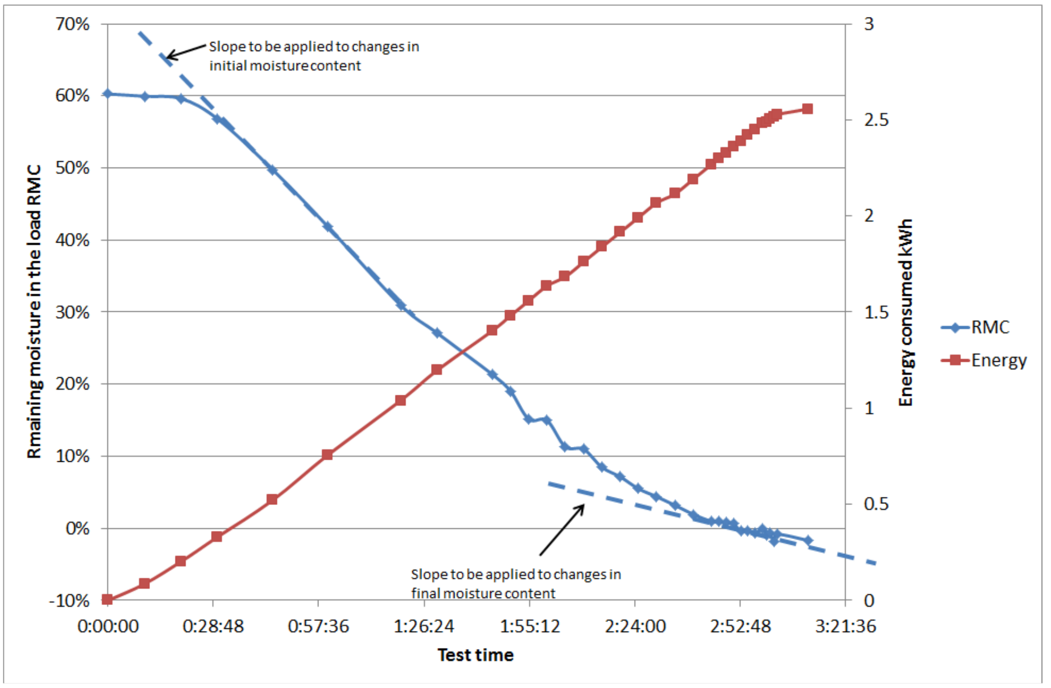

Figure 2: Continuous measurement of energy and moisture content for a test

Figure notes: Source [5]. Test run on a Miele condensing heat pump dryer at rated capacity (8 kg).

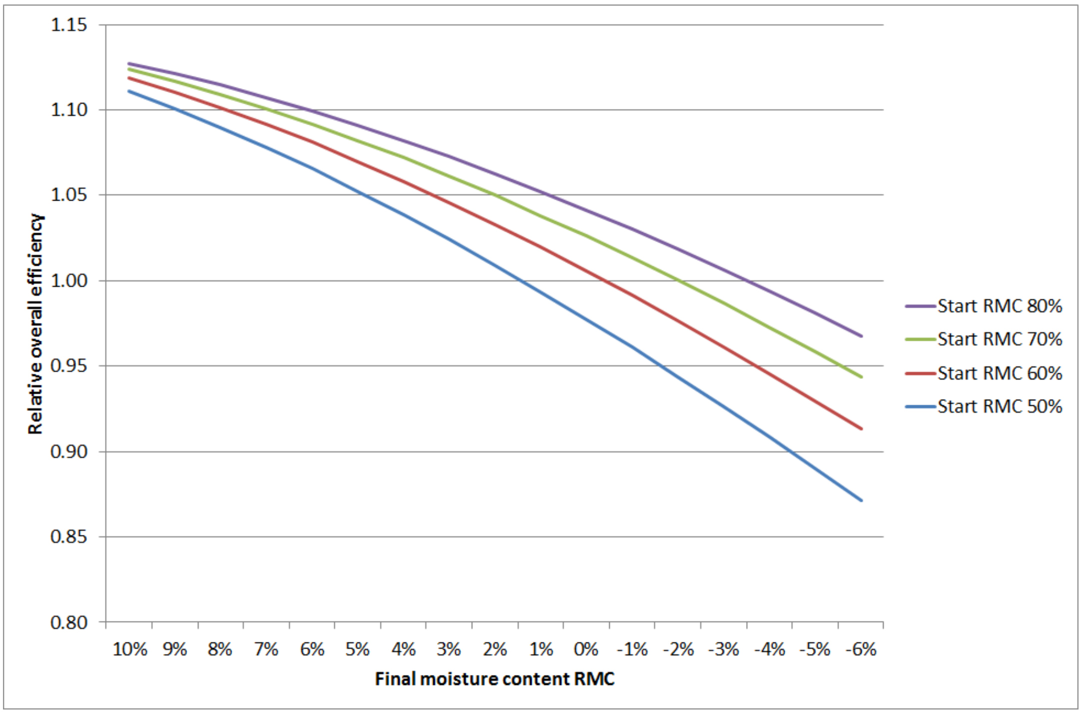

Figure 3: Suggested dryer efficiency corrections for various initial and final moisture contents

Figure notes: Source [5]. All values normalized to a value of 1.00 for an initial RMC of 60% and a final RMC of 0% as per IEC61121 target values.

Assessment of clothes dryer end use measurement data

Based on analysis of data from the dryer round robin [5] and data published by the local Australian consumer magazine called Choice at part load [6], the expected dryer energy consumption as a function of initial load size was developed, as shown in Figure 4. This allows the load size to be estimated from the measured energy consumption of each load cycle. Full details on the approach used are set out in [7].

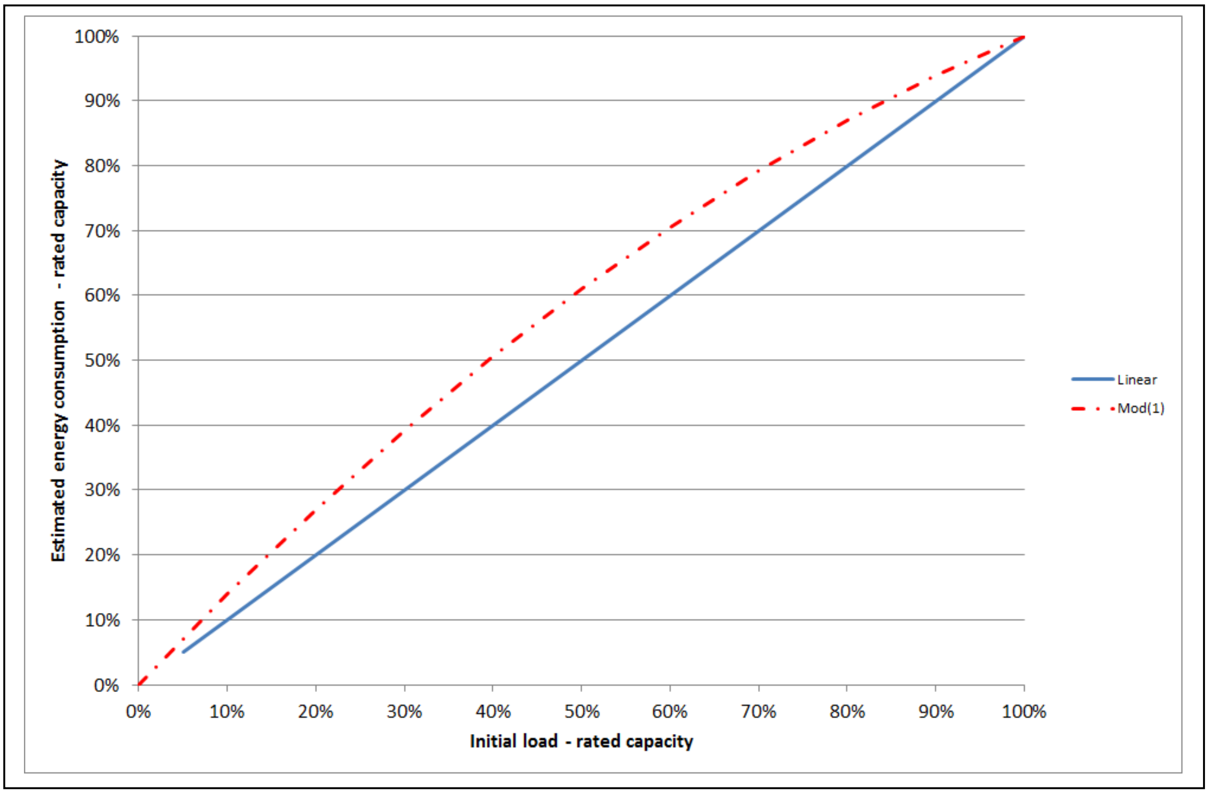

Figure 4: Estimated dryer energy as a function of initial load

The red curve in Figure 4 can be depicted as an equation. An adjustment is required to take into account the expected spin performance of an average clothes washer in the Australian stock (an RMC of around 60%) compared to the moisture content assumed in the test standard AS/NZS2442.1 (an RMC of 79.2%). The mass of load items dried can then be estimated from the measured energy consumption per cycle where the rated capacity and tested energy consumption of the dryer is known.

Load dried kg (Mod1) = $$\left| 0.43 \times \left(\frac{E_{load}}{E_{rated}} \right)^2 + 0.57 \times \left(\frac{E_{load}}{E_{rated}} \right) \right| \times Load_{rated} \times 1.29$$

Where E_{load} is the measured energy consumption in the field for a dryer cycle, E_{rated} is the energy consumption of the dryer to dry a full load at rated capacity under AS/NZS2442.1 and $Load_{rated}$ is the rated capacity under AS/NZS2442.1. Using this approach it is possible to estimate the mass of load items dried for each cycle from field data.

Monitoring data for a total of 28 dryers from 24 homes was subjected to this analysis approach. These homes were selected on a random basis through a range of campaigns and can be considered fairly representative of the residential sector in Australia. The key results of the analysis are summarized in Table 1. Note that dryers SVCD1a and SVCD1b were old and new dryers in the one home (and similarly for houses SVCD2, SVCD3 and SVCD4). The data covers over 4,100 days of measurements and some 2,800 individual dryer cycles in homes.

Table 1: Summary of field measured for clothes dryers in Australian homes

Dryer ID	Days of data	Cycles	Cycles/day	Average kg/load	Rated Capacity kg	% rated
EESCD01	42	39	0.93	0.67	3.5	19%
EESCD02	176	85	0.48	1.11	3.5	32%
EESCD03	163	132	0.81	0.86	5.0	17%
REMP3	368	196	0.53	1.22	4.5	27%
SVCD1a	36	52	1.43	1.67	6.0	28%
SVCD1b	85	135	1.60	1.83	7.0	26%
SVCD2a	50	16	0.32	0.55	3.5	16%
SVCD2b	68	15	0.22	0.48	7.0	7%
SVCD3a	39	90	2.30	1.72	4.0	43%
SVCD3b	85	274	3.23	1.73	7.0	25%
SVCD4a	46	99	2.15	2.39	5.0	48%
SVCD4b	53	165	3.12	1.80	7.0	26%
SVCR1	68	43	0.63	3.07	5.0	61%
SVCR2	68	56	0.82	1.86	4.0	47%
SVCR3	69	57	0.83	1.06	5.0	21%
SVCR5	74	16	0.22	2.37	5.0	47%
SVCR7	114	75	0.66	0.97	5.0	19%
SVCR8	118	15	0.13	0.89	4.0	22%
SVCR9	109	52	0.48	1.66	5.0	33%
EESN03	256	124	0.48	2.65	5.0	53%
EESN08	264	196	0.74	1.95	7.0	28%
EESN16	178	10	0.06	2.39	4.5	53%
EESN18	258	201	0.78	2.32	5.0	46%
EESN23	295	212	0.72	0.71	4.5	16%
EESN27	215	40	0.19	0.87	4.5	19%
EESN29	253	122	0.48	1.49	4.5	33%
EESN30	328	236	0.72	1.64	5.0	33%
EESN49	224	52	0.23	1.25	4.0	31%
Average/ Total	**4101**	**2805**	**0.90**	**1.54**	**5.00**	**31%**

For 19 dryers, the monitoring interval used was a mixture of 1 min, 2 min and 10 min data. Data collected at 1 min and 2 min generally allowed the automatic separation of individual cycles that were run consecutively (one load removed and a new load added within a minute or two). Data measured at 10 min intervals required some review of each cycle and manual separation of cycles in some cases. For the nine dryers EESNXX, data was only available at 30 min intervals (the raw data was measured at 1 min intervals but some missing data made analysis of raw data problematic for this paper). Most of these dryers required manual separation of a few loads where the dryer was run consecutively (around 1 in 10 loads). However, some consecutive loads (especially where these are smaller loads) may have been missed and counted as a single load. This may mean that the number of cycles and cycles per day is undercounted slightly for these dryers and the average size of loads dried is overestimated slightly. However, these houses have data that is broadly consistent with the other houses, so this issue does not seem to skew the data significantly.

The most surprising finding from this data analysis was that the average size of load dried was very small – around 1.5 kg across the 24 houses (and 28 dryers) monitored. While there was a mixture of load sizes dried in each house, the average of all houses was considerably below rated capacity, typically around 30% of rated capacity or less. A typical load distribution for house SVCD1 for the old and new dryer is shown in Figure 5. As shown in Table 1, the average load per cycle for SVCD1a was 1.67 kg while the average load per cycle for SVCD1b (different dryer, same house) was 1.83 kg. The new dryer had a rated capacity of 7 kg compared to the old dryer at 6 kg. This household was a relatively heavy dryer user in terms of average load size and loads dried per day.

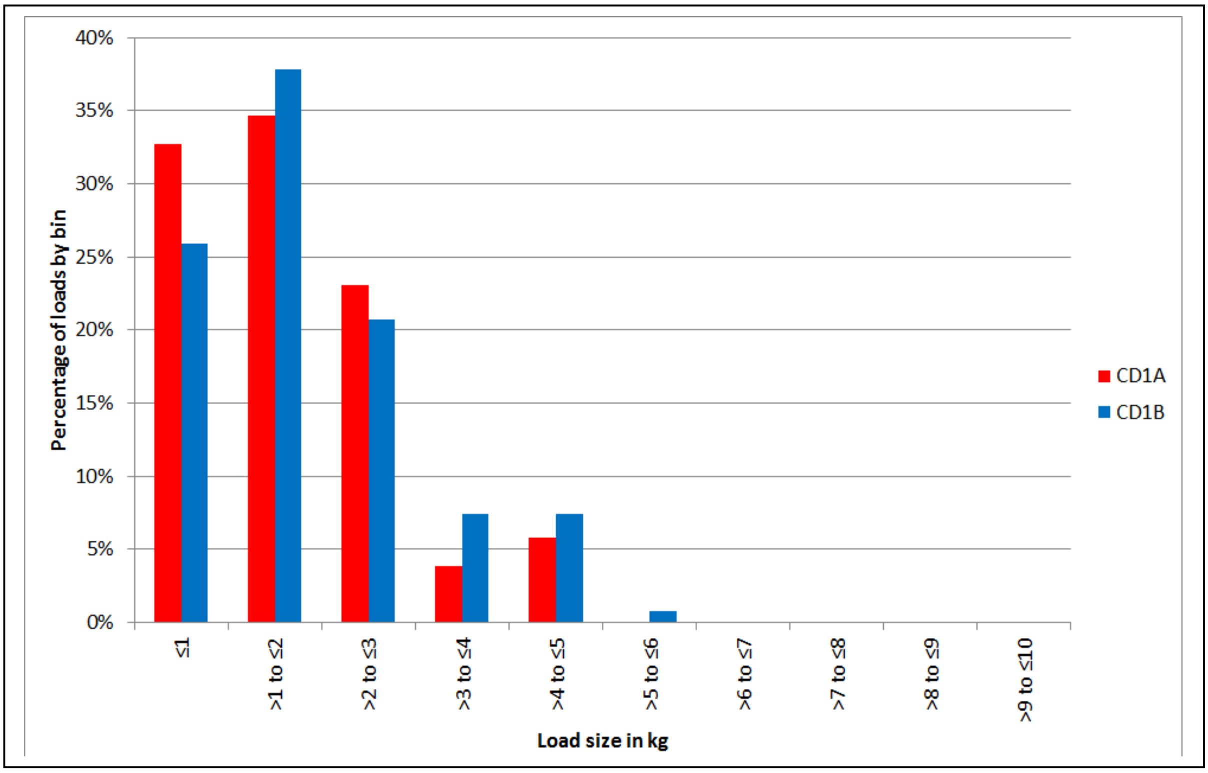

Figure 5: Comparison of energy per load before and after dryer replacement – house SVCD1

This data suggests that some reappraisal of how dryers are tested needs to be undertaken. Currently in Australia the assumption is that 52 loads at rated capacity are dried per year. While the data analyzed for this paper has a mixture of average and heavier dryer users, better data on overall average use is required. This data suggests that around 200 to 250 loads dried per year may be typical, but these loads are at an average of around 25% of the rated capacity. It is important that dryers are tested in a way that allows regulators to reflect more typical usage patterns. Testing at rated capacity and part load can be combined to provide a more accurate assessment of energy consumption during normal use. European energy labelling current assesses label performance on a mixture of rated capacity and half load, but even half load may overstate the average consumer load size in normal use.

Several other data sources in Australia [3, 4] suggest that dryer usage in Australia varies considerably across households. This is likely to be due to relatively warm, dryer weather in most parts of Australia for much of the year and very high incidence and use of outdoor clothes lines in homes. Many householders only use a dryer as a backup appliance during poor weather or to finish off some items that have been partly line dried. The wide range of annual energy consumption for dryers is illustrated in Figure 6 [8] for 12 dryers measured over one year. This wide usage distribution presents some special problems for policy makers, as mandating heat pump dryers would clearly benefit heavy users but would have significant net costs for low or infrequent users. Encouraging heavy users to select heat pumps is a challenge. Even identifying heavy users in the absence of measured data for the home is problematic.

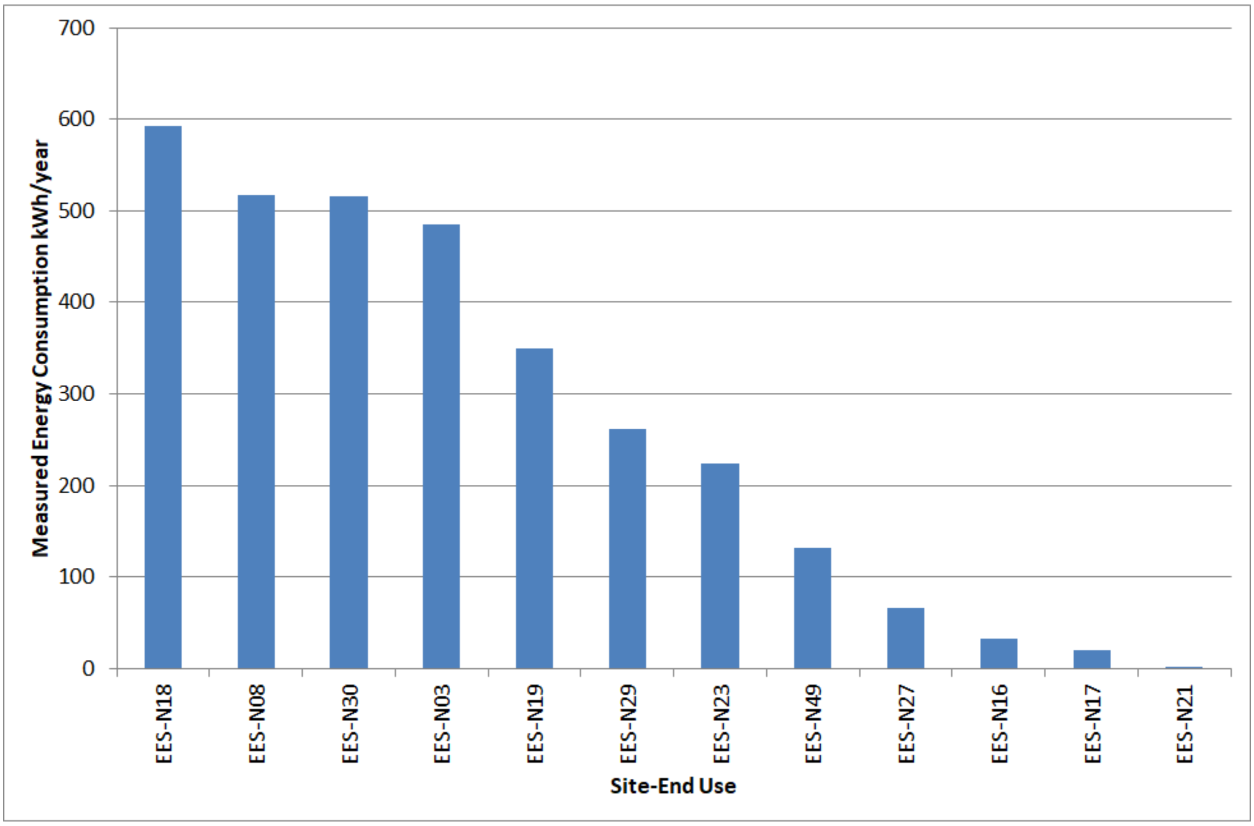

Figure 6: Measured annual energy consumed by 12 homes in 2012

Assessment of energy savings from heat pump clothes dryers

In 2014, Sustainability Victoria, a state agency that undertakes a range of efficiency programs, undertook a Clothes Dryer Retrofit Trial that involved the replacement of an existing conventional electric clothes dryer with a high efficiency heat pump clothes dryer in four houses located in Melbourne. Households with higher dryer use were targeted for the trial, so these households were not representative of average use. Existing dyers were monitored for a period of around 6 weeks in order to establish dryer usage patterns. After the dryers were replaced with heat pump units, the new dryers were monitored for a further 8 weeks. This allowed the usage and energy consumption to be directly compared and the energy savings to be calculated. Full details of the trial are given in [7]. Sustainability Victoria also undertook a householder satisfaction survey.

One specific area of investigation in the retrofit trial was whether the existing conventional dryers generated any excessive indoor humidity issues. Two of the houses reported condensation issues with the old dryers: the other two houses did not have issues because one exhausted air outside and the other was a condensing dryer. Note that in Australia, it is common for dryers to vent to the room (typically a laundry) without any external exhaust. Monitoring of temperature and humidity in the dryer room showed that dryer operation certainly increased the room air temperature during operation. Examining the relatively humidity was of little value as this parameter is strongly affected by room temperature. However, data analysis of a large number of cycles for each house showed that dryer operation increased the humidity ratio by around 0.5 g water vapour/kg dry air (from a background base of around 8 g water vapour/kg dry air) and the dew point temperature by around 0.7 K (from a base of 10°C to 11°C). This humidity increase was present even for the heat pump dryers, which are the condensing type. By any measure these increases in humidity are quite small and are not likely to cause issues unless the indoor temperature is already close to dew point. The houses that originally had condensation issues had low average room temperatures and used dryers that vented to the room. The laundry area in Australian houses are typically unheated.

Detailed data analysis revealed that three of the houses increased the frequency of use slightly after their old dryer was replaced with a new heat pump dryer. On average, cycles per day increased by around 30%. However, the average load size dried in the new dryers stayed at a similar level across all houses (decreased by 7% on average) suggesting that user drying requirements (or at least the approach to using the dryer) had not changed significantly. As the old dryers were monitored in late autumn and the new heat pump dryers were monitored in the middle of winter (July, August) the increased usage may be part of the natural change in seasonal pattern in the house, rather than any rebound effect on usage. Longer monitoring periods would be required to accurately establish seasonal patterns for each home.

In order to calculate energy savings from the replacement of the conventional dryer with a new heat pump dryer, a standardized load size and frequency of use was estimated for winter and applied to both dryers. In order to estimate annual savings more accurately, a typical seasonal profile was applied to the average winter data based on a review of available data from all monitored homes around Australia, with 50% usage assumed for summer and a smoothed curve through the seasons. Headline results are shown in Table 2.

Table 2: Summary of energy savings by house – Sustainability Victoria Retrofit Trial

House ID	Ref loads/ week	Ref load size kg	Energy before kWh/y	Energy after kWh/y	Energy savings kWh/y	Energy savings kWh/y
CD1	10.5	1.73	625	224	401	64%
CD2	1.8	0.25	41	12	29	71%
CD3	19.6	2.8	1,370	422	948	69%
CD4	18.2	2.6	1,572	460	1,112	71%
Average	**12.5**	**1.85**	**902**	**280**	**623**	69%

Notes: Source [7]. Old dryer in house CD1 was a relatively new condensing dryer. Old and new dryers were subjected to the same average reference load size, frequency of use and seasonal pattern in order to calculate annual energy and savings.

This data shows that usage varied considerably across the four houses, both in terms of uses per week and average load size. All load sizes were considerably lower than the rated capacity. Despite the variation in use, the average energy savings were quite consistent across households, averaging 69%. In contrast, the estimated savings based on the energy label is an average of 53%, which is somewhat lower than actual savings. This suggests that the tested energy used for energy labelling does not reflect the relative efficiency of different dryers for small loads. Of course the economics of the new heat pump dryer varies considerably, with a simple payback of around 5 years for house CD4 to over 100 years for house CD2 [7].

Conclusions

This paper shows that new heat pump dryers are able to achieve substantial energy savings in the field during normal use. The savings are even larger than are currently suggested by the current test procedures and energy label in Australia. However, analysis of field data shows that typical users in Australia only dry very small loads (on average). This suggests that there needs to be a reappraisal of the approach to testing and rating of clothes dryers in Australia. While the results of the analysis may have limited global applicability, it does show that detailed and intelligent analysis of field data is required in order to understand normal use in the home. It is highly likely that both washer loads and dryers loads in other regions are considerably smaller than rated capacity in normal use.

Detailed analysis of the IEC dryer test method shows that it is important to understand the behavior of dryers at part load. Elements of the current standard do not provide robust corrections for variations in initial and final moisture content, which can vary from run to run. Making the test standard more versatile so that performance at a range of part load conditions can be estimated without an undue additional test burden is critical if we are to have a test procedure that is globally applicable and relevant.

Acknowledgements

Data for some of the households was provided by Sustainability Victoria and was analyzed by the author under contract for inclusion in [7]. The Department of the Environment and Energy contracted the author to prepare analysis on the Australian IEC round robin. The cooperation of Sustainability Victoria and the Department of the Environment and Energy through the provision of data and access to reports for this paper is gratefully acknowledged.

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12 ICT

Behavior Adaptive Scalable Energy Management for Electronics – a demonstration in Home Appliances and Displays

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ABSTRACT

Connected devices enrich user experience for a wide range of consumers. However, with an increasing number of such connected devices, improving the intelligence and coordination of energy management solutions becomes more impactful. In this paper, we propose an intelligent power management architecture for the next generation of energy efficient electronics informed by consumer behaviors. The system architecture is built upon scalable, on-demand active power and intelligent sleep/standby modes. User presence and engagement sensors are used for power management control. This system seeks to minimize both user intervention and overall energy consumption. One application of this technology is set top box (STB) power control in addition to other elements of a home entertainment setup, whether it is in a single-user or a shared-use space. For and implementation of our approach focused on STBs, during a two-month stress test, the energy consumption was reduced by over 50% in simulated usage laboratory testing. Implementation of the demonstrated approaches can occur by design integration at the OEM or be provided as low cost energy management retrofits. Direct energy savings can be achieved in existing stock by applying this behavior-adaptive management system to a wider range of consumer electronics with retrofit style solutions for existing units. A consumer behavior based intelligent power management architecture has been demonstrated as a platform for enabling energy savings in consumer plug load electronics. We extend the demonstration discussion to show application to other entertainment equipment, with specific focus on projection based displays.

INTRODUCTION

Residential electricity consumption, together with its associated generation and distribution losses, accounts for approximately 15% of the total US energy consumption as of 2010 [1]. A 2010 residential consumption survey found that about 30% of a home's electricity is used by miscellaneous plug loads (presumably dominated by electronics), and the latest Department of Energy projections estimate that this will grow to almost 40% by 2035, while the energy demands of white goods and lighting will remain relatively stable. Energy usage for plug loads in the home is centered around home entertainment systems and home offices, with approximately 2/3 of home plug load energy being used on average for home entertainment systems [1] [2].

SYSTEM ARCHITECTURE

The system architecture for behavior adaptive energy management is illustrated in Figure 23. The consumers and plug load devices are both integral components of the decision making process for individual device energy management. The context information collected by this system includes environment (temperature, lighting, humidity etc.), network (remote access, local clients, etc.) and behavior. A number of sensors, from low level physical sensors to high level attention and "emotion" sensors, are utilized to monitor behavioral changes of multiple users. Emotion and attention can be *inferred* from facial expressions. A hierarchy of inputs is defined with direct user inputs taking precedence over sensor inputs and recorded patterns. This reflects the core behavior adaptive principle, where user inputs and behavior sensing can override any device level decisions.

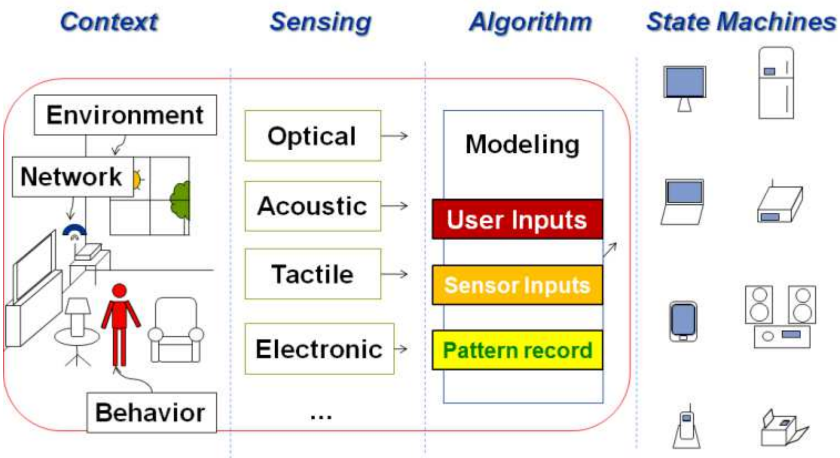


Figure 23: System architecture for behavior adaptive energy management.

Another core concept for this system architecture is that both users and the devices are defined with finite numbers of operational "states" (Figure 24). Users, for example, are attributed with their location and activity states as they perform different daily tasks at home or work. Traditional energy management seeks to "train" users to modify their habits. On the contrary, this user-centric system treats user behaviors as primary inputs to influence device state-machines. Depending ion implementation, devices may or may not be coordinated to improve system-wide integrated management. Devices managed by the system are able to shift to lower energy consuming states most effectively while providing uncompromised services to users.

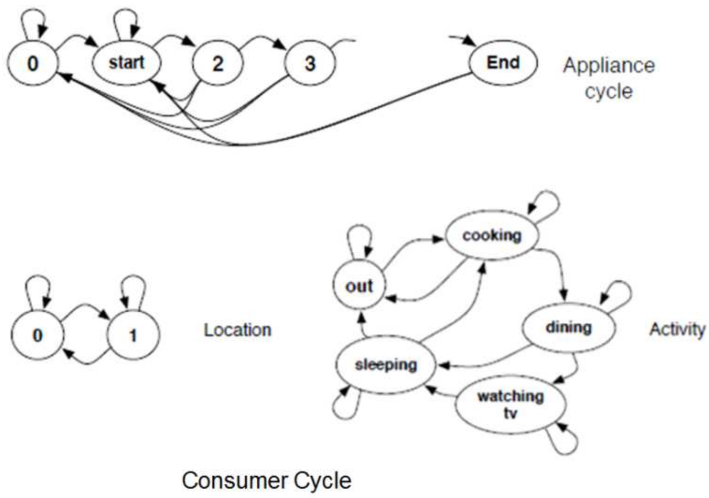


Figure 24: State-machine models for both appliances and consumer cycles.

In practical implementation, larger numbers of users, lack of visibility of user action on the part of the device, and effective unpredictability of users' interaction with a device provide challenges. To overcome these, a perturbation allowance permits optimization with allowance for differing usage.

A significant amount of research has been conducted in search of plug load power management solutions at program, incentive, components, packaging, device and system levels [3] [4]. However, consumers have always been the largest unknown factor, exhibiting unique usage behavior of their own plug load devices [5]. The concept of "Personal Energy Footprint" (PEF) was proposed at CalPlug to integrate consumers into plug load energy management. Here PEF refers to the energy needed for an individual to utilize plug load devices to support his/her daily activities such as doing the work, having entertainment, preparing food, etc. Contrary to traditional power management where user intervention is essential, the behavior adaptive architecture (artificial intelligence) proposed in this paper seeks to liberate users from the burden of user intervention while minimizing PEF. User behavior sensing and learning modules are defined at device and system level, and their power standards specified. The inclusion of multiple users and stand-alone, unconnected devices adds to challenges in this model. When practically implemented, perturbations to actions must be gracefully handled in a manner that does not decrease device usability. In this demonstration, elements of PEF are implemented on a device used to actively seek and act on periods of non-user interactions to save energy. Scalable active power mode and intelligent sleep mode are tested and implemented on a television set-top-box (STB) with further discussion of application to projection based displays.

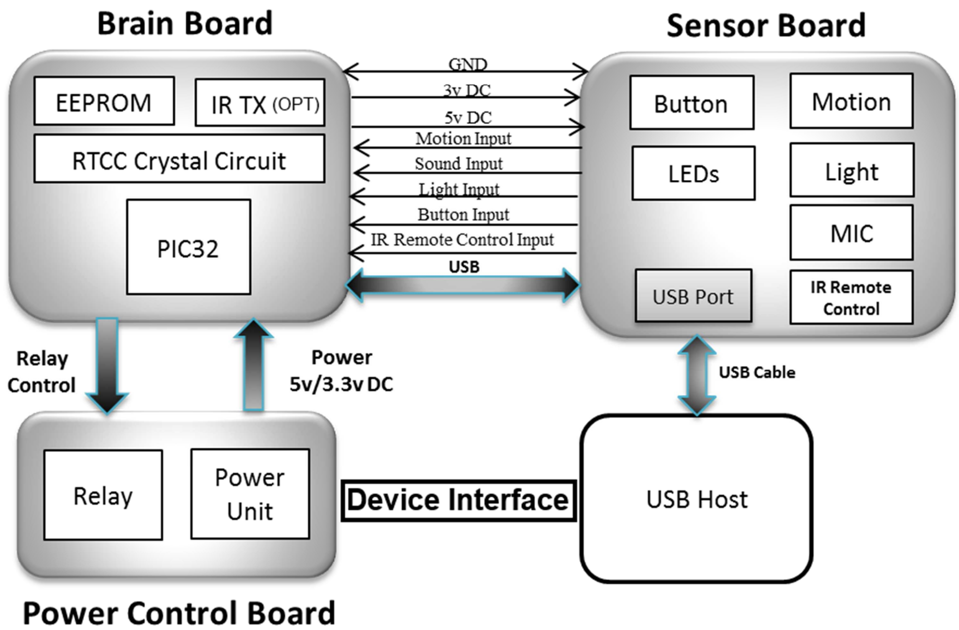
SET TOP BOX IMPLEMENTATION

To the surprise of many, the quiet, inscrutable, STB that sits next to their TVs are among the largest energy users in the plug load category [6]. It has caught national attention since the combined annual energy consumption of all STBs across the US is estimated to be four nuclear power plants' annual output [7]. There are technical and non-technical issues that may impede further power reductions. The most popular pay TV service infrastructures, including cable and satellite, must maintain high quality and security of the content delivered through the network. To introduce effective energy saving solutions, such as various sleep mode(s), one needs to consider both potential interference with user experience and upstream communication.

A CalPlug prototype solution code named "5W5s" is introduced as an implementation of the behavior adaptive architecture. The device can retrofit most modern STBs and put connected STBs into light and/or deep sleep at less than 5 watts of power consumption, and recover for full service within 5 seconds. Internal power savings modes (preferable if available) and power cuts to the STB (using an additional power controller) can both be leveraged for control. A USB prototype which was demonstrated is pictured visually and diagrammatically in Figure 25 and Figure 26, respectively. In Figure 25, a commercial STB under 5w5w management is shown in the background. This module prepares the STB by getting ready ahead of time by sensors built-in and usage patterns recorded.

1. **Figure 25: External view of the 5W5S prototype device.**

To base an estimation of how much energy can be saved, we first make a set of assumptions about basic patterns of daily user activities. Albeit with more uncertainty, patterns such as these can apply to families or multiple users on a similar schedule. In the example case, the user gets up at 7:00am and leaves home for work at 8:30am. The user returns at 6:00pm and is interested in watching TV between this time and approximately an 11:30pm bedtime (after this time the user is assumed to be asleep until 7:00 am). Using elements of a programmed (or learned) schedule, actions can be anticipated and acted upon. For example, anticipating the user has left the home, the power control box turns off the STB at 9:30am (user expected to leave the home). The STB stays completely off until the user comes back home at 6:00pm. Then, the user watches TV or walks around until 11:30pm, during which the STB is on all the time. One hour after the user goes to sleep the box turns off the STB at 12:30am. A time-based scheduling is augmented by sensor controls to permit early wakeup and overriding (or delay) of shutdown events. Based on the example case above, the STB stays off for 15 hours a day, i.e. 62.5%. Operational cycling is recorded on the on-board EEPROM of the 5w5s device for later inspection. If the 5W5s device consumes 1.5 watts inherently and stays on permanently, assuming the STB consumes 12 watts in operation, and 10 watts when idle, the energy consumption would decrease by at least 40% through intervention. The non-intervention case assumes no power management in use.



2. **Figure 26: The 5w5s prototype hardware block diagram.**

From the above discussion, it becomes clear that detecting and predicting the state and activity of the consumer is of paramount importance to provide a satisfactory Quality of Experience (QoE) while reducing energy consumption. The audio sensor (a low-pass sound envelope detector) uses changes in room sound as an indicator for user presence. The sudden appearance of sound with voice envelope modulation can indicate the presence of users in the vicinity of the device. Similarly a light and motion sensor set provides environmental operational cues due to device user induced local environmental changes. Other, more subtle environmental patterns that change with user presence are currently being investigated as extended user interaction prediction mechanisms. Direct human interaction is inferred through detection of Infrared (IR) remote control signals. Detection of user activity in periods where none is expected can lead to temporary device power control overriding in the short term and new usage pattern learning to improve control for similar future events. Temporal correlation is used as an element of the self-learning algorithm. Sound and motion triggers are used to identify usage activities prior to device interaction. These can permit pre-emptive device startup to ensure the device is operational by the time the user requests content. The STB device control is accomplished either through USB mediated control of a power management API or by device power cutting. Herein, we propose a Finite State Machine (FSM) model capturing the joint consumer-STB state. The consumer is characterized in terms of presence, attention to the device, and current device usage activity. The model enables the use of mathematical tools such as dynamic programming and Hidden Markov Model that empowers the system with classification, analysis and long-term optimization (self-learning) capabilities [8]. Based on the sensors' output, the statistics of the state transitions are matched to elements of a predefined reference set. The estimated statistics then allow the 5W5s control algorithm to perform maximal likelihood detection of the current state, and to implement techniques to optimize the long-term performance measured in terms of energy consumption and waiting time.

A two-month stress test of the prototype is carried out between two identical operating STBs, one with 5w5s and one without. During the two-month period, daily activities in the engineering laboratory of CalPlug are used as user behavior inputs. Students (15 total) were invited to watch TV during the day and into the evening for both the control and experimental setup which were operated simultaneously. The pay TV service remains uninterrupted throughout the testing period for both STBs. The final savings using the 5w5s solution reached 57.9% in this usage testing scenario.

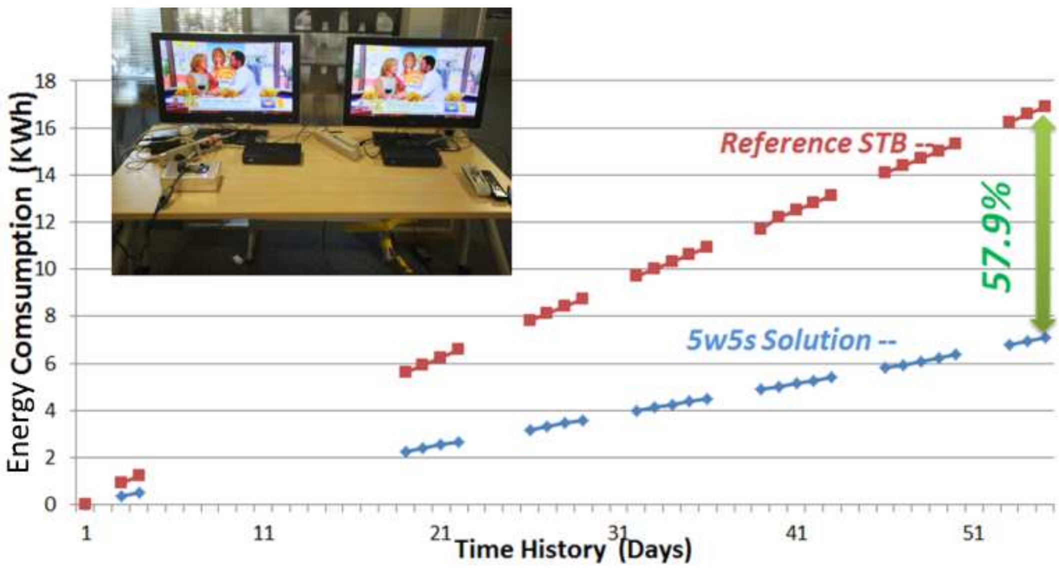


Figure 27: Stress test of energy savings potential with and without 5w5s solution.

PROJECTOR IMPLEMENTATION

Control of projection based televisions (TVs) remains challenging due to the startup and shutdown periods required for the projection bulb to warm up and cool down. While this type of device has low penetration in homes, this technology is in common use in educational and office environments and provides a test model for devices requiring soft-shutdown control in challenging usage environments. Projectors also are commonly video muted – the active projector may not be identified by a user as remaining on and never actively turned off. If prevented from internal power management control, the device can be left on indefinitely. Energy saving solutions such as Tier 2 Advanced Powerstrips do not typically provide the control needed to provide proper shutdown of loads that cannot be directly unpowered as a means to turn off operating equipment. To apply and extend 5w5s technology CalPlug developed a control system codenamed "Projector Buddy" for the management of projection displays. This system uses control elements of 5w5s for energy management along with IR emitter to mediate shutdown of projectors. Similar to 5w5s, this solution uses multiple detectors focused on discerning relevant user behavior to intelligently manage the connected device. This system uses a modulated light, sound envelope, and motion detection in addition to monitoring connected device power load with respect to time. The motion sensor identifies local motion in the area of the device while the modulated light sensor is used to infer if the projection screen is active and if images are changing – an inference metric for active usage. For Digital Light Processing (DLP) color wheel based projectors, this is accomplished by tracking the color refresh rate and overall changes in image intensity. In Tier 2 APS devices, a one to two hour timer is commonly used for shutdowns. If an onboard sensor does not detect occupancy in this period, then a shutdown is initiated. The Projector

Buddy device uses a variable timer duration that uses sensor input to identify likelihood for interaction, similar in approach as the 5w5s solution. Beyond the 5w5s, if projectors are used in a work or school environment, patterns in sensory input can be used to infer the users' activities and use inferred intent to improve power management. Key sensor inputs allow for immediate task detection and permit improved inference if a mediated shutdown for power savings is likely required in the near future. For specifically detected situations activities where shutdown is likely (a quiet classroom with a still image projected) the delay to shutdown can be hastened.

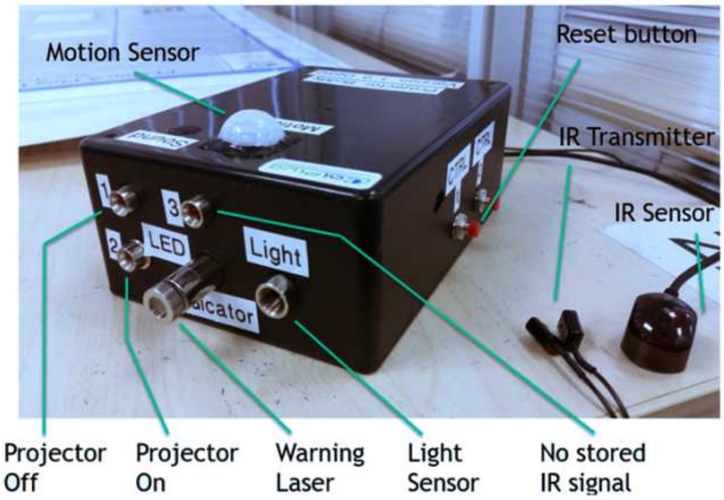


Figure 28: Projector Buddy prototype external view.

Commonly, projectors are used in classrooms and conference rooms - outside of residences and in shared work environments. In such shared environments, the intuitive nature of controls becomes even more important for maintaining user satisfaction for this type of solution, and inferring the type of usage (i.e. the task performed in the classroom or conference room) can lead to less obtrusive power management control actions and improve overall user satisfaction. Identification of user tasks and correctly inferring if intervention is required is key for proper operation. In some cases (such as an educational environment) inferring tasks of the occupants provides a powerful means of power management decision making. There are challenges with this approach – common sensor readings can be used to reasonably infer different usage scenarios. The addition of additional *relevant* sensor inputs can help distinguish scenarios. The use of task based decisions helps guide sensor selection and prioritization as well. Laboratory demonstrations have shown the feasibility of the task based usage for classroom environments as described, but power savings potential measurements are still under investigation based on real world usage of projection based displays.

By using projector operation current and the status of onboard sensors, the Projector Buddy (Figure 28 and Figure 29) can identify the operation environment and the power state of the projector. The user(s) must be made aware of an imminent shutdown event. In the prototype, a laser based indicator provides an infinite focused alert logo for a pending shutdown event. This logo is projected on the screen. Users can abort an attempted shutdown by providing sensed motion to the control system after an alert is issued.

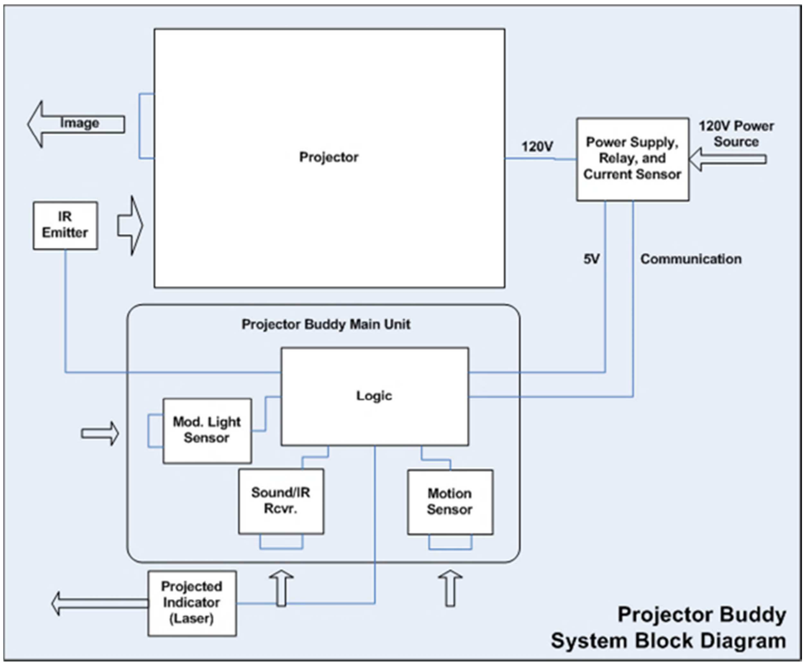


Figure 29: Projector Buddy prototype block diagram.

DISCUSSION

The PEF model permits tracking and optimization of energy usage. While valid on a user-by-user basis, the predictive power of this model for intervention based power management begins to become more difficult to implement practically with an increasing user base with less predictable actions. Inherently anticipating patterned interaction with some degree of random variability permits a more flexible model that improves the balance between user satisfaction and energy savings. This is maintained via self-learning by referencing past usage via pattern correlation to provide a model for predicted current and future usage. This model can work for single and small groups of commonly oriented users (a family), yet begins to break down with a larger volume of uncoordinated users, low connectivity or poor data from external sensing/user tracking sources, and/or changes in regularly observed patterns. Expansion of this model to allow for tracking patterns of group user interaction can add to the robustness of a practical approach at the loss of predictive precision. In this case, probability of interaction is used to adjust the length and depth of savings measures and activity/pattern based correlation control needs less specific user information to be effective. The usage of task-based inference based on sensor inputs provides an additional element of granular control to reduce the period of time where a device is in operation and waste is occurring. This can be performed with or without past operational control. When the sensors indicate a condition where user presence is unlikely, the period of delay for sensing inputs can be shortened. This may be scaled based related to the probability of interaction or by fixed amounts. If this usage fits a pattern based on past usage, this information can be used conceptually as another sensory input to improve decision acuity. CalPlug is also investigating positive and negative reinforcement mechanisms that allow users to indicate when the control system behaved inappropriately. This “scolding” behavior can be accomplished passively or actively. In a passive implementation, a rapid repowering of the device can be interpreted as an unwanted shutdown and knowledge of this event can be used to improve future control decisions. In an active implementation, the user can provide an input to the control device indicating an inappropriate action was taken. If a proper action was taken that the user noticed, a positive feedback could be given to reinforce and increase the aggressiveness of current control schemes.

Extending the capability of sensor pre-processing and fusion can expand capabilities for control. For example, an audio system that can interpret footsteps or a door opening could potentially improve user experience. With expanded sensing capability always follows privacy concerns. These must be managed, especially for connected devices.

Intelligent sensor based, user-centric power control approaches can be expanded beyond minor power control for other classes of plug load devices. The current state power usage of some devices can be modulated. An example of this is automatic brightness control (ABC) in TVs, or manipulation of display brightness by a power control system as an alternative means of energy control beyond a power cut or the activation of standby modes. In this way a TV left on but not used for a short period can be dimmed rather than shut off. This approach could help save energy for TVs where the TV is left on for companionship but not directly watched. This control approach also has potential for control of commercial displays where flat panel displays are used. Further evaluation of this approach is merited.

CONCLUSION

A behavior based, adaptive energy management architecture is proposed for energy management at home and work. The behavior of users and device usage preferences are factored in as the most important inputs for decision making. Devices are managed for maximum energy savings without compromising the quality of service and experience. A STB management system was implemented to test the architecture. Over 50% of energy savings was achieved with a prototype system. An extension of user behavior control was demonstrated for projectors. The approaches to user-centric power control could find a promising future as internal controls or external retrofit modules to affect deep energy savings in residential and commercial plug loads. Further investigation is in progress to evaluate and extend a number of the control approaches discussed.

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Shining a Light on Small Data Centers in the United States

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Abstract

Large data centers are well known for their high-energy intensity and have made dramatic efficiency improvements over the past decade. Small closet and room data centers have received much less attention, yet constitute about one-quarter of all servers in the United States. The often makeshift, ad-hoc nature of small data centers leads to data center design with little attention paid to energy efficiency and inadequate cooling equipment. The small physical footprint of these data centers, typically embedded within a larger building, makes it difficult to identify and target for efficiency measures. These conditions make small data centers notoriously inefficient relative to their larger counterparts. In this paper, we present an analysis of small data centers in the US, drawing from surveys of commercial building stock. We identify industries where small data centers are most prevalent, finding that the highest saturations are in medical, retail, and education sectors. Small data centers typically lack dedicated cooling equipment, often relying on building HVAC equipment for cooling. We further find that the type of cooling equipment used is highly correlated with the number of operational server racks, with less efficient cooling options used with fewer racks. We develop geospatial maps of small data centers to visually identify regions of high server concentration and the associated CO_2 emissions. We find that small data centers consume 13 billion kWh of energy annually, emitting 7 million metric tons of carbon dioxide--the equivalent of emissions from two 500 megawatt coal-fired plants. Finally, we discuss efficiency measures that could be implemented in small data centers and estimate associated potential energy and CO_2 savings.

1. Introduction

The digitization of the modern economy has made data centers essential infrastructure for commercial businesses across all industries. Modern data centers are populated by computing equipment, which remain continuously operational to support on-demand network requests. They range in size from individual servers found in literal closets to expansive warehouses filled with thousands of servers. Data centers of all sizes are used to manage communications, support business and government operations, and control access to data.

At the heart of data center operations are servers, networking, and storage equipment. Servers typically run dedicated applications and process requests received via a distributed network. Even during periods of low utilization, a server power draw may be as much as 150-350 W. Factoring in space conditioning and other facility overhead equipment can often double data center electricity consumption. Consequently, data centers have a high-energy intensity relative to other types of commercial buildings. In aggregate, data centers are estimated to consume 70 billion kWh anually, representing approximately 1.8% of US electricity consumption (Shehabi et al., 2016).

Significant attention has been paid to large data centers that house thousands of servers, which have achieved dramatic efficiency improvements. Shehabi et al. (2016) found that although there is overall growth in the size and number of large data centers over time, the total energy consumption attributed to large data centers has remained relatively constant. This result is a product of concerted efforts to optimize operations for the largest data centers, which benefit the most efficiency improvements. Technology companies operating large data centers benefit from economies of scale and have the resources to invest in efficiency measures. Upfront capital expenditures on efficiency measures are quickly recouped by operating cost savings. Google presents a case study in which a $25,000 expenditure on efficiency measures led to annual savings of $67,000 - a return on investment of 5 months (Google, 2011). For this particular data center, Google estimated a yearly energy savings of 670 MWh. When considering the large number of data centers operated by technology companies similar to Google, undertaking efficiency measures leads to millions of dollars in savings.

Significantly less attention has been paid to small scale data centers, typically referred to as data closets and data rooms, despite accounting for nearly one-quarter of all servers in the US (Bailey et al., 2007). The small physical footprint of these data centers, typically embedded within a larger building, makes it difficult to identify and target them for efficiency interventions. These spaces are generally run by institutions less familiar with information technology systems and best practices for data center management. The often makeshift, ad-hoc nature of small data centers leads to data center design with little attention paid to energy efficiency and inadequate cooling equipment. These conditions make small data centers considerably less efficient relative to their large counterparts.

A study performed by Cheung et. al (2014) surveyed 30 small server closets and rooms with four sites selected for detailed assessments. The authors found that most sites were not designed for efficient server operation and noted many examples of poor server room management. For example, in many cases conditioned cool air was inefficiently directed within the server room leading to mixing with exhausted warm air. Many of the potential efficiency measures outlined in Cheung et. al range from no- to low-cost. However, the authors note barriers impeding more efficient operation are organizational rather than technological. Few organizations had policies to promote efficiency and most lacked properly trained staff to research and implement efficiency measures.

Bennett and Delforge (2012) performed a survey of 30 businesses operating small data centers looking specifically at the penetration of efficient operating practices. The survey covered data centers operating between 1-30 servers. In general, they found a lack of awareness and organizational prioritization of efficiency measures. Data center operators were typically not responsible for paying energy bills, limiting motivation for pursuing efficiency. Similar to the findings of Cheung et al., barriers to efficiency were organizational as opposed to technological. Bennett and Delforge highlight the need for local and state policy measures to create incentives to promote efficiency measures specifically aimed towards small data centers.

To date, no study has analyzed a representative sample of commercial businesses operating small data centers due to a dearth of data. The lack of data has limited the ability of policy makers and data center operators to effectively craft measures to address energy waste in small data centers. In this paper, we use recently released survey data of commercial building stock to analyze characteristics of small and midsize data centers. We use the recently released 2012 Commercial Building Energy Consumption Survey (CBECS) administered by the federal Energy Information Administration (EIA) to analyze how servers are distributed geographically and identify the industries in which they are most used. These data represent a nationally representative survey detailing energy consumption practices of US commercial buildings. Combining these data with occupation data from the Bureau of Labor Statistics (BLS) we construct maps of geographic location of small data centers in commercial enterprises. Using these data we construct maps of server location and CO_2 emissions for closet and room servers in the US. Additionally, we perform an analysis of the more limited 2014 Commercial Building Stock Assessment (CBSA) administered by the Northwest Energy Efficiency Alliance (NEEA). Although limited to data centers in the Pacific Northwest region, the survey provides a detailed glimpse into the space cooling and server virtualization practices within small data centers.

The paper is organized as followed. In Section 2, we discuss the data sources and methodology used in our analysis. Although the focus of this paper is small data centers, we also include analysis of mid-size data centers, which fall in the gap between small data closets and rooms and large warehouse data centers (i.e., hyper-scale data centers). In Section 3, we discuss the results of our analysis and present geospatial maps of server and CO_2 intensity related to small and midsize data centers. In Section 4, we discuss aggregate results of our analysis and potential energy savings from efficiency measures. Section 5 provides a summary of results presented in this paper.

2. Data and Methods

Commercial Building Energy Consumption Survey (CBECS) 2012

CBECS is a nationally representative survey of commercial buildings in the United States conducted by the U.S. Energy Information Administration (EIA). The survey provides a snapshot of energy-related building characteristics of U.S. commercial building stock. CBECS defines commercial buildings as those that are not primarily (i.e., > 50% of floor space) used for residential, industrial, or agricultural purposes. For CBECS 2012, EIA surveyed 6,720 buildings and weighted their sample to by nationally representative of commercial building stock. The publicly released dataset is anonymized to remove any characteristics that could possibly be used to identify individual buildings. As part of this process, the location of buildings is only made available at the Census division level (groups of 4-9 states).

In 2012, EIA included survey questions to specifically target server usage in commercial buildings. When questioning respondents, CBECS defined servers as "usually just the CPU, or 'case,' portion of a computer that manages network resources such as computer files, printers, databases, or network traffic; servers do not require much human operation, so most do not have keyboards or monitors."

CBECS characterizes the principal building activity (PBA) of each sampled building into categories to group buildings with similar energy consumption patterns. Activities cover a broad range of categories from 'Education' to 'Warehouse and Storage'.[44] Although CBECS includes a PBA for 'Data Centers' (separate from a question of whether there is a data center of server farm in the building), there are no building categorized as such in the data set.

For this work, we adopt a classification system of either a small or midsize data center for each building in CBECS based on the number of reported servers. Our classification is rooted in the data center taxonomy defined by market reports released by the market research firm IDC. IDC categorizes data centers into 5 types ranging from small closets (1-4 servers) to enterprise-level, high-end data centers (> 500 servers). In descriptions of each space, IDC reports that both closet and room data centers are housed in relatively small spaces (< 500 square feet), often lack dedicated space cooling (Bailey et al., 2007), and are used primarily by small businesses. For our paper, we define a small data center as having between 1-25 servers, capturing both closet and room servers. All other data centers having more than 25 servers, but less than 500 are classified as a midsize data center. Table 1 shows our classification system relative to the IDC data center taxonomy.

It is possible that CBECS results may suffer from various forms of reporting bias depending on how respondents chose to estimate the number of servers in their building. Respondents answering questions in CBECS are not necessarily the individuals maintaining IT equipment. CBECS relies on estimates from respondents and responses are not verified independently. In particular, our data center categorizations assume that the respondent can (1) positively identify servers and (2) provide a reasonably accurate estimate to the number of servers on-premise. There is little we can do towards characterizing uncertainties due to the first assumption. The survey could potentially under- or over-report the number of servers depending on each respondent's ability to recognize and quantify servers. For the second assumption, our classification of data centers as either small, large, and high-end de-emphasizes the need for exact estimates for classification. For example, a respondent may potentially confuse 5 servers for 7 or 8 servers, but is unlikely to confuse 5 servers for more than 25.

Table 1 Data center characteristics

Classification in this Work	Taxonomy IDC	Square Footage (ft^2)	Typical Range of Servers
Small Data Center	Closet	≤ 100	1-4
	Room	101–1000	5-25
Midsize Data Center	Localized Data Center	1,001– 2,000	26-100
	Mid-tier Data Center	2,001 – 20,000	101-499
Not Analyzed	High-end Data Center	> 20,000	≥500

Commercial Building Stock Assessment (CBSA) 2014

The 2014 CBSA survey was conducted by the Northwest Energy Efficiency Alliance (NEEA) in order provide a snapshot of energy-consuming devices found in regional commercial sites (Navigant Consulting, 2014; Northwest Energy Efficiency Alliance, 2014). The survey is specific to commercial buildings in the Pacific Northwest covering Oregon, Washington, Idaho, and Montana. Detailed audits of commercial stock were gathered for 859 randomly selected commercial sites across twelve building types. Selected sites covered both urban and rural commercial locations. Data were anonymized to avoid identification of individual sites and weighted to be representative to the Pacific Northwest.

[44] For definitions see
http://www.eia.gov/consumption/commercial/building-type-definitions.cfm

CBSA 2014 included many questions specific to data center characteristics and operation. Unlike CBECS, which provides server data for each building, CBSA data are provided at the data center level, allowing for a single commercial site to report multiple data centers. For each data center, the survey recorded the total number of racks in the server room, data center floor space, and type of space cooling. Although there were additional questions regarding the presence of uninterruptible power supplies (UPS), most responses were left blank. The survey did not include rack dimensions or the number of servers in each data center, making direct comparisons to CBECS difficult.

NEEA specifically surveyed heating ventilation and air-conditioning (HVAC) characteristics for the each site. Onsite surveyors recorded the presence of dedicated data center cooling and the type of conditioning provided, even if conditioned air was shared with space outside of the data center.

Energy Calculations

The most common industry standard for quantifying overall data center energy efficiency is measurement of the Power Usage Effectiveness (PUE) coefficient. PUE is defined as the ratio of the total energy used for data center operations to the electricity drawn by IT equipment:

$$PUE = \frac{E_{datacenter}}{E_{IT}}$$

PUE captures the overhead energy required to maintain data center operations including space cooling, lighting, electricity distribution, etc. For example, a PUE of 2 indicates that for every kilowatt-hour drawn by IT equipment, another kilowatt-hour is required to maintain server operations.

The energy draw of IT equipment can be expressed as the sum of the energy required to power servers, network, and storage equipment

$$E_{IT} = E_{servers} + E_{network} + E_{storage}$$

The total data center energy consumption can be expressed as

$$E_{datacenter} = E_{IT} \times PUE$$

$$E_{datacenter} = \left(E_{servers} + E_{network} + E_{storage}\right) \times PUE$$

By the very nature of data center operations, servers operate continuously in an active mode. Server power draw depends on utilization. Studies have found that servers are rarely operate at high levels of utilization. Shehabi et al. (2016) found that small data centers typically operate at 10% utilization.[45]

We assume that a typical server found in a small or midsize datacenter consumes, on average, approximately 180 W (Shehabi et al., 2016).

Following Masanet et al. (2011), we use a top-down approach to estimating energy consumption from network and storage devices. We assume network and external storage energy consumption is proportional to the energy consumption of server hardware. External storage is 20% of server power consumption based on their calculations for the number of external hard drives in large data centers. Estimates for external hard drive shipments are derived from Bailey et al. (2007). We attribute 10% of server energy consumption to network equipment for both small and midsize data centers.

Previous work has found that smaller data centers are more likely to exhibit higher PUE values due to poor space cooling (Cheung et al., 2014; Shehabi et al., 2016). Detailed onsite case studies of small data centers performed by Cheung et al. (2014) found that data rooms and closets were often fashioned out of repurposed space not intended for servers. Many closets and rooms started as temporary housing for small-scale server needs which incrementally expanded overtime to a dedicated server space. The lack of attention paid to proper space cooling led to warm air exhaust from IT equipment mixing with cooled air from cooling equipment. In some cases, the authors noted that server cooling was provided by building cooling equipment. Detailed assessments of four small data spaces found PUEs ranging from 1.5-2.1. For comparison, large data center operators are able

[45] The authors assumed 10% of servers are inactive, “zombie” servers that are connected to power but never utilized.

to achieve PUEs of 1.1 through concerted efficiency efforts. For this work, we adopt an average PUE value of 2.1 for small and midsize data centers found in Shehabi et al. (2016) .

Occupational Employment Statistics

CBECS provides geographic data at the resolution of Census division (i.e, groups of 4-9 states). To produce higher spatial resolutions, we make the assumption that servers are spatially distributed proportionally to workers who would work in a building with a server. For this purpose, we make use occupational employment data, available at a higher geographic resolution, to approximate the number of servers by US zip code.

We utilize Occupation Employment Statistics (OES) released in May 2014 from the Bureau of Labor Statistics (BLS). The survey is conducted semi-annually via mail and designed to collect employment and wage estimates for 821 occupations. The data are provided for over 650 geographical areas that are a combination of metropolitan statistical area (MSA) and non-metropolitan areas. The U.S. Office of Management and Budget defines MSAs as having a relatively high population density with close economic ties through the area. MSAs generally include a large city and associated surrounding areas, often covering multiple counties. Regions within each state that do not fall into an MSA as “nonmetropolitan areas”. Although a state may have multiple non-metropolitan units for a state in OES, we combine employment statistics all non-metropolitan areas within a state.

The BLS collects data on the number of employed persons in 209 detailed occupations that are grouped into 22 major occupation categories for each regional unit. We use the major occupation categories provided by BLS and identify CBECS PBAs where those occupations are most likely to be found. For some occupations there is a direct relationship between occupation and PBA. For example, “Legal Occupations” can be mapped directly to “Office” buildings. However, a majority of occupations in OES have a one-to-many mapping of occupation to PBAs. In such cases, workers for that occupation, in a given MSA/non-metropolitan area, are split proportionally according the number of workers in those CBECS PBAs for the census division corresponding to the area.

This mapping allows us to estimate the fraction of workers within a given census division associated with a PBA in a given statistical area. This is a relative measurement of how workers of a given PBA are distributed across the USA. We multiply the number of servers in a given PBA to get the number of servers by MSA/non-metropolitan area for that PBA. This process is repeated for each PBA to arrive at the number of servers in each MSA/non-metropolitan area. Lastly, servers within an MSA are distributed evenly across the zip codes in that MSA.

Our method to disaggregate server location by zip code explicitly assumes that the spatial distribution of employed workers in buildings with servers is a reasonable proxy for servers.

3. Results

Servers by data center space type

In Table 2, we report general statistics for small and midsize data centers found in CBECS. We find approximately 3.7 million servers reside in small data centers corresponding to 72% of installed stock in CBECS buildings. Small data centers are found in 31% of all commercial buildings in CBECS.

Table 2. Summary of Data Centers and Servers in CBECS

Data center	Number of Buildings (millions)	Number of Servers (millions)	Average Number of Servers	% of Servers in CBECS	Number of CBECS Records
Small	1.725	3.70	2.1	72%	3163
Midsize	0.021	1.47	69.4	28%	360

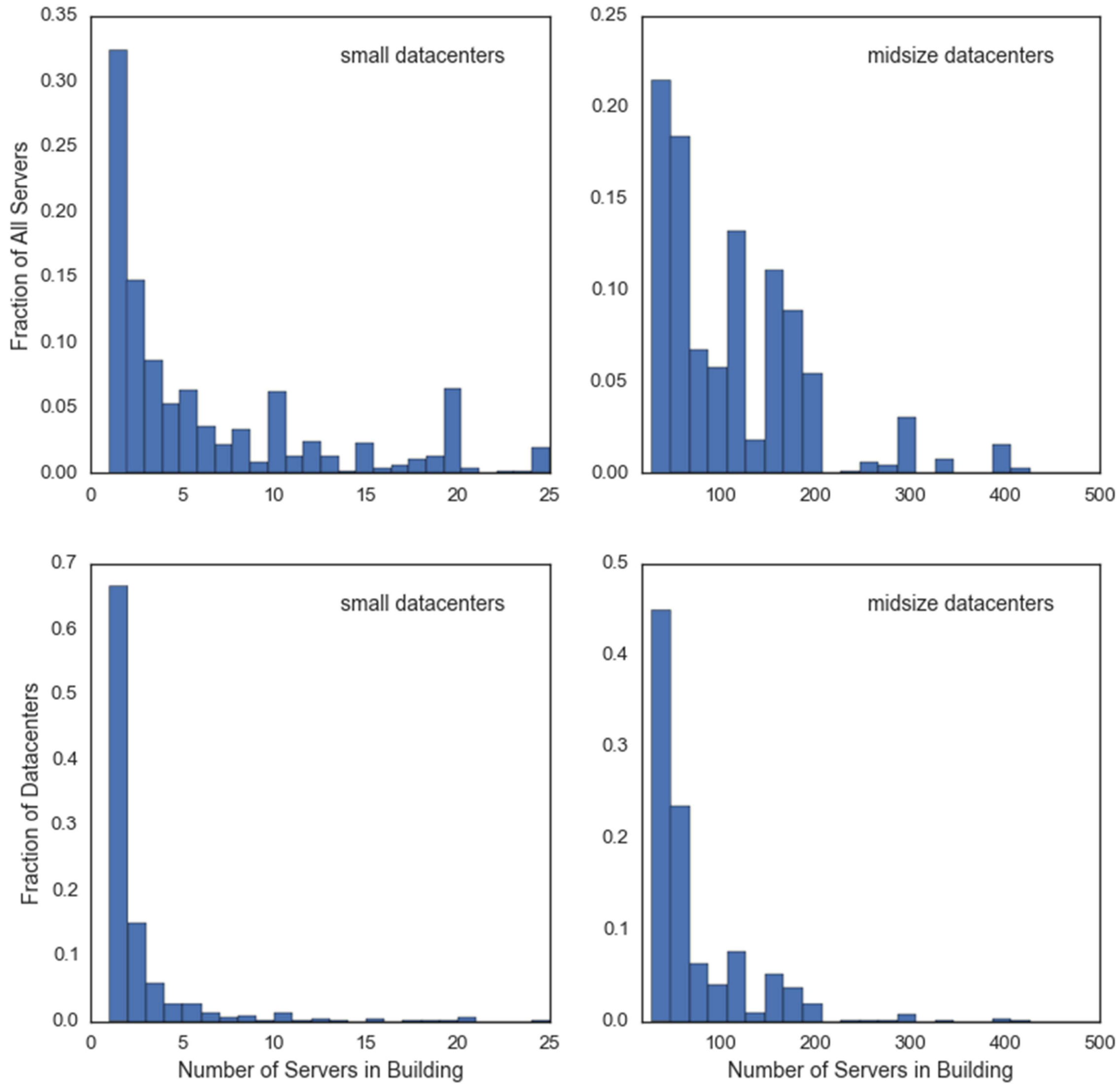

Figure 1. Distribution in the number of servers by data center type

Figure 1 provides a detailed look at the distribution in the number of servers within our data center classifications. The top two panels display the distribution in the number of servers per building relative to the total number of servers for small and midsize data centers, respectively. Each distribution is normalized by the total number of servers in that data center space type. The bottom panels display the distribution in the number of servers per building relative to the number of small and midsize centers. In these panels, each distribution is normalized by the total number of data centers in each data center space type.

The top-left panel shows that approximately 30% of the total number of servers in small data centers are found in locations with only one server. An interesting feature in this panel is the slight, yet significant, increase in frequency at 10 and 20 servers. This may be a reporting bias towards a value rounded to the nearest 10 or possibly an indication that server operators are biased towards owning servers in increments of 10 servers. As seen in the bottom-left panel, an overwhelming majority of commercial buildings with small data centers operate one server (~70%). The frequency of small data centers with multiple servers drops off dramatically, with less than 6% having more than 5 servers. This result indicates that although single server data centers only make up 30% of the fraction of servers in small data centers, such data centers are far more prevalent and represent a popular use case for businesses. It is possible that some of these small data centers are used as onsite “backup servers” in the event of a failure of a primary data center. However, the distinction between primary and backup data center is not made in any of the data sources.

When looking at midsize data centers, most locations have less than 100 servers. There is a notable relative dearth of data centers between within the range of 200-500 servers indicating this may be an intermediate scale of infrastructure that does not serve a practical purpose in industry.

Servers by Principal Building Activity

Table 3 shows the percentage of servers by PBA for each data center type. Although small data centers are found in a diverse variety of settings, the plurality of servers associated with small data centers are found in office buildings. This is unsurprising given the utility that servers provide within office settings such as file storage across a network, access to databases, and running shared enterprise applications. Looking at specific PBAs within office buildings, we find that 26% of servers in small data centers are found in administrative offices.

Similar to small data centers, servers in midsize data centers are primarily found in office buildings, specifically within administrative offices (38%). Medical buildings also house a significant number of servers within midsize data centers.

Table 3. Percentage of servers by building activity for each considered data center type

Building Activity	Small Data Centers	Midsize Data Centers
Education	9.8%	7.4%
Food Sales	1.8%	0.0%
Food Service	3.0%	0.0%
Lodging	1.2%	0.9%
Medical	6.9%	22.2%
Office	42.5%	56.6%
Public Assembly	3.3%	5.4%
Public Order	2.1%	1.7%
Religious Worship	2.0%	0.0%
Retail	12.7%	0.1%
Service	4.4%	0.2%
Warehouse	8.2%	5.4%
Vacant	0.7%	0.0%
Other	1.4%	0.3%
Total	100.0%	100.0%

Another way of investigating the prevalence of data centers is by looking at the market saturation of data centers in each PBA. For a given building activity, the data center saturation is defined as the number of buildings of that activity with a given service space by the total number of buildings of that activity.

Table 4 shows saturation rates of small and midsize data centers across PBA. For small data centers, saturation rates range from 14% for religious worship up to 59% for medical care facilities (not including administrative medical offices) with typical values are in 20-30% range. These results show that small data centers are relatively common in a wide range of industries. Again, we find that small data centers are especially prevalent in office settings.

Although we find high saturation rates in medical buildings (56%), there are federal privacy laws barriers may impede adoption of some types of efficiency measures. Data centers storing patient data are required to comply with standards laid out in §164.308(a)(1)) of the Code of Federal Regulations. For example, privacy law may prevent medical companies from moving their in-house data center to a cloud-based system operating from a larger, more efficient hyper-scale data center. However, high saturation rates for private businesses such office and retail may provide an opportunity for substantial energy savings via cloud-based solutions.

Table 4. Server saturation by building activity for each considered data center type

Building Activity	Small Data centers	Midsize Data centers
Education	37.9%	0.5%
Food Sales	31.4%	0.0%
Food Service	22.5%	0.0%
Lodging	22.1%	0.2%
Medical	58.9%	2.2%
Office	56.1%	1.1%
Public Assembly	19.8%	0.2%
Public Order	28.2%	0.6%
Religious Worship	14.1%	0.0%
Retail	39.6%	0.0%
Service	18.8%	0.0%
Warehouse	21.5%	0.2%
Vacant	3.0%	0.0%
Other	32.3%	0.0%

Space Cooling in Data Centers

The CBSA survey allows us to analyze HVAC as a function of space type and number of server racks. Although these data are weighted to be representative of the Pacific Northwest, we note that the data may not reflect space conditioning across other geographic regions. Different geographic regions will have different space cooling requirements when determining HVAC needs for the building. The Pacific Northwest covers 'Marine' and 'Cold' climate zones as defined by the Building America program (Pacific Northwest National Laboratory, 2015), sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). Buildings in these zones generally have lower cooling loads compared to higher temperature climate zones which will be factored into HVAC system considerations. This could potentially impact space conditioning for data center sites.

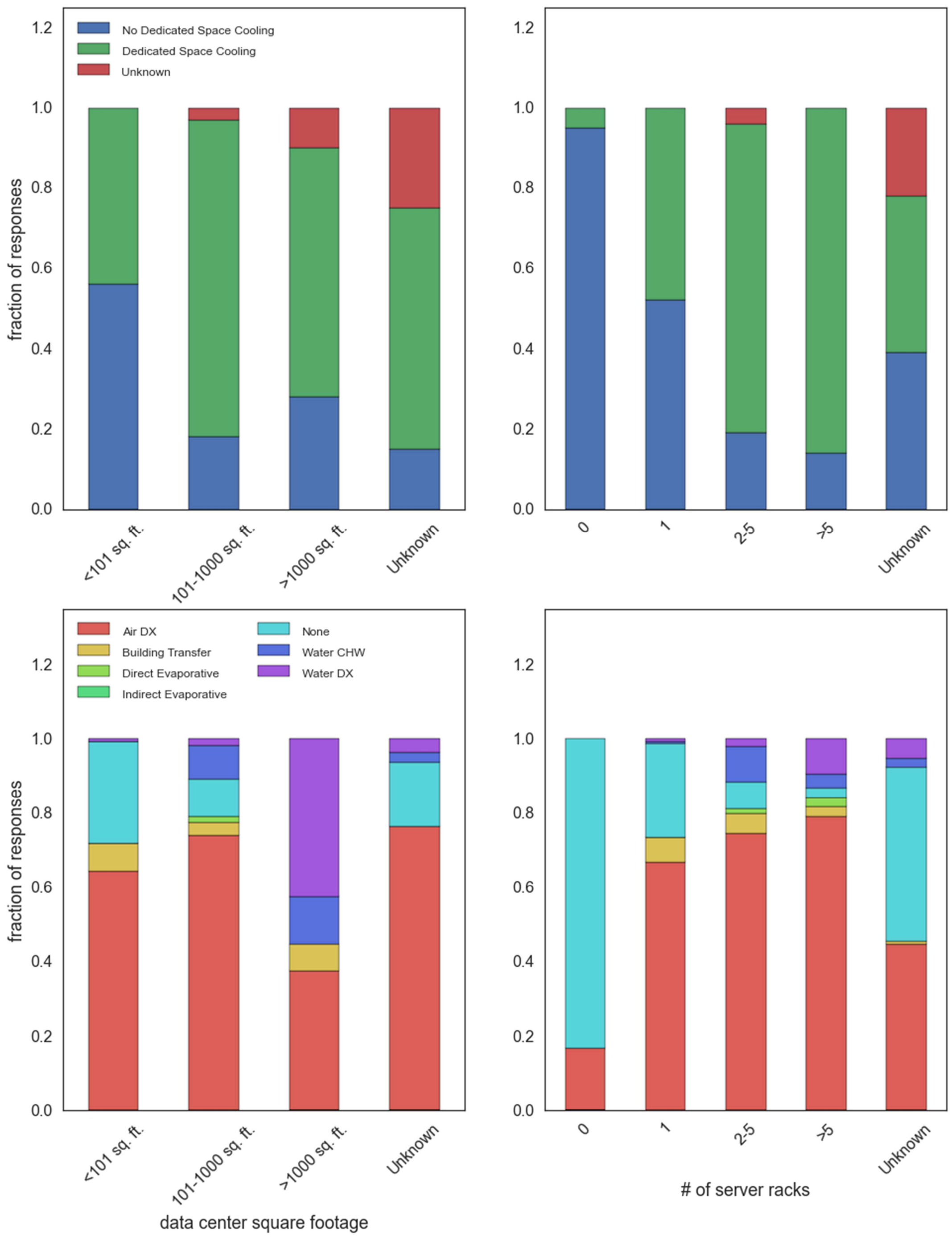

Figure 2. Space cooling characteristics of small and midsize data centers

The top panels of Figure 2 display results for data centers with dedicated space conditioning. When categorizing data centers by square footage (top left panel), we find that a majority of closet data centers do not have dedicated space conditioning, relying on cooling systems that service a larger part of the building or no cooling system. This lack of cooling could negatively impact the performance or longevity of the equipment itself. Surprisingly, room data centers have a larger proportion of dedicated cooling (79%) compared to midsize data centers (62%). In the top, right panel, we find that the proportion of data centers without dedicated cooling decreases as the number of operational server racks increases.

The bottom panels show stacked bar plots indicating the proportion of data centers that use different types of cooling systems. Note that these systems do not necessarily correspond to dedicated conditioning for only the server space and may also be used for conditioning other parts of the building. The left panel shows the fraction of responses by space type and the right panel by number of operational server racks. A majority of data centers in rooms less than 1000 square feet use air-cooled computer room air conditioners (labeled 'Air DX'). A sizable fraction of these data centers rely on building air-handling units (labeled 'Building Transfer'). Closets have the largest fraction of respondents that use no conditioning (27%). Data centers larger than 1000 square feet rely mostly on water cooled direct expansion systems (42%). The bottom, right panel shows similar results by number of operational server racks. Over 80% of data centers with 0 racks replied they have no HVAC system. Servers in these sites may rely on "free cooling" using ambient air as a cooling source. This is an attractive cooling option for small data centers with a low cooling load for the Pacific Northwest, given the mild climate. Notably, data centers with one or rack primarily rely on air-cooling direct expansion units, which represent a less expensive, but less efficient cooling solution.

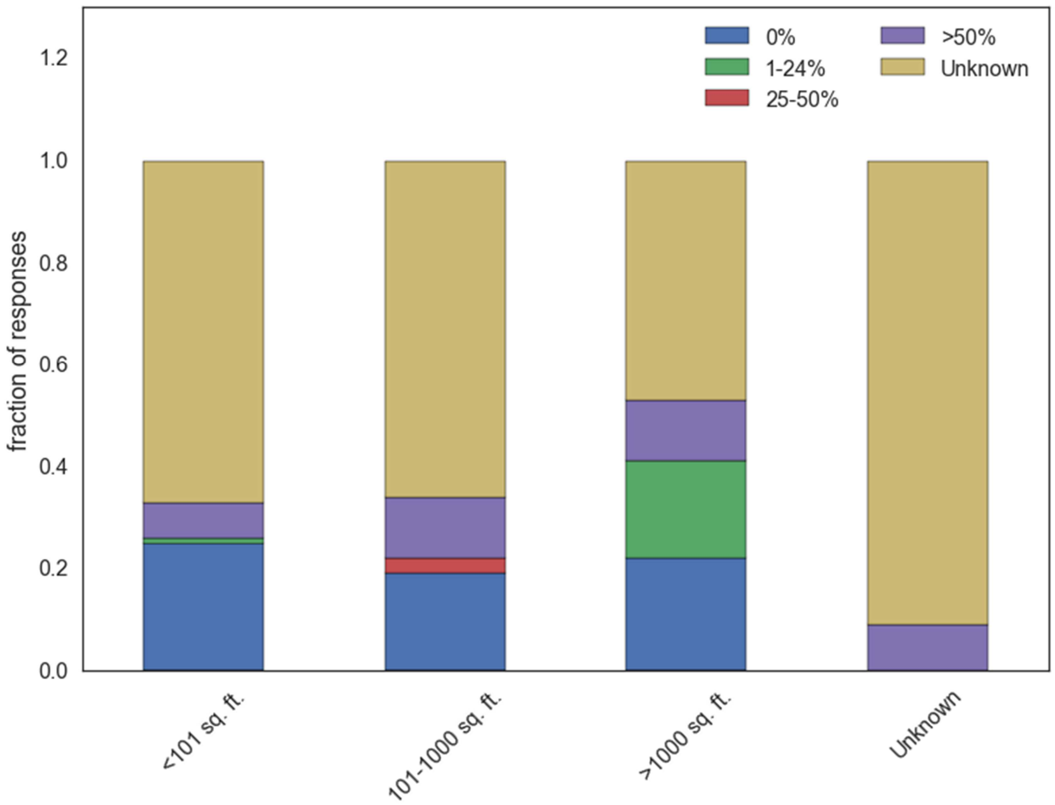

Figure 3. Degree of server vitualization by data center space type

Server Virtualization

Server virtualization allows a single physical server act as multiple virtual machines running independent tasks and applications (e.g., e-mail, database storage, web-hosting, etc.) rather than dedicating individual servers for each application. By creating virtual machines, data center operators can consolidate hardware and more adequately utilize sever processing power. However, previous research on small business data center practices indicates that server virtualization is not heavily practiced. Bennett and Delforge (2012) found only 37% of small businesses practice server virtualization in a survey performed in 2011. The authors note that many small businesses had never heard of server virtualization or did not think the investment in virtualization would be cost-effective. A survey of large-scale enterprises in 2011 found that approximately 92% of businesses utilized virtualization (Vanson Bourne, 2011).

The CBSA study recorded the degree of virtualization undertaken by IT staff for each data center. Notably, most sites did not provide a response. Given the lack of virtualization in small businesses with virtualization knowledge (Bennett and Delforge, 2012), it is likely that most of these sites do not make use of data virtualization. However, there may be some sites where the respondent may not have been an IT professional capable of properly answering the question. Given the uncertainty, unknown responses are separately identified in our reporting.

In Figure 3, we show results for the degree of virtualization by data center square footage. Data centers less than or equal to 1000 square feet show a high proportion of unknown and no virtualization responses. Only 8% of data centers less than 1000 square feet have any degree of virtualization, with 7% reporting more than 50% virtualization. Approximately 15% of data centers between 101 and 1000 square feet operate with server virtualization. Data centers larger than 1000 square feet operate with the highest proportion of server virtualization with 31%. We would expect that larger centers have more opportunity to consolidate and would benefit the most from virtualization.

4. Discussion

Spatial Distribution of Servers and CO_2 Emissions

In this section we combine data from CBECS, OES, and CO_2 emission factors[46] to construct spatial maps of server and CO_2 emissions intensity (i.e, per unit area). As discussed in Section 2, occupation statistics at the zip code level are used as a proxy to estimate the spatial distribution of servers. Combining this spatial distribution with typical power consumption values and geographic-specific with carbon emission factors we estimate regional carbon dioxide emissions.

Figure 4 shows server and carbon emission intensity by zip code for both small and midsize data centers. For the server intensity plots in the left panels, the number of servers in each zip code is divided by the area of the zip code in square miles. Similarly, for the carbon intensity maps in the right panels, carbon emissions associated with each zip code are divided by the area in square miles of the zip code.

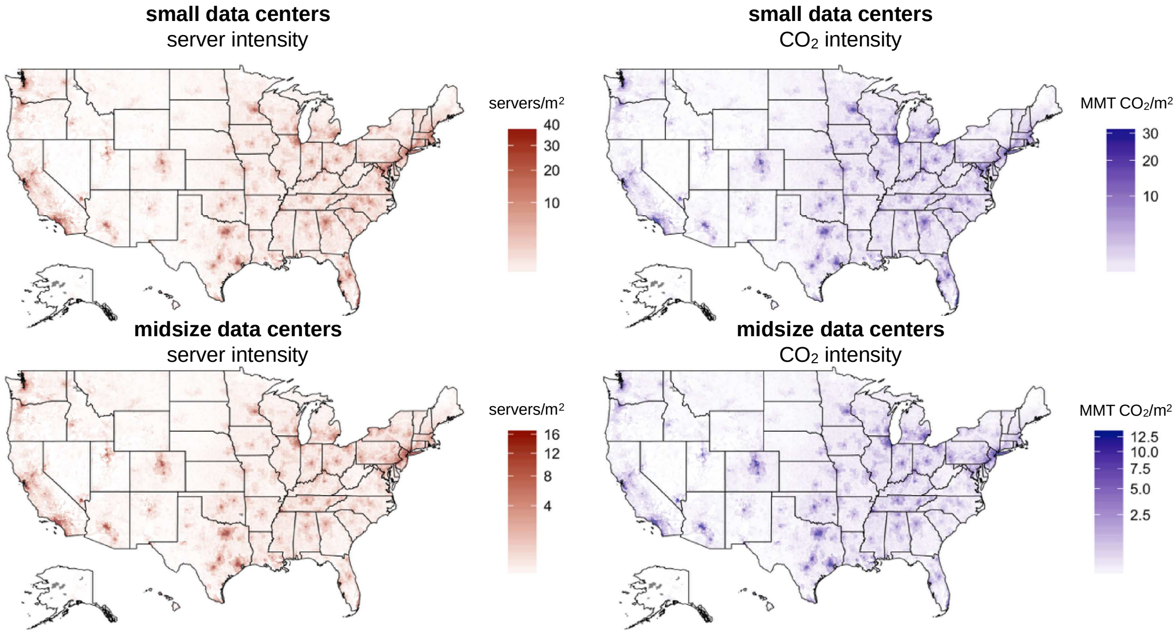

Figure 4. Geospatial distribution of server and CO_2 emissions

Although there is a strong correlation between server and carbon emission intensity, there are subtle differences dependent on the regional mix of resources used for electricity generation. For example,

[46] Download from the U.S. EPA's Emissions and Generation Integrated Database (eGrid).

the Denver metropolitan region of Colorado shows pronounced carbon emission intensity due to the strong dependence of coal for electricity generation. The Pacific Northwest, which relies heavily on hydropower for a majority of its electricity generation, has lower carbon emission intensity relative to the number of servers in the region. These maps allow for a more accurate estimate of CO_2 emissions accounting for the most likely location of servers within census region.

Small data centers are mainly concentrated in metropolitan regions as expected based on employment statistics. Both small and midsize data centers follow a similar trend with highest concentrations on the east and west coast.

U.S. Energy Use and CO_2 Emissions

In this section, we aggregate our results to estimate the annual server energy use, total energy site energy use including energy used to maintain and operate the data center, and total CO_2 emissions including gross grid losses for the considered data center types. Results are presented in Table 5.

Table 5. Aggregate energy consumption and CO_2 emissions by data center type

Data center	Server Energy Use (billion kWh)	Total Energy Use (billion kWh)	Total CO_2 Emissions (million metric tons)
Small	5.72	13.23	6.91
Midsize	3.35	6.52	3.39
Total	9.07	19.75	10.30

In aggregate, small and midsize data centers consume 20 billion kWh and emit 10.3 million metric tons of carbon dioxide, equivalent to the annual electricity use of 1.5 million homes.[47]

The average sever in a small data center is responsible for 1.73 metric tons of CO_2 per year and for a midsize data center is 1.78 metric tons of CO_2. The slight difference in average emissions is due to differences in geographic distribution of small and midsize data centers.

Energy Savings Opportunities

Server Virtualization

Results from the CBSA 2014 show that server virtualization remains mostly unutilized in small data centers. Similarly, Bennett and Delforge (2012) report 26% server virtualization saturation in small businesses surveyed in 2011. Our analysis of CBSA data in Section 3 found approximately 10% of data centers utilized some level of server virtualization. These low estimates of virtualization indicate there is significant available energy savings potential from increasing saturation.

Bennett and Delforge (2012) estimate that data centers with 10 or more servers would benefit from virtualization. As a scenario, we assume that 50% of data centers with 10 or more servers in CBECS are able to reach virtualization ratio of 5 to 1, reported as an “average” use case by WSP and the National Resource Defense Council (2012). In this scenario, we estimate annual site energy savings of 3.8 billion kWh, corresponding to 2 million metric tons of CO_2 emissions.

We note that the rapid improvement in server chip technology will lead to greater efficiency gains from server virtualization. Increased memory and input/output capacities will facilitate greater virtual machine density.

There are many barriers to the adoption of virtualized servers in small businesses. In many cases, businesses pay a flat fee for energy services eliminating energy costs as an incentive to reduce energy demand. Organization barriers may include lack of capital to upgrade and lack of IT knowledge. Additionally, virtualization will not benefit small data centers that operate few servers with little room to eliminate excess hardware.

[47] Using EPA’s greenhouse gas equivalency calculator: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

Cloud Computing

The rise cloud computing over the past decade has provided a new means for businesses to meet IT needs. The availability of Software as a Service (SaaS), Infrastructure as a Service (IaaS), and Platform as a Service (PaaS) cloud solutions has moved computing demand away from small, on-premise data centers into highly optimized cloud-computing data centers. In a small data center, individual servers are often used for running individual applications or tasks. This leads to servers that, on average, operate at very low utilization levels. In large, hyper-scale datacenters, applications and tasks are distributed across a huge number of servers and operationalized to run at utilization levels closer to 50% (Shehabi et al., 2016).

Cloud-computing data centers benefit from economies of scale and are able to make upfront infrastructure investments to support efficient data center operations (WSP Environment & Energy and Natural Resources Defense Council, 2012). Given the large cost of operating thousands of servers, even small improvements in efficiency can lead to significant operating cost savings. The Uptime Institute (2014) estimated an average PUE of 1.7 for data centers that self-reported the PUE for their largest data center. Some cloud computing have achieved even lower PUEs. For example, Google has reached a fleetwide average PUE of 1.12 (Google, 2016). Pushing the limits even further, Gao (2014) presents a framework for applying machine-learning artificial intelligence to operational data to potentially decrease Google data center PUEs below 1.10. For comparison, small data centers have typical PUEs closer to 2.0 (Cheung et al., 2014; Shehabi et al., 2016).

Here we perform a simple analysis to estimate the potential savings from moving computing needs away from a small datacenter to a cloud-computing datacenter. We assume that server loads from private-run office and retail stores can easily shift server load away from in-house datacenters to cloud computing centers. Shehabi et al. (2016) estimate a cloud-computing server running under typical conditions consumer approximately 280 W. However, moving an application or task from a small data center to a cloud-computing server will only consume a fraction of the server's computing power. Previous studies estimate that the load of a small data center server is approximately equivalent to 1/5 the load of high-end cloud server (Masanet, 2014; Shehabi et al., 2016). If we assume a conservative 10% of reduction in servers from industries other than financial, health, and government related fields, we estimate a potential 1.2 billion kwh reduction in energy and 0.85 MMT of CO_2.

A survey of business owners with small data centers found that many found that main barriers to cloud adoption stem from privacy and security concerns (Bennett and Delforge, 2012). However, these are concerns that are not necessarily rooted in reality. Cloud computing data centers often take more measures to ensure customer data is maintained securely and dedicate resources to this purpose. Additionally, many cloud computing operators private cloud solutions for companies that wish to silo their data from public cloud resources. Increasing penetration of cloud deployment within smaller data centers will take a concerted effort to educate IT professionals.

Although cloud computing offers energy savings potential by shifting loads away from small datacenters to more efficient hyper-scale data centers, easy access to cloud services could lead to increased demand for computing needs that were not needed previously. For example, businesses that previously relied on paper records that move to cloud will add to overall energy demand or start providing services that require cloud-computing resources. These businesses will likely benefit from the efficiency of digitizing records and online management. For some new users, the cloud offers an ease of setup and maintenance in that it does not require a dedicated IT professional to install system.

Conclusion

Targeting smaller data centers remains challenging due to the ad-hoc nature of small datacenters, which are often situated in confined spaces within larger buildings. We make use of recently released data on servers and data centers in commercial buildings to characterize the small and midsize data center market and construct spatial maps of their locations across the United States.

We categorize buildings with less than 25 servers as small datacenters and buildings with more than 25 but fewer than 500 data centers as mid-tier datacenters. We find approximately 5 million servers (approximately 40% of installed server stock) consistent with previous estimates (Bailey et al., 2007; Delforge and Whitney, 2014). Additionally, we find the vast majority of servers are found in small server rooms.

A majority of small data centers are found in offices and retail buildings. The highest saturations are in medical, retail, and education sectors. We find that approximately 26% of servers in small data centers are found in administrative offices.

Based on data from the CBSA conducted in the Pacific Northwest, a majority of small data centers with more than one operational rack make use of air-cooled CRACs for space conditioning. The majority of data centers with one or less operational server rack did not report using any specialized cooling system and likely relying on the building HVAC system. Sites with two or more operation racks tend to rely on dedicated space cooling with air-cooled CRACs being the most common. Water-cooled CRACs are mainly used in data centers that are larger than 1000 square feet, making up approximately 40% of cooling units in these sites.

In aggregate, we find that small and midsize data centers combined consume approximately 20 billion kWh of site energy consumption energy. Using data from the Bureau of Labor of Statistics, we correlate the number of servers found in the CBECS data sets to employment data within fields identified as using data centers. This allows us to disaggregate results by zip code to create detailed geospatial maps of server intensity across the US. Unsurprisingly, highest server intensities are located in dense metropolitan areas, with highest concentrations on the East and West Coasts. In total, small and midsize data centers emit over 10 MMT on CO_2 emissions annually.

Server virtualization provides a means for an individual server to act as multiple machines allowing for server consolidation. Although a practical means to decrease data center energy consumption, we find that it is not a common practice in small datacenters. The vast majority of data centers responded that they did not employ virtualization or did not know the degree of virtualization within their datacenter. Only 15% of small data centers reported having any level of virtualization within their fleet. Modest consolidation of hardware through virtualization in data centers with more than 10 servers could save 3.8 billion kWh annually, corresponding to 2 million metric tons of CO_2. The most challenging barrier to adoption of virtualization is not technical. Most small businesses have either never heard of server virtualization or did not think the investment in virtualization would be cost-effective (Bennett and Delforge, 2012).

The era of cloud computing an opportunity to shift resources from inefficient small data centers to highly optimized hyper-scale data centers. Although, there are industries where privacy regulations may prevent the use of third party cloud datacenters, such as in healthcare, many industries that currently rely on small data centers should be able to move computing to cloud centers. Assuming industries other than healthcare offices (due to privacy concerns) can shift 10% of their load to the cloud, we calculate approximate savings of 1.2 billion kWh.

Despite increasing consolidation of small data centers into larger ones, there remains a sizable number of small data centers. This paper takes a first step towards identifying and characterizing how these centers operate. However, as discussed throughout this paper, a main barrier impeding efficient operation is lack of education about best practices and opportunities. Future progress will be made by measures and policies that are able to directly target small data centers.

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