European Commission

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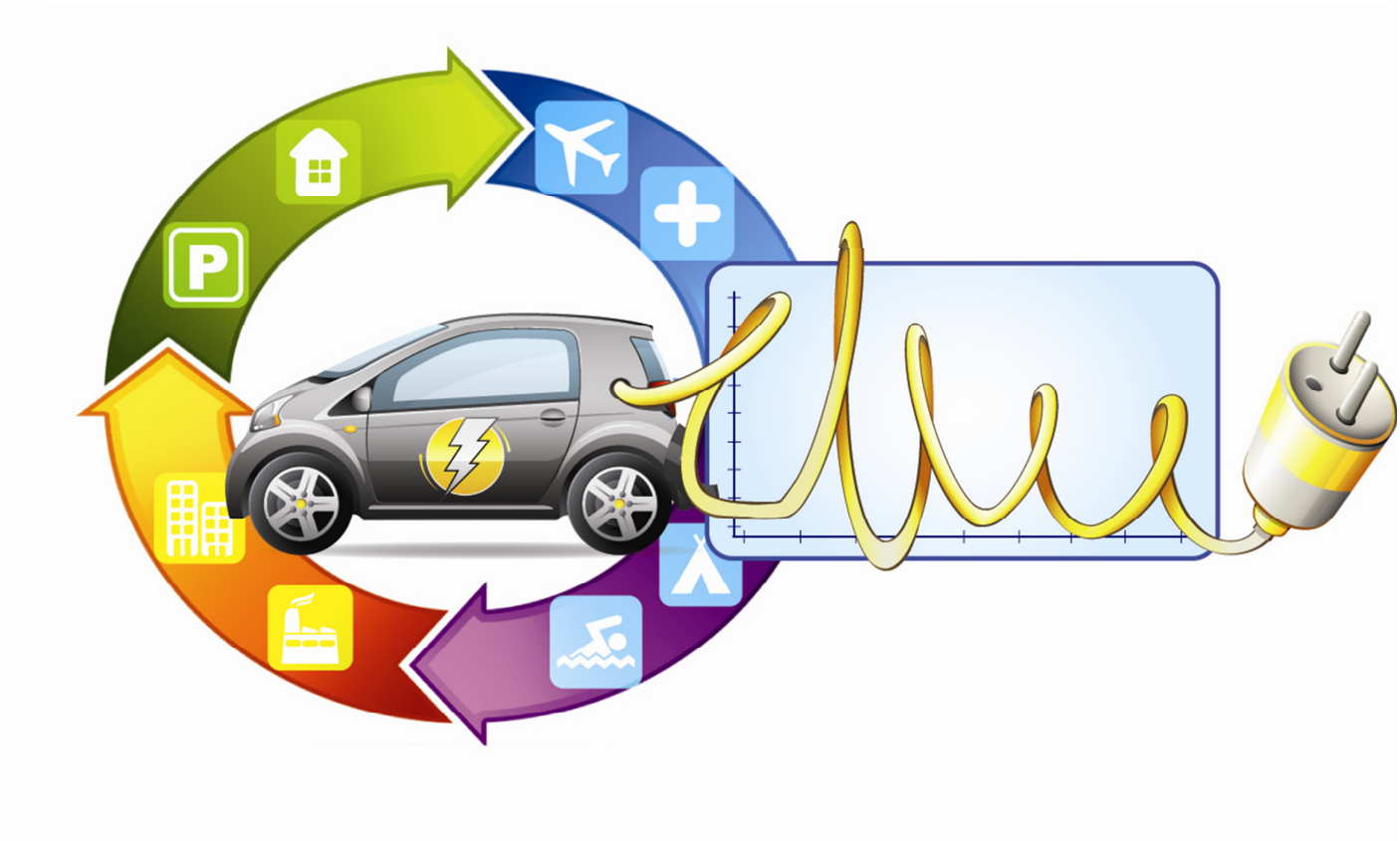
Projections for Electric Vehicle Load Profiles in Europe Based on Travel Survey Data



Authors

G. Pasaoglu ([1]), D. Fiorello ([2]), L. Zani ([2]), A. Martino ([2]), A. Zubaryeva ([1]), C. Thiel ([1])

([1]) European Commission, DG JRC, Institute for Energy and Transport, Petten, the Netherlands

([2]) TRT Trasporti e Territorio srl, Milan, Italy

2013

Report EUR 25993 EN

Joint Research Centre

European Commission

Joint Research Centre

Institute for Institute for Energy and Transport

Contact information

Christian Thiel

Address: Joint Research Centre - IET, P.O. Box 2, 1755 ZG, Petten, the Netherlands

E-mail: christian.thiel@ec.europa.eu

Tel.: +31 224 56 5143

http://iet.jrc.ec.europa.eu/

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This publication is a Reference Report by the Joint Research Centre of the European Commission.

JRC82307

EUR 25993 EN

ISBN 978-92-79-30387-6 (pdf)
ISBN 978-92-79-30388-3 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi:10.2790/24108

Luxembourg: Publications Office of the European Union, 2013

Printed in the Netherlands

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Acronyms, abbreviations and units

BEV	battery electric vehicle
DECC	Department of Energy and Climate Change (DECC)
EDV	electric-drive vehicle
EPA	Environmental Protection Agency
EU	European Union
EV	electric vehicle
h	hour(s)
ICE	internal combustion engine
km/h	kilometre(s) per hour
kWh/km	kilowatt-hour(s) per kilometre
min	minute(s)
MW	megawatt(s)
PHEV	plug-in hybrid electric vehicle
TWh	terawatt hour(s)
Wh	watt hour(s)

Executive Summary

This study aims to build a database of load profiles for electric-drive vehicles (EDVs) based on car-use profiles of current conventional vehicles in six European countries (Germany, Spain, France, Italy, Poland, and the United Kingdom). Driving profiles were collected by means of sample travel surveys carried out in the six countries. The report presents the load profiles resulting from analysis of the travel survey data, and obtained by associating assumptions on technical features of EDVs with behavioural elements. The document explains in detail the methodology used and the assumptions adopted for the driving profiles estimation, discusses the results of scenarios for the six European countries, and presents an alternative scenario to assess how load profiles might change under different parameters. The load profiles, obtained from the scenario analysis, reveal that some differences between countries do exist; however, notably, the assumptions concerning when and where individuals can/want to recharge EDVs explain the amount of electricity demanded from the grid over time. Analysis of the scenarios confirms that uncontrolled recharging could lead to artificial electricity-demand spikes when certain time windows for lower tariffs exist network-wide. This can be prevented by means of controlled recharging supported by smart grids. It is worth mentioning at this point that the methodology applied in this study constitutes an intermediate step, taken before the field data from EDV users become available.

1 Introduction

This report describes the results of a study that focused on building a database of load profiles for electric-drive vehicles (EDVs) ([1]) based on car-use profiles of current conventional vehicles in six European countries: Germany, Spain, France, Italy, Poland, and the United Kingdom. The complete study comprised three tasks: 1) analysis of existing travel survey data and databases, and survey design; 2) collection of additional car travel data, and 3) development of representative load profiles induced by EDVs under given deployment scenarios.

The results of the first two tasks were presented in the reports *Driving and parking patterns of European car drivers – a mobility survey* by Pasaoglu et al. (2012) and *Attitude of European car drivers towards electric vehicles: a survey* by Thiel et al. (2012).
The present report documents the outcome of Task 3, which aimed to produce the interface and methodology for use in the driving patterns database for estimating:

- charging profiles at the car level;
- load profiles at the grid level.

The outcome of Task 3, i.e. the final outcome of the overall study, represents a relevant achievement in the field, analysing possible electricity demand induced by EDV scenarios. Indeed, the load profiles are built on very detailed driving- and parking-patterns data of a representative sample of individuals in six different European Union (EU) countries (the largest EU countries in terms of population — they cover 70 % of the population). In terms of the EU passenger car market, they represented 75 % of the total new sales of passenger cars in 2011 (European Commission, 2012).
It is hard to find an estimation of electricity demand using detailed individual driving data from Europe in the existing literature. The impact of EDVs on electricity demand has been addressed before, but this has generally been done in a much more aggregated fashion or without using representative data. Therefore, the estimation of load profiles according to the methodology introduced in this report is a unique example of the use of individual driving profiles of a representative sample of individuals, coupled with assumptions on the penetration of different types of EDVs in the fleet, and with energy consumption functions dependent on average speed. The structure of the report is as follows: Chapter 2 describes the structure of the databases; Chapter 3 illustrates the procedure for estimating the charging profiles and the load profiles building on the

([1]) For the purposes of this study, EDVs are plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs). A PHEV is an externally chargeable hybrid EV with limited electric performance and electric range, although driving in electric mode is enhanced by the possibility of plugging the battery into the grid. A BEV is a true BEV, since there is no internal combustion engine (ICE), only an electric motor to propel the vehicle, with full performance in electric mode and enlarged — but still limited — electric range (JEC, 2011).

driving patterns; Chapter 4 discusses an example of load profiles estimated using the database; and Chapter 5 presents our conclusions.

2 Description of the data

This report accompanies the final result of the study — the data for the driving profile data as well as the derived charging profiles and the load profiles.

The data are arranged as follows.

- *Individuals*: information on the socioeconomic features of the individuals. Responses to questions concerning attitudes towards EVs are also reported in this table.
- *Cars*: provides the features of the cars available to the individuals.
- *Days*: indicates on which calendar days the individuals made trips (e.g. it can be ascertained that Day 1 for one individual was Thursday 12 April 2012, while for another, it was Monday 16 April 2012).
- *Trips*: contains the information about the trips made by the individual (time, distance, purpose, etc.).
- *Municipalities*: specifies where the surveyed individuals live (region and city).

As mentioned by Pasaoglu et al. (2012), the original data of the survey were checked for inconsistencies, and corrections were made on the recorded trip data (e.g. to render the destination place and trip purpose coherent). A revised set of data was therefore generated.

Trip chains are a different way to display the sequence of car trips made by individuals in one day. The 'Trips' table (in the original databases as well as in the revised databases) is structured so as to indicate one trip as a separate record. This format is the most useful for analysis and also as starting point for the definition of the detailed driving profiles (at 5-min intervals) used in the estimation of the charging profiles (see Chapter 3 below). The trip chains report details all trips made in the day, arranged in one record. Tables for trip chains were produced for some further analysis of data, documented in Pasaoglu et al. (2012).

3 Estimation of charging and load profiles

This chapter presents the procedure for the estimation of charging profiles and load profiles, the assumptions used, and the various parameters and steps required.

3.1 Building driving patterns

Load profiles are based on the individual driving patterns that were collected. For their use in the estimation of charging and load profiles, individual driving patterns are described in detail: each day of the sampled week is divided into 5-min intervals, and each 5-min interval is marked as either a driving period or a parking period for each sampled individual. Other relevant data collected by the survey are also considered (e.g. the parking space is associated to each interval belonging to a parking period). Another element drawn from the survey is the average speed of the trip: this speed is associated to each interval belonging to a driving period.
Ultimately, building driving patterns means reformatting the information derived from the original survey.

3.2 Building charging profiles

The construction of charging profiles corresponding to driving and parking patterns consists in estimating the amount of electricity requested from the grid when electric cars are parked, and their users can and want to recharge them. The driving and parking patterns provide several inputs for this estimation. First, they provide data for appraising the amount of consumed electricity which needs to be recharged from the grid. Second, they convey information on parking time, place and duration, which help to associate a parking period to the batteries' recharge period.
It should be noted that the inputs above are based on the recorded travel behaviour of generic car drivers, and not on current EDV usage. In other words, driving patterns are descriptions of how individuals travel, irrespective of the type of vehicle (EDV or internal combustion engine (ICE)) they currently drive. Indeed, the estimation of the charging profiles is made under certain assumptions:

- an individual uses an EDV for all trips made in the day;
- that EDV is used only by one individual (i.e. the energy consumption is explained only by the driving pattern of a single individual);
- one individual uses the same EDV on all days of the week.

These assumptions are simplifications that are necessary in order to reconcile the information taken from the survey — which concerns individuals' behaviour — with the daily (and weekly) use of vehicles. Nevertheless, since the survey was based on a sample

of individuals and is related to their mobility, it cannot be used to describe the mobility of vehicles beyond the use reported by those people surveyed.

There are two main steps to generating charging profiles: one is the estimation of electricity use in the driving periods, and the other is the estimation of electricity requested from grid during the parking periods. A description of these steps follows.

3.2.1 Estimating energy use in driving periods

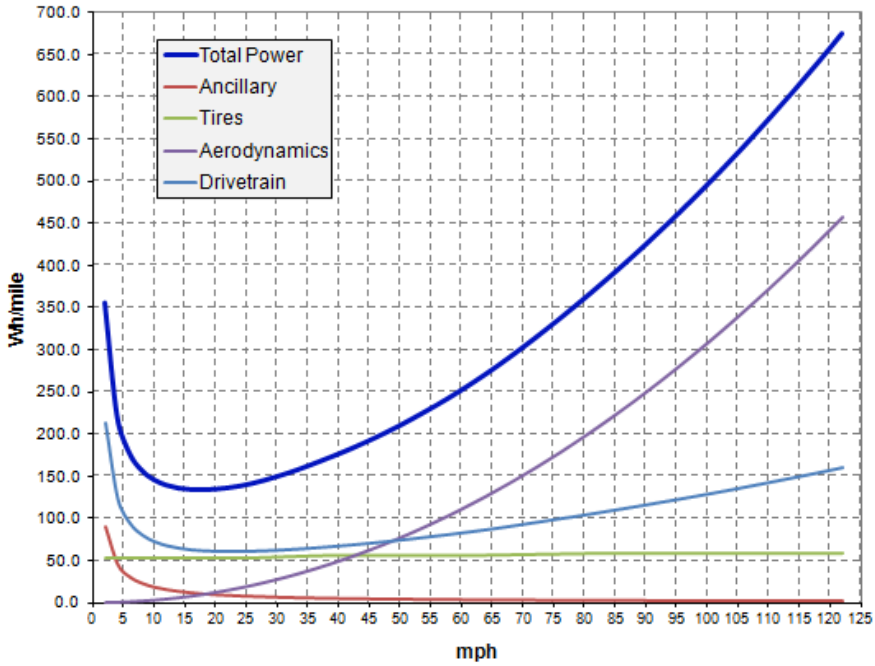
During the driving period, the EDV uses electricity from onboard batteries. The amount of electricity used is assumed to be dependent on two elements:

- the EDV type
- the travel speed.

The first element is handled by assuming market shares of alternative EDV types in the fleet and associating individuals to each type on a random basis. Shares are not predefined; they can be varied based on the scenarios employed.

The effect of travel speed is managed by electricity consumption functions. Instead of using average values of energy consumption per unit of distance, a speed-dependent function was defined. Van Haaren (2011) provides this in the form of empirical curves based on consumption of a Tesla Roadster at different constant driving velocities (see Figure 3.1).

Figure 3.1 Empirical speed-dependent energy consumption curves



Source: Van Haaren, 2011, using data from Straubel, J. B., 'Roadster Efficiency and Range'.

These curves indicate the amount of electricity demand per unit of distance (namely 1 mile). However, it is straightforward to convert this into consumption per period of time (5 min), in order to get consumption values which can be applied to the driving patterns defined from the survey data.
If *ECd* is the consumption per mile at the speed of S miles per hour (h), it follows that the consumption per hour at a given speed is:

$$ECd * S$$

and the consumption per a period of 5 min is:

$$ECd * S / 12$$

So, using the data in Van Haaren (2011) and the conversion above, energy consumption was computed for each speed (expressed in kilometres per hour (km/h)) and for each 5-min period.
Plotting the values obtained, it was observed that a quadratic function provides a good approximation of EV energy consumption in relation to speed:

$$Energy\ consumption = ParA * Speed^2 + ParB * Speed + Constant \quad [1]$$

Since this function is obtained by interpolation of point estimations of energy consumption and different speeds, the parameters (*ParA*, *ParB* and *Constant*) do not have a physical meaning; they are only used to align the calculated data with the data observed.

The actual energy consumption of electric cars was estimated as follows.
First, the consumption in kilowatt-hours per kilometre (kWh/km) corresponding to the curve obtained by interpolating the data in Van Haaren (2011) was compared to other sources. It was found that the consumption obtained (0.08–0.20 kWh/km) was lower than the theoretical consumption reported by other sources (0.12–0.25 kWh/km (Peugeot, 2012; RWTH, 2010). Consequently, the parameters of the quadratic curves were increased so as to have the consumptions fall more in line with the literature.
Second, as mentioned above, the consumption curve makes reference to the consumption at constant speed, based on driving tests in predefined conditions determined by the US Environmental Protection Agency (US Department of Energy, 2012).
In the real world, cars are hardly ever used at constant speeds, especially in urban contexts where most trips are made. Acceleration, deceleration and braking phases alternate in real driving cycles, leading to higher consumption: for instance, it is

estimated that accelerating from 80 km/h to 130 km/h and then braking to return to 80 km/h results in an additional consumption of 100 Wh (Van Haaren, 2011). In order to take the real driving conditions into account, and in line with the approach of the Environmental Protection Agency (EPA) (Van Haaren, 2011), a 30 % upward adjustment factor is applied to the parameters of the quadratic function.

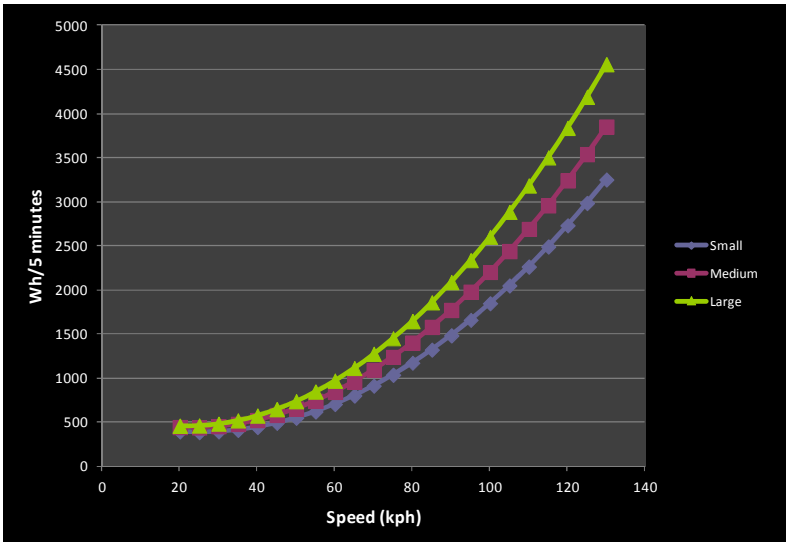
Finally, since in our calculations we consider different EDV sizes, three ([2]) different sets of parameters were defined (see Table 3.1 and the corresponding curves in Figure 3.2). The three sizes of EDVs refer to theoretical models of large, medium and small cars, and are defined arbitrarily. These parameters can be changed in future calculations, so that assumptions can be easily revised and adapted to future development of EDV features and the most recent evidence from laboratory and field tests.

Table 3.1 Speed-dependent energy consumption curve parameters

Vehicle size	ParA	ParB	Constant
Large	0.26	-13.0	546
Medium	0.30	-14.0	600
Small	0.35	-15.2	620

([2]) Five EDV types are considered in the estimation of load profiles: three BEVs and two PHEVs. In terms of energy consumption, given the level of approximation of the parameters, PHEVs in our initial calculations have been considered equivalent to BEVs of the same size. These parameters can be differentiated in alternative scenario calculations. BEVs and PHEVs are assumed to have a different range.

Figure 3.2 Estimated quadratic speed-dependent energy consumption curves



Speed is the input required to estimate the energy consumption of EDVs during the driving periods. Such speed is estimated trip by trip, using the driving profiles data at 5-min intervals. However the average speed computed only as a ratio between distance and travel time is not representative — either of the instantaneous speed of the vehicle, or of the actual average speed when the car is moving — because travel time includes stops at traffic lights, parking manoeuvres, etc. Given that this discrepancy is particularly significant for shorter trips, a minimum average speed is assumed: 40 km/h for trips shorter than 20 min and 50 km/h for trips longer than 20 min. We computed the average speed per trip from the driving profiles data, and took the maximum between that average and the minimum value.

By applying equation [1], the energy consumption for each 5-min period belonging to a driving phase is computed. In the same period, the amount of energy consumed is subtracted from the load level of the battery.

So, for a given 5-min period, it holds:

Level of charge = Previous level of charge – Energy consumption [2]

where *Energy consumption* is computed according to equation [1].

If the driving phase exceeds the range available given the battery level of charge at the beginning of the trip, the battery runs out of power. In the calculation, this corresponds to negative level of charge values. When this happens in the case of battery electric vehicles (BEVs), the specific driving pattern is considered unfeasible and is subsequently excluded from the following steps. Plug-in hybrid electric vehicles (PHEVs) are never excluded; even if their batteries are depleted, they can always continue, using the ICE.

The calculations described above can be adapted in future scenario work when more field data become available in the context of demonstration activities, allowing for a better approximation of the relation between trip distance, time and energy usage.

3.2.2 Estimating electricity consumption in parking periods

During parking periods, EDVs can use energy from the grid to recharge batteries. This occurs under certain conditions: first, the parking space should provide recharging facilities; second, the parking time should be long enough to allow completion of the recharge process or a reasonable top-up; and third, the car driver should actually want to recharge her or his car. So, when estimating electricity use during the driving process, the only 'non-technical' assumption required concerns the type of EDV used; the estimation of electricity consumption from the grid requires several hypotheses.

As for the shares of EDV types, non-technical hypotheses cannot be based on literature or evidence, as they depend on local conditions or behavioural choices. Indeed, they can be considered major elements of alternative scenarios. The idea of building an interactive database that allows users to set up their own assumptions and compare various conditions is also due to the awareness that at least some elements needed for the estimations are rather arbitrary. Notwithstanding this, we have made some initial assumptions about the availability of recharge facilities at parking spaces.

Namely, it is assumed that:

- recharging at home is always possible (at the normal recharge rate; see after formula [3]);
- availability of recharging at parking spaces at work refers to a share of drivers rather than to a share of spaces.

The first assumption is required because otherwise many driving patterns would become incompatible with the use of BEVs and would be useless for the estimation of load profiles. Indeed, it can be assumed that very few people will buy an EDV without the capacity to recharge it it at home. As mentioned by Thiel et al. (2012), this capacity is one of the elements describing some of the most popular definitions of the 'ideal' electric car as per our survey. Other research (e.g. Cassinis (2011)) confirms this point. So, when the share of EDVs in the fleet is assumed (see Section 3.3), it is reasonable to assume that all individuals who use an EDV can recharge it when parked at home (in a private garage or even at the kerbside).

The second assumption is used in the estimation process in order to ensure consistency. Non-work-related trips can have different destinations for the same individual. Therefore, the assumption about the availability of recharging in relation to a certain trip is not linked to another trip (even if the individual and the purpose is the same). In contrast, most work-related trips (namely commuting trips) are repeatedly taken to the same destination: once it is assumed that charging is possible, this must be the case for

all trips. Therefore the assumption is attached to individuals concerning parking at work, while it is attached to places for other parking.

Availability of charging stations is one of the preconditions mentioned above, but a car that is parked in a place where recharging is available is not necessarily taking advantage of this facility. If the car is only parked for a short time, for instance, it would be inconvenient to recharge. Standard batteries of EVs need several hours (between five and eight) to be fully recharged at a normal rate (Nissan, 2012; Peugeot, 2012). A faster recharge at a higher power rate can be used for certain BEVs to fill batteries to least for 80 % of their capacity (Nissan, 2012b; Peugeot, 2012). However, even faster recharges require at least 30 min. In our calculations, we have used a threshold of 30 min to identify parking periods in which the car driver does not recharge the car. This threshold can be changed in alternative scenarios.

Finally, even if a charging station is available and the parking time is long enough, some individuals might not be willing to recharge the car. For instance, if purchasing a recharge in a private garage during the day is more expensive than recharging at home (maybe even with discounted night-time charging), the latter solution is preferable if the driver has enough power to get home. Since range anxiety seems to be a relevant issue (see, for example, Cassinis (2011)) one might argue that individuals would take advantage of any opportunity to recharge their car. On the other hand, as noted above, the possibility to recharge at home is greatly valued. So, again, any assumption on this aspect is arbitrary.

The assumptions described above are used to calculate the power demand on the grid. In every 5-min period belonging to a parking phase associated to a recharge, the amount of electricity taken from the grid is added to the load level of the battery.

So, for a given 5-min period, it holds that:

Level of charge = Previous level of charge + Electricity recharge [3]

When the battery is fully loaded, the electricity flow is set to zero even if the car is still parked. The amount of power drawn from the grid is not a fixed value, owing to two elements.

- First, the recharge can be made either at a normal or at a fast rate. When the latter is applied, the amount of energy needed in a 5-min period is higher than in the case of a normal recharge. The rates used in the calculations are not fixed; they depend on the assumption of how long it takes to recharge a (medium-sized) battery. On average ([3]), a normal recharge corresponds to 3.1 kWh per hour, and a fast recharge to 16.7 kWh per hour.
- Second, it is assumed that when the battery is close to its full capacity, the recharge rate declines. Li-ion batteries are charged in two phases (Fairchild,

([3]) For a medium BEV with a battery range of 160 km.

2010), with a declining charge rate in the second phase. The point at which the rate changes as well as the curve of the charge rate in the second phase depend on the battery. In order to reflect this behaviour, albeit in a simplified way, we assumed that the charge rate is reduced when the battery reaches the level of charge of 80 % of its capacity. It is assumed that the reduction is as much as 30 %: the normal recharge rate falls from the average level of 3.1 kWh per hour to nearly 2.2 kWh per hour; and the fast rate from an average value of 16.7 kWh per hour to 11.7 kWh per hour.

Another aspect to be considered is electricity losses during the charge process, for example, through heat dissipation. Therefore, in our calculations we used an efficiency ratio of 0.8. In alternative scenarios, this value can be modified.

Apart from the limitation of the minimum parking time required to make the recharge feasible, there are no other limits assumed in the process. So, for instance, the recharge is assumed to continue until the battery is fully charged, or until the car is no longer parked.

Since the simulation needs a starting point, another hypothesis underlying the calculations is that at the beginning of the first day of the diary (midnight of the first day described by the user), the EV is charged at its maximum level.

3.2.3 Estimating load profiles

Using the assumptions and following the procedure explained above, we have estimated the individual charging profiles corresponding to the driving patterns. The calculation of the load profiles is a matter of two major tasks: selection of a share of individual profiles and expansion to the overall population.

A selection is made, in order to assume that only a share of individuals uses EDVs; the share can be defined in the scenarios. This selection occurs after the calculation of the individual charging profiles, i.e. we computed the electricity usage and demand from the grid for each individual. As noted above, depending on the various assumptions made in the estimation of charging profiles, some of the driving profiles may be incompatible with the use of an electric car. These profiles are excluded before the selection phase, so that the share of EDV owners as assumed in the scenarios is actually reflected in the computation of the load profiles. In practical terms, if the scenario requires that x% of the total reference population are EDV owners (e.g. 20 %) and the assumptions made during the calculation of the charging profiles lead us to exclude y% of driving patterns (e.g. 15 %), the calculation algorithm selects a share of x/(1-y)% from the remaining valid profiles.

This adjustment takes also into account the predefined market shares of the different EDV types. That is, the selection is not only expected to produce the expected share of EDV owners in the whole population, but also to reproduce the expected composition of the EDV fleet.

The selection of the individuals is made through a 'constrained' random procedure, as follows. First, 1 out of 10 alternative random sequences is selected. When the share of EDVs owners is defined, the database picks up the first *n* record from the selected sequence. The reason for using such a 'constrained' procedure is to guarantee repeatability in estimating load profiles. Different individuals have different driving habits, so including or excluding certain individuals in the sub-sample used for load profile calculation does affect the results. While on the one hand, it is useful to see the effect of different sub-samples on loading profiles, on the other hand, it is crucial that experiments are repeatable by different users each time they design scenarios. The 'constrained' random extraction ensures that once a sequence and sub-sample size are selected, exactly the same individuals are always selected. This guarantees repeatability of different scenarios with same random numbers and simulation of the same scenario with different random numbers.

Sample load profiles result from the weighted sum of the selected individual charging profiles for each 5-min period of each day. Weights are attributes of each individual resulting from the comparison between the composition of the reference population and the composition of the sample. For instance, if a certain segment represents s% of the sample and S% of the population, the weight of all individuals belonging to that segment is weighed S/s.

Hence, our calculations actually produce population load profiles rather than sample load profiles; population profiles are computed by expanding the sample profiles by the sample ratio. In each country, the sample consisted of 500 to 600 car drivers, representing the entire driver population. Therefore, each individual counts for some thousands of people. Since the population/sample ratio is quite high, including or excluding one driving pattern can sometimes change the load profiles significantly.

4 Load profiles scenarios

The methodology for charging profiles and load profiles estimations highlights how several elements play a part in the estimation. Some of these are technical aspects, while others are behavioural ones. Within the former group, there are parameters reflecting features which are relatively well established — at least at the current level of the technical advancement — and others which are more uncertain. The elements in the latter group are inherently less predictable, as the number of actual EDV users is so limited that we lack experience on which to base recharge periods, for example. Even relatively well-defined technical characteristics (e.g. battery range) could become obsolete in the near future as research brings about improvements.

For these reasons, this study is more focused on exploring alternative scenarios than on estimating a specific set of load profiles. Two initial scenarios are presented here to indicate what kind of results can be produced under the given assumptions.
Initially, a base scenario was defined, with common assumptions across all six countries. These assumptions are presented in Section 4.1, and the load profiles estimated in this scenario are presented in Section 4.2.
Then, a scenario with a different hypothesis was tested on the countries. The alternative scenario helps to identify the role of the parameters in generating the load profiles. The content and results of this scenario are presented in Section 4.3.

4.1 Base scenario assumptions

4.1.1 Share of EDVs in the fleet

Various studies predict the share of electric cars in the EU-27 fleet in the future. For instance, Van Hessen and Kampman (2011) estimate that the share of EDVs will be around 6 % in the year 2025 and around 17 % in the year 2030. In the GHG-TransPoRD project (Fiorello et. al., 2012), the projections for the same years are 19 % and 31 % respectively, in a scenario where political and technological efforts are explicitly aimed at achieving market penetration of EDVs (a kind of best scenario for the electric car). The *EV City Casebook,* the product of a joint study of several organisations (International Energy Agency, 2012), presents target values of EDV shares expected in some European countries. Germany and the Netherlands both have the target of 1 000 000 EVs in their fleets (in 2020 for the former, and in 2025 for the latter) which would correspond to nearly 2.5 % of the fleet in Germany and 13 % in the Netherlands.
In light of these different estimates, we considered the share of EDVs to be 10 % in the medium term for this scenario.

4.1.2 Market shares of EDV types

In the European research project 'Grid for vehicles' (Dederichs, 2011) a projection of market shares of different EDV types has been performed: PHEVs are assumed to constitute 53 % of all EDVs, while 47 % are assumed to be BEVs, with 10 % being small BEVs.
These shares have been used as a basis for the base scenario assumptions. We additionally distinguished between medium and large BEVs and PHEVs. We assumed that there are more medium BEVs and PHEVs than large ones. The detailed fleet composition used for the simulation is reported in Table 4.1.

Table 4.1 Market shares of EDV types in the scenario

EDV type	EDV fleet share (%)
Small BEV	10
Medium BEV	25
Large BEV	10
Medium PHEV	40
Large PHEV	15

4.1.3 EDV range

The assumed range for the different EDV types is based on current models available on the market: for small BEVs this is the G-Wiz REVA range (Boxwell, 2010); for medium and large BEVs, it is the Nissan LEAF and the Tesla Roadster respectively (Van Haaren, 2011). For medium PHEVs, the Prius Plug-in hybrid range has been used (Toyota, 2012). For large PHEVs, no references were found, so we assumed a range double that of a medium PHEV. Table 4.2 summarises the ranges adopted in the scenario.

Table 4.2 Range of EDV types in the scenario

EDV type	EDV range (km)
Small BEV	80
Medium BEV	160
Large BEV	200
Medium PHEV	20
Large PHEV	40

4.1.4 Battery recharge time

The recharge time for the battery of a small BEV has been set to 8 h (normal recharge) and 0.5 h (fast recharge). A minimum time of 0.5 h has been also assumed to allow at least a minimum recharge with a completely discharged battery. As mentioned above, these durations correspond to a certain recharge rate, given the assumed capacity of batteries (i.e. for a medium-sized EDV). Also, this recharge rate is not constant, but it is reduced by 30 % after the battery charge status reaches 80 % of the battery capacity.

4.1.5 Availability of recharge facilities at parking spaces

The *EV City Casebook* (International Energy Agency, 2012) presents a review of the attitude of 16 cities worldwide towards EVs. Single city programmes are not always adequately representative for countrywide planning, but some sense of foreseeable trends can be gauged. In particular, there is a clear indication that stations for normal recharge will outnumber those for fast recharge. The ratio ranged from 400:1 (in Japan)

to 180:1 (in the Netherlands). Based on this information, assumptions on the availability of recharge facilities at different parking spaces are summarised in Table 4.3.

Table 4.3 Availability of recharge stations at parking spaces in the scenario

Parking type	Places with normal recharge available (%) ([a])	Places with fast recharge available (%)
Work	50	0
Open air private	50	5
Open air public	50	5
Private garage	50	5
Public garage	50	5
Kerbside regulated	20	2
Kerbside unregulated	20	2

([a]) This does not mean that the percentage of parking places is equipped with charging stations, but that the percentage of EDVs will find a parking place with a recharge point.

4.1.6 Attitude to recharging throughout the day

The base scenario load profiles are built on the assumption that people have no preference concerning recharging time; this means that recharging is not time-constrained, but occurs whenever a car is parked and a charging station is available. In this scenario, load profiles are therefore strictly correlated to car-use patterns.

4.2 Base scenario results

By applying the assumptions introduced above to the database, we calculated the daily load profiles in each country, as described in the following sections.

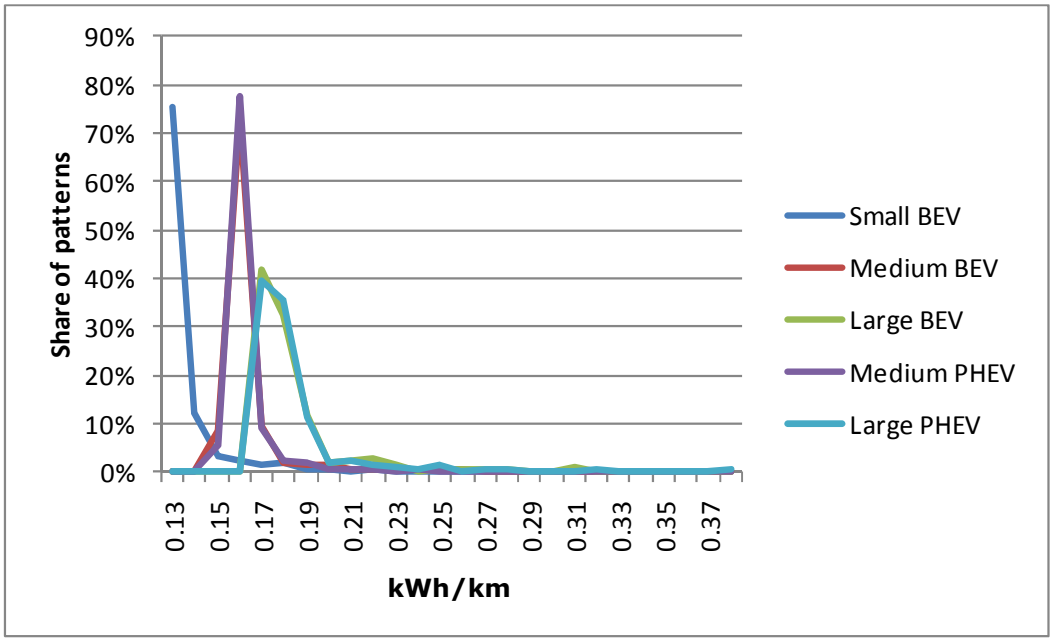
4.2.1 Average energy consumption in driving phases

The electricity required for recharging electric cars depends on the energy consumed in driving these vehicles. In turn, the energy consumed is a function of the distance travelled and the speed. The relationship between speed and electricity consumption is an input of the procedure (see Subsection 3.2.1) and thus the estimated unitary consumption in the scenario will depend on the average speed of the vehicles, according to the driving patterns. Figure 4.1 shows the distribution of consumption in kilowatt-hours per kilometre for the five different EDV types modelled in France. Given that the average distance and average driving time are generally quite similar across countries, as reported by Pasaoglu et al. (2012), it can be deduced that the average speed — and therefore consumptions — are also comparable.

For the simulated patterns, the average electricity consumption is in the range of 0.14 kWh/km (for small BEVs) to 0.19 kWh/km (for large BEVs). Distributions are highly asymmetrical, with long tails of cases with much higher consumptions due to higher

average speeds. These consumption values are comparable to the figures reported by G4V (RWTH, 2010) and are derived from real driving cycles of a BEV. Depending on the context, the observed energy consumption of a real EDV is between nearly 0.13 kWh/km (driving on roads) and nearly 0.2 kWh/km (driving on motorways or in traffic jams). Considering that the estimation in the database is made using an average speed, the adopted consumption curves seem to provide a realistic level of energy consumption per kilometre. At the same time, the description of mobility (e.g. average travelled distance) can be considered reasonably accurate. Therefore, the quantification of electricity demand on the grid in the load profiles can also be regarded as realistic.

Figure 4.1 Distribution of electricity consumption during driving phases: France



4.2.2 Load profiles

Charts in Figure 4.2 provide a comparison of load profiles among the different days for each country. The charts in Figure 4.2 show that in all countries, the profiles of the working days (from Monday to Friday) are generally different from those of the weekend. The figures illustrate that there are several peaks across the day, with higher values generally registered in late afternoon, but with some significant spikes in the morning and in early afternoon, too. In the unconstrained scenario, in Germany the highest peak load is noted between 3.30 p.m. and 8.00 p.m., reaching approximately 5 500 megawatts (MW), while morning spikes are registered in the hours between 7 a.m. and 10 a.m. Interestingly, the same type of load profile in Germany, albeit attenuated in terms of MW, is also registered on Saturday, while the Sunday peak is noted only in the afternoon. The United Kingdom, Italy and France have somewhat similar profiles to the ones in Germany across weekdays; at weekends, however, higher

peaks are seen during lunchtime (roughly between 11 a.m. and 3 p.m.). In Spain, morning spikes are rare on weekdays; peaking occurs mostly in the afternoons starting from 13.00. Weekend load profiles in Spain differ from Saturday to Sunday: Saturdays are generally higher from 11.00 am to 5:00 pm. Differentiation in load profiles at weekends is also registered in Poland, where generally lower peaks are seen between 11 a.m. and 4 p.m. on Saturday, with two peaks on Sundays.

4.2.3 Load profiles by EDV type

The load profiles shown in the previous figures result from the energy demand of all individuals using an EDV. Five different electric car types are assumed to exist in our calculations — three battery vehicle types and two plug-in hybrid vehicle types — with each contributing to the electricity demand. Certainly, the contribution of each type depends on different elements. The first element is the market share of each type. It is expected that the amount of energy demanded by a given EDV type is proportional to its diffusion in the fleet. However, only a slight proportionality is expected because of the different technical features (namely battery capacity) of each vehicle type, and especially because of the different use of each specific car.
The contribution of different EDV types clearly indicate that driving and parking patterns heavily influence the form of the load profiles. To illustrate, Figure 4.3 shows the charts of unconstrained recharge for the United Kingdom for each day. Generally speaking, medium and large BEVs and medium PHEVs are major contributors to the load during most days of the week, including weekends. Load profiles for small BEVs are significantly lower in terms of megawatts, with spikes registered mostly in the afternoon hours during weekdays and in the morning on Sundays. Large PHEVs show different load profiles between different days of the week in the United Kingdom: higher profiles on Tuesday, Thursday and Friday during weekdays in the afternoon, and higher peaks between 12:00 a.m. and 4:00 p.m. on Sundays.

From the chart, it clearly emerges that driving and parking patterns are the major determinants of the load profiles.

4.2.4 Electricity demand and electricity generation capacity

The load profiles help to assess one important aspect, namely whether the additional demand on electricity due to EDV recharging is problematic for the electricity generation capacity or the grid. A British study (Department of Energy and Climate Change, 2012) estimated that with an EDV penetration of 18 % of the fleet in the United Kingdom, the annual electricity demand would be of 22 terawatt hours (TWh), i.e. about 5 % of the total electricity demanded. The same study estimates a consumption of 33

TWh per year (also equivalent to 5 % of total demand) for Germany, assuming that the share of EDVs in the fleet is 25 %. These estimates are obtained assuming a quite high unitary consumption of EDVs (0.25 kWh/km).

In the base scenario, the estimated total consumption of electricity for recharging EDVs in one year is 4.6 TWh in the United Kingdom and 7.7 TWh in Germany. Taking into account that in our scenario the assumed penetration of EDVs in the fleet is lower (10 %), and that unitary energy consumption (0.13–0.20 kWh/km — see above) is close to two-thirds of that used in the British study, the differences in the annual consumptions estimated in our scenario for the United Kingdom and Germany versus those of the Department of Energy and Climate Change (DECC) study can largely be explained by the differences in the market share and in technical assumptions.

However, this kind of comparison made on total annual electricity demand does not take into account that impacts can be different day by day and over the day. Here, the analysis of load profiles can be helpful. In Table 4.4, the weekly peak in power (MW) demand from the grid in the six countries is indicated, alongside statistics on the countries' electricity capacity.

Figure 4.2 Load profiles by country for the unconstrained time scenario

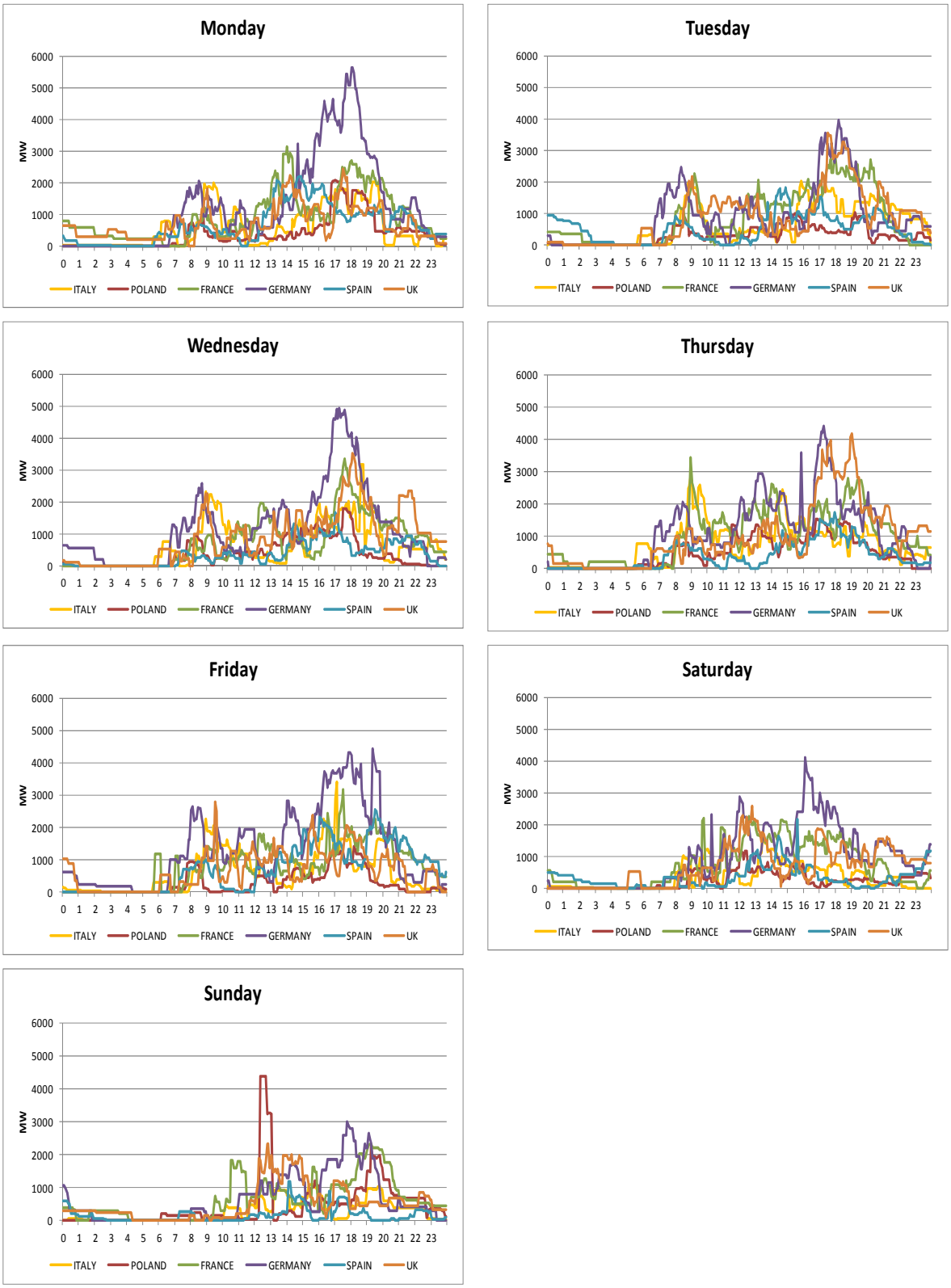


Figure 4.3 Load profiles by day and EDV type for the unconstrained time scenario: United Kingdom

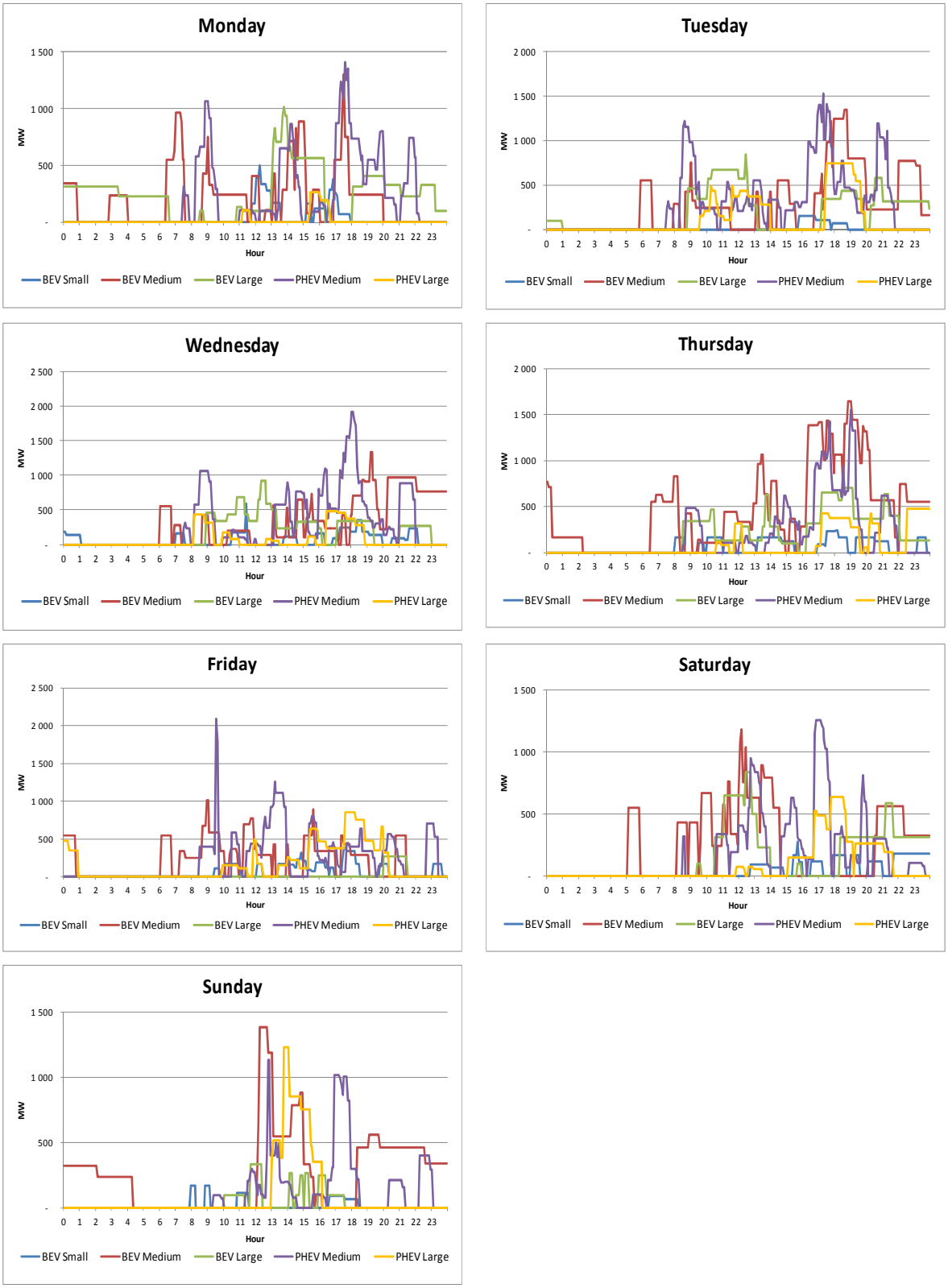


Table 4.4 Weekly peak power by country — summary statistics ([a])

Country	Peak power demanded (MW)	Day of the week when peak occurs	% of peak on installed electricity capacity	% of peak on reliable available capacity	% of peak on remaining capacity([b])
France	3 360	Wednesday	2.7	3.8	15.0
Germany	5 649	Monday	3.5	6.2	36.8
Italy	3 403	Friday	3.2	5.0	23.1
Poland	4 371	Monday	12.7	19.7	175.6
Spain	2 564	Friday	2.7	5.0	17.4
United Kingdom	4 175	Thursday	5.0	6.8	30.5

([a]) The source for electricity capacity data used to compute the statistics in the table is ENTSO-E (2011). Averages between 11:00 a.m. and 7:00 p.m. data for the year 2011 have been used.

([b]) Remaining capacity is the difference between reliable available capacity and existing load.

The energy demand peak for recharging EDVs in this scenario is generally well below installed capacity as well as reliable capacity, which is a more representative value of electricity supply. Indeed, installed electricity capacity is a theoretical value; available capacity is normally lower, due, for example, to plants closed for maintenance or non-dispatchable variable renewable electricity. As reported by ENTSO-E (2011) data, in the six countries being studied, reliable available capacity ranges from 54 % of installed electricity capacity (in Spain) to 73 % of installed electricity capacity (in the United Kingdom).

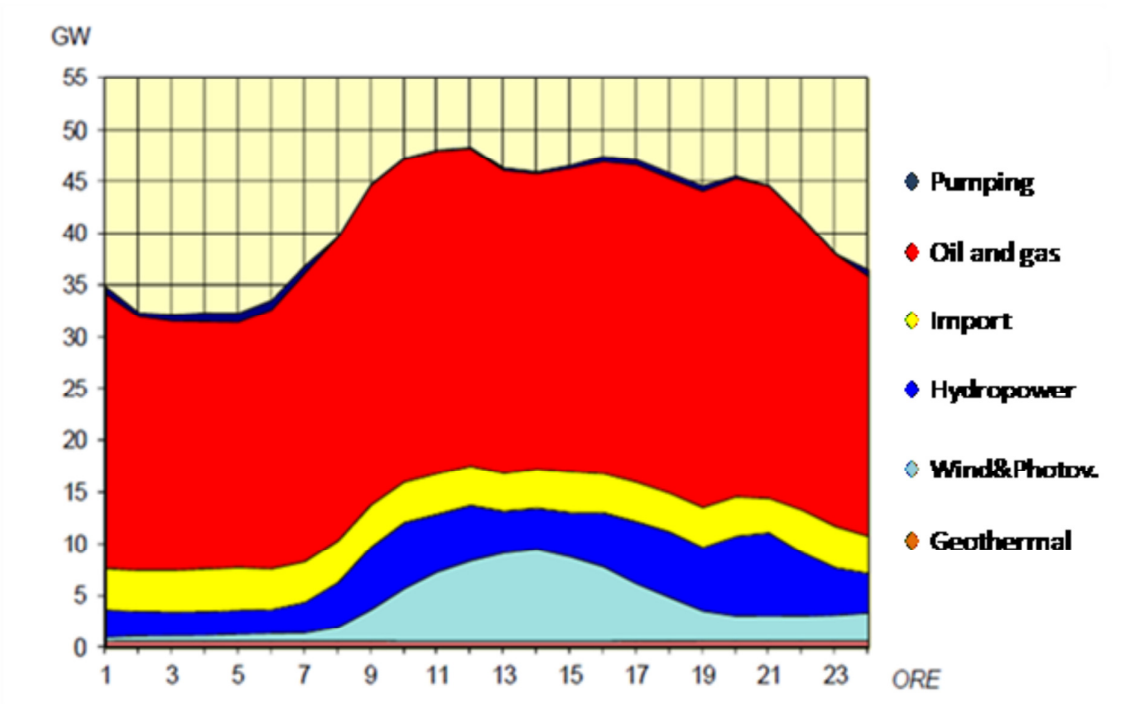
Poland is an exception: the peak of power required for recharging EDVs amounts to nearly 20 % of available capacity. Although this share seems low, we must remember that that a large part of the supplied power is already used by other electricity consumers. ENTSO-E data on loads reveal that in all countries the power load amounts to more than 70 % of reliable capacity — in Germany this is more than 80 % and in Poland close to 90 %. Taking into account other electricity uses, in Poland the peak electricity demand for recharging EDVs exceeds the residual power actually available. For other countries, the peak demand for EDVs is in the range of 15 % to 35 % of remaining capacity, with France and Spain on the lower threshold, Germany and the United Kingdom on the upper limit, and Italy in between.

Another aspect to be considered is that the scenario assumes only 10 % of EDVs in the vehicle fleet. In the hypothetical case of the whole fleet being made up of electric cars, about ten times the power estimated in our scenario would be needed. According to the data, this would be impossible to manage in all six countries.

This conclusion is partially mitigated by the fact that the power supply percentages in Table 4.4 are merely indicative values, because the energy actually available changes over the day — when the recharge peak occurs in the scenario (10:00 p.m.), other types of consumptions are generally lower (hence the reduced electricity prices). Therefore, the ratio between additional energy and residual power would be lower. Nevertheless,

consumption never falls that much below the peak, as seen, for example, in Table 4.4. The electricity consumption curve in Italy in a sample day (TERNA, 2012) shows that despite consumptions at 10:00 p.m. being below the peak, the difference is low. Therefore, the warning of the burden on electricity networks due to EDV recharging under certain conditions remains valid.

Figure 4.4 Daily electricity consumption curve in Italy in a sample day



Source: TERNA, 2012.

4.3 Alternative scenario

The G4V study (Dederichs, 2011) suggests that people are willing to recharge EVs in the time window from 10:00 p.m. to 6:00 a.m. owing to lower energy costs; because of this, the percentage of drivers willing to recharge during this period has been set to 100 %. Small percentages are assumed in the early morning (6:00 a.m. to 8:00 a.m., when many individuals need to use their car) and in the early evening (6:00 p.m. to 10:00 p.m., when it is assumed that people are likely to wait for the next discounted charging period). During the rest of the day, it is assumed that one driver out of two is willing to recharge the car to avoid range anxiety. Table 4.5 summarises these assumptions.

Table 4.5 Willingness to recharge EDVs in the alternative scenario

Time window	% of drivers willing to recharge EDVs
00.00–6.00	100
6.00–8.30	10
8.30–18.00	50
18.00–22.00	10
22.00–00.00	100

We used the database to estimate daily load profiles in each country, under the same assumptions as those applied to the base scenario. This is described briefly in the following sections.

4.3.1 Load profiles

The charts in Figure 4.5 provide a comparison of load profiles among the different weekdays for each country. The charts report the amount of power (in MW) required for EDVs recharging in each 5-min period of the different days of the week. The profiles in the charts help identify the variation of demand across hours. By comparing profiles for a given country on different days or for the same day in different countries, the similarities and difference can be detected.

Since the assumptions made for estimating the load profiles are the same for all countries (and for all days), differences between the countries are explained by different (driving and parking) behaviour or by sampling. Driving behaviour affects the load profiles in terms of number of cars used and of periods when cars are used or parked. The more cars used, the higher the electricity demand for recharging will be when the cars are parked. Dissimilar parking habits can also explain differences between load profiles: the number of drivers using different parking types (e.g. kerbside, private lots at work, and so on) varies from country to country. Since the share of parking spaces equipped with recharging facilities is assumed to vary across parking types, the resulting profiles are not the same.

Finally, the curve of electricity demand can change from day to day or from country to country as a result of the random selection of individuals. In other words, different samples — corresponding to different sets of driving patterns — could correspond to partially diverse profiles.

The charts in Figure 4.5 show that in all countries the working day profiles (from Monday to Friday) are generally different from those of the weekend. This is most apparent in Italy, Germany and Spain, while in countries like France and Poland the difference is smaller. The common feature of load profiles in all countries and on all days is the evening peak at 10:00 p.m. This peak is clearly a result of the assumptions that

only 10 % of the individuals are willing to charge their car between 6:00 p.m. and 10:00 p.m., and that 100 % of cars will be charged after 10:00 p.m. and until 6:00 a.m. of the following morning. In the real world, this evening peak might be scaled down as many people would not start to recharge exactly at 22.00. However, it is realistic to expect a peak during the evening, when most people would plug their car in to the grid.

The weekend is generally characterised by a lower peak in the load profile, but this is not the case in the United Kingdom, where the peak of power requested is lower on Monday and Friday than on Saturday. However, the difference is due to low energy demand on those two days and not to high energy demand at the weekend. Results obtained with other random samples and with a different share of EDVs in the fleet should be considered before concluding that in the United Kingdom, less power is required from the grid on Monday and Friday.

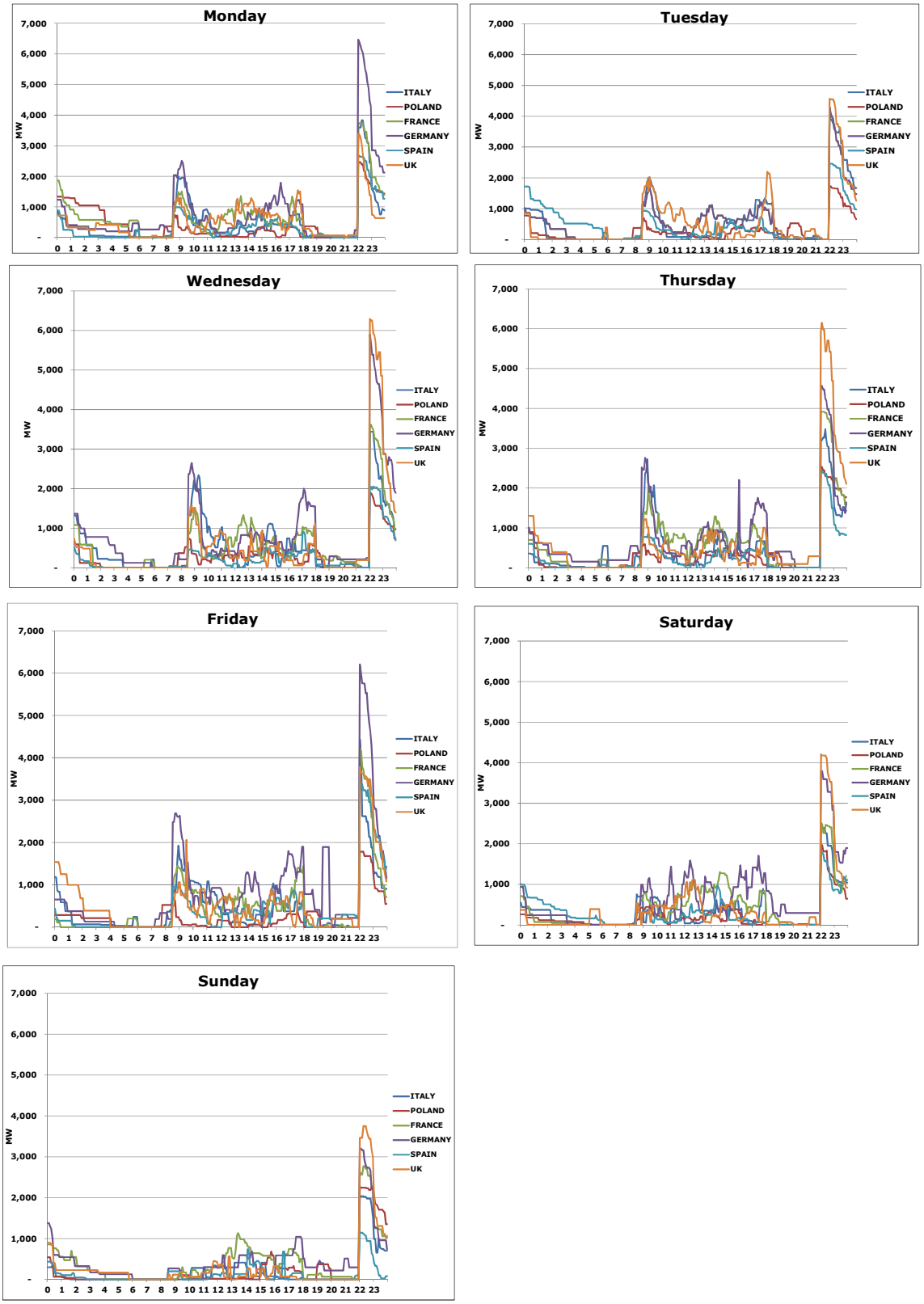
Country profiles reveal also some regularity. For instance, in Italy, profiles on working days are invariably characterised by a daytime peak in the morning (around 9.00 a.m.) which is probably due to commuters. A similar morning peak can be observed in Germany, where a second daytime peak occurs in the afternoon (around 5:00 p.m.), something that is much less evident in Italy. Spain holds an intermediate position: there is a clear peak in the afternoon (as in Germany), but this peak is generally less sharp than the morning one. At the same time, on Saturday and Sunday the load profiles of Spain present two significant peaks in the middle of the day. Again, however, other samples and other conditions should be tested before drawing conclusions about structural differences.

In Italy, load profiles are also different between Saturday and Sunday. On both days, the morning peak basically disappears; while on Saturday the recharge still begins around 8.00,a.m. on Sunday, power is demanded from the grid starting from 10.00 a.m.. A time shift onwards on Sunday is reasonable, despite the fact that this result might also depend on the randomly selected individuals.

In France, three peaks are evident in the daytime on working days: at 9.00 a.m., 1:00 p.m. and 5.00 p.m. The same pattern is somewhat visible on the weekend too, even though the central peak at 1:00 p.m. is more evident, and on Sunday the first peak at 8.00 a.m. is not so sharp.

In Poland, the power demand from the grid is quite flat every day during the daytime. On Sunday, electricity is demanded significantly only after 3:00 p.m. This might be an effect of sampling, however, and it should be verified by other tests.

Figure 4.5 Load profiles by day of the week



4.3.2 Load profiles by EDV type

The load profiles shown in Figure 4.5 result from the energy demand of all individuals using an EDV. Five different electric car types are assumed to exist in the fleet (three battery vehicles and two plug-in hybrid vehicles), each one contributing to the energy demand. Of course, the contribution of each type depends on different elements. The first element is the market share of each type. It is expected that the amount of energy demanded by a given EDV type is proportional to its diffusion in the fleet. However, only a vague proportionality is expected because of the different technical features (namely battery capacities) of each vehicle type, and especially because of the different use of each specific car.

Figure 4.6 and Figure 4.7 show the load profile separately for each EDV type in Germany and Poland. From the charts, it clearly emerges that driving patterns are the major determinants of load profiles. Indeed, although the familiar evening peak is visible, the contribution of car types to the profile does not follow any explicit pattern; it largely depends on the mobility of individuals assumed to use one or another EDV model. Overall, it is evident that for many hours PHEVs are responsible for much of the energy demand, since in the scenario they are assumed to represent the largest share of the electric fleet. Nevertheless, the charts show peaks for other EDV types here and there. For instance, in Poland the evening peak is attributable to medium BEV demand, while PHEVs are recharged throughout the whole day. This is partially explained by the lower capacity of batteries in hybrid cars, which can be more easily recharged when the car is parked for a few hours during the day. However, the main factor is the different mobility habits of individuals associated with BEVs and PHEVs in Poland (otherwise, in Germany too, the evening peak would be more associated with battery vehicles). Apparently, in Poland, more BEV users than PHEV users end their driving day with the need to recharge, while in Germany this does not happen.

The technical aspects come into play with the recharge time. Our analysis shows that the load profiles of hybrid vehicles present more 'spikes', i.e. high energy demand in short periods. Instead, the profiles for battery vehicles are more 'flat'. This difference is clearly visible in the night periods, when the energy demand is almost entirely attributable to BEV use, whereas PHEVs are not greatly represented. Of course, this depends on the smaller batteries assumed for hybrid vehicles, which can be recharged in a short time. In contrast, BEV vehicles may need several hours to restore their energy load.

4.3.3 Electricity demand and electricity generation capacity

In Table 4.6, the weekly peak in power (MW) demand from the grid in the six countries is reported, together with statistics relating to their electricity capacity.

Incidentally, it is noted that the weekly peak occurs on different days across countries. In Italy and Spain it is Friday, in Germany and Poland it is Monday, in France it is Tuesday and in the United Kingdom it is Thursday. Whatever the day, as in the base

scenario, the peak of the energy demanded is a fraction of the installed electricity capacity in the countries, ranging from nearly 5 % in France, Germany and Italy to more than 10 % in the United Kingdom.

Table 4.6 Weekly peak power by country — summary statistics ([a])

Country	Peak power demanded (MW)	Day of the week when peak occurs	% of peak on installed electricity capacity	% of peak on reliable available capacity	% of peak on remaining capacity ([b])
France	5 821	Tuesday	4.6	6.6	26
Germany	8 603	Monday	5.3	9.4	56
Italy	6 043	Friday	5.7	8.9	41
Poland	2 887	Monday	8.4	13.0	116
Spain	4 856	Friday	5.1	9.4	33
United Kingdom	9 025	Thursday	10.9	14.8	66

([a]) The source for electricity capacity data used to compute the statistics in the table is ENTSO-E (2011). Averages between 11 a.m. and 7 p.m. data for the year 2011 have been used.

([b]) Remaining capacity is the difference between reliable available capacity and existing load.

Nevertheless, the peak power demand is higher than in the base scenario (with the exception of Poland), so the considerations for that scenario concerning the feasibility of catering for the power needs of EDVs once other uses are accounted for remain valid. For France and Spain, the share of the remaining capacity corresponding to the theoretical energy peak for EDV recharging is relatively low (nearly 30 %). In Italy, it is 40 %, in Germany and the United Kingdom, it is more than 50 % and in Poland, it is again higher than 100 %, i.e. in accounting for the existing load, the extra power required for recharging EDVs under the assumptions made in the scenario would exceed the available power.

Furthermore, also in the alternative scenarios, only 10 % of EDVs are assumed to be in the vehicle fleet; if this share were larger, the energy demand would be higher.

Analysis of the alternative scenario confirms that uncontrolled recharging could lead to artificial electricity-demand spikes when certain time windows for lower tariffs exist network-wide. These effects would need to be avoided by means of controlled recharging supported by smart grids.

Figure 4.6 Load profiles by day of the week and EDV type: Germany

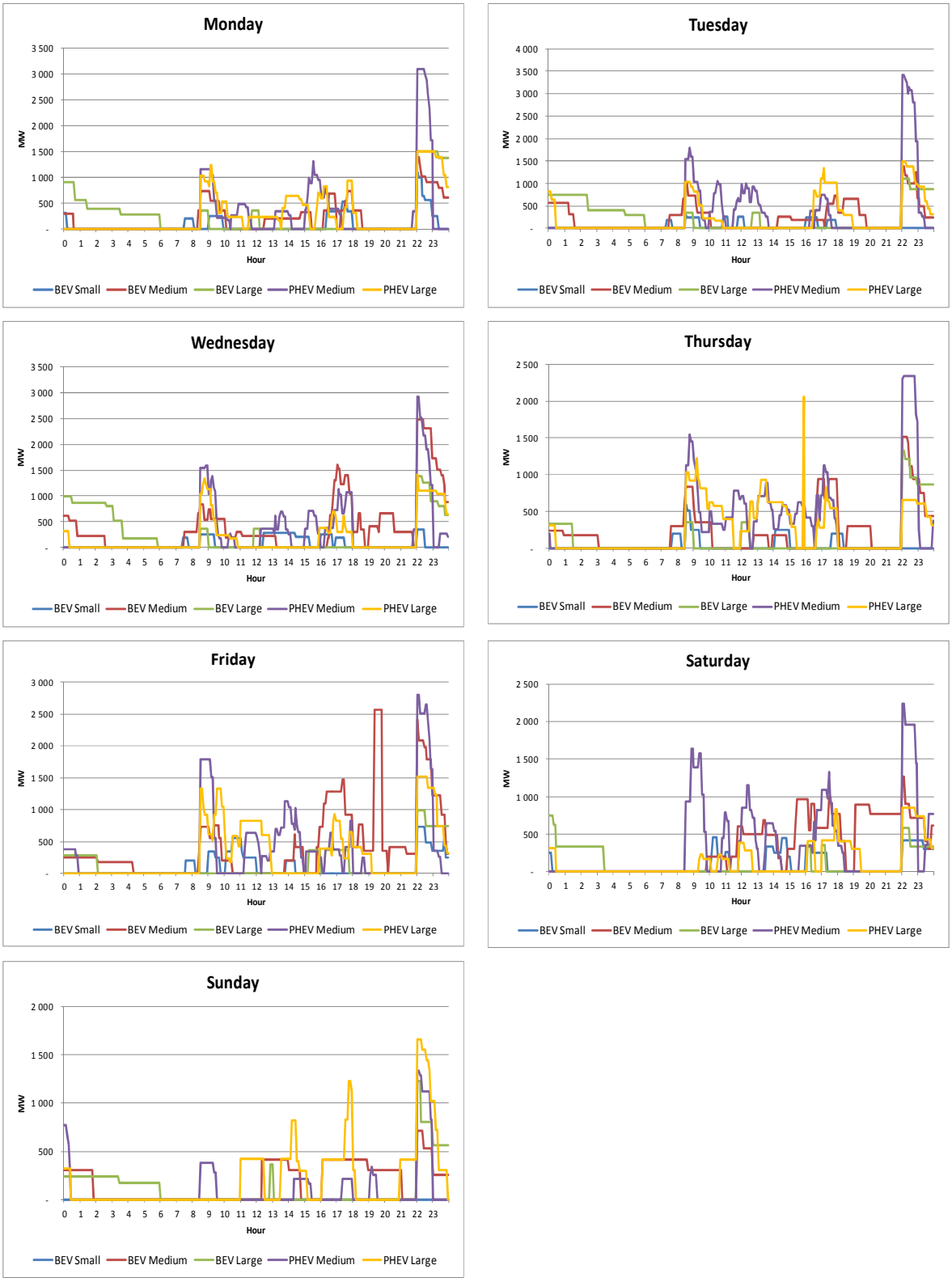
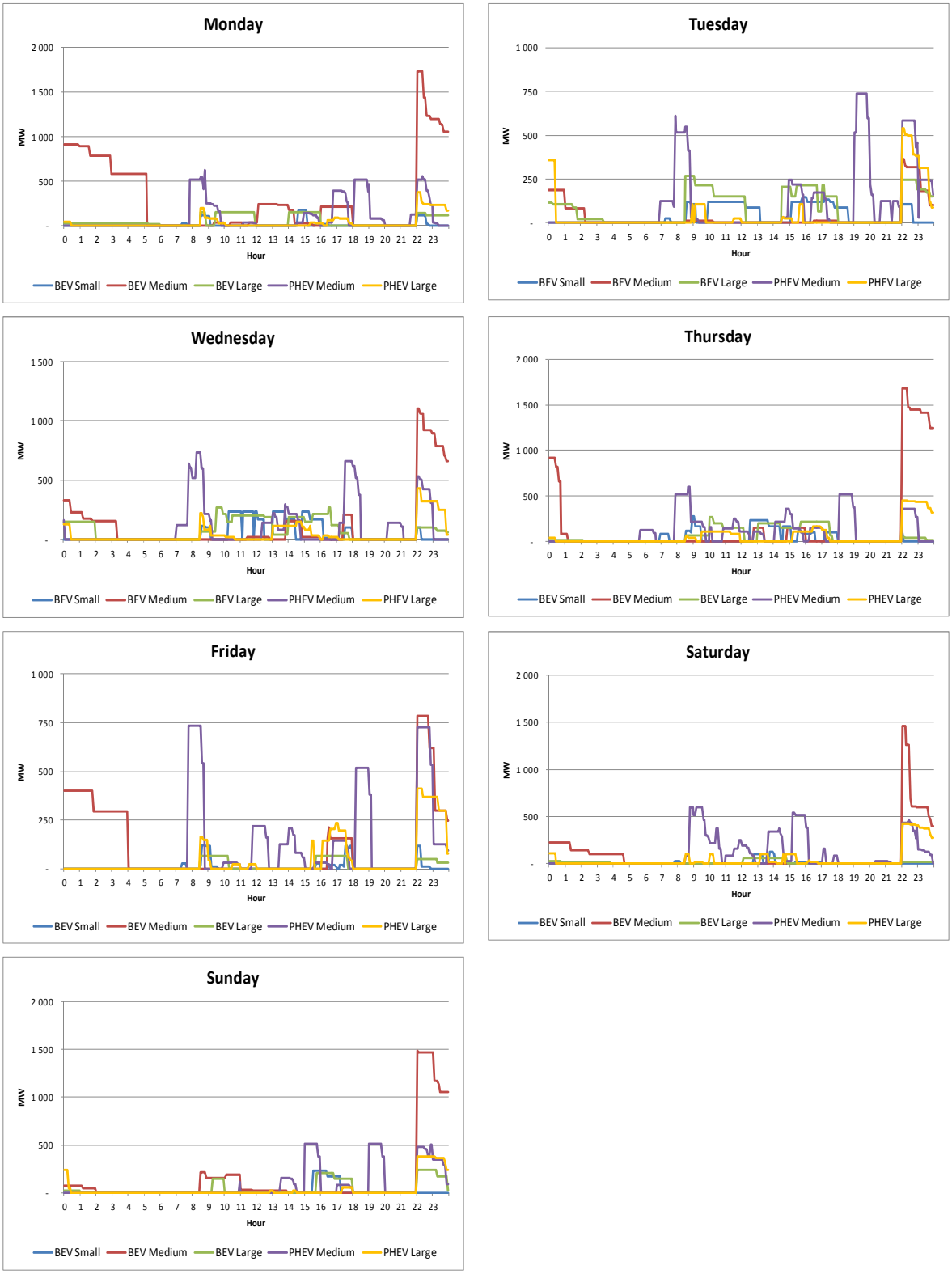


Figure 4.7 Load profiles by day of the week and EDV type: Poland



5 Conclusions

This report concludes the study of projecting load profiles for EDVs based on car-use patterns in six European countries. The data collected by the sample survey are documented in Pasaoglu et al. (2012). The survey data were used in this study to calculate individual charging profiles and aggregated load profiles by setting several different parameters. Indeed, the load profiles are built on very detailed driving patterns data of a representative sample of individuals in six different EU countries.

There is scant evidence of electricity demand being computed by using detailed individual driving data in the literature. The impact of EDVs on electricity demand has been addressed in earlier work, but this is generally in a much more aggregated fashion or without using representative data.

For instance, MEC Intelligence (2011) provides estimations of individual charging profiles using driving patterns derived from real EDV use, but the small number of vehicles (37) complicates the generalisation of the results at grid level. Anair and Mahmassani (2012) make reference to the American travel survey data but they just derive an average daily driving distance. Van Haaren (2011) uses the American travel survey data to derive parking profiles over the 24 hours for each day of the week, but these profiles are not associated to assumptions about the number of EDVs in the fleet or on the share of parking lots where recharging is available. Wu at al. (2011) use individual driving patterns derived from the American travel survey data for the year 2009; however, only four 'typical cases' (e.g. a working day in an urban context) are considered. Moreover, the individual driving patterns are not used separately; instead, aggregate functions related to an average 'representative' individual are defined, using random functions to deal with the heterogeneity of driving behaviour. And in all of these studies, average electricity consumption is used rather than a speed-dependent one.

Therefore, the estimation of load profiles according to the methodology introduced in this report is an unprecedented example of the use of individual driving profiles of a representative sample of individuals coupled with assumptions on the penetration of different types of EDVs in the fleet and with speed-dependent energy consumption functions. Although this study uses several simplifying assumptions (e.g. a constant speed for each trip), it also provides significant added value in relation to the existing literature.

In this study, we developed two scenarios, the baseline scenario and the alternative scenario. The former assumes that recharging time is not time-constrained, but occurs whenever a car is parked and a charging station is available. In this scenario, load

profiles are therefore strictly correlated to car-use patterns. The alternative scenario emphasises the preference for recharging during the night. As expected, the load profiles of the alternative scenario are quite different from those obtained in the baseline scenario. In the baseline scenario, several peaks across the day with higher values are generally registered in late afternoon, but with some significant spikes in the morning and in early afternoon too. Examining the contribution of different EDV types confirms that driving patterns lead the form of the load profiles.

The load profiles obtained reveal that some differences between countries do exist, but it is the assumptions concerning when and where individuals can/want to recharge EDVs that explain the amount of electricity demanded from the grid over time. For instance, discounted electricity tariffs are often available at night-time, and it is assumed that people are willing to postpone their recharge in order to exploit the lower electricity rates. Under this assumption, a strong peak of energy demand in late evening might be expected. The results of the scenarios suggest that peaks could be avoided only if there is no reason for preferring certain periods of the day over others. Also, widespread availability of recharging stations does not seem to be a sufficient condition for evening out the peaks. The reason is that cars are generally parked at home longer than in any other place, and therefore in most cases, an EDV will be charged while parked at home (which is also what individuals would prefer, according to the literature).

Importantly, what this means in policy terms, is that providing the possibility to recharge at home is a key factor for promoting the diffusion of EDVs. Since many individuals do not own a private garage or rent a private parking space, but instead park their cars on the kerbside, the challenge lies in finding means for these EDVs to be recharged.

The infrastructure challenge regarding the charging stations is not the only one suggested by the simulated scenario. Even with a limited number of EDVs in the fleet (a 10 % share is assumed in the scenario), the total energy demanded in an evening peak like the one shown in the simulated profiles (i.e. when many motorists would start simultaneously to charge their car in order to exploit the reduced power tariffs) could be a significant share of the available power capacity (i.e. net of existing load). In some cases, it might be even above the current residual capacity.

In comparing the estimated load peak with the available capacity, one must consider the worst conditions: the simulations warn about the possible need for additional electricity capacity (more so in some countries than in others) to accommodate a significant share of EDVs.

From the perspective of electric cars replacing most of the conventional ICE vehicles, all countries would probably need to increase their available capacity. In other words, a policy for promoting the diffusion of EDVs might need to be complemented with a policy for expanding the capacity of electricity supply, and in particular of electricity supply from renewable or low-carbon sources (otherwise most of the rationale for replacing ICE vehicles with EDVs would disappear). If the charging time and rate is managed through smart charging, it can be ensured that the EDV-induced loads are planned mainly during periods of lower general electricity loads, thus mitigating the need for capacity expansion.

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European Commission
EUR 25993 – Joint Research Centre – Institute for Energy and Transport

Title: Projections for Electric Vehicle Load Profiles in Europe-Based on Travel Survey Data

Authors: G. Pasaoglu, D. Fiorello, L. Zani, A. Martino, G. A. Zubaryeva, C. Thiel.

Luxembourg: Publications Office of the European Union

2013– 42 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series –ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-30387-6 (pdf)
ISBN 978-92-79-30388-3 (print)

doi:10.2790/24108

Abstract

This study is aimed at building a database of load profiles for electric-drive vehicles (EDVs) based on car use profiles in six European countries (Germany, Spain, France, Italy, Poland, and the United Kingdom). Driving profiles were collected by means of sample travel surveys carried out in the six countries. Here, we present the resulting load profiles obtained by associating assumptions on technical features of EDVs and on behavioural elements. The document provides details on the methodology and the assumptions used for driving profiles estimations, discusses the results of a common scenario for six countries and presents an alternative scenario to assess how load profiles might change under alternative parameters and assumptions. The report draws conclusions on this subject, and puts forward suggestions for follow-up studies.

LD-NA-25993-EN-N

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