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Electric Vehicles – Consumers and Suppliers of the Electric Utility Systems

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Additional information is available at the end of the chapter

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1. Introduction

Electric vehicles (EVs) have been gaining attention in the last few years due to growing public concerns about urban air pollution and other environmental and resource problems. The technological evolution of the EVs of different types: Hybrid electric vehicles (HEV), battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), will probably lead to a progressive penetration of EV's in the transportation sector taking the place of vehicles with internal combustion engines (ICEV). The interesting feature of EVs (only available for BEVs and PHEVs) is the possibility of plugging into a standard electric power outlet so that they can charge batteries with electric energy from the grid.

While a large penetration of plug-in EVs is expected to increase electricity sales, extra generation capacity is not needed if the EVs are recharged at times of low demand, such as overnight hours. EVs, as a local zero emissions' vehicle, could only provide a good opportunity to reduce CO₂ emissions from transport activities if the emissions that might be saved from reducing the consumption of oil wouldn't be off-set by the additional CO₂ generated by the power sector in providing for the load the EVs represent. Therefore, EVs can only become a viable effective carbon mitigating option if the electricity they use to charge their batteries is generated through low carbon technologies.

In a scenario where a commitment was made to reduce emissions from power generation, the build-up of large amounts of renewable power capacity raises important issues related to the power system operation (Skea, J, et al., 2008), (Halamay et al., 2011), as a result, power system operators need to take measures to balance an increasingly volatile power generation with the demand, and to keep the system reliability. To perform these actions, the SO (system operator) needs to access active and reactive power reserves which are either contractually established with the power generators or traded in the ancillary system market

(Estanqueiro, A. et al., 2010). These requirements represent an extra cost for the system which might adequately quantify the negative effect of the variability and uncertainty of each renewable generation technology.

Practically speaking, there are additional external costs of integrating renewable inflexible generation in the power systems, namely in terms of backup capacity, needed to balance power generation and demand when the renewable generation is lower than forecasted, and some kind of storage or demand shift, needed to integrate excesses of renewable generation, especially likely to occur in the off-peak periods.

In this context, electric vehicles can bring techno-economical advantages for the electric power system because of their great load flexibility and increase the system storage capacity. In fact, EVs are parked 93% of their lifetime, making it easy for them to charge either at home, at work, or at parking facilities, hence implying that the time of day in which they charge, can easily vary and, furthermore, for future energy systems, with a high electrification of transportation, Vehicle to Grid (V2G), where the EV works also as an energy supplier, can offer a potential storage capacity and use stored energy in batteries to support the grid in periods of shortage (Kempton and Tomic, 2005). Although each vehicle is small in its impact on the power system, a large number of vehicles can be significant either as an additional charge or a source of distributed generating capacity.

While the aggregate demand for electricity is increasing, decentralized power generation is gaining significance in liberalized electricity markets, and small size electricity consumers are becoming also potential producers. Prosumer is a portmanteau derived by combining the word producer, or provider, with the word consumer. It refers to the evolution of the small size passive consumer towards a more active role in electricity generation and the provision of grid services.

This chapter is concerned with studying how the electric vehicle can work as a “prosumer” (producer and consumer) of electricity. The benefits to the electric utilities and the costs of services provided by EVs in each type of power market will be addressed. The potential impacts of the EVs on the electricity systems, with a great amount of renewable sources in the generation mix will be studied with a focus on the additional power demand and power supply an EV can represent, the role of a new agent on the power market – The EV aggregator – and the economic impacts of EVs on electric utilities.

The analysis of the impact on the electric utilities of large-scale adoption of plug-in electric vehicles as prosumers will be illustrated with a real case study.

Many studies regarding battery electric vehicles and Plug in hybrids have been, and continue to be performed in different countries. In the US, for instance, the capacity of the electric power infrastructure in different regions was studied for the supply of the additional load due to PHEV penetration (Kintner-Meyer et al., 2007) and the economic assessment of the impacts of PHEV adoption on vehicles owners and on electric utilities (Scott et al., 2007). Other studies (Hadley, 2006) considered the scenario of one million PHEVs added to a US sub-region and analyzed the potential changes in demand, impacts on generation adequacy, transmission and distribution and later the same analysis was extended to 13 US regions

with the inclusion of GHG estimation for each of the seven scenarios performed for each region (Hadley, 2008). The ability to schedule both charging and very limited discharging of PHEVs could significantly increase power system utilization. The evaluation of the effects of optimal PHEV charging, under the assumption that utilities will indirectly or directly control when charging takes place, providing consumers with the absolute lowest cost of driving energy by using low-cost off-peak electricity, was also studied (Denholm and Short, 2006). This study was based on existing electricity demand and driving patterns, six geographic regions in the United States were evaluated and found that when PHEVs derive 40% of their miles from electricity, no new electric generation capacity was required under optimal dispatch rules for a 50% PHEV penetration. A similar study was made also by NREL (National Renewable Energy Laboratory) but here the analysis focused only one specific region and four scenarios for charging were evaluated in terms of grid impact and also in terms of GHG emissions (Parks et al., 2007). The results showed that off-peak charging would be more efficient in terms of grid stress and energy costs and a significant reduction on CO₂ emissions was expected though an increase in SO₂ emissions was also expected due to the off peak charging being composed of a large amount of coal generation. Studies made for Portugal (Camus et al., 2011) of the impacts in load profiles, spot electricity prices and emissions of a mass penetration of EV showed that reductions in primary energy consumption, fossil fuels use and CO₂ emissions of up to 3%, 14% and 10% could be achieved by year 2020 in a 2 million EVs' scenario, energy prices could range 0.9€ to 3.2€ per 100 km according to the time of charging (peak and off-peak) and the electricity production mix. A recent report (Grunig M. et al., 2011) that analyzed the EV market for the next years concluded that, the market penetration of EVs will remain fairly low compared to conventional vehicles. The estimation based on several government announcements, industry capacities and proliferation projects sees more than five million new Electric Vehicles on the road globally until 2015 (excluding two- and three-wheelers), the majority of these in the European Union. The main markets for Electric Vehicle are in order of importance the EU, the US and Asia (China and Japan). Some further target markets like Israel and the Indian subcontinent are also expected to evolve. In the long term, the share of EVs will most likely increase as additional countries adopt technologies and initiate projects.

The first description of the key concepts of V2G appeared in 1996, in an article (Kempton and Letendre, 1996) written by researchers at the University of Delaware. In this report the approach was to describe the advantages of peak power to be supplied by EDVs connected to the grid. Further work from the same researchers was continued (Kempton and Letendre, 2002) and the possible power services provided for the grid by vehicles were increased by the analysis of spinning reserve and regulation. The formulation of the business models for V2G and the advantages for a grid that supports a lot of intermittent renewable were described specially for the case of wind power shortage (Kempton and Tomic, 2005a; Kempton and Tomic, 2005b). The use of a fleet for providing regulation down and up was studied and how the V2G power could provide a significant revenue stream that would improve the economics of grid-connected electric-drive vehicles and further encourage their adoption were evaluated (Tomic and Kempton, 2007). The potential impact of renewable generation on the ancillary service market, with a focus on the ability of EVs to provide such services via de-

mand response (DR) and V2G were analyzed. The document also presents a revenue model that incorporates potential scenarios regarding EV adoption, electricity prices, and driver behavior. The output of the model determines the overall revenue opportunity for aggregators who plan to provide DR-EV (Leo M. et al., 2011), although, there is a significantly large market for these services, the limited revenue opportunity for aggregators on a per car basis is unlikely to be compelling enough to justify a business model. According to a recent report from Pike Research (Gibson B., Gartner J., 2011), EVs compete with traditional generation sources as well as emerging technologies, such as stationary battery storage, for revenue from ancillary services such as frequency regulation and demand response.

2. Electricity generation

Electricity generation faces nowadays a greater number of challenges related to reliability, sustainability and security of supply. The use of renewable resources in power generation has been adopted in most OECD countries as an answer to the climate change problems originated by the burning of fossil fuels in the traditional thermal plants to supply the ongoing increase in electricity demand.

In this section, a description of the electric power systems demand is done emphasizing its evolution along a day and seasonal profile, the different technologies available for power generation are also presented, their main features and when and how each of them produces and the emissions associated with electricity production from thermal units are also addressed in this section. A description of the renewable sources, identifying the factors that influence the value of each renewable technology for the power system is done. These factors include the variability, uncertainty, complementarities with other sources and with the demand and implications for reserve requirements. The impacts of EVs recharge in the typical load profiles will be assessed and also the effects of EVs working as electricity suppliers.

2.1. Electricity demand and supply

Electric power systems are designed to respond to instantaneous consumer demand. One of the main features of power consumption is the difference in demand along the day hours, the week days and seasons. This evolution along the day, with a valley during the night that represents about 60% of the peak consumption, has great financial consequences with the need of having several power plants that are useless and an underutilized network during the night.

To supply this load, there are a different set of technologies, from renewable sources (hydro, solar, wind, biomass and waves) to conventional thermal units (natural gas, coal, fuel oil and nuclear).

These different technologies, with different load factors (ratio of average load to capacity), supply the system in different periods and power levels. There are mainly two types of power plants in the electric system: base load or peak power plants. Base load plants are

used to meet some of a given region's continuous energy demand, and produce energy at a constant rate, usually at a low cost relative to other production facilities available to the system. Peak power plants are used few hours a year only to fulfill the peaks at higher unit energy prices.

The intermittent renewable sources like the hydro run-of-river and wind are not included in this definition as they are not controllable, but have to be included in the power supply with the highest priority according to the energy and climate policies established (EC, 2009) so they can be considered as base load power plants.

Sometimes the renewable production has an average production profile that works in opposition with demand. Fig. 1 shows as an example, the average production profile of wind power in Portugal verified in year 2010.

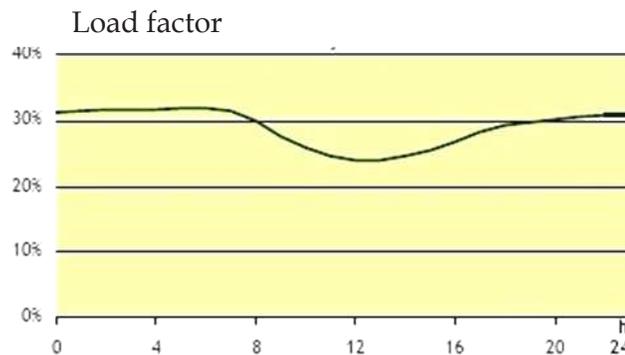


Figure 1. Average wind power profile for year 2010 in Portugal (REN, 2011)

In fact, it has been observed along the years that the wind power production has in average this same profile, with more power production during the night hours.

This situation is even sharper in summer months. In Fig. 2 are the average power produced by wind, solar and small hydro in July 2011 in Portugal.

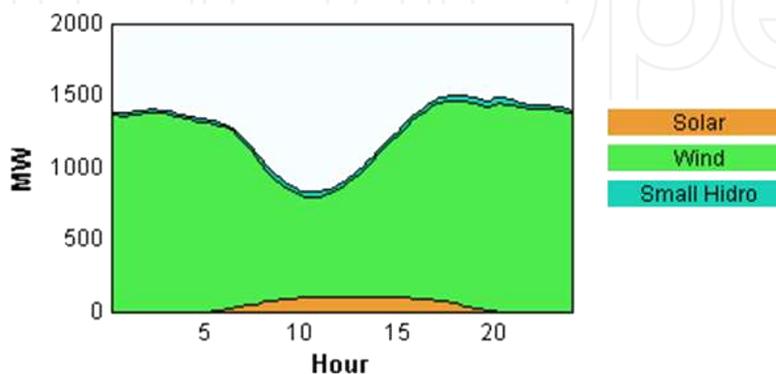


Figure 2. Average power production profile of the renewable sources in July 2011 in Portugal

In summer months, the renewable production is lower when the demand is higher.

For this same case study, Fig. 3 shows the July average power profile with the production technologies. The lowest renewable production level coincides with the peak consumption.

This situation gives the opportunity for electric vehicles contribution for levelling the power consumption diagram and allowing the penetration of more renewable production, by increasing the load during the night hours and supplying the system at the peak hours (Fig. 4).

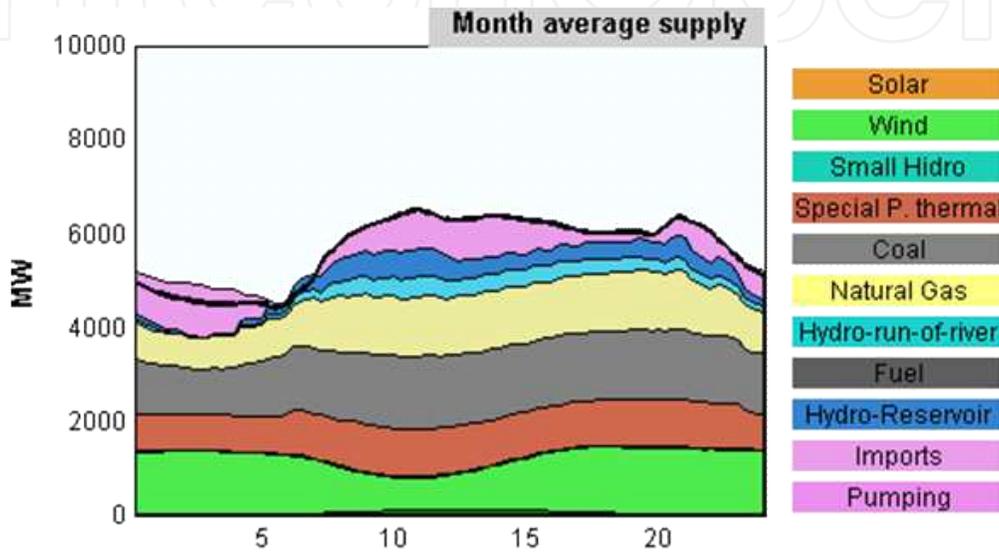


Figure 3. Average load profile with production technologies in July 2011 for Portugal.

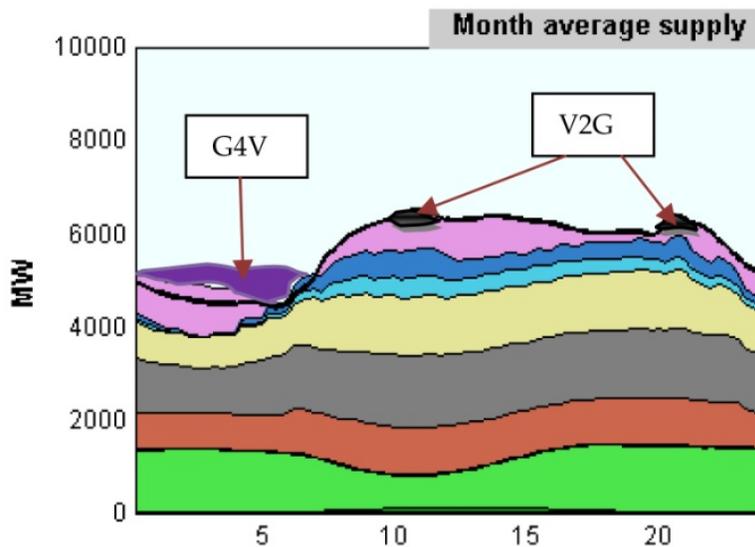


Figure 4. Example of the effect EVs can produce in the electricity demand profile as consumers and suppliers of electricity through G4V (Grid for Vehicle) and V2G respectively.

2.2. The main technologies for electricity generation and the merit order

As described in the previous sub-section, there are many technologies available for electricity production.

The aim of a power plant in a power system is to supply the load in an economical, reliable and environmentally acceptable way. Different power plants can fulfill these requirements in different ways. Different power plants have different characteristics concerning how they can be controlled in the power system. When operating a power system, the total amount of electricity that is provided has to correspond, at each instant, to a varying load from the electricity consumers. To achieve this in a cost-effective way, the power plants are usually scheduled according to marginal operation costs, also known as merit order. Units with low marginal operation costs will operate almost all the time (base load demand), and the power plants with higher marginal operation costs will be scheduled for additional operation during times with higher demand. Wind power plants as well as other variable sources, such as solar and tidal sources, have very low operating costs. They are usually assumed to be zero therefore these power plants are at the top of the merit order. That means that their power is used whenever it is available.

In parallel with marginal operation costs of the power plants are the environmental costs, nowadays assessed by the GHG emissions, they represent. In Table 1, are the average emission rates considered for the typical thermal power plants to compute the GHG emissions from power generation. Those average values can increase if the power plants are subjected to many start-up cycles.

Technology	Emission rate (kg/MWh)		
	CO ₂	NO _x	SO ₂
Coal	900	2.8	6.3
Fuel	830	3.9	4.5
Nat gas (Comb. Cycle)	360	0.13	0
Cogeneration (N.Gas)	600	0.5	

Table 1. Emission rates considered for the thermal power plants for GHG emission computation (EDP, 2008).

Summarizing, we can dispose of flexible plants, where the power output can be adjusted (within limits), and inflexible plants, where power output cannot be adjusted for technical or commercial reasons. Examples of flexible and inflexible power plants are in Table 2.

As mentioned, the output of the inflexible power plants is treated as given when optimizing the operation of the system.

Not all the flexible power plants can be used the same way to adjust to power demand. The hydro plants with reservoir are the more flexible. Thermal units must be “warmed up” before they can be brought on-line, warming up a unit costs money and start-up cost depends

on time unit has been off. There is the need to “balance” start-up costs and running costs. For example a Diesel generator has a low start-up cost but a high running cost, while a Coal plant has a high start-up cost and a low running cost.

Flexible Plants	Inflexible Plants
Coal-fired	Nuclear
Oil-fired	Run-of-the-river hydro
Open cycle gas turbines	Renewable sources (wind, solar,...)
Combined cycle gas turbines	Combined heat and power (CHP, cogeneration)
Hydro plants with storage	

Table 2. Available power plants for electricity generation.

2.3. The renewable sources

The percentage of renewable production depends on the location (the endogenous resources available) and the energy policy of the local economy.

Many sources of renewable energy, including solar, wind, and ocean wave, offer significant advantages such as no fuel costs and no emissions from generation. However, in most cases these renewable power sources are variable and non-dispatchable. The utility grid is already able to accommodate the variability of the load and some additional variability introduced by sources such as wind. However, at high penetration levels, the variability of renewable power sources can severely impact the utility reserve requirements.

For instance, at low penetration levels, the variable output of wind power plants is easily absorbed within the variability of the load. However, as the penetration level increases, the added variability of the wind resource can cause greater ramp-rates, greater inter-hour variability, and greater scheduling error. This ultimately increases the amount of generation the system operators must hold in reserve (i.e., the reserve requirement) to accommodate the unplanned excursions in wind generation.

2.3.1. Wind, solar, and wave generation characteristics

Wind power is now a very mature and established renewable resource throughout the world. However, other renewable power sources such as solar (PV or concentrating/thermal) and ocean wave energy also have significant potential. Each of these renewable power sources can be described by three major characteristics.

1st –Variable. The output power of a large-scale wind, solar, or wave power plant varies over time. The vast majority of the time, the variability from one minute to the next is very small, and even the hourly variation is usually small. However, on occasion the output of a large plant, as high as several hundred MW, may go from full output to low production or vice versa over several hours (Fig. 5);

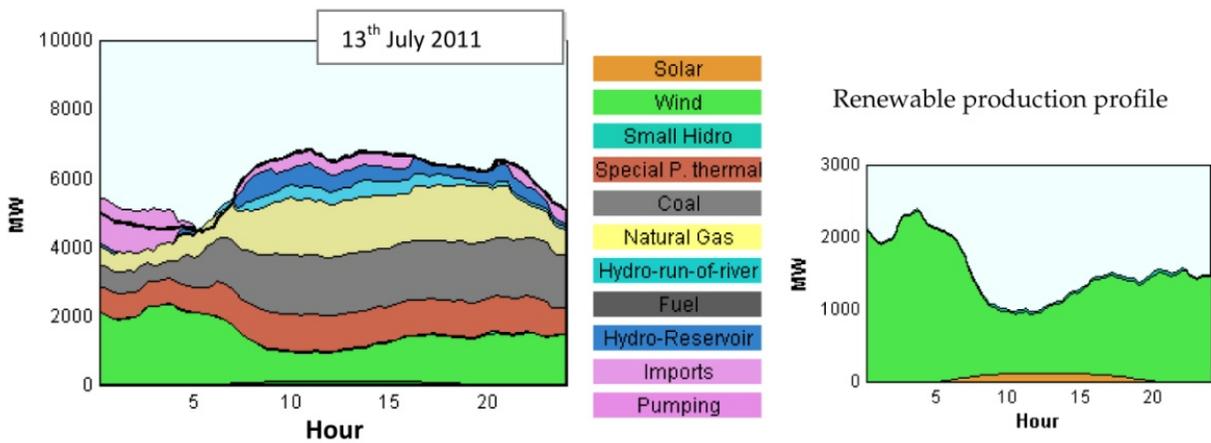


Figure 5. Example of the consumption and production on the 13th July 2011 in Portugal where, in less than 5 hours, a loss of more than 1000MW in renewable production occurred.

2nd –Non-dispatchable. As implemented now, the system operator has very limited control of the output of large scale renewable generation. In general, the operator must deal with whatever the renewable generation outputs are in much the same manner as dealing with the load. Therefore it is common in the analysis of the impact of renewable power generation to subtract its contribution from the load: renewable power generation appears as a negative load;

3rd – Energy source. Due to the non-dispatchable nature of wind, solar, or wave, they generally have a relatively low capacity credit. That is, they do not make a significant contribution to the power requirements of the grid for planning purposes. However, each Joule of energy converted by a renewable source is one Joule saved for “traditional” generation, such as coal. Therefore, renewable energy sources can make a significant impact on the energy requirements of the grid.

2.3.2. Adequacy of renewable production with power demand

The variable, non-dispatchable nature of wind, wave, and solar has a significant impact on the utility reserve requirements. Analyzing the effect of these renewable energy sources on the reserve requirements provides a meaningful and concrete method of characterizing the variability of a given renewable energy source, including its short and long-term correlation with the load.

In order to balance generation with load on a minute-by-minute, hourly, or daily basis, the variability of both the generation and the load must be examined.

With renewable resources like wind, solar, and ocean wave, forecasting of the available generation can present a particular challenge, which, while having a large impact on the hourly or daily reserve requirements, often has less of an impact on the intra-hour requirements. Given the focus on reserve requirements, it readily becomes apparent that a clear understanding of the different types/timescales of reserves is necessary.

Three different timescales are currently used to calculate reserve requirements.

The first, regulation, is defined as the difference between the minute-to-minute power generation/load and the 10-minute average power generation/load. This timescale accounts for small changes in power demand or supply that can be readily met through Automatic Generation Control (AGC) via spinning reserves.

The second timescale of interest, following, is defined as the difference between the 10-minute average power generation/load and the hourly average power generation/load.

This timescale accounts for larger changes in the power demand or supply.

The final timescale, imbalance, is defined as the difference between the hourly average power generation/load and the forecasted generation/load for that hour. The imbalance component of the reserve requirements is directly impacted by the accuracy and frequency of the forecasted generation/load. With the large increase in wind power generation, the imbalance component of the reserve requirement is forecasted to grow rapidly.

In order to calculate imbalance reserve requirements, the scheduled or forecasted power must be determined for both the renewable resource and the load.

2.3.3. Energy storage needs

Reliability is an important feature of power systems. A reliable power system implies that there is always enough generating capacity to satisfy the power demand. In reality this aim can only be achieved to a certain security level. As the installation of power plants is a long process, future power portfolios and their ability to cover the demand must be assessed in advance. The contribution of wind power to the availability of generating capacity becomes important with increasing wind penetration. The capacity value of wind power is therefore identified for future, potentially large wind power penetration levels.

Capacity value designates the contribution of a power plant to the generation adequacy of the power system. It gives the amount of additional load that can be served in the system at the same reliability level due to the addition of the unit. It is a long established value for conventional power plants. Over recent years similar values have been calculated for wind power. A higher correlation between wind and load will lead to higher capacity values. In the case of low correlation between wind and load, there will be need of more storage capacity to respond to renewable and load in-balances.

The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily due to the fluctuations in power output generated from wind. A part of the fluctuations is predictable for 2 h to 40 h ahead. The variable production pattern of wind power changes the scheduling of the other production plants and the use of the transmission capacity between regions.

This will cause losses or benefits to the system as a result of the incorporation of wind power. Part of the fluctuation, however, is not predicted or is wrongly predicted. This corresponds to the amount that reserves have to take care of.

The economic, social and political costs of failing to provide adequate capacity to meet demand are so high that utilities have traditionally been reluctant to rely on intermittent resources for capacity. Dimensioning the system for system adequacy usually involves estimations of the LOLP (loss of load probability) index. The risk at system level is the probability (LOLP) times the consequences of the event. For an electricity system, the consequences of a blackout are large, thus the risk is considered substantial even if the probability of the incident is small.

The loss of load expectation (LOLE) is a measure of system adequacy and nominates the expectation of a loss of load event. The required reliability of the system is usually in the order of one larger blackout in 10–50 years.

Since no generating plant is completely reliable, there is always a finite risk of not having enough capacity available. Variable sources may be available at the critical moment when demand is high and many other units fail. Fuel source diversity can also reduce risk.

3. Electricity market

In terms of the economic model, the electricity industry has evolved from a vertically integrated state-owned monopoly company (not subjected to the normal rules of competition) to a liberalized market where generators and consumers have the opportunity to freely negotiate the purchase and sale of electricity. In this section the typical electricity markets are described and the more adequate markets for EVs are addressed.

3.1. Electricity market structure

Electric power systems include power plants, consumers of electric energy and transmission and distribution networks connecting the production and consumption sites. This interconnected system experiences a continuous change in demand and the challenge is to maintain at all times a balance between production and consumption of electric energy. In addition, faults and disturbances should be cleared with the minimum effect possible on the delivery of electric energy.

Power systems comprise a wide variety of generating plant types, which have different capital and operating costs. When operating a power system, the total amount of electricity that is provided has to correspond, at each instant, to a varying load from the electricity consumers. To achieve this in a cost-effective way, the power plants are usually scheduled according to marginal operation costs, also known as merit order. Units with low marginal operation costs will operate almost all the time (base load demand), and the power plants with higher marginal operation costs will be scheduled for additional operation during times with higher demand. Wind power plants as well as other variable sources, such as solar and tidal sources, have very low operating costs. They are usually assumed to be zero therefore these power plants are at the top of the merit order. That means that their power is used whenever it is available.

The electricity markets operate in a similar way, at least in theory. The price the producers bid to the market is slightly higher than their marginal cost, because it is cost-effective for the producers to operate as long as they get a price higher than their marginal costs. Once the market is cleared, the power plants that operate at the lowest bids come first.

If the electricity system fails the consequences are far-reaching and costly. Therefore, power system reliability has to be kept at a very high level. Security of supply has to be maintained both short-term and long-term. This means maintaining both flexibility and reserves that are necessary to keep the system operating under a range of conditions, also in peak load situations. These conditions include power plant outages as well as predictable or uncertain variations in demand and in primary generation resources, including intermittent renewable sources.

3.2. Base load power

Base-load power is the “bulk” power generation that is running most of the time. Base-load power is typically sold via long term contracts for steady production at a relatively low price and can better be provided by large power plants because they last longer and cost less per kWh.

3.3. Peak power

Peak power is used during times of predictable highest demand. Peak power is typically generated by power plants that can be switched on for shorter periods, such as gas turbines and hydro plants with reservoir. Since peak power is typically needed only a few hundred hours per year, it is economically sensible to draw on generators that are low in capital cost, even if each kWh generated is more expensive.

3.4. Spinning reserve

Spinning reserves are supplied by generators set-up and ready to respond quickly in case of failures (whether equipment failure or failure of a power supplier to meet contract requirements). They would typically be called, say, 20 times per year; a typical duration is 10 min but must be able to last up to 1 h (spinning reserves are the fastest-response and highest-value component of the more general electric market for “operating reserves”). Operation reserves include several types of reserves in place to respond to short-term unscheduled demand fluctuations, or generator/other system failure. Operating reserve represents generators that can be started or ramped up quickly. There are several categories of operating reserves, often referred to as ancillary services.

Quick-start capacity includes combustion turbines and hydroelectricity, while spinning capacity represents other partly loaded fossil and/or hydroelectric plants. The introduction of wind power into a grid can increase these operation-reserve requirements, due to the variability in wind generation.

3.5. Balancing

Balancing or regulation is used to keep the frequency and voltage steady, they are called for only one up to a few minutes at a time, but might be called 400 times per day; Spinning re-

serves and balancing are paid in part for just being available, a capacity payment per hour available; Base-load and peak are paid only per kWh generated.

The variability in wind generation precludes wind from contributing fully to the reserve margins required by utilities to ensure continuous system reliability.

Planning reserves ensure adequate capacity during all hours of the year. Typical systems require a “peak reserve margin” of 10%-18%. This means a utility must have in place 10%-18% more capacity than their projected peak power demand for the year. This ensures reliability against generator or transmission failure, underestimates of peak demand, or extreme weather events.

Due to the resource variability of wind generation, only a small fraction of a wind farm’s nameplate capacity is usually counted toward the planning reserve margin requirement. In fact, as wind penetrates further into an electric grid, this “capacity credit” for wind generally declines, especially if the wind farms are developed near each other, i.e. if their output is well correlated.

3.6. The aggregator

To access to the electricity market means, among other aspects, to have access to the so called “market prices”. Under this concept, an EV does not have individually the capacity to access to the electricity market, as each quantity of energy produced is insignificant when compared with the regular power players’.

There arises then a new element for the interconnection between the micro-generation and the electricity market, that it can be called by “commercial agent” or “aggregator”. The commercial agent or aggregator adds a set of small power producers so that they can become, in a certain way, a fair concurrent in the market by the fact of dealing with a substantial quantity of energy. Under the point of view of the aggregator, there is also the possibility of dealing either with energy generation and/or energy consumption to maximize the economic value of the EV to the consumer and at the same time revenue to the aggregator, it is almost certain that the charging and discharging vehicle will be done in order to allow the vehicle to be charged with the lowest-cost electricity, and also allows the vehicle to provide high-value ancillary services. EVs could be connected to the power system through the aggregator that sells the aggregated demand of many individual vehicles to a utility, regional system operator, or a regional wholesale electricity market. The idea is that EVs respond intelligently to real-time price signals or some other price schedule to buy or sell electricity at the appropriate time so that the vehicles would be effectively “dispatched” to provide the most economical charging and discharging.

4. Electric vehicle as a consumer and supplier of electricity

Given the nature and physical characteristics of EVs, their integration into the grid is performed at the distribution voltage level. Such an interconnection allows each EV to be plug-

ged into the grid to get the energy to charge up the battery. The EVs, when aggregated in sizeable numbers, constitute a new load that the electricity system must supply. However, an EV can be much more than just a simple load given that bi-directional power transfers are possible once the interconnection is implemented. Indeed, the integration allows the deployment of EVs as a generation resource as well as a storage device for certain periods of time when such deployment aids the system operator to maintain reliable operations in a more economic manner. We refer to the aggregated EVs as a generation/storage device in this case. The entire concept of using the EVs as a distributed resource – load and generation/storage device—by their integration into the grid is known as the vehicle-to-grid (V2G). Under this concept, the EVs become active players in grid operations and play an important role in improving the reliability, economics and environmental attributes of system operations. Such benefits include the provision of capacity and energy-based ancillary services, the reduction of the need for peakers and load levelization.

4.1. Electric vehicle modeling

Electric vehicles constitute a variety of vehicle types with different battery capacities, vehicle ranges, and vehicle drive trains. Such differences are important to the electric industry because of their influence on daily vehicle electricity consumption. The common characteristic of EVs and PHEVs is that they require a battery, which is the source of all or part of the energy required for propulsion. For EVs, the original energy consumption unit in kWh and the energy consumption per unit distance in kWh/km is generally used to evaluate the vehicle energy consumption. The battery energy capacity is usually measured in kWh and the driving range per battery charge can be easily calculated.

A typical electric vehicle (EV) traction battery system consists of a chain of batteries connected in a series, forming a battery pack with nominal voltages ranging from 72 to 324 V and capable of discharge/charge rates of several hundred amperes.

As vehicles, EVs are not always stationary and, therefore, may be dispersed over a region at any point in time. In a moving state, EVs may be used for commuting purposes or, possibly for longer trips – if the battery capacity is large or if the EV is a PHEV.

For the EVs used for commuting, we can view, therefore, that the vehicles are idle an average of 22 h a day. We note that as the commuting distance is smaller than the potential range of the EVs, not all the energy in the batteries is consumed by the commute. We may see each EV as a potential source of both energy and available capacity that can be harnessed by the grid in addition to supplying the load of the EV to charge up the battery.

In addition to the storage capacity, there are some other aspects of interest in characterizing the batteries. A critically important one is the state of charge (s.o.c.) of the batteries. It is defined as the ratio of the energy stored in a battery to the capacity of the battery. It varies from 0 when the battery is fully discharged to 1— often expressed in percentages as a variation from 0% to 100% – when the battery is fully charged and provides a measure of how much energy is stored in the battery. The s.o.c. typically decreases when energy is withdrawn from the battery and increases when energy is absorbed by the battery. Thus, for a

day during which the EV owner goes to work in the morning, parks the EV, goes back home in the late afternoon and then plugs the EV for charging during the night, the s.o.c. will evolve along a pattern illustrated in Fig. 6.

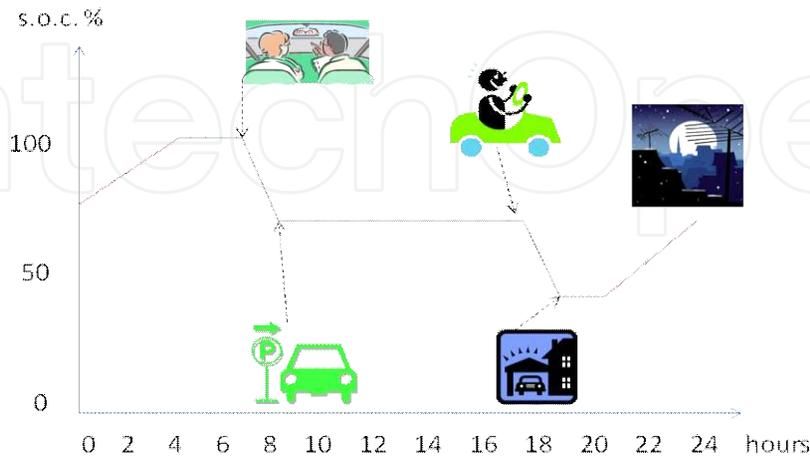


Figure 6. S.o.c. evolution for an EV along a typical working day with only home charging

Batteries release energy more easily when their s.o.c. is high or more exactly above a tolerance level. We stipulate 60% to be the tolerance level in the examples of this work. When the s.o.c. is lower than 60%, a more appropriate utilization of this battery is for energy absorption. If the battery releases energy, then the EV acts as a supply-side resource. If it absorbs energy, the EV acts as a demand-side resource. We can view the battery store present supply-and demand-side resources as a function of the s.o.c. The diagram in Fig. 7 summarizes this information.

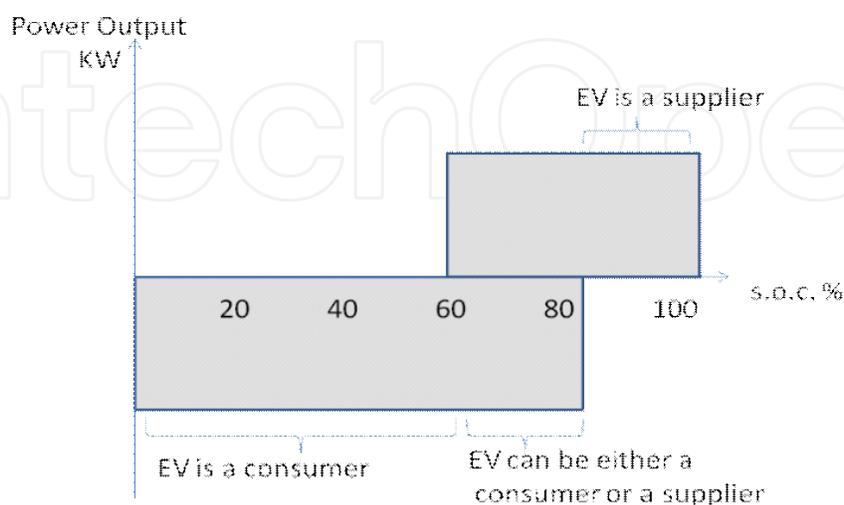


Figure 7. Relation between the s.o.c. and the function of the EV

The frequent switching of the s.o.c. may cause a decrease in battery storage capability which is defined as the battery degradation.

4.2. EVs aggregation

The battery storage of an individual EV is too small to impact the grid in any meaningful manner. An effective approach to deal with the negligibly small impact of a single EV is to group together a large number of EVs – from thousands to hundreds of thousands. The aggregation, then, can impact the grid both as a load and a generation/storage device.

The basic idea behind such aggregation is the consolidation of the EVs, so that together they represent a load or a resource of a size appropriate to exploit economic efficiencies in electricity markets. The Aggregator is a new player whose role is to collect the EVs by attracting and retaining them so as to result in a MW capacity that can impact beneficially the grid. The size of the aggregation is indeed the key to ensuring its effective role. In terms of load, an aggregation of EVs represents the total capacity of the batteries, an amount in MWs that constitutes a significant size and allows each EV to benefit from the buying power of a large industrial/commercial customer. There are additional economic benefits that accrue as a result of the economies of scale. The aggregated collection behaves as a single decision maker that can undertake transactions with considerably lower transaction costs than would be incurred by the individual EV owners. So, the aggregated entity can make purchases – be it electricity, batteries or other services – more economically than the individual EV owners can and can pass on the savings to each EV owner. As a resource, the aggregated EVs constitute a significant capacity that may beneficially impact the operations of a system operator. The SO deals directly with the Aggregator, who sells the aggregated capacity and energy services that the collection of EVs can provide. The Aggregator's role is to effectively collect the distributed resources into a single entity that can act either as a generation/storage device capable of supplying capacity and energy services needed by the grid or as a controllable load to be connected to the ESP to be charged in a way so as to be the most beneficial to the grid. It is the role of the Aggregator to determine which EVs to select to join the aggregation and to determine the optimal deployment of the aggregation. A single aggregation may function either as a controllable load or as a resource, as depicted in Fig. 8.

The charging of the EVs introduces a new load into the system. For every SO, the load has a typical daily shape formed of on-peak and off-peak periods as described in section 2.

The EV aggregation can act as a very effective resource by helping the operator to supply both capacity and energy services to the grid. To allow the operator to ensure that the supply–demand equilibrium is maintained around the clock, the EV aggregation may be used for frequency regulation to control frequency fluctuations that are caused by supply–demand imbalances. The shape of the regulation requirements varies markedly from the on-peak to the off-peak periods. We define regulation down as the absorption of power and regulation up as the provision of power. A battery may provide regulation up or regulation down service as a function of its s.o.c. Depending on its value for each EV in the aggregation, the collection maybe deployed for either regulation up or regulation down at a point in time. Resources that provide regulation services are paid for the capacity they offer.

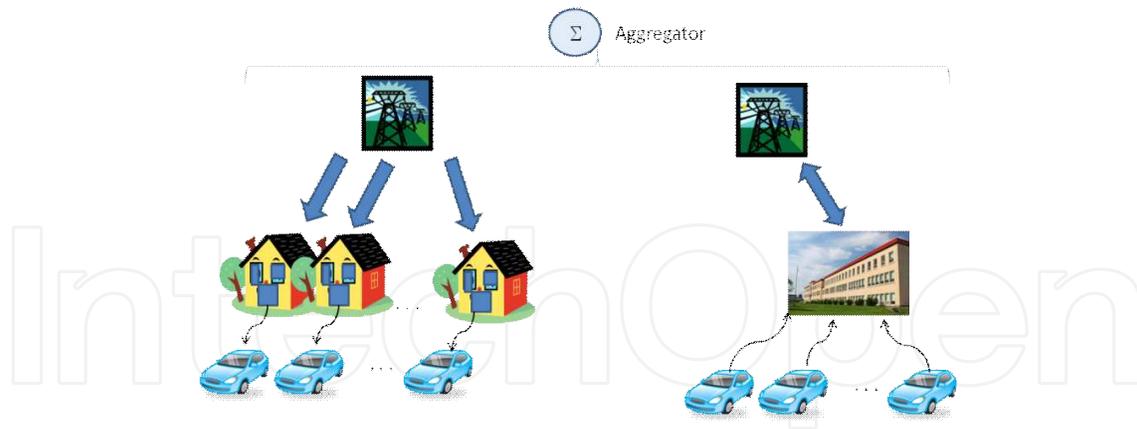


Figure 8. EVs working as load and as supplier of electricity

4.3. The adequate electricity markets for EVs

EVs, with their fast response and low capital costs, appear to be a better match for the quick-response, short-duration, electric services, such as spinning reserves and balancing. The equivalent of those markets in the Portuguese Electric sector, are secondary and tertiary regulation (REN, 2012).

Spinning reserves are paid for by the amount of time they are available and ready even though no energy was actually produced. If the spinning reserve is called, the generator is paid an additional amount for the energy that is actually delivered (e.g., based on the market-clearing price of electricity at that time). The capacity of power available for 1 h has the unit MW-h (meaning 1MW of capacity is available for 1 h) and should not be confused with MWh, an energy unit that means 1MW is flowing for 1 h. These contract arrangements are favorable for EVs, since they are paid as “spinning” for many hours, just for being plugged in, while they incur relatively short periods of generating power.

Regulation or balancing, also referred to as automatic generation control (AGC) or frequency control, is used to fine-tune the frequency and voltage of the grid by matching generation to load demand. Some markets split regulation into two elements: one for the ability to increase power generation from a baseline level, and the other to decrease from a baseline. These are commonly referred to as “regulation up” and “regulation down”, respectively. Compared to spinning reserves, it is called far more often, requires faster response, and is required to continue running for shorter durations.

4.4. Estimation of costs and revenues for vehicles owners

4.4.1. Estimation of revenues for vehicles owners

Calculating revenue for vehicle owners depend on the market that V2G power is sold into. Equation 1 can be used for markets that pay for available capacity and for energy (Kempton and Tomic, 2005a).

$$r = p_{cap} P t_{plug} + p_{el} R_{d-c} P t_{plug} \quad (1)$$

Where r is the total revenue [€], p_{cap} is the market price for capacity [€/kW-h], P is the contracted capacity available less or equal to P_{V2G} [kW], t_{plug} is the time the EV is plugged in and available [h], p_{el} is the price of electricity for the plugged in hours [cents/kWh], R_{d-c} is the dispatch to contract ratio given by $E_{disp} / (P \cdot t_{plug})$.

Capacity payments are an important part of revenue and compensation for energy delivered generally nets out taking into account the energy that must be purchased to charge the vehicle and the cost of batteries depreciation. Furthermore, to compute energy payments, a profile of grid services provided by the vehicle must be defined.

In Portugal, the average capacity prices for regulation between 2007 and 2011 and for the first months of 2012 were shown in Table 3.

Year	Capacity Price	Power range [MW]	Regulation [€/MW]	
	[€/MW-h]		up	down
2007	18.5	188	45.7	32.7
2008	21.4	158	63.5	42.2
2009	28.9	197	48.5	21.5
2010	27.2	290	53.8	13.5
2011	27.8	286	73.7	12.6
2012	36.3	291	64,9	24,4

Table 3. Average prices and capacity for regulation services in Portugal (REN, 2012)

In Fig. 9 is depicted the annual average regulation band evolution and the weighed unit capacity price. The average power range for regulation has increased in the last 5 years, representing from 2.8% of average power in 2007 till 5% in 2011.

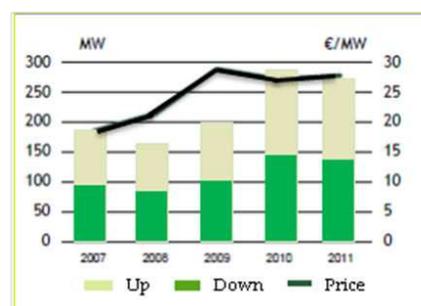


Figure 9. Evolution of regulation band and unit capacity price (REN, 2012)

Looking at the percentage of wind power production in the same 5 years, it increased from 9.3% in 2007 to 18% in 2011. It can be assumed that the increase of intermittent power sources like wind, in the electricity generation mix, leads to an increase of need of power band reserves to assure the same level of system reliability.

In Fig. 10 it is depicted the evolution of capacity installed and energy production in Portugal among the different technologies.

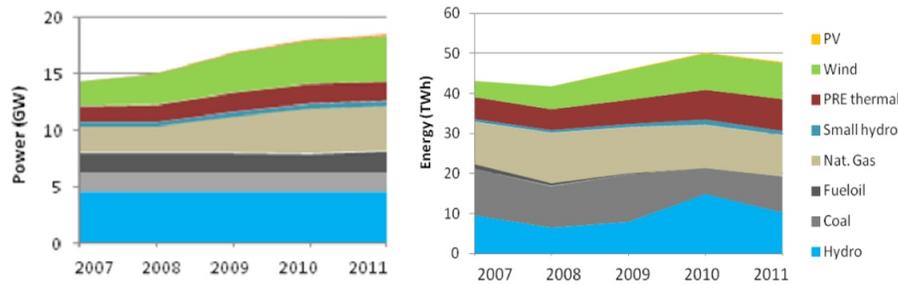


Figure 10. Evolution of capacity installed in the different technologies (left-side) and of annual production from the different technologies (right-side) (REN, 2012)

The increase needs for ancillary services (spinning reserves and regulation) had been fulfilled by the dispatchable technologies in the proportion described in Table 4.

Years	2007	2008	2009	2010	2011
Hydro	67%	39%	18%	28%	27%
Coal	10%	3%	16%	12%	14%
Nat.gas	23%	58%	66%	60%	59%

Table 4. Evolution of the contracted power band among the dispatchable available technologies in Portugal (REN, 2012)

From 2007 till 2011 the power band has increased in 100 MW. To fulfil this 100MW needs, about 30000 EVs at a 3.5 kW each should be plugged. If only 20% of total EVs were available to supply this service, 140000 EVs should be necessary (3% of the total actual light duty fleet). For instance considering the average prices occurred in the first 2012 months and depicted in Table 5.

Capacity	Power range	Regulation [€/MW]			
		Valley		off-valley	
Price		up	down	up	down
[€/MW-h]	[MW]				
36,3	291	64,9	24,4	61,3	35

Table 5. Average prices and capacity for regulation services in Portugal in 2012 (REN, 2012)

An EV can expect to achieve a daily revenue of 2.3 € for providing ancillary services to the power grid (Table 6).

	Capacity	Energy	
		valley	Peak
p_{cap} [cents/kW-h]	3.6		
P [kW]	3.5		
t_{plug} [h]	16	9	7
E_{disp} [kWh/day]		3.0	3.0
P_{elup} [cents/kWh]		6.5	6.1
P_{eldown} [cents/kWh]		2.4	3.5
R_{c-d}		0.10	0.12
Revenue [€/day]	2.02	0.13	0.14

Table 6. Expected daily revenues for an EV that provides ancillary services in Portugal

4.4.2. Estimation of costs for vehicles owners

The cost of V2G is calculated from purchased energy, wear and capital cost. The energy and wear for V2G are those incurred above energy and wear for the primary function of the vehicle, transportation. Similarly, the capital cost is that of additional equipment needed for V2G, but not for driving. The general formula for annual cost is (equation 2):

$$c = c_{en} E_{need} + c_{ac} \quad (2)$$

c is the total cost per year [€], c_{en} the cost per energy unit produced for V2G [€/kWh], E_{need} is the electric energy needed to be dispatched in the year [kWh] considering the conversion's efficiencies (equation 3).

$$E_{need} = E_{disp} / \eta_{conv} \quad (3)$$

c_{ac} is the annualized capital cost for additional equipment needed for V2G including also the cost of equipment degradation (wear) due to extra use for V2G (equation 4).

$$c_{ca} = c_d + c_c \frac{d}{1 - (1+d)^{-n}} \quad (4)$$

c_d represents the annual costs of battery degradation, c_c the capital cost of extra equipment, d the discount rate and n the investment's life time.

The costs for battery degradation depend on the cycling regimes. As V2G extra cycling would increase battery replacement and additional cost for that should be taken into account. For example considering that a lithium-ion battery could have a 3000 cycle life time (Tomic and Kempton, 2007) at a 100% of discharge and could last almost 10 years with less than a daily charge, an extra shallow, 4% cycling for regulation services occurring in average 10 times in a day it would shorten batteries life in 40% so that after 6 years they should have to be replaced. To compare investments with different life times we use the annuity method (equation 5).

$$c_d = c_{bat} \left(\frac{d}{1 - (1+d)^{-n_1}} - \frac{d}{1 - (1+d)^{-n_2}} \right) \quad (5)$$

c_{bat} is the cost of battery and n_1 and n_2 are the expected life times without and with V2G.

The estimated costs for EVs' owners for providing ancillary services are depicted in Table 7.

	Costs
Bat Cap [kWh]	16
E_{disp} [kWh]	900
η_{conv}	0,8
E_{need} [kWh]	1125
c_{en} [cents/kWh]	7
c_{bat} [€/kWh]	700
c_d [€/yr]	754
c_c [€]	500
d [%]	8%
n_1 [yr]	10
n_2 [yr]	6
c_{ca} [€/yr]	828
c [€/yr]	907

Table 7. Expected annual costs for an EV that provides ancillary services in Portugal

4.4.3. Estimation of financial results for vehicles owners

In this way, estimates for annual profits for EVs' owners, as a result of capacity payments providing regulation capacity could be computed considering the values in table 8.

	Revenue	Costs
Capacity [€/yr]	605	
Reg. Up [€/yr]	43	
Reg. down [€/yr]	40	
sav. in recharge [€/yr]	63	
c [€/yr]		907

Table 8. Estimation of costs and revenues for V2G providing regulation services in Portugal

As V2G is connected at low voltage this regulation service should be purchased by a distribution company that could act as an aggregator to provide enough regulation power to sell in the power markets subjected to the prices shown in Table 5.

We consider that the EVs provide regulation during valley and off-valley hours. During valley hours they are mainly used for charging for further use (for driving and for grid support) but also could provide regulation up and down during this time. For providing regulation up and down we considered the vehicles are plugged-in daily during at least 7 off-valley hours and 9 valley hours. If the vehicles offer this service for 300 days per year a total of 605€ could be earned only for providing. If an average energy of 3.0 kWh is supplied daily to the grid, an annual revenue of 43.2€ could be expected for regulation up and a total revenue of 40€ for regulation down plus 63€ in savings for recharging (due to energy input). Unfortunately, under the described assumptions, total annual costs exceed total revenues in 156€. This loss is very sensitive to battery degradation, if we consider $n_2=7$ years instead of $n_2=6$ years, total annual costs decrease to 635€ and a result of 116€ could be obtained (318€ with $n_2=8$, table 9).

	$n_2=6$	$n_2=7$	$n_2=8$
Total revenue [€/yr]	751	751	751
Total costs [€/yr]	907	635	433
Result [€/yr]	-156	116	318

Table 9. Estimation of costs and revenues for V2G for different assumptions of battery life

It should not be forgotten that, it is the aggregator that trades directly to the grid for offering regulation services with V2G and works with the market prices showed in table 5 and so a percentage of the earnings should go to the aggregator. Considering a 4% revenue for the aggregator services, the EV's owner profits could range from -156€ to 305€.

5. Conclusion

Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs), which obtain their fuel from the grid by charging a battery, are set to be introduced into the mass market and expected to contribute to oil consumption reduction. PHEVs and EVs can also provide a good opportunity to reduce CO₂ emissions from transport activities if the electricity they use to charge their batteries is generated through low carbon technologies. In addition to the environmental issue, EVs bring techno-economical challenges for utilities as well, because EVs will have great load flexibility as they are parked 93% of their lifetime, making it easy for them to charge either at home, at work, or at parking facilities, hence implying that the time of day in which they charge, can easily vary. EV aggregations can act as controllable loads that contribute to level the off-peak load at night or as generation/storage devices that can provide up and down regulation service when the vehicles are parked.

This chapter described how the electric vehicle can work as a “prosumer” of electricity. The benefits to the electric utilities and the costs of services provided by EVs in each type of power market were addressed, the role of a new agent on the power market – The EV aggregator – and the economic advantages for EV owners considered the Portuguese energy market as a case study.

There are still many doubts about the life time of EV batteries and battery degradation when providing V2G. Global costs are very sensitive to battery costs and degradation assumptions so that profits can range from -155€/yr to 305€/yr considering respectively 40% to 20% in batteries life range reduction due to V2G supply.

The pressure to generate electricity from endogenous low carbon resources in the majority of the countries makes naturally transport electrification a solution to lower emissions and fossil fuels use from the transportation sector. On the other hand, the increasing of intermittent renewable sources in the power systems, forces the increase of the regulation power band in order to assure the same level of reliability to the power system which would increase the power installed and fixed costs to the power system.

EVs can be a benefit to the environment by reducing emissions and noise in the cities while, at the same time, by providing ancillary services to the power grid, reduce the investments and operation costs in thermal generation and allows the integration of more renewable production. To provide a 100 MW of band power a total of 30000 EVs at a 3.5 kW each should be plugged-in. If only 20% of total EVs are available to supply this service, 140000 EVs should be necessary which corresponds of 3% of the total actual light duty fleet in the Portuguese case study.

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The authors would like to acknowledge FCT- Fundação para a Ciência e Tecnologia through the national project Power demand estimation and power system impacts resulting of fleet penetration of electric/plug-in vehicles (MIT-Pt/SES-GI/0008/2008).

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