Grid to vehicle and vehicle to grid systems for large-scale penetration of renewable generation

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Abstract

The electric power system is quickly changing due to the growing penetration of intermittent and non-dispatchable renewable energy sources. Simultaneously, the demand should ideally be able to be adapted to the renewable generation availability, directly with demand response or indirectly using energy storage technologies. The transport sector with electric vehicles (EVs) is increasingly an important consumer of electricity, and as fleets increase, EVs can be used as controllable loads, charging in periods of high renewable generation or low prices, using the Grid to Vehicle (G2V) system. With adequate technology, in addition to absorbing power from the grid, EVs can also use some of their storage capacity to inject energy into the grid, in order to ensure the balance between the generation and demand, using the Vehicle to Grid (V2G) system. However, the additional charging cycles due to V2G will accelerate the degradation of batteries and therefore its associated cost must be taken into account.

This paper discusses the technologies and methodologies for the implementation of Grid to Vehicle and Vehicle to Grid systems, as well as their potential benefits for the grid in a scenario with large-scale penetration of renewable generation. To assess such impact a case study for the Portuguese grid is presented, considering three scenarios of penetration of EVs in the Portuguese vehicle fleet (in which EVs constitute 10 %, 25 % or 50 % of the fleet). The obtained data allowed to assess the potential of V2G to transfer the generation surplus between hours of low and high demand. Additionally, the economic benefits from the grid and user point-of-views were assessed considering the degradation of the batteries (evaluated through a model developed in Simulink environment), associated with the use of V2G, and their replacement cost. The results show a high impact on the compensation of renewable generation surplus, as well as economic benefits from the grid point-of-view. Even considering the battery degradation, in some scenarios, there is also a potential economic benefit for the user.

Introduction

With the use of electricity and the internal combustion engine, humanity entered a spiral of fossil energy consumption that would only inflict with the first oil crisis in the 1970s. Access to fossil fuels was responsible for a revolution with great repercussions in the general well-being of society, but the consequences were massive emissions of greenhouse gases responsible for climate changes and pollution in large urban centers. However, information and communication technologies and power electronics made possible a great technological diversification and improved energy efficiency after the 1980s, with most technologies using electricity. Throughout this course, it was possible to understand that despite the abundance of some fossil sources such as coal, it is imperative to use more alternative sources with lower emissions. Success in the energy transition has exceeded all expectations in terms of installed capacity and cost reduction since wind and solar power already have the lowest cost in several locations. There is, therefore, the emergence of a new energy economy, where energy is generated and delivered almost without emissions, as opposed to the hydrocarbons economy based on capture, transport, and consumption of fossil energy, whose combustion is responsible for high emissions of greenhouse gases. It is estimated that this transition takes place at around 10 % per decade and that at the end of the 21st century a 100 % decarbonization can be achieved (Balibar 2017).

Advances in energy storage technologies have enabled Electric Vehicles (EVs) to be an increasingly competitive alternative to conventional vehicles, helping to mitigate many concerns, namely:

- Environmental – by reducing greenhouse gas emissions;
- Economic – by the use of endogenous energy with low cost;
- Supply security – by reducing dependence on distant sources and unstable countries;
- Energy efficiency – by reducing the losses in the infrastructures used in the capture and transport of energy and in their final use.

Despite these advantages, several studies show important barriers to the rapid adoption of EVs, such as the acquisition price, autonomy, and access to a network of recharging points that reduces range anxiety in users (Ryu et al, 2018). However, following the major investments in R&D in the battery sector and the beginning of its mass production, there has been a reduction in the price of 80 % in recent years, from $1,000/kWh in 2010 to about $200/kWh in 2017, and are expected to reach $96/kWh by 2025 (Bloomberg, 2018). At the same time, there was a great improvement in performance with increased energy and power density and a greater number of charging cycles that made it possible to offer EVs increasingly competitive, with larger autonomy and longevity. These facts prove that many concerns related to the autonomy cease to make sense.

Additionally, several facts are accelerating the perception that it is imperative to decarbonize the energy sector in general and transport in particular, which are: the visible impact of climate changes with successive records of high temperatures, biodiversity reduction, floods and large fires (Climate Nexus, 2019); the rejection of diesel technology as consequence of the dieselgate scandal and the disclosure of studies that correlate particulate emissions from diesel engines with diseases responsible for thousands of deaths (EPHA, 2018). As a result, several countries are restricting the circulation of combustion vehicles in urban areas and announcing the phased ban on diesel vehicles (Nieuwenhuijsen and Khreis, 2016).

As a consequence of these facts, the transport sector is under an unprecedented revolution in its history with manufacturers abandoning traditional motorizations and intensifying the electrification of their supply. The increasing market of EVs is responsible for the growing consumption of electricity generated with endogenous renewable energy sources (RES), in a distributed form and near the consumption points. Simultaneously, the generation mix is increasingly based on a mix of distributed, intermittent and non-dispatchable sources, being more difficult to ensure the balance between generation and demand.

In this context, it will be fundamental to have new technologies to provide flexibility, mainly energy storage and Demand Response. One important option is to increase the loads that enable demand management in order to consume energy mainly in periods with high renewable generation. In such context EVs can have an important role, being used as controllable loads, charging in periods with a high renewable generation or low prices, using the Grid to Vehicle (G2V) system. Additionally, EVs can also use some of their storage capacity to inject energy into the grid, contributing to the balance between the generation and demand, using the Vehicle to Grid (V2G) system. However, with current electrochemical technologies, batteries degrade according to age, depth of discharge (DoD) and charging cycles and such degradation must be taken into account in the evaluation of costs.

This paper analyses the technologies and methodologies for the implementation of G2V and V2G systems, as well as their potential benefits for the grid in a scenario with large-scale penetration of renewable generation. To assess such impact, a case study for the Portuguese grid is presented. The remainder of the paper is structured as follows. Section 2 discusses the impacts and requirements of G2V and V2G systems, analyzing the use of EVs as a controllable (G2V) and intelligent (V2G) load, as well as the required supporting technologies. Then, a case study assessing the potential impacts of V2G programs in the Portuguese grid is developed, being the methodology presented in Section 3 and the results in Section 4. Finally, Section 5 summarizes the paper, emphasizing its main conclusions.

G2V and V2G Systems

EV AS CONTROLLABLE AND INTELLIGENT LOAD

The typical profile of the vehicle use is mainly based on pendular movements, traveling on average about 35 km per day in Europe (Figure 1), and being the vehicle parked about 95 % of the time (Pasaoglu et al, 2012). When parked, if the EV is connected to the grid, it can act as a controllable load, providing the service of demand following generation. By means of relatively simple mechanisms, this option allows the vehicle to be charged when there is renewable generation surplus, a situation that occurs with increasing frequency at night due to larger wind power generation and lower consumption (Delgado et al, 2018). The owner will only have to specify the time until the EV is available and the required minimum autonomy, being such information easily forecasted for most users.

In order to extend the autonomy of the EVs, a requirement imposed by the customers, the capacity of the batteries continues to increase and is already between 30 kWh and 100 kWh per vehicle. Taking into account the daily distances mentioned above, it can be observed that only 5 to 10 kWh of this energy will be consumed per day. Therefore, there is a surplus of stored energy, almost always available, that can be used for other purposes provided that: (i) there is an incentive to the owner of the EV to do it, (ii) the owner feels that the EV is always available and (iii) this operation is automated and does not requires major interventions from the user. The EV can thus be used as a controllable load when there is renewable generation surplus (G2V) and can return some of this energy to the grid when the generation is low, using V2G. The V2G capability is being integrated by more and more manufacturers allowing their EVs to act as large Power Banks.

Regardless of whether the EV recharge is carried out using the G2V or V2G methodology, each vehicle can contribute as a controllable load with a power of a few tens of kW and with tens of kWh of energy storage capacity. With the fleet of EVs in each country strongly growing and considering the potential control of the EVs connected to the grid, when not used in transportation, it can be expected a strong contribution to the system flexibility with the use of fleets of controllable loads and stored energy located in each vehicle. The coordination of large groups of fleets with the capacity to adapt to instantaneous generation in a demand following generation approach can be an alternative to the traditional reserve systems, in a so-called Virtual Power Plant, as presented in Figure 2 (An et al, 2017).

With the current technologies, it is possible to respond in real time to the intermittent generation variations by adapting groups of controllable loads and to contribute to maintaining the quality of service parameters of the grid, such as nominal voltage and frequency, within predefined thresholds. In the context of the proliferation of the Internet of Things concept, vehicles are also increasingly computer-based systems on wheels that integrate powerful communication and information processing capabilities that can support multiple intelligent systems. The decision of an EV connected to the grid to act at any moment as a load or as a virtual generator (injecting energy into the grid) needs to be taken with precise information that should be based on the requirements defined by the user and according to the instantaneous situation of balance between generation and demand in the grid.

In order to use fleets of EVs as controllable loads to support G2G and/or V2G, a complex and costly centralized management system to dispatch loads by groups in a given region is usually proposed (Aluiso et al, 2017). Another common option is the use of the real-time pricing and its diffusion with the use of communication technologies, as a signal to induce a demand increase when there is a renewable generation surplus, using a decrease in the price, or the opposite to induce a demand decrease (Rahbari-Asr et al, 2016). Another proposal is the use of a control mechanism, triggered by physical parameters, in which each load (EV or charger) is equipped with sensors and intelligence to detect a tendency for the generation capacity to exceed the load or vice versa. This signal is intrinsic to the operation of the electrical systems and is detectable throughout the grid by the increase of the effective value of the voltage and/or upward deviation of the frequency, which give signs that the generating power is exceeding the power of the loads connected to the system (Liu et al, 2017). Based on such information, the intelligence of each dispatchable load can trigger the connection, under the order of an algorithm that could introduce a random delay (to avoid peaks), contributing to the balance between generation and consumption.

In such systems, the degradation of the battery is an important concern. The degradation of the current electrochemical cells depends on the number of charging cycles, the depth of discharges (DoD) and age (Assunção et al, 2016). Thus, using the battery of an EV to dynamically contribute to the balance of the electric system has different implications depending on whether it is G2V or V2G. If the EV is used as a controllable load, using the G2V methodology, this operation has a reduced impact on the battery, since the charging is controlled, but the user-defined charging requirements in terms of available time

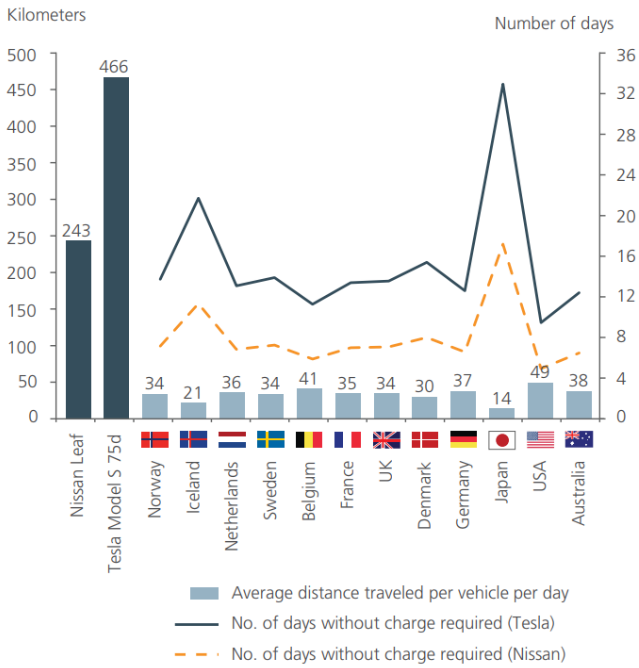


Figure 1. Battery life versus daily travel distance by country (Ryu et al, 2018).

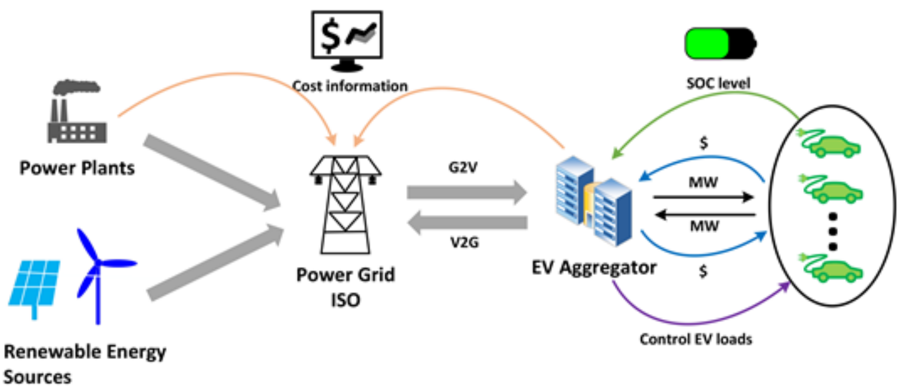


Figure 2. Potential G2V and V2G framework (An et al, 2017).

and desired autonomy remain the same, therefore preserving the number of charging cycles and DoD. However, if the EV is used as a support for V2G, this operation requires an increase of the number of partial or full charge/discharge cycles, therefore decreasing the life span of the battery cells. The economic impact of such degradation needs to be evaluated since the incentive to be provided to the user must exceed the cost associated with such degradation.

SUPPORT TECHNOLOGIES FOR G2V AND V2G

Cabled Solution

The current recharging systems are characterized by the use of cables and plugs without uniformity, being one of the main disadvantages of this solution the need to handle, and sometimes to carry, bulky cables. Another aspect is the need for recharging the EV more frequently than in the supply of traditional vehicles. In the single-phase AC recharge, standards as the SAE J1772, from the USA and IEC 62196 from Europe, can be highlighted. The standard IEC 62196 supports single and three-phase recharge in the same plug and cable (Mennekes Type 2). For fast recharging in DC, the CHAdeMO protocol created in Japan is used, a modified version of SAE J1772.

In the domestic and private environment, the recharging with cables will continue to make sense due to lower cost, easy implementation, and lower losses. However, in an external environment, this solution entails risks since the points of energy availability and cables constitute obstacles in the public road and are exposed to the possibility of vandalism and theft. Therefore, it is necessary to find solutions that meet the interests of all parties, such as customers, EV and charger manufacturers, and power grid operators. Other important aspect is the new tendencies of car sharing and mainly the autonomous vehicles that, due to having no one on board, need to be autonomously recharged.

Wireless Solution

The overcoming of the current system limitations includes the implementation of wireless inductive recharge systems and the technology for the identification of users in the system with minimal or no need for human intervention. The requirements of the new generation recharge infrastructure, in order to facilitate the implementation of G2V and V2G technologies, can be broadly grouped around the following domains:

1. Universality and interoperability – The standardization of the recharging infrastructure is a key element to enable the massification and interoperability of solutions. Therefore, all vehicles should be able to recharge on all chargers anywhere.
2. Ease of use – The recharging of EVs should minimize the need for human intervention and in the medium term suppress it when the autonomous EVs are a reality. The identification in the system should be carried out automatically, for instance using RFID.
3. Reliability and availability – The implementation of the new systems must be supported by simple, robust and durable technology in order to provide high reliability and availability at the lowest possible cost of operation and maintenance.
4. High energy efficiency – With the wired option the efficiency in transmission of power from the network to the EV is close to 100 %. With inductive recharge systems, the current efficiency is about 91 %, but 97 % efficiency was already achieved with the use of silicon carbonate (SiC) components in the transmitter's power electronics and the receptor (Askey, 2018). Energy losses of 3 % are negligible when compared with the benefits provided by this solution.
5. Physical robustness and ease of integration in an urban environment – The main components involved in wireless power transmission are power electronic devices and coils, which are static and durable components, with little or no maintenance that can be hermetically encapsulated at ground level, protecting the equipment.
6. Safety – Safety is a crucial requirement in technologies that co-exist with people and animals. With this solution, the possibility of electrocution is mitigated, and the standards of electromagnetic compatibility are fulfilled, being the mechanisms of service interruption ensured when required by the operating conditions.
7. Low implementation and exploitation cost – The adoption of a universal standard allows maximizing the production of the same type of components with a reduction in prices and economic benefits due to the massification.

In order to meet the above requirements, many entities have been developing R&D in the field of inductive recharge and co-operating in the definition of a standard that culminated in the approval of the SAE J2954 standard in 2016 and its implementation in 2018 (SAE, 2016). Such standard sets out the general guidelines for use, giving the utmost importance to safety and stipulating the requirements for the inductive transfer of energy between a ground level transmitter and a receiver attached to the base of the vehicle.

The implementation of inductive recharging systems, already initiated by major manufacturers, according to the SAE J2954 standard, introduces a great simplification in the operation of recharging the EVs eliminating completely the cabling and the human intervention in the operation. The EV, when not in use in its transport function, only needs to be immobilized on a power transfer point and to allow or not, by the pre-programmed indication of its owner, the use of the battery in G2V or V2G programs, as well the required available battery capacity, DoD and operating period.

Methodology

The potential impacts of V2G technology on the Portuguese grid were assessed considering three scenarios of penetration of EVs in the Portuguese vehicle fleet. The obtained data allowed to analyze the potential of V2G to transfer the generation surplus between hours of low and high demand, considering three typical days for winter, spring and summer. The daily degradation of the batteries, associated with the use of V2G, was also evaluated in order to assess the potential economic impact associated with V2G.

EV DATA

Six EVs were considered in the assessment, taking into account their actual share in the Portuguese market (Nissan Leaf, Renault Zoe, BMW i3, Kia Soul EV, VW e-Golf and Tesla

Table 1. Autonomy, capacity and battery costs from the considered EVs (EV Database, 2018.

EV	*Autonomy (km)*	*Total Capacity (kWh)*	*Available Cap. (kWh)*	*Battery Cost (€)*
Nissan Leaf	193	30	28	€5,610
Renault Zoe	298	41	39	€7,000
BMW i3	193	33.2	27.2	€7,000
Kia Soul EV	201	33	30	€5,900
VW. e-Golf	233	35.8	32	€6,400
Tesla Model S	555	100	94	€16,300

Table 2. Number of EVs and capacity available for V2G in each scenario.

Scenario	*EVs (#)*	*Capacity V2G (MWh)*
10 % of EVs	460,000	11,971
25 % of EVs	1,150,000	29,928
50 % of EVs	2,300,000	59,856

Model S). The autonomy of the EVs (considering a combined range with mild weather), total capacity, available capacity and battery cost were characterized using data from (EV Database, 2018) and presented in Table 1.

Three scenarios of penetration of EVs in the Portuguese vehicles fleet were considered, in which EVs constitute 10 %, 25 % or 50 % of the national fleet of about 4.6 million vehicles. In each scenario the number of EVs was divided between the six models of EVs, considering the actual market share. Then, the battery capacity available for V2G in each EV was assessed considering the used capacity with mobility (in order to ensure an average of 30 km/day), the minimum capacity to avoid a quick degradation and a reserve capacity of 10 %. Table 2 presents the considered data for each scenario regarding the number of EVs and the available capacity to be used in V2G.

TECHNICAL IMPACT

The obtained data allowed to analyze the potential of V2G to transfer the generation surplus from hours of low consumption to hours of high demand. This study considered three typical days for winter, spring and summer in order to have scenarios with a high, medium and low renewable generation surplus (the different consumption of the vehicles depending on temperature was not considered in the assessment). The data from 2016 was used since 2017 was not a typical year in terms of renewable generation due to the low hydropower generation (the use of an average considering different years would smooth the variations attenuating the impact of renewable generation). Figure 3 presents the monthly average renewable generation surplus in Portugal, as well as the average price of electricity on the wholesale market. As can be seen, the largest generation surplus occurs during the winter, when windy and rainy periods occur, favoring hydro and wind power, which are the renewable energies that have most installed capacity in Portugal. The low values of average monthly surplus in November and December are due to the proximity of the calendar year of 2017 and the already mentioned low water flow. In summer, although there is no available renewable surplus, it is observed that typically when the average monthly surplus decreases the average tariff increases, so V2G can also be used to take advantage of the daily price variation.

To assess the impact on the electricity demand profile of the charging and discharging processes the availability and location of EVs must be taken into account. Therefore, based on (Alonso et al., 2014) it was considered that after 24h 96 % of EVs are parked at home and available for charging. The same rationale was made for the discharging, with more than 90 % of EVs out of the house after 10h, being considered that a large share of such EVs are typically at work and available for discharge in a V2G process (a maximum availability of 80 % of EVs was considered). The parking location does not influence the model, but only the number of EVs parked in each period, being such a profile base on (Alonso et al., 2014). Knowing the time period in which the EVs preferentially charge and discharge, as well as the required duration for the charging process, the impact on the electricity demand profile can be assessed.

ECONOMIC IMPACT

Associated with the impact on the electricity demand profile, the potential economic savings can also be assessed. Such savings were assessed from the grid point-of-view, considering the price difference on the wholesale market between the charging and discharging period, as well as the user point-of-view, considering a future real-time tariff. Such tariff was designed with the same average value has the presented by the most typical tariff option nowadays used in Portugal (a time-of-use tariff with two periods), but with an hourly variation proportional to the wholesale market. In the assessment from the user point-of-view the daily degradation of the batteries, associated with the use of V2G, and their replacement cost, were considered. This degradation was evaluated through a model developed in Simulink environment and presented in (Assunção et al, 2016). The degradation is affected by several conditions, and such results cannot be seen as a reliable impact assessment, but only as an approximation of the typical impact.

It was considered that 30 % is the limit of degradation of the EV batteries for the use in the EV. For each scenario, the lifetime of the battery in the EV was assessed with the Sim-

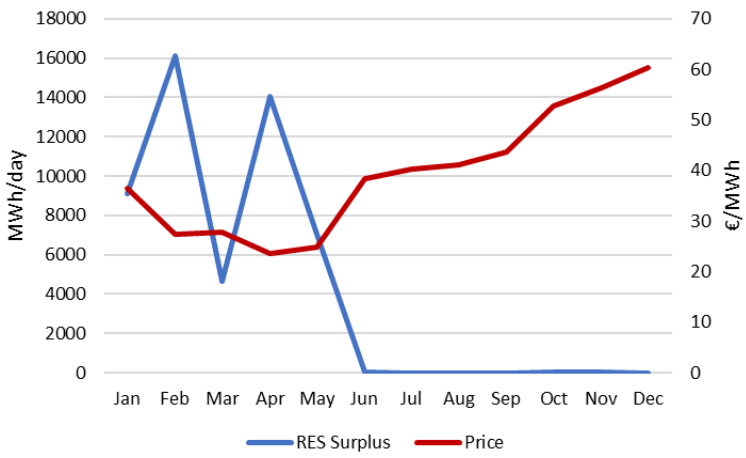


Figure 3. Renewable generation surplus and electricity price on the wholesale market in Portugal (REN, 2018).

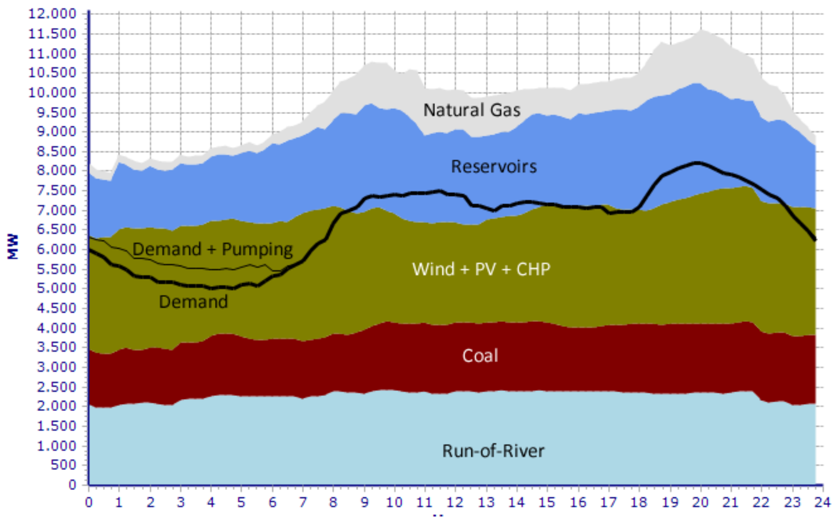


Figure 4. Generation by source and demand on February 18th 2016 (REN, 2018).

ulink model, being then assessed the daily degradation percentage, considering the assumptions presented in (Assunção et al, 2016). The degradation was then divided between the use in mobility and V2G considering the percentage of the capacity used in V2G each day. It was then possible to calculate the cost associated with the degradation due to V2G, considering the daily percentage of degradation due to V2G and the cost of replacing the batteries. The economic impact, due to V2G, from the user point-of-view was then assessed considering the charging and discharging profiles and associated economic benefit and the cost of degradation.

Results

LOAD DIAGRAMS

The criterion for the selection of the representative winter day was the daily renewable generation surplus, being selected February 13, 2016, which presents a surplus identical to the monthly average. Figure 4 presents the diagram with the generation by source and demand, where it can be observed that there is a renewable generation surplus almost all day, with a total surplus of 16,055 MWh.

Figure 5 presents the wholesale electricity market price on the same day, which presents an average of €35.36/MWh. As can be observed such price is lower during periods with higher renewable generation surplus and lower demand, being, therefore, lower in the period typically used for charging EVs (night time).

As a criterion for the selection of the representative day of spring, it was also chosen the day with the renewable generation surplus nearer to the average, being selected May 18, 2016. As can be seen in Figure 6 (a), it has an intermediate level of renewable generation surplus, with a daily surplus of 8,424 MWh. Usually, there is no renewable generation surplus in summer, so the criterion for selecting the representative summer day was the average monthly energy price of the wholesale market, with a value of €41.52/MWh on August 29, 2016, as presented in Figure 6 (b).

TECHNICAL IMPACT

Figure 7 presents the impact of the charging of EVs for the scenario with 10 % of EVs in the fleet. It can be observed the previous demand and the new increased demand due to EVs charging, as well as the energy consumed in the charging process compared with the renewable generation surplus. It was considered the existence of an aggregator with the ability to select which EVs can charge (taking into account the requirements and preferences of the user) at all time periods. The first objective of the control was to consume or store all renewable generation surplus, which corresponds to approximately 59.75 % of the stored energy. After this, since there was still available capacity in the EVs, the second objective was to concentrate the charging in the hours with the lowest wholesale prices, but with a maximum limit to the number of EVs charging in each hour in order to avoid peaks in the load diagram.

Figure 8 presents the discharge period, with demand and net demand with the impact of V2G (considering that the injection of energy into the grid will decrease the consumption in such location), as well as the energy discharged during V2G. The energy was injected preferentially in the hours when the wholesale prices were higher. Moreover, by analyzing the new demand curve, it can be observed that it has become flatter, respecting the second proposed objective.

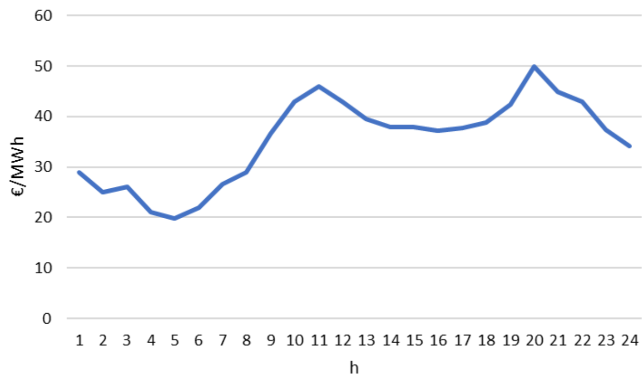
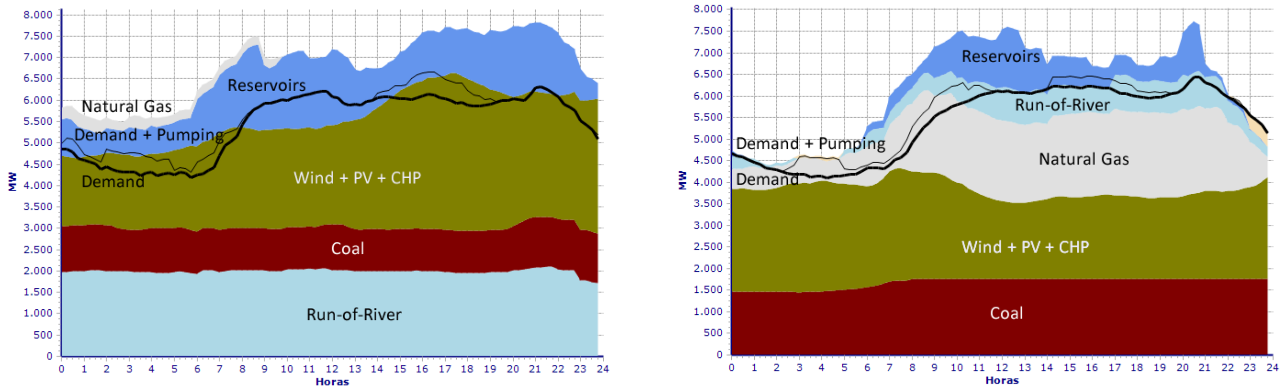


Figure 5. Wholesale electricity market prices on February 18th 2016 (REN, 2018)



(a) (b)

Figure 6. Generation by source and demand on May 18th 2016 (a) and August 29th 2016 (b) (REN, 2018).

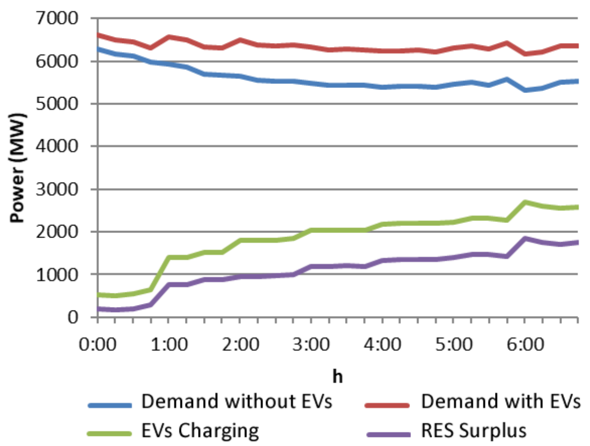


Figure 7. Demand with and without EVs, and RES Generation Surplus during the charging process.

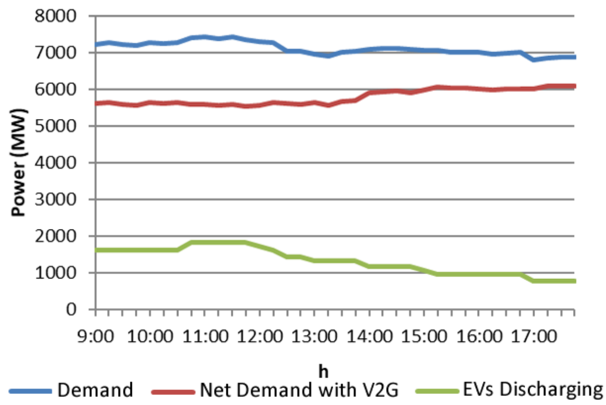


Figure 8. Demand and Net Demand with V2G during the discharging process.

Table 3. Technical impact in each scenario.

Scenario	Impact	Winter	Spring	Summer
10 % EVs	Stored Energy (MWh)	12,940	12,940	12,940
	Stored RES surplus (%)	100	100	–
	RES surplus in charging (%)	59.8	15.8	0
25 % EVs	Stored Energy (MWh)	32,350	32,350	32,350
	Stored RES surplus (%)	100	100	–
	RES surplus in charging (%)	23.9	6.32	–
50 % EVs	Stored Energy (MWh)	64,690	64,690	64,690
	Stored RES surplus (%)	100	100	–
	RES surplus in charging (%)	12.0	3.2	–

Table 4. Economic impact in the grid in each scenario.

Scenario	*Winter*	*Spring*	*Summer*
10 % EVs	59.4	33.1	15.8
25 % EVs	55.6	28.8	15.8
50 % EVs	54.3	26.2	15.7

During summer there is no renewable generation surplus and the charging had the objective of prioritizing the periods with the lowest wholesale market price. Despite achieving such an objective, the charging cost is higher due to the higher wholesale prices, when compared with winter, due to the lower availability of renewable generation. In spring there are intermediate values of renewable generation surplus, being 15.8 % of the charging ensured with renewable generation surplus. In both scenarios, during the discharging period, it was possible to ensure a flatter load profile and simultaneously prioritize the periods with higher wholesale prices.

Table 3 presents the achieved impacts. As can be seen, it was possible to absorb all the renewable generation surplus in winter and spring, with 59.8 % and 15.8 % of the energy required to charge all EVs, in winter and spring, respectively, ensured by RES surplus. Increasing the share of EVs to 25 % and 50 % does not have any impact from the renewable generation surplus point-of-view since 10% was enough to compensate for the actual levels or renewable generation surplus. Such results can be compared with the results achieved without V2G. Using G2V in one scenario with 10 % of EVs in the fleet only 19.4 % and 37 % of the RES surplus, in winter and summer, respectively, is consumed (and later used in the same day). Therefore, in a scenario, only with G2V it would be necessary to have 52 % of the fleet with EVs to compensate all the RES generation surplus.

ECONOMIC IMPACT

The assessed scenarios had as objective not only the compensation of renewable generation surplus but also to ensure economic advantages from the grid point-of-view, by storing energy in periods of low wholesale market price and injecting energy into the grid in periods with the highest price. Table 4 presents the economic savings (the difference between the charging cost and discharging benefit), from the grid point-of-view, being the savings presented as a percentage of the charging costs. As can be seen, the savings are higher in winter and lower in summer. Such a difference is associated with the variation of the wholesale market price which presents a strong correlation with the availability of renewables, as presented in Figure 3. Increasing the share of EVs to 25 % or 50 % slightly reduces the savings. This is justified by the objective of ensuring a flatter load profile, since with a higher number of EVs and to avoid the concentration of the charging in periods that would create peaks on the load profile, there is a higher charging in periods with a slightly higher wholesale market price.

From the user point-of-view the economic impact is affected by the electricity tariff and the period used for charging and discharging, but also by the degradation of the battery, therefore depending on the used EV. As an example, Figure 9 presents the result of the degradation model for the battery of a Nissan Leaf according to the number of cycles, in a charging and discharging regime imposed by the conditions used in the assessment of the technical impact for winter with 10 % of EVs. A complete cycle per day is performed corresponding to the daily use in V2G and in transportation.

In the case of the Nissan Leaf it is possible to observe in Figure 9 that, considering the use for V2G, the battery degrades 30% of its nominal capacity after approximately 1,850 cycles (lifetime of 5.1 years). Considering a linear relationship, the total degradation is 0.0162 %/day. Such degradation includes not only the V2G use but also transportation, therefore, the degradation due to the use in V2G was assessed considering the percentage of the capacity used in V2G each day. In the case of Nissan Leaf, knowing that the use of V2G corresponds to 82 % of total consumption, it is estimated that V2G is responsible for 0.0147 % of the daily degradation. Considering the cost of battery replacement, it is possible to calculate the daily cost associated with battery degradation, being in the described scenario €0.75/day. Therefore, from the profit obtained with the price difference between the charging and discharging periods, the degradation cost must be subtracted, to obtain the V2G profit, being in such scenario €0.59/day.

However, in different seasons or in scenarios using a different share of EVs the daily charged and discharged energy is different, leading to slightly different degradation percentages and associated costs. Therefore, due to the high differences in the profit between the charging and discharging period in different seasons and in scenarios using a different share of EVs there a is a decrease on the V2G profit for summer and for scenarios with a higher number of EVs. As explained, due to the lower renewable share, during summer, the electricity prices in the wholesale market are higher and present a lower variation during the day (reducing the impact of the optimization). Since the considered real-time tariff presents variations proportional to the wholesale market price variations, the profit between the charging and discharging period is much lower during summer. As previously mentioned, by increasing the share of EVs the profit is reduced due to the required use of periods with higher wholesale price to avoid peaks on the load diagram. Therefore, as presented in Table 5, during summer the use of V2G does not present economic profit for the user. During spring the profit is low and in the scenario with 50 % of EVs, there is no profit.

Conclusions

This paper discusses the implementation of G2V and V2G systems in scenarios with large-scale penetration of renewable generation and assesses the potential impacts in a case study for the Portuguese grid. The requirements for the implementation G2V and V2G systems were analyzed, being concluded that EVs are about 95 % of the time parked, and if connected to the grid, they can be controlled to provide services to the grid. It was also concluded that EVs are used for traveling in average 35 km per day, only consuming 10 to 20 % of the stored energy, thus having a surplus of stored energy that can be injected into the grid, using V2G. The support technologies for the implementation of G2V and V2G systems were characterized regarding the needed requirements and defined standards, being concluded that the currently available technology can already allow an efficient implementation of such systems.

Then, a case study assessing the potential impacts of V2G programs in the Portuguese grid was presented. The case study considered three scenarios in which EVs constitute 10 %, 25 % and 50 % of the Portuguese vehicle fleet and three typical days for winter, spring, and summer, in order to present different conditions regarding the availability of renewable generation.

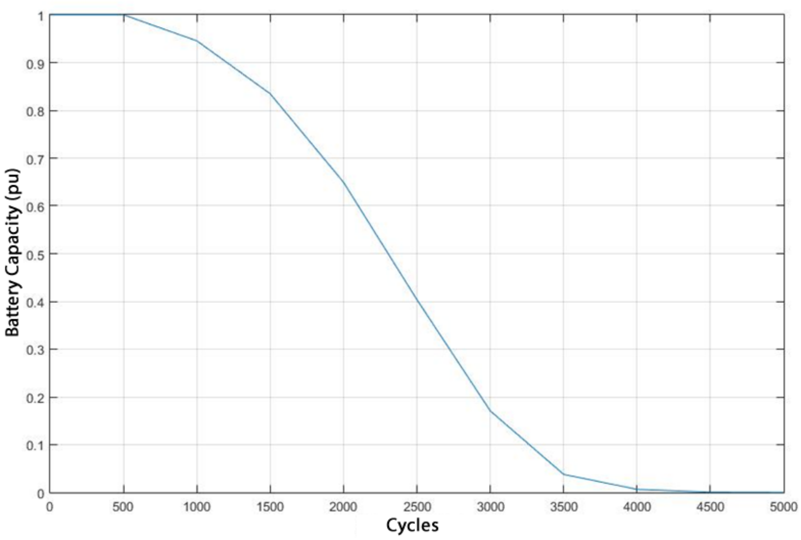


Figure 9. Degradation of the battery of a Nissan Leaf according to the number of cycles, in a typical day of winter with 10 % of EVs.

Table 5. Economic impact for the user in each scenario.

Scenario	Impact	Winter	Spring	Summer
10 % EVs	Charge/Discharge Profit (€/day)	1.45	0.93	0.49
	V2G Degradation (%/day)	0.0134	0.0134	0.0136
	Degradation cost (€/day)	-0.75	-0.75	-0.76
	V2G Profit (€/day)	0.69	0.18	-0.35
25 % EVs	Charge/Discharge Profit (€/day)	1.37	0.82	0.49
	V2G Degradation (%/day)	0.0136	0.0136	0.0136
	Degradation cost (€/day)	-0.76	-0.76	-0.76
	V2G Profit (€/day)	0.61	0.06	-0.27
50 % EVs	Charge/Discharge Profit (€/day)	1.35	0.74	0.46
	V2G Degradation (%/day)	0.0136	0.0136	0.0133
	Degradation cost (€/day)	-0.76	-0.76	-0.74
	V2G Profit (€/day)	0.59	-0.02	-0.28

The potential of V2G to store the surplus of renewables generated during the night and to inject it into the grid in periods of high demand was assessed. Even with only 10 % of EVs, it was possible to absorb all the renewable energy generation surplus, being the charging of EVs in winter ensured in 59.8 % by such surplus.

This result was compared with the results obtained with G2V in which it was only possible to store 19.4 % of the renewable generation surplus in winter. In a scenario only with G2V, a fleet constituted in 52 % by EVs would be needed to store all the renewable generation surplus. It was then concluded that only with G2V a much larger penetration of EVs would be needed to integrate renewable generation

In the scenarios with 25 % and 50 % of EVs the share of renewable generation surplus used in the charging is lower and such reduction has impacts on the economic benefits. From the grid point-of-view, the assessed scenarios had savings between 15.7 % and 59.4 % of the charging costs, being such savings higher in winter and with a lower share of EVs. This is due to the higher wholesale market price in summer due to the lower availability of renewables and the need to use periods with a higher cost to ensure the charging of a large number of EVs without creating peaks on the load profile. The economic benefits from the user point-of-view were assessed considering the daily degradation of the batteries, which was simulated with a Simulink model. Even considering the cost associated with such degradation it was possible to ensure profit in winter, but the impact during spring is not relevant and during summer the benefits are not enough to compensate the degradation costs, with the current technology of battery cells. These are important indicators that should be taken into account in the design of incentives for V2G programs.

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