Economic Impact of Plug-In Hybrid Electric Vehicles on Power Systems Operation

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Abstract

This paper analyses the impact that the introduction of Plug-In Hybrid Electric Vehicles (PHEVs) with different charging strategies have on the operation of power systems with high penetration of renewable generation. For this purpose, a medium-term electricity production model was used in order to perform a detailed analysis of the power system operation when: 1) PHEVs are "dumbly" charged; 2) PHEVs are smartly charged; and, 3) PHEVs are smartly charged and have vehicle-to-grid (V2G) capability. A reference scenario without PHEVs was also considered for comparison purposes. Results for the three charging strategies demonstrated that smartly charged vehicles improves system operation by flattening the demand curve and reducing operational reserves requirements, especially when V2G strategy is adopted. As a consequence of this, total and average system operation costs are reduced.

I – Introduction

Climate change combined with the search for energy autonomy and economic competitiveness has resulted in a binding target of 20% of renewable energy consumption in the European Union by 2020. Achieving this objective will require a future massive penetration of renewable generation in power systems, an increase in final consumer responsiveness to system conditions and a smarter grid operation. The required adaptation process will not end in 2020 but will continue far beyond, especially if we take into account the much more ambitious targets considered for the 2050 horizon, which may require the implementation of very ambitious future energy projects such as DESERTEC[2] – Solar and Wind Energy from the Deserts in North Africa and the Middle East – or gas supply in Europe coming from North Africa via Spain or Italy.

In Spain, renewable energy sources (RES) are being strongly promoted by public policies. Generous feed-in tariffs have allowed an important expansion of renewable generation, especially wind and solar power. For instance, currently, Spain has more than 18 GW of wind installed capacity [1] and it is expected that this capacity will increase to 40 GW in 2020.

Wind generation is characterized by a great level of intermittency. In other words, its output is highly variable (not controllable) and unpredictable, which may result in an excess or a deficit of production in certain hours as well as forecasting errors, which may be large. Generally speaking, the higher is the level of penetration of intermittent generation, the higher the need for conventional backup units will be so that system reliability is not deteriorated.

In this context, plug-in hybrid electric vehicles (PHEV) are a promising opportunity to reduce problems caused by wind generation intermittency. However, their impact on the system functioning will certainly be

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[2] The DESERTEC Concept describes the perspective of a sustainable supply of electricity for Europe, the Middle East and North Africa up to the year 2050. Webpage: http://www.desertec.org/.

conditioned by the charging strategy adopted. If smartly charged, PHEVs can absorb the excess of electricity generated during off-peak hours, thus making the load curve flatter and avoiding wind curtailment, water spillage and costly variations in conventional power plants production. Assuming that these vehicles are also capable of injecting electricity back into the grid (vehicle-to-grid capability), they may reduce conventional generation capacity and operational reserve needs. On the other hand, if vehicles' owners are free to charge their vehicles whenever they want ("dumb" charging), the integration of PHEVs will probably increase electricity demand variability.

Therefore, different charging strategies and vehicle-to-grid (V2G) capabilities will have different impacts on power systems operation and, therefore, on power system costs. Assuming that electric vehicles will be in fact integrated into the future power systems, this paper analyses the economic impact of a high penetration of electric vehicles on power systems operation.

For this purpose, the Spanish power system in 2030 will be analyzed. For this year, it will be considered that the renewable share of total electricity production is around 50%. Regarding PHEVs, it will be assumed a penetration level of 20% of the Spanish vehicle fleet by 2030. Two charging strategies –"dumb" and smart – will be considered. Apart from that, the effect of V2G capability (assuming smart charging and discharging) will be also analyzed. Finally, a "reference" scenario with no PHEVs will be compared to the three previous cases.

This paper is divided into three sections besides this introduction. Section II contains the assumptions and the operational model description. Section III contains the analysis of results. Finally, Section IV presents the conclusions.

II – Methodology

In order to achieve the proposed research objective, firstly, assumptions regarding PHEVs and the Spanish generation system in 2030 are specified. After that, a medium-term operational model is used with the aim of analyzing the impact of the integration of PHEVs with different charging strategies on the Spanish power system operation.

II.1 – Assumptions

II.1.1 – PHEVs

A Plug-In Hybrid Electric Vehicle (PHEV) is a vehicle with both an internal combustion engine (ICE) and a battery capacity, which can be charged from an external source, namely, the electric grid. PHEVs can operate in two basic energy modes: the charge depleting mode (CD) and the charge sustaining mode (CS). It is important to mention that in order not to deteriorate the vehicle's battery, its state of charge (SOC), which measures the amount of electrical energy stored in the battery, must remain always within a certain range.

The fully charged vehicle operates in the CD mode. In this case, the vehicle is powered by only (or almost only) the energy stored in the battery. The charge depleting mode can operate in two ways: CD blended mode, under which the ICE is on, and the CD all electric mode, under which the ICE is off and the vehicle behaves as a pure electric car [2]. In the CD mode, the battery SOC is gradually reduced up to its minimum level. When the battery is depleted to a minimum level, the vehicle switches to the CS mode and behaves as a conventional hybrid electric vehicle. Under the CS mode, the vehicle relies primarily on the ICE, sustaining the battery SOC [3].

PHEVs have larger batteries than traditional hybrid ones, varying from 5 to 22 kWh [4]. Larger batteries, combined with relatively short driven distances, allow PHEVs to function as electricity storages. In the case of the USA, for instance, transportation data for driving patterns indicates that 60% of average domestic daily driving is less than 50km and approximately 70% of driving is 65km or less [4]. Assuming that the specific consumption of electric vehicles is around 0.20kWh/km, total electricity consumption would range from 10kWh to 13kWh to cover distances from 50 to 65km.

In this analysis, it is considered that PHEVs have a battery useful capacity of 12kWh and a specific consumption of 0.20kWh/km. As for the vehicle fleet in Spain, it is estimated that there will be 30 million vehicles by 2030 [5] and 20% of this fleet are PHEVs. Apart from that, three types of vehicle uses are considered based on the study presented in [6]: commuter, business and private. Table I provides the main characteristics of these three types of use. It is assumed that during the hours in which vehicles are not being used, they are plugged-in, which means that they can be charged or discharged in those hours.

Table I – Main assumptions regarding the types of use of PHEVs

Types of use	Time of use	Average daily driven distance(km)
Commuter	7am - 10am; 5pm - 8pm	35
Business	7am - 8pm	60
Private	7am - 8pm	13
Private	8pm - 12pm	13
Private	12pm - 7am	13

Finally, as previously mentioned, two charging strategies – "dumb" and smart – and V2G capability (only for the smart charge option) will be analyzed. When dumb charging is assumed, drivers are free to charge their vehicles whenever they want [7]. In this paper, it is considered that these charges will be equally distributed among the hours in which the vehicles are plugged-in. In other words, the total electricity consumption in one day by each type of vehicle will be equally divided by the number of hours in which the vehicles are not being used.

In the second one, smart charging, vehicles are charged when it best suits the system. In this case, vehicles are not able to inject electricity back to the grid. In the last case, V2G, vehicles are smartly charged and are not only able to charge from the grid but they are also able to inject electricity back into the grid. For smartly charged vehicles (smart charging and V2G cases), it is assumed that charging (and discharging) is done when costs are minimized, considering the needs of electricity for transportation purposes, and maximizing vehicles' owners benefits from that. In such a case, vehicles will be charged when electricity marginal production costs are low. In practice, smart charging strategies would be implemented through smart meters that would transfer hourly market prices to end customers.

II.1.2 – Spanish power system in 2030

The optimal expansion of the Spanish electricity generation capacity from 2020 to 2050 was computed by a long term generation expansion model. This expansion model is based on the one presented in [8]. The objective of this tool is to minimize the net present value of system costs considering as input data investment costs of each technology, fuel costs, CO2 prices, demand growth and environmental constraints. Under the hypothesis of costs minimization, the model simulates the investments that would be made in generation capacity in order to supply demand in the period of study. The model's main outputs are total annual installed power and energy production by technology, annual investment costs, marginal cost of electricity, optimal premiums to achieve specific RES targets and CO2 emissions.

In this analysis, RES installed capacities in 2020 and 2050 were considered as fixed RES targets and therefore they were included as input data in the model. For conventional technologies, the resulting installed capacity is the most economically profitable one that meets net demand (the result of subtracting RES generation from total demand).

In order to take into account in the analysis the installation of new generation groups and the shutdown of power plants which useful life have ended, a large time horizon is considered (from 2020 to 2070). Due to this long period of study (50 years), the detailed system operation, such as hourly demand, behavior of intermittent generation and ramps, is not represented by this model. For this reason, once the evolution of RES and conventional capacities was computed, the analysis of the operation of the power system in 2020 and 2050 was carried out an operational model. The main results from this analysis are presented in [9].

Fig. 1 presents the generation mix composition in Spain in 2008 and the estimated installed capacity for the main technologies in 2030. From this figure, it can be observed that RES capacity, especially wind, is expected to increase to a great extent up to 2030 –from 52% in 2008 to 75% in 2030. According to the estimates, wind capacity alone would correspond to 31% of total installed capacity in 2030. The existence of high shares of wind generation capacity increases system intermittency since wind production is not controllable.

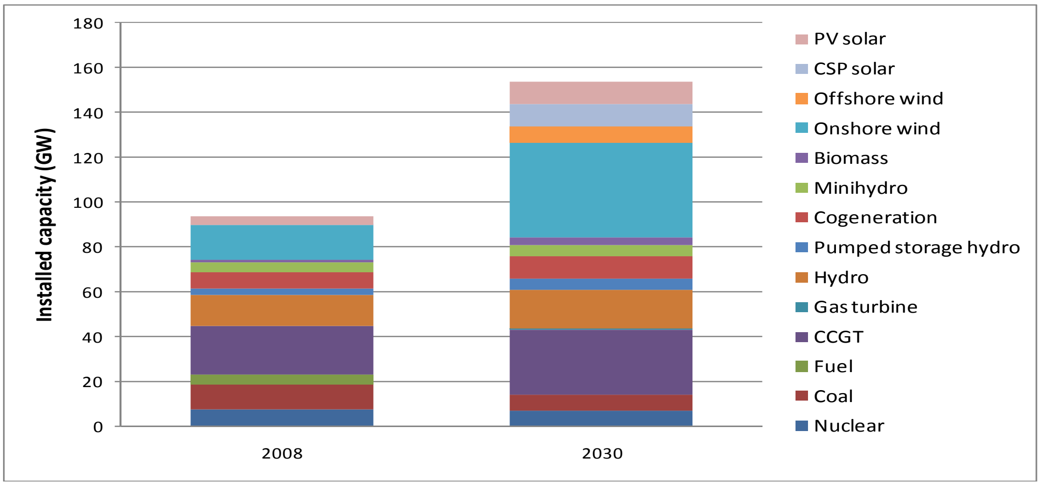

Fig. 1 - Installed Capacity (GW) in 2008 and 2030

Through the detailed analysis of the system operation, it was observed that a high penetration of intermittent generation may increase system production variability and cause higher levels of Energy Not Supplied (ENS), wind curtailment and water spillage[3], up and down reserve[4] needs and, therefore, higher system costs. In order to avoid these undesirable outcomes it is essential that integration technologies are added to the

[3] Spillage (or generation surplus) refers to the case when, for some hours, there is too much generation to be injected into the grid. In other words, no generator can reduce its production and demand cannot be increased by pumped hydro. For this reason, there is a "spillage or curtailment" of hydro and/or wind energy.

[4] Up and down reserve refers to the generating capacity available to the system operator within a short interval of time to meet demand in case of lack or excess of generation, respectively. Up reserve includes wind forecast error, a percentage of the peak load and the power of the largest unit. Down reserve includes wind forecast error and a percentage of the load peak.

system, such as more accurate forecasting methods, conventional backup generation, storage capacity and/or other flexible resources, and higher interconnection capacity. In this sense, electric vehicles are a potential source of flexibility that could help the System Operator to integrate higher shares of renewables.

II.2 – Operational model

As already mentioned, a tool was used in order to analyze the system operation resulting from the generation mix computed with our long term expansion model. This tool, described in [10, 11], is a daily operation model with hourly subperiods and a one-year scope. Operational decisions – daily unit commitment and economic dispatch – are deterministically optimized. Detailed operation constraints such as minimum load, ramp rate of thermal units and up and down reserve procurement are included into the daily optimization model.

Other input data are hourly demand, intermittent generation, and distribution generation profiles, apart from PHEVs data. The stochasticity of wind is implicitly modeled by considering wind production time series that are representative of real ones (and, therefore, of the different wind conditions that may occur) when simulating the operation of the system along the whole year. The process of adaptation of the system operation resulting from the day-ahead market to the real time one is simulated through the consideration of stochastic outages of generation units and wind forecast errors. These two result in a global forecast error that must be compensated by adapting the program of generation units. Synthetic series of wind forecast errors have been produced based on the real ones corresponding to the use of the prediction tool employed by the Spanish SO.

The main outcomes from this model are the hourly generation output by technology, including pumped storage hydro and electric vehicles generation, pumped storage and electric vehicles consumption, generation surplus, energy not supplied, fuel and CO2 costs, up and down reserve marginal costs, and the system marginal cost.

The model's main objective is to analyze the impact of a large penetration of intermittent generation on system operation. This allows its user to quantify the amount of intermittent generation that can be integrated into the system while meeting certain security criteria and to identify measures that allow higher penetration levels of intermittent generation without compromising system reliability. In this paper, this model will be used in order to analyze how PHEVs charging (and discharging) causes technical, and, consequently, economic changes to the system operation.

III – Analysis of Results

The operational model was run taking into account the installed capacity presented in Fig. 1 and considering the following scenarios for electric vehicles penetration and charging: 1) no electric vehicles (reference scenario); 2) 6 million PHEVs (20% of the vehicle fleet) with three different charging approaches – dumb charging, smart charging and V2G. Table II presents the total electricity demand in the four cases.

III.1 – Demand

First, demand without considering PHEVs and pumped storage consumption is the same in the four cases. It can be observed that PHEVs demand is highest when the V2G strategy is applied. This is due to the fact that, in this case, the vehicle is charged not only for transportation purposes but also to store energy which will be partly injected back into the grid. For the smart charging and V2G strategies, vehicles' consumption and hours of charging are decided by the model. In the case of the dumb charging approach, PHEVs' demand is calculated by multiplying the specific consumption (in kWh/km) by the distance (in km) covered by each type of vehicle in the whole year. As previously mentioned, in this approach, vehicles' total charging is equally divided by the hours they are not being used.

Table II – Total Electricity Demand in 2030 (TWh)

	Reference scenario	Dumb charging	Smart charging	V2G
Demand without PHEVs	344.15	344.15	344.15	344.15
PHEVs consumption	0	16.35	14.51	18.62
PS hydro consumption	9.57	9.80	8.22	6.52
Total demand	**353.72**	**370.30**	**366.88**	**369.29**

Pumped storage hydro plants (PS hydro) functions as electricity storages. When electricity generation is high and demand is low (low electricity prices), water is pumped from a lower elevation reservoir to a higher elevation reservoir; when electricity generation is low and demand is high (high electricity prices), the water is released and electricity is generated. The efficiency of this process is approximately 70%.

Batteries of PHEVs may function as well as energy storage devices when vehicles consume electricity during low price hours and/or generating electricity during high price hours. In this respect, [12] considers battery charging and discharging inefficiencies of 4.6% each, which means a round trip efficiency of 91%, while [13] assumes a lower battery charging efficiency of 85%. In both cases, the efficiency rate of the pumping processes is lower than that of the PHEVs' charging-discharging process[5].

As observed in Table II, pumped storage hydro consumption decreases in the reference scenario with respect to the V2G one – the consumption of electric vehicles in valley hours is replacing pumped storage use. The dumb charging approach is an exception, since vehicles, in this case, are being charged regardless of whether demand is high or low. Fig. 2 represents the net demand curve[6] in one random week in the four cases.

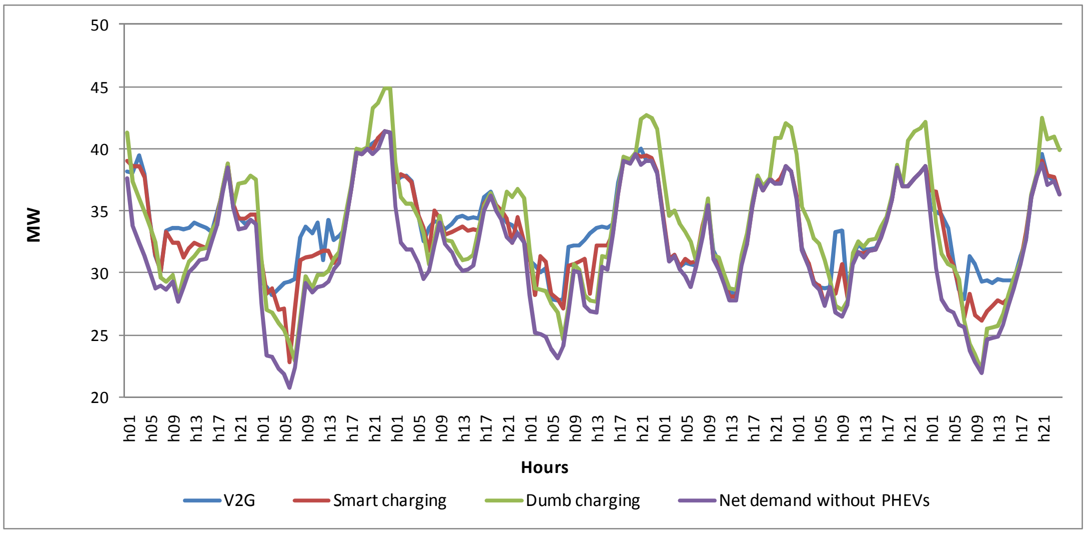

Fig. 2 – Hourly demand in one random week

[5] Since the operational model used in this analysis did not include inefficiencies of charging and discharging, it was implicitly considered that the efficiency rate of the charging-discharging process is 100%.

[6] Net demand is a result of subtracting wind and solar generation curves from the original demand curve.

Firstly, it can be noticed that in all of the three cases in which PHEVs are considered, demand in valley hours is increased in comparison to the reference case. As for peak hours, the charging strategy which most increases demand is the dumb charging. In this case, it can be observed in Fig. 2 that while peak demand increases, valley demand do not change considerably in comparison to the reference scenario. These higher peaks and low valleys increase demand variability. On the other hand, when vehicles are smartly charged valley reductions are significant (especially if the V2G strategy is considered) and peak demand is not increased, which reduces demand variability. Fig. 3 presents the net demand and PHEVs consumption and generation curves.

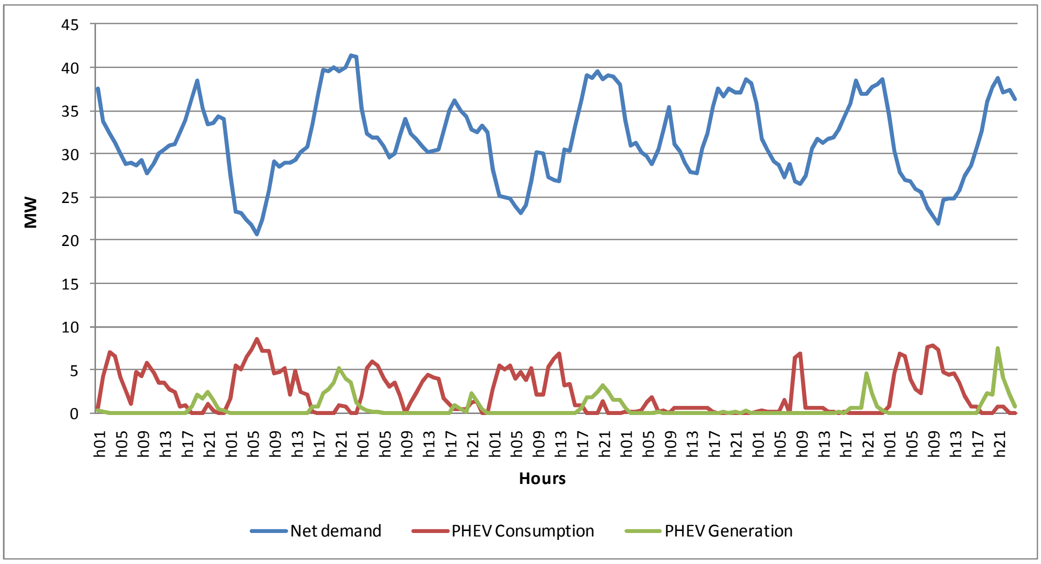

Fig. 3 – Net demand, PHEVs consumption and generation

Observing the PHEVs' consumption curve, it can be noticed that vehicles are being charged when production with non-intermittent technologies is low. In contrast, when non-intermittent generation is high (and, consequently, more expensive generation is high), PHEVs are providing electricity to the grid.

III.2 – System Operation

Table III summarizes the main changes to the system operation variables caused by the introduction of PHEVs with different charging strategies. Comparing the three charging approaches – dumb, smart and V2G, it can be observed that thermal generation is highest for the dumb charging and decreases when smart charging is used and even more when the V2G strategy is implemented. This indicates, as observed in Fig. 2, that vehicles in the dumb charging approach are generally consuming electricity when net demand is higher and, therefore, more thermal generation being used.

Table III – Energy Production, Reserves and CO2 Emissions

	Reference scenario	Dumb charging	Smart charging	V2G
Thermal generation	135.87	148.67	145.91	145.44
RES generation	213.36	216.67	217.12	217.02
PS hydro generation	4.48	4.95	3.85	2.70
PHEVs generation	0	0	0	4.13
Total (TWh)	**353.72**	**370.30**	**366.88**	**369.29**
Wind curtailment and water spillage (TWh)	9.39	6.34	5.71	5.67
Average up and down reserve (MW)	7,766	7,855	6,698	6,695
CO2 Emissions (Millions of tons)	23.60	29.30	28.47	28.66

Regarding renewable generation, at first glance, it seems that the smart charging approach allows a slightly higher penetration of RES than the V2G case. However, if PHEVs generation is taken into account, RES generation turns out to be higher under V2G strategy since, for many hours, PHEVs are consuming the excess of wind generation of the system and, afterwards, they give part of this energy back to the grid. This can be confirmed by the fact that the generation surplus (mainly composed by wind curtailment) is lowest in this case.

Pumped storage generation is highest for the dumb charging approach. This is a result from the fact that net demand variability is highest in this case, which is caused by the vehicles' "dumb" consumption. In this sense, when vehicles are smartly charged, demand variability and, consequently, pumped storage use are reduced. In the same line, wind curtailment and water spillage is also avoided when smart charging is applied.

As for operation reserve, it is needed to cope with demand variability. As variability in consumption increases, the higher is its unpredictability, and, consequently, the requirements of up and down reserve. Not surprisingly, it can be observed in Table III that reserve requirements are reduced with respect to the dumb charging approach, when the smart charging or the V2G strategies are applied. Comparing only the smart charging and V2G approaches, reserve needs are even lower in the latter case. This is due to the fact that in the V2G strategy, vehicles are not only able to consume electricity in hours of low net demand (reducing down reserve needs) but they can also give electricity back to the grid in hours of high net demand (decreasing up reserve needs).

Finally, CO2 emissions are reduced as well when vehicles are smartly charged due to the higher use (lower spillage of) production from RES generation, in that case. However, the lowest level of CO2 emissions is observed in the reference scenario. The reason for this is that when PHEVs are introduced, total electricity demand significantly increases. Thus, not only RES generation increases but also thermal generation does. It is important to have in mind, though, that this analysis does not include the significant CO2 emissions' reduction that is expected to occur in the transportation sector after the introduction of electric vehicles [14]. For instance, in [15] it is projected that 500 million tons of CO2 could be saved per year worldwide in 2030 and 2.5 billion tons per year by 2050.

III.3 – Operation costs

The aforementioned technical changes in the system operation caused by the use of PHEVs have important impacts on system operation costs. Table IV shows the main results produced by the operation model regarding costs. Wind curtailment and water spillage costs were evaluated using the system marginal cost. Up and down reserve costs were estimated by multiplying up and down reserve requirements by their respective marginal costs.

Table IV – System Operation Costs

	Reference scenario	Dumb charging	Smart charging	V2G
Fuel and CO2 costs	3,512	4,489	4,238	4,180
Wind curtailment and hydro spillage costs	490.45	360.59	329.38	306.60
Up and down reserve costs	455.83	483.60	320.14	308.56
Total (M$)	**4,458**	**5,333**	**4,888**	**4,795**
Average total costs ($/MWh)	**12.60**	**14.40**	**13.32**	**12.98**

It can be observed in Table IV that costs resulting from the model are in line with the results presented in Table III. First, when the three charging approaches are compared, it can be observed that the lowest fuel and CO2 emissions costs appear in the V2G case. This indicates lower production with thermal technolgies and, consequently, higher generation share coming from RES.

The reduction of generation surplus and reserve needs caused by the demand curve flattening when the V2G strategy is applied had a positive impact on system operation costs, which are both lower in the smart charging and V2G approaches than those in the reference scenario. Besides reducing reserve needs, electric vehicles with V2G capability are also able to provide up and down reserve, reducing even more operation costs [16].

Finally, total and average system operation costs are lower for the V2G approach and higher for the dumb charging one. However, the reference scenario is the one which presents the lowest operation costs due to the lower level of energy generation, resulting in lower fuel and CO2 costs. In this respect, it is important to point out that the improvement of system operation conditions when smart charging and V2G strategies are applied resulted in relatively low increment of system costs when compared to the reference scenario. Besides, the positive impacts of PHEVs in other sectors, such as the reduction of the reliance of the transport sector on fossil fuels and the corresponding reduction of CO2 emissions, have not been taken into account in this analysis.

IV – Conclusions

The growing concern regarding climate change and energy security added to the constant search for economic competiveness will certainly lead to a future with a massive penetration of renewable generation. In this context, electric vehicles do not only represent a means to improve fuel efficiency and, consequently, to reduce reliance on fossil fuels and production of CO2 emissions, but they are also capable of increasing the potential level of integration of renewable generation.

For all these reasons, governments of many countries are supporting the development of vehicles powered by electricity. However, it is essential that these vehicles are managed in an efficient way in order not to negatively affect power system operation. The analysis presented in this paper shows that the integration of PHEVs with a dumb charging strategy would not only deteriorate system operation conditions but would also increase its costs.

On the other hand, when vehicles are smartly charged, an improvement in system operation conditions can be achieved and costs can be reduced. This is especially true when an intelligent V2G approach is followed. Assuming that electric vehicles will be a reality in the future, this paper points out that the investments needed in order to allow smart charging strategies to be implemented could be more than compensated by those savings resulting from a more efficient power system operation.

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