EVS24
Stavanger, Norway, May 13-16, 2009

Smart Charging Strategies for Electric Vehicles: Enhancing Grid Performance and Maximizing the Use of Variable Renewable Energy Resources

J. A. Peças Lopes[1], F. J. Soares[1], P. M. Almeida[1], M. Moreira da Silva[1]
[1] *Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto) and Faculdade de Engenharia da Universidade do Porto (FEUP), Porto, Portugal.*

Abstract

In this paper the behaviour of a Portuguese typical Low Voltage (LV) grid and the changes in the Portuguese global generation profile were analyzed, in a daily period, regarding different levels of Electric Vehicles (EVs) integration. The impacts provoked by EVs deployment on the network voltage profiles, branches' congestion levels, grid losses and imbalances between phases were evaluated using a three phase power flow. The first part of this work focused on the determination of the maximum share of electric vehicles, defined as the percentage of conventional vehicles replaced by EVs, which can be integrated into the selected grid, without violating the system's technical restrictions and complying with drivers' requests concerning the foreseen use of vehicles. The maximization of the EVs connected to the grid was performed using two distinct charging strategies: dumb charging and smart charging. The second task was to analyse the impacts of both charging approaches (dumb charging and smart charging) on the prevention of wasting renewable energy surplus. For the purpose of this analysis, a 2011 wet and windy day was considered, where large hydro and wind generation exists. For that specific case, in some periods of the day (mainly valley hours), the hydro and wind generation, added to the must run thermal generation units, will surpass the consumption and renewable energy can be wasted. The results obtained for the LV grid were extended to a National level and the changes in the Portuguese load/generation profiles were computed.

Keywords: Charging, electric vehicle, emissions, energy storage, load management.

1 Introduction

Nowadays the transportation sector accounts for over half of the world's consumption of oil and much of this is used by road vehicles. The broad adoption of vehicles powered wholly, or in part, by batteries would create a noteworthy contribution for the urban air quality enhancement. However, the environmental effectiveness of the electric vehicles (EVs) implementation depends mostly on each generation mix. The higher the renewable share in the generation mix, the larger the environmental benefits from EVs presence.

As a result of the exposed, a generation mix that is likely to have renewable power surplus in some special periods (e.g. power systems with high penetration of hydro power plants and large amounts of wind power), requires the adoption of specific management strategies in order to use renewable generation [1]. One intelligent way to use the renewable electricity generation surplus relies on the replacement of traditional vehicles by EVs [2]. The capability of controlling battery charging, when EVs are plugged in the grid, allows then adopting smart charging strategies that enable the increase of renewable generation deployment, minimizing the risk of energy spillage. However, the large scale deployment of EVs is not an easy task. A few problems might appear, related with electricity network constraints, which need to be understood and overcome in order to develop further the EV concept. As the first bottlenecks are likely to occur in the Low Voltage (LV) distribution grids, this paper focuses its attention into this type of distribution networks.

In this paper the behaviour of a Portuguese typical Low Voltage (LV) grid and the changes in the Portuguese global generation profile were analyzed, in a daily period, regarding different levels of Electric Vehicles (EVs) integration. The impacts provoked by EVs deployment on the network voltage profiles, branches' congestion levels, grid losses and imbalances between phases were evaluated using a three phase power flow.

The first part of this work focused on the determination of the maximum share of electric vehicles, defined as the percentage of conventional vehicles replaced by EVs, which can be integrated into the selected grid, without violating the system's technical restrictions and complying with drivers' requests concerning the foreseen use of vehicles. The maximization of the EVs connected to the grid was performed using two distinct charging strategies: dumb charging and smart charging.

The second task was to analyse the impacts of both charging approaches (dumb charging and smart charging) on the global load profile and in the prevention of wasting renewable energy surplus. For the purpose of this analysis, a 2011 wet and windy day was considered, which means large hydro and wind generation. For that specific case, in some periods of the day (mainly valley hours), the hydro and wind generation, added to the must run thermal generation units, will surpass the consumption and renewable energy will be wasted.

The results obtained for the LV grid were extended to a National level and the changes in the Portuguese load/generation profiles were computed. In this work network reinforcements will not be considered as a solution to increase EVs deployment.

2 Grid Architecture

Fig. 1 shows the electricity distribution network used in this research, corresponding to a typical urban LV grid (400 V). The clients of this type of grid are mainly residential consumers, providing a good platform for studying the impacts of EVs' connection.

This grid has a radial configuration and one feeding point energizing all the area, represented by the round shape in the figure. The specified voltage in the feeding points is 1.0 p.u..

Typically, in these networks there are some problems that arise with an increase in load. The branches around the feeding points may reach high congestion levels, while the buses more electrically distant from the feeding points are expected to face voltage drop problems.

Another issue that may occur is the imbalance between phases. Although statistically these imbalances are negligible at the LV substation level, as bigger are the single phase loads connected to the LV grid, larger will be the imbalances if the load growth it's not balanced among phase. As EVs represent large single phase loads, the system may be operated with larger load imbalances.

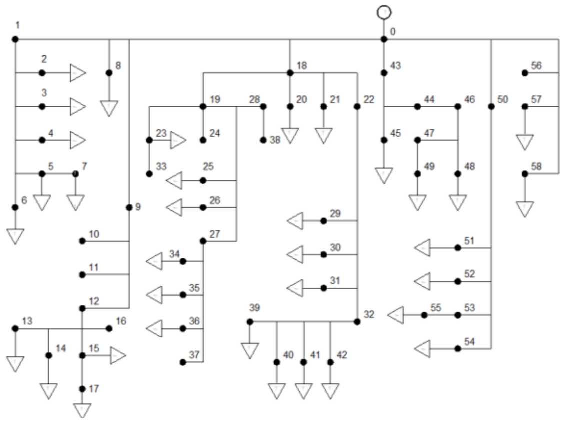

Figure 1: Low voltage distribution network (400 V)

In order to perform a 24 hours simulation, a typical daily load diagram for a LV grid was used. For this purpose, typical load diagrams for Portuguese consumers, as depicted in Fig. 2, were used.

The household and commercial diagrams were combined taking into account the proportion of installed power related with each type of these consumers. Thus, the final load diagram has a contribution of nearly 92% of the household loads and 8% of commercial consumption.

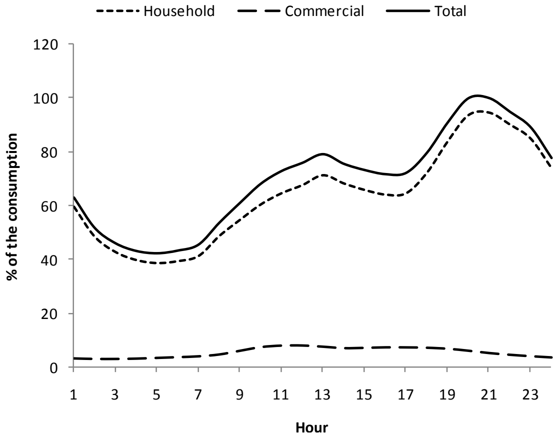

Figure 2: Load profile during a day

The network's peak load is 549.34 kW and the energy consumption in a typical day is 9.17 MWh.

3 Load/Generation Scenarios Characterization

3.1 EVs Characterization and Modelling

For the case study addressed in this work, the total number of vehicles considered to be enclosed in the grid geographical area was 375. This figure was determined considering an average value of 1.5 vehicles per household.

The EVs fleet considered includes plug-in hybrid vehicles and two types of full electric vehicles, each one of them with a different rated power: 1.5 kW for the hybrid (PHEV), 3 kW for the medium EV (EV1) and 6 kW for the large EV (EV2). These three types of vehicles intend to represent cars with different driving ranges developed by automotive manufacturers to face different customers' needs. It was considered that the share of PHEV was 20% regarding the total number of EVs. The remaining 80% was equally split by EV1 and EV2.

Each EV load was connected to the phase of the corresponding household (or phases, in case of a three phase connection).

Regarding the implementation of the two charging strategies under study, it was determined, for each hour of the day, the average number of EVs that are parked at home and connected to the grid. This data, shown in Fig. 3, allows defining the maximum amount of power that can be consumed by EVs at each hour of the day.

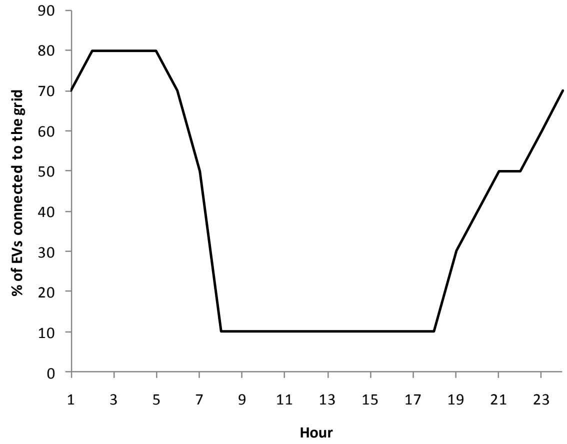

Figure 3: Percentage of EVs connected to the grid during one day

The average recharging time of each EV was assumed to be 4 hours, while the connection time was assumed to be greater. These assumptions were made taking into account typical traffic diagrams for Portugal and a typical annual and daily mileage of 12800 and 35 km, respectively. The vehicles autonomy considered, regarding electric consumption from the battery, was 30 km for the PHEV, 75 km for EV1 and 150 km for EV2. Thus, the average charging frequency and charging energy per day should be, respectively, 3.3 kWh on a daily basis, 10.9 kWh every two days and 22.4 kWh every 4 days. However, due to the high number of uncertainties related with the drivers' behaviour and the charging frequencies, it was considered a worst case scenario where all EVs charge their batteries in the same day requiring 4 hours for charging purposes.

3.2 Forecasts for Generation and Load Profiles

The policy followed by the Portuguese government to increase renewable generation by exploiting both wind power and hydro resources, defined namely in [3], will lead to high levels of installed capacity of hydro and wind power in the midterm range.

Such prospects will require the development of specific strategies capable of tackling the possibility of renewable generation surplus, since at times of low demand and favourable renewable generation conditions [4] this scenario is likely to occur. As a matter of fact this situation already took place in the winter of 2008/2009.

During a typical windy day, the maximum wind generation is likely to reach 70% of the total installed power.
When it comes to a typical wet and windy day, the hydro power plants will operate continuously and, together with the wind generation, the thermal units' participation will have to drop. It was assumed, watchfully, that the bulk thermal generation ought to stay above 450 MW all over the day. Despite the decrease on thermal power, the generation surplus will be very significant, as it is depicted in Fig. 4.

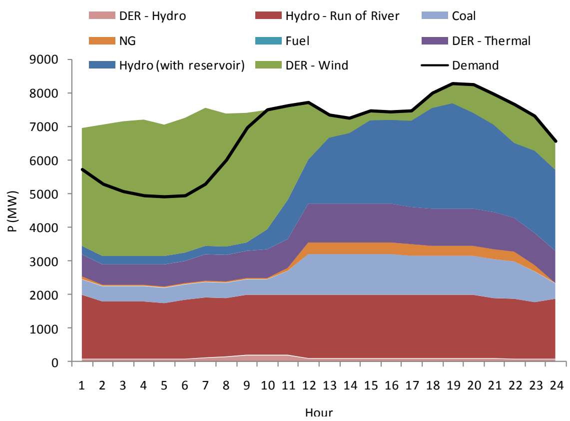

Figure 4: Load/Generation profile during a wet and windy day by 2011

From these specific load/generation profiles the benefits of new controllable loads or the storage of the surplus of electricity produced by the system are easily understandable.
This generation diagram will serve as an input for the operation on the EV smart charging mode.

4 Results and Analysis

4.1 EVs Charging Strategies

As aforementioned, the maximum number of EVs that could be reliably integrated into the grid was determined using two different methodologies: a dumb charging approach and a smart charging strategy, as defined in [5].
In the dumb charging approach it was assumed that EVs' owners are completely free to connect and charge their vehicles whenever they want. The charging starts automatically when EVs plug-in and lasts for the next 4 hours. This approach should be described as a no control strategy but it is particularly important as it provides a measure for a comparative assessment of the efficacy of the smart charging strategy.

The rationale to quantify the maximum share of EVs, when the dumb charging is adopted, was to increase their share in small steps until a violation occurs, for voltage values, branches congestion limits or Medium Voltage (MV)/LV transformer capacity.
Fig. 5 shows a reasonable EVs load distribution, along a typical day, when this charging approach is used. The allowable share of EVs that could be integrated into the LV network was only 11%.

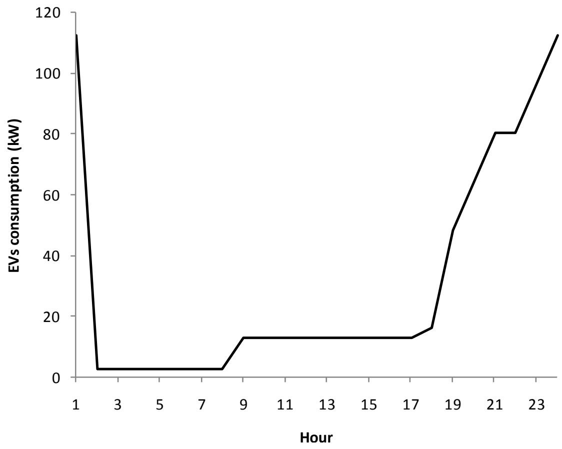

Figure 5: EVs consumption along a typical day for the dumb charging – 11% EVs (kW)

The smart charging strategy envisions an active management system, where there is a hierarchical control structure. It continuously monitors all the elements connected to the grid and its state exploiting the concepts used for the management of Microgrids and Multi-Microgrids [6], [7]. This type of management provides the most efficient usage of the available energy resources, dealing simultaneously with grid restrictions at each moment, enabling branch congestion prevention and avoiding excessive voltage drops.
In order to make of this a winning concept, it is crucial to guarantee the commitment of EVs' owners to it. Thus it was assumed that the economic incentive provided to EVs' owners was sufficient to make 50% of them to let the hierarchical control structure manage their batteries charging. Hence the system has flexibility to charge EVs during the period they are connected (Fig. 3), instead of the charging taking place automatically when they plug-in.
For this approach, the maximum share of EVs that can be safely connected to the grid, as well as its distribution along the day, was determined by solving the optimization problem described in (1). It was found that the allowable share of EVs that

could be integrated into the LV network, using the smart charging, was 61%.

$$\text{Max } EVs\ integration$$

$$\text{subject to} \quad V_i^{\min} \le V_i \le V_i^{\max}, i \in [1, l] \qquad (1)$$
$$S_j \le S_j^{\max}, j \in [1, m]$$
$$E_{k,\Delta t}^{EV} = E_{k,\Delta t}^{EV\ required}, k \in [1, n]$$

Where:

l	is the number of buses;
m	is the number of branches;
n	is the number of EVs;
V_i	is the voltage at bus i;
$V_i^{\min} / V_i^{\max}$	are the minimum/maximum allowable voltages at bus i;
S_j	is the apparent power flowing at branch j;
$S_j^{\max}$	is the maximum allowable apparent power flow at branch j;
$E_{k,\Delta t}^{EV}$	is the battery energy level of the EV k at the end of the connection period Δt;
$E_{k,\Delta t}^{EV\ required}$	is the required battery energy level for EV k at the end of the connection period Δt.

The smart charging strategy was then implemented. Using forecasts of load, generation and EV parking periods, at local and national levels, this charging strategy provides the most efficient way of verifying the following objectives, for a 24h period ahead, sorted according to the following merit order:

1. Assist the operation of the LV grid, meaning that EVs are scheduled to charge in periods of time that do not jeopardize the system's operation due to technical constraints violations;
2. Respond to any grid operational request from an upper hierarchical level, which means that the previous objective is also applied to upper voltage levels;
3. Given the forecasted electricity to be generated from renewables and the forecasted load, at a national level, minimize the renewable energy spillage in periods where a surplus of generation exists, by shifting charging periods to those of renewable energy surplus.

Fig. 6 shows the daily load distribution attained for the EVs maximum integration scenario, after implementing the described smart charging strategy.

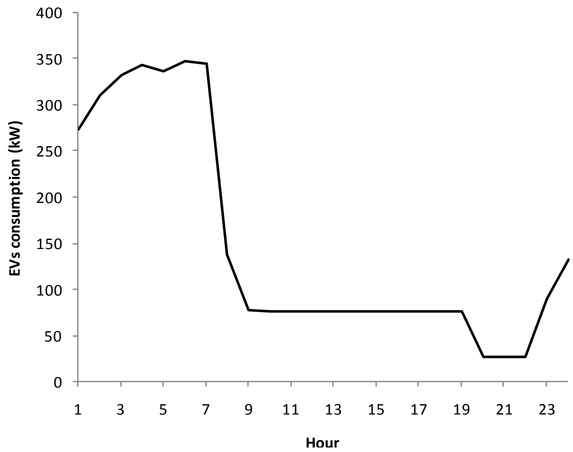

Figure 6: EVs consumption along a typical day for the smart charging – 61% EVs (kW)

Table 1 shows the allowable share of EVs attained for both charging strategies mentioned above, as well as the conditions of the base scenario, where no EVs are considered to be connected to the grid.

Table 1: Scenarios description

Scenario	0	1 (Dumb charging limit)	2 (Smart charging limit)
N.º of Vehicles	375	375	375
EVs %	0%	**11%**	**61%**
N.º of EVs	-	41	229
PHEV Share	-	20%	30%
EV1 Share	-	40%	40%
EV2 Share	-	40%	40%
Energy consumption for the selected day (MWh)	9.17	9.81	12.74

To weigh against both charging strategies, the dumb charging was applied to scenario 2 (smart charging limit) and the smart charging was applied to scenario 1 (dumb charging limit). Thus, two more EVs load distributions were obtained, as shown in Fig. 7 and 8.

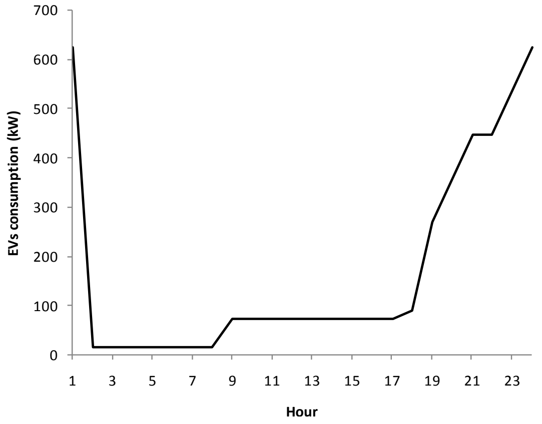

Figure 7: EVs consumption along a typical day for the dumb charging – 61% EVs (kW)

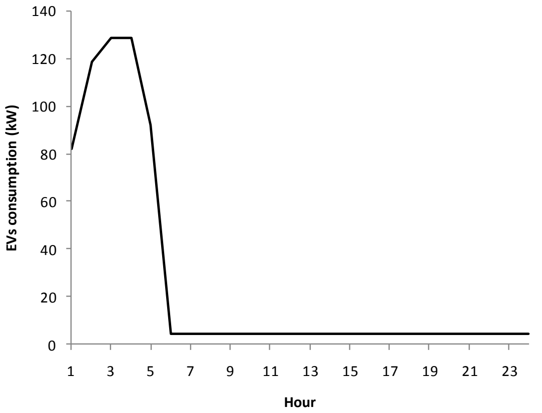

Figure 8: EVs consumption along a typical day for the smart charging – 11% EVs (kW)

4.2 Impact on the LV Grid

In order to assess the impact of the previously described EVs load distributions on the selected LV distribution grid, a three-phase power flow simulation tool was used [8] to perform steady-state simulations. Power flow studies were conducted for the full day period and the results achieved were compiled into the tables and figures presented along this section. For simplicity, regarding voltage profiles, branches' congestion levels and load imbalances, only results for the peak hour will be presented. To simplify the analysis of the next subsections, Table 2 shows the peak hours for all the scenarios considered.

Table 2: Peak hours for all the scenarios studied

		Peak hour
Base scenario	-	21h
11% EVs	Dumb charging	21h
	Smart charging	21h
61% EVs	Dumb charging	24h
	Smart charging	1h

4.2.1 Base Scenario

The results shown in Table 3 were obtained when the three phase power flow was run over the base scenario, for the peak hour, considering no EVs connected to the LV network.

Table 3: Scenario 0 results (no EVs)

Phase	R	S	T
Voltage (p.u.)	0.960	0.959	0.954
Highest Congestion Level		63.4%	
Load Imbalance		4.8%	

The worst voltage found was 0.954 p.u., in bus 39, and the highest congestion level was 63.4% in the branch between buses 0 and 18.
The load imbalance, at the LV side of the MV/LV substation, was obtained by computing the difference between the phases with higher and lower load over the average load between phases, as described in (2).

$$LI(\%) = \frac{P_{MAX}^{R,S,T} - P_{MIN}^{R,S,T}}{P_{AVERAGE}^{R,S,T}} \cdot 100 \qquad (2)$$

For the base scenario, the LV substation load imbalance was 4.8%.

4.2.2 Scenarios with EVs

For the forecasted wet/windy day, the results attained for the peak hour, with 11% of EVs, are presented in Table 4.
For the dumb charging approach, the worst voltage found was 0.950 p.u., in bus 39, and the highest congestion level was 72.2% in the branch between buses 0 and 18. Concerning the smart charging strategy, the same bus and branch registered a 0.954 p.u. voltage value and a congestion level of 72.2%, respectively.
The load imbalance, at the LV substation, was 6.0% for the dumb charging and 4.7% for the smart charging.

Table 4: Results with 11% EVs

	Dumb charging			Smart charging		
Phase	R	S	T	R	S	T
Voltage (p.u.)	0.952	0.954	0.950	0.960	0.959	0.954
Highest Congestion Level		72.2%			63.7%	
Load Imbalance		6.0%			4.7%	

Fig. 9 shows the impact of 11% of EVs in the LV grid load diagram when both charging strategies are applied.

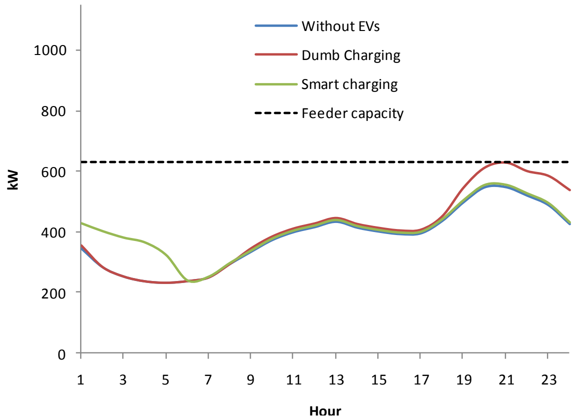

Figure 9: LV grid diagram with 11% EVs

This share of EVs is the limit for the dumb charging approach for two different reasons: it makes the voltage at bus 39 drop to the lower allowable value (0.950 p.u.) and makes the load at the peak hour reach the MV/LV transformer capacity (630 kW).
The smart charging strategy allows accommodating the 11% of EVs without any problem once it shifts a large part of these new loads to the valley hours. EVs are mobilized to start charging around 1h, in order to consume the existing renewable energy surplus. At 6h all EVs energy needs are fulfilled and they cease to consume. From 6h until 9h, renewable energy is wasted due to the lack of consumption. A higher share of EVs present in the grid would avoid wasting this "clean" energy, as it is shown, in the 61% EVs integration scenario.
The results obtained when 61% of the EVs are deployed into the grid are presented in Table 5.

Table 5: Results with 61% EVs

Phase	Dumb charging R	Dumb charging S	Dumb charging T	Smart charging R	Smart charging S	Smart charging T
Voltage (p.u.)	0.938	0.941	0.927	0.962	0.964	0.956
Highest Congestion Level	123.8%			75.0%		
Load Imbalance	14.2%			14.0%		

As this share of EVs represents a considerable load increase, the voltages and the branches' current ratings suffer considerable changes.
For the dumb charging approach, the worst voltage found was 0.927 p.u., in bus 49, and the highest congestion level was 123.8% in the branch between buses 0 and 18. Both these values exceed by far the respective limits, emphasizing the idea that a no control approach is insufficient to handle a high number of EVs connected to the grid.

Regarding the smart charging strategy, the same bus and branch registered a 0.956 p.u. voltage value and a congestion level of 75.0%, respectively.
The load imbalance, at the LV substation, suffered a considerable increase: it reached 14.2% with the dumb charging and 14.0% with the smart charging. Despite the huge improvements in the voltages profiles and in the congestion levels yielded by the smart charging strategy, the results presented show that EVs grid connections should also be carefully revised and properly addressed in order to prevent high load imbalances at the LV substation.
Fig. 10 shows the impact of 61% of EVs in the LV grid load diagram when both charging strategies are applied.

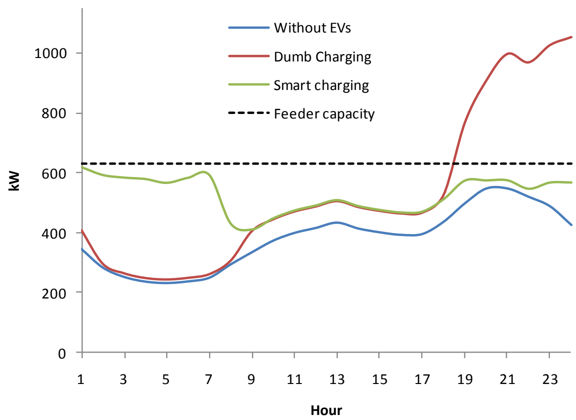

Figure10: LV grid diagram with 61% EVs

To accommodate this share of EVs within the grid with a dumb charging approach, reinforcements would have to be made. For instance, Fig. 10 shows that the peak load almost doubled, which would demand for a MV/LV transformer with a doubled capacity.
This share of EVs is the limit for the smart charging strategy, once the load at the peak hour reaches the MV/LV transformer capacity (630 kW). A large number of EVs are mobilized to make their charging from 1h until 8h, in order to consume the existing renewable energy surplus. The remaining EVs do their charging along the day. As it will be shown later on, 61% of EVs are enough to prevent wasting renewable energy.

4.3 Grid Losses

As it is obvious, the additional consumption of EVs will increase the current flows and, consequently, the losses in the LV grid.
Fig. 11 shows the increase in the LV grid losses, for the forecasted wet/windy day, when comparing

scenarios with EVs against the base scenario, where no EVs are present.

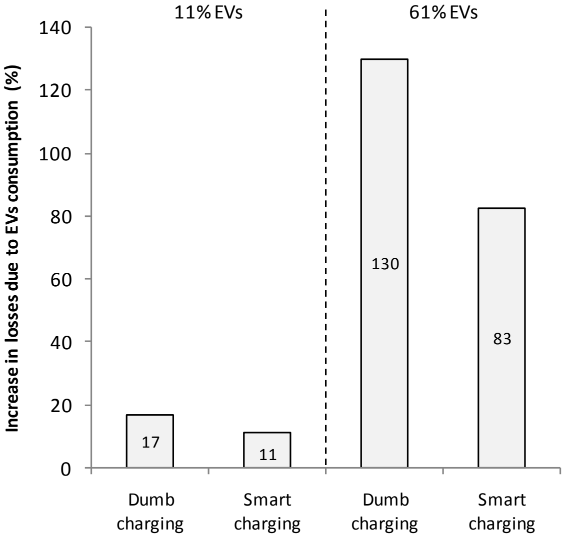

Figure 11: Increase in losses due to EVs electricity consumption (%)

By reducing the peak load, the smart charging strategy reduces considerably the grid losses, when comparing with the dumb charging approach. As expected, these benefits increase with the number of EVs connected to the grid.

4.4 Impact on the Generation Profile

In the present work it was assumed the existence of 10% of energy losses owing to the electricity transmission and distribution through the grid. Therefore, these losses will be added to the EVs consumption profiles throughout the day, which were presented in the previous sections. Hence, the new EVs load profiles were built up by performing an extrapolation based on the number of vehicles in the analyzed grid (375) and in Portugal. Bearing in mind that by 2010 Portugal will have about 4895000 light vehicles [9] and assuming an annual growth of 2% (taking into consideration the previous trend [10]), by 2011 there will be about 5000000 light vehicles.

Accordingly, Fig. 12 and 13 show the new 2011's generation profiles for the forecasted wet/windy day, as a result of 11% and 61% of EVs integration.

In regards to the case of 11% EVs integration, the percentage of surplus power usage is roughly 52.5%, on account of EVs smart charging. Alternatively, during off-valley hours there is no energy surplus, so, thermal cogeneration Dispersed Energy Resources (DER) power plants move up their outputs in order to fill the gap between the new load and the preceding generation.

Concerning the case of 61% EVs integration, the surplus power is not enough to fill the demand with EVs, during valley hours. Thus, the follow-up of the new load is performed by increasing the generation of Natural Gas (NG) and DER thermal power plants.

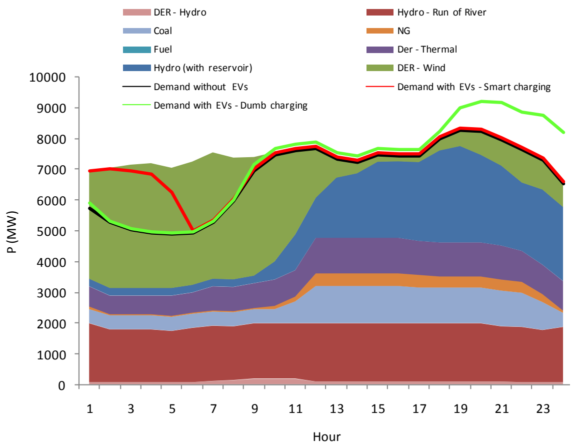

Figure 12: Portuguese generation profiles for the forecasted wet/windy day in 2011 – 11% EVs

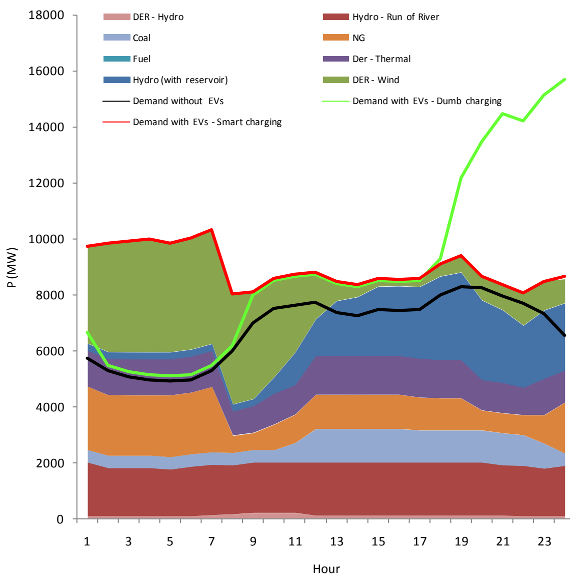

Figure 13: Portuguese generation profiles for the forecasted wet/windy day in 2011 – 61% EVs

For the selected day, with 11% EVs integration, in the absence of a smart charging strategy, the demand will increase considerably in the end of the day and, therefore, the EVs won't absorb the energy surplus occurring during valley hours. If the described smart charging procedure is not applied for the scenario with 61% of EVs integration, the generation mix won't be capable to follow the increase in demand.

4.5 CO_2 Emissions

As it was stated previously, Portugal is expected to have about 5000000 light vehicles by 2011 (assuming 54% gasoline and 46% diesel [11]). In what regards the typical annual and daily mileage, as mentioned previously, it was assumed 12800 km and 35 km, respectively [12]. When it comes to CO_2 emissions, for Internal Combustion Vehicles (ICVs) the addition of pre-combustion emissions (extraction, refining, transport, etc) typically adds another 10-18% to the "tank to wheel" figure. So, the *well-to-wheel* emission factors, calculated for vehicles manufactured in 2010, are the following: 172 gCO_2e/km for gasoline ICVs; and 156 gCO_2e/km for diesel ICVs [13]. Consequently, it can be calculated the CO_2 from Portuguese light vehicles in 2011, as it is depicted underneath.

Table 6: Total daily and annual CO_2 emissions from light vehicles

Year	2011
Total daily well-to-wheel emissions (ktonCO_2)	28.8
Total annual well-to-wheel emissions (ktonCO_2)	10522

These forecasts are in line with the ones developed by the Portuguese Environment Ministry [9].
Concerning the generation system, the estimation of CO_2 emissions is made up by affecting the previous generation profiles with the corresponding emission factors (gCO_2/kWh for each unit type) presented in the literature [14]. The referred emission factors gather the following stages: generation; transport of raw material; processing and extraction. This assessment is carried out for the considered day, with and without EVs integration. In what regards EVs charging, the present work considers the aforementioned patterns of charge for both 11% and 61% of EVs integration.
Fig. 14 depicts the obtained results, which corroborate the CO_2 emissions slump, with the EVs smart charging implementation. As it can be observed, the daily CO_2 emissions are reduced from 59 kton in the scenario without EVs to 47 kton with 61% of EVs.

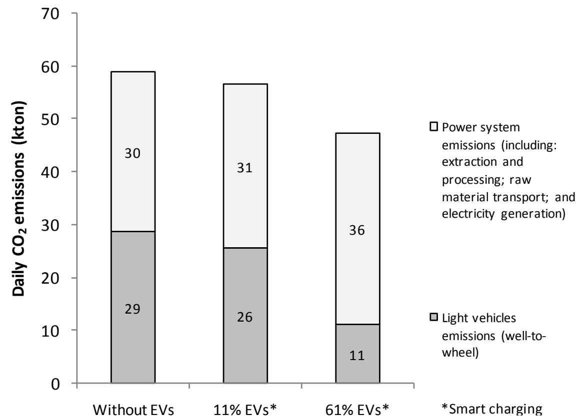

Figure 14: Total daily CO_2 emissions: Transports + Power System

5 Conclusions

Analyzing the results presented before, by adopting a dumb charging approach, it is easy to understand that the system can handle, up to a certain level, the penetration of EVs without changes in the electricity generation and distribution infrastructures. It is verifiable that, for this case study, there is the need to reinforce the grid when the share of EVs reaches 11% of the total existing vehicles in this residential area (41 EVs), if no control is imposed to EVs charging. This result is rather interesting as it shows that grid restrictions may limit the growth of EV penetration, if no additional measures are implemented.
A different approach, based on a hierarchical smart control structure, can be adopted to deal with this problem, allowing the integration of a higher share of EVs, while avoiding capital expenditures by the utility in network reinforcements. Results obtained show that, when implemented, this smart charging mechanism allows the integration of up to 61% of EVs without reinforcing the grid, only by actively controlling the charging of 50% of those EVs. Furthermore, this type of management provides the most efficient usage of the resources available at each moment, like the renewable energy surplus, enabling congestion prevention and voltage control at the same time.
Despite the huge improvements in the voltages profiles and in the congestion levels yielded by the smart charging strategy, the results presented show that EVs grid connections should be carefully revised in order to prevent high load imbalances between phases at the LV substation. As results show, these load imbalances increase from 4.8% in the base scenario to 14% with a 61% EVs

integration even when the smart charging is implemented.

Concerning EVs impact on the LV grid load diagrams, with the dumb charging approach, results show that 11% integration pushes the system to its technical limits (both voltage and MV/LV transformer capacity). For the same share of EVs, the smart charging yields better results, namely concerning the peak load, which assumes almost the same value as in the no EVs scenario. With 61% of EVs, for the dumb charging, peak load reaches the unbearable value of 1051 kW. On the other hand, with the smart charging, peak load is 620 kW, which is a considerably lower value that still below The MV/LV transformer's limit.

In relation to the energy losses in the LV grid due to EVs consumption, as the number of EVs increases, the benefits arising from the smart charging strategy are higher.

In what regards EVs impact on generation profiles, it can be concluded that for the analyzed day with 11% EVs integration, the absence of a smart charging strategy, leads to a considerable load increase in the end of the day and, therefore, the EVs do not absorb the energy surplus occurring during valley hours. The lack of smart charging strategies performs even worst for the scenario with 61% of EVs integration, as the generation mix is not capable to follow the demand soar.

Concerning CO_2 emissions, the present work shows there are major environmental benefits on account of EVs integration, when accompanied with smart charging strategies.

Acknowledgments

This work was supported in part by Fundação para a Ciência e Tecnologia under Grants SFRH/BD/48491/2008 and SFRH/BD/47973/2008.

References

[1] A. Estanqueiro, J. Ferreira de Jesus, J. Ricardo, Amarante dos Santos, J. A. Pecas Lopes, "Barriers (and Solutions...) to Very High Wind Penetration in Power Systems", Power Engineering Society General Meeting 2007, pp. 1-7, 24-28 June 2007.

[2] W. Kempton, J. Tomic, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy", Journal of Power Sources, 144, pp. 280-294, 2005.

[3] "Resolução do Conselho de Ministros nº. 169/2005", Diário da República – I Série-B, October 24th, 2005.

[4] P. B. Eriksen, T. Ackermann, H. Abildgaard, P. Smith, W. Winter, Rodriguez Garcia," System operation with high wind penetration", Power and Energy Magazine, IEEE, vol. 3, no. 6, pp. 65-74, Nov-Dec 2005.

[5] J. A. Peças Lopes, F. J. Soares, P. M. Rocha Almeida, "Identifying Management Procedures to Deal with Connection of Electric Vehicles in the Grid", to be presented at the PowerTech'2009, Bucharest, Romania, June/July 2009.

[6] J. A. Peças Lopes, C. L. Moreira, A. G. Madureira, "Defining Control Strategies for MicroGrids Islanded Operation", IEEE PWRS - IEEE Transactions on Power Systems, vol.21, no.2, pp.916-924, June 2006.

[7] N. J. Gil, J. A. Peças Lopes, "Hierarchical Frequency Control Scheme for Islanded Multi-Microgrids Operation", Proceedings of IEEE Lausanne Power Tech 2007, Lausanne, Switzerland, July 2007.

[8] Carol S. Cheng, Dariush Shlrmohammadi, "A three-phase power flow method for real-time distribution system analysis", IEEE Transactions on Power Systems, vol. 10, no. 2, May 1995.

[9] Ministério do Ambiente e do Ordenamento do Território, "Plano Nacional para as Alterações Climáticas – Transportes", 2006.

[10] Associação Automóvel de Portugal, www.acap.pt.

[11] J.A. Peças Lopes, F.J. Soares, P.M. Rocha Almeida, P.C. Baptista, C.M. Silva, T.L. Farias, "Quantification of Technical impacts and Environmental Benefits of Electric Vehicles Integration on Electricity Grids", to be presented at the Electromotion 2009, Lille, France, June 2009.

[12] Carlos Lima Azevedo, "Métodos de estimativa de volumes anuais de tráfego rodoviário - um modelo para Portugal, *Master Thesis in Transports*", Instituto Superior Técnico, Universidade Técnica de Lisboa 2008.

[13] Department for Business Enterprise and Regulatory Reform, "Investigation into the scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles", 2008.

[14] C.A. Lewis, "Fuel and Energy Production Emission Factors", 1997.

Authors

J. A. Peças Lopes (M'80–SM'94) received the electrical engineering degree and the Ph.D. degree in electrical engineering from the University of Porto, Porto, Portugal, in 1981 and 1988, respectively.
In 1996, he received the Aggregation degree from the University of Porto.
Currently, he is Full Professor in the Department of Electrical Engineering of the Faculty of Engineering of University of Porto.
He is also Coordinator of the Power Systems Unit of Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto).

F. J. Soares received the Physics degree (five-year course) in 2004 from the Faculty of Science and an Electrical Engineering (Renewable Energies) Post-Grad in 2007, both in Porto University, Porto, Portugal.
He is currently pursuing the Ph.D. degree in electrical engineering from Porto University and Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto).
He is a Researcher in the Power Systems Unit of INESC Porto. His main research interests are focused on V2G impacts assessment.

P. M. Rocha Almeida received the Electrical Engineering degree (five-year course) in 2007 from the Faculty of Engineering, Porto University, Porto, Portugal.
He is currently pursuing the Ph.D. degree in electrical engineering from Porto University and Instituto de Engenharia de Sistemas e Computadores do Porto (INESC Porto).
He is a Researcher in the Power Systems Unit of INESC Porto. His main research interests are focused on V2G dynamics and control.

M. Moreira da Silva received the Electrical Engineering degree (five-year course), in 2006, and a Post-Grad in Sustainable Energy Systems (MIT Portugal Program), in 2008, both from the Faculty of Engineering – University of Porto, Porto, Portugal.
Presently, he is pursuing the Ph.D. degree in Sustainable Energy Systems (Power Systems field) from University of Porto, under the MIT Portugal Program.
He is a Researcher in the Power Systems Unit of INESC Porto. His main research interests are focused on energy storage strategies and sustainable mobility.