

Managing the Charging of Electrical Vehicles: Impacts on the Electrical Grid and on the Environment

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Abstract—Electric vehicles are seen as an option to reduce greenhouse emissions, directly related with the electricity generation mix and with the time of charging due to the variations of the generation sources during the day. At the same time, with their widespread adoption the increase in the demand for electricity to charge these vehicles could pose significant challenges to the electrical grid in terms of additional load due to unmanaged charge strategies. In order to mitigate these problems, the charging of the electrical vehicles must be managed. This paper presents the development of a system architecture to dynamically control the charging of electric vehicles to maintain the proper operation of the local distribution grid and minimize the environmental impact. The hardware consists of two modules, a meter and controllable plugs both with communication capabilities, while the software consists in a forecast and scheduler module. The forecast module calculates the load based on the power consumption behavior and uses the renewable generation forecast to assign the best time slot to charge the vehicle. The system aims to minimize the load peaks and flatten the load profile, while minimizing the environmental impacts. Based on the user preferences, system characteristics, consumption and renewable generation forecast, the system will assign the most suitable time slot to charge the electric vehicle. For the case of multiple electric vehicles, the system will schedule their charge based on a calculated priority level, in order to maintain a reliable operation of the local electrical grid.

Index Terms—Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, Charge Management, Demand Response, Smart Grid, Environmental Impacts

I. INTRODUCTION

Electric Vehicles (EVs) are expected to have a large share in the future of the transportation system, which will cause an additional load on the electric grid. The introduction in the market of vehicles with the capability to be plugged into the grid associated with a daily commute distance under 50 km (which requires up to 10 kWh of energy) for the majority of the users will make the EV one of the major energy consuming devices in a household. An EV charging, using a Level 2 charging station will draw 3.6 kW of power during around 3 hours per day for a 50 km commute.

Currently, due to the EVs low penetration rate the additional load imposed to the grid by the vehicles charging is not an issue, however in the future, with a higher penetration rate, this could bring serious consequences to the grid reliability [1]. The main problem is not in the extra energy required to charge

the batteries, but the peak load of the charging [2]. Since the majority of EVs will be charged at home, it is expected that the vehicle will be plugged in when their owners get home, at the end of the afternoon. The simultaneous charging of several EVs will lead to a considerable additional load that can overload the grid.

In order to mitigate these problems, the charging cycle of EVs must be managed. This concept of coordinate charging is being explored due to the wake of smart grids, where the exchange of information using several communication technologies can improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity [2]. Coordinate charging can also be beneficial for grids with a large share of renewable energy sources by concentrating the charging phase in periods of high renewable generation and therefore contributing to the grid reliability and to minimize the Greenhouse Gas (GHG) emissions [3].

Coordinated charging approaches are currently being investigated by using devices with bi-directional communication capabilities [4] [5]. This type of coordination is intended to minimize the negative impacts on the grid, due to a large number of vehicles charging at the same time by distributing this charge over a large period of time, flattening the load peak. Intelligent control over the introduction of new loads into the grid has the potential to provide economic benefits since peak demands affect the grid investments and operational costs [6] [7]. Minimizing demand peaks by distributing the load over a longer period of time in each household will contribute to reducing the transmission and distribution losses and stress in the grid equipment [8]. Despite the benefits for the grid in terms of increased reliability, this service can also bring economic advantages to the users [9].

Based on the commute profile of the users, it is reasonable to expect that EVs will be plugged in at least during 8 hours per day which is more than the required time to restore the energy spent, resulting in a flexibility that also can be harnessed to provide grid services while ensuring the requirements of the user. EVs could be an excellent demand dispatch resource given their potential for rapid response (can be turned on or off in a matter of seconds), the significant amount of power that they can draw during large periods of time and expected market penetration.

This paper presents the development of a hardware and software architecture for demand response, where the main goal is to manage in real time the additional load introduced by EVs when charging at home, avoiding triggering the installation protections due to overload, thus flattening the load profile in order to increase the reliability of the grid. Such system also reduces the energy costs of the charging process as well as minimizes the GHG emissions based on user preferences, EV battery State of Charge (SoC) and local installation power capabilities. The reminder of the paper is structured as follows: on Section II the hardware and software of the system architecture is presented. Then, the benefits that can be achieved with such architecture are assessed in Section III in terms of impact on the load diagram and in Section IV in terms of environmental impacts. Finally, section V summarizes the paper and draws conclusions.

II. SYSTEM ARCHITECTURE

To implement a system able to optimize the load profile and associated GHG, while achieving the user preferences, the following parameters are required from the user:

- **Contracted power:** Defines the maximum power that can be used from the grid without tripping the installation protections. To avoid such effect, if at a given moment the present or foretasted power reaches 80% of the contracted power, the EV is disconnected or the time slot is considered invalid for charge.
- **Vehicle charger power:** Specifies the amount of power that the electric vehicle will draw during the charging cycle (for a Level 2 charger this value is about 3.6 kW).
- **Battery SoC required:** Specifies the State of Charge (SoC) that is required by the user for the EV at a given time.
- **Unplug time:** This time defines the deadline to achieve the required battery SoC.
- **Energy tariffs:** Specifies the different costs of the consumed energy to different time periods. If several time slots are suitable to charge the electric vehicle, the chosen one will be the one with the lower tariff.
- **Renewable generation forecast:** This data is obtained from the Transmission System Operator (TSO) website and is used to determine the periods with higher available renewable generation. If several time slots are suitable to charge the electric vehicle, the chosen one will be the one with higher renewable generation.

A. Hardware Architecture

The system, described as SMARTplug, is composed by two main devices, an energy meter and a smart plug (Figure 1), both with communication, data storage and local processing capabilities. The energy meter module is intended to be installed on the feed point of the infrastructure, to measure in real time the global energy consumption, while the smart plug will replace the standard plug used to charge the EV. Such plug does not provides just energy as in a standard plug, but also ensures the control (ON/OFF) and the consumption monitoring. To ensure it, it has a solid state relay to ensure

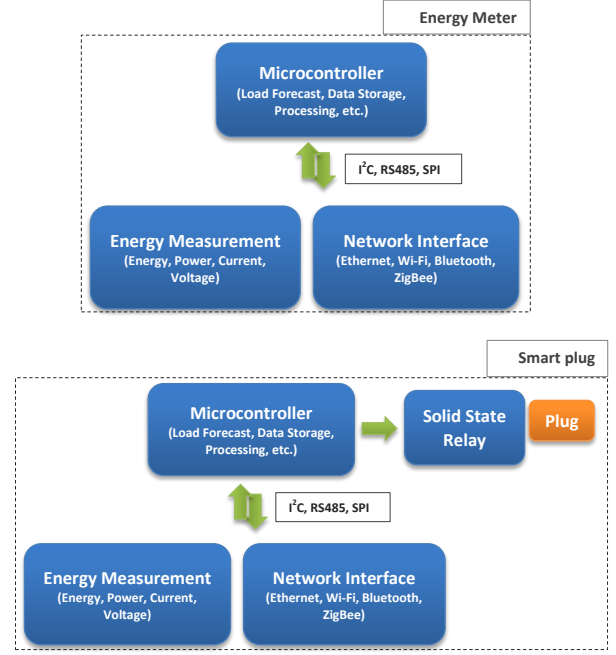


Fig. 1. SMARTplug system architecture with the energy meter (top) and the smart plug (bottom).

the control and the energy measurement unit and the micro-controller for communication, energy monitoring and data processing. The energy meter module will store the load diagram data from, at least, the previous three weeks to be used to forecast the future energy consumption.

The system architecture was intended to be modular, as such the communication between the different components of each module can be made through several standard communication interfaces, such as RS485, Inter-Integrated Circuit (I2C) or Serial Peripheral Interface (SPI). The communication between the energy meter and smart plug modules follows the same principle and can be implemented using Ethernet, Wi-Fi, RS485, etc. Any given communication interface can be used as long the software module that allows to use that interface is implemented in the micro-controller of the module.

Depending on the number of charging points for EVs, it is possible to have multiple intelligent plugs in the same infrastructure, but only one energy meter module is required. In the same building or infrastructure could be necessary to charge several EVs. To do it, multiple smart plugs are required (one for each EV). However, since the energy should be controlled globally to the building or infrastructure, only one meter for the global energy consumption of the building/infrastructure is needed. For a single charging point it is possible to integrate these two devices into one to avoid complexity and reduce costs.

The stored data is used to forecast the load during the time when the electric vehicle is plugged in and to assign a time slot to charge the EVs. If the EV is plugged in eight hours and only two hours are required to achieve the desired SoC,

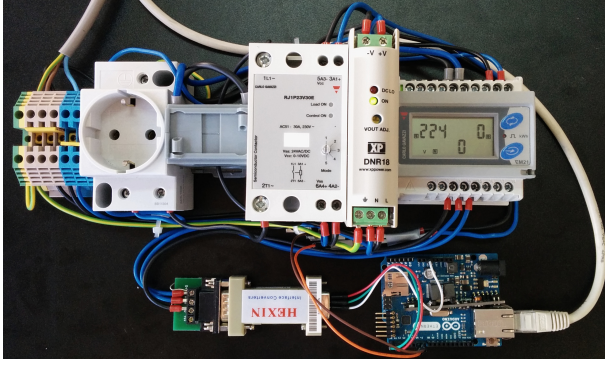


Fig. 2. Smart plug module prototype built using off the shelf DIN rail compatible components.

the time slot chosen will be the one with the lower tariff, with the highest share of RES (based on TSO RES forecast) and the lower impact on the load diagram in terms of peak power. This is presented in the software architecture.

In the current implementation, shown in Figure 2, the communication between the micro-controller and the energy measurement unit is through RS485, while the communication between the smart plug and the energy meter is through Ethernet (with Power over Ethernet comp ability). For testing purpose the energy meter module is emulated in a PC using load diagrams obtained from several monitored households.

B. Software Architecture

In terms of software architecture the SMARTplug system is composed by three main modules: a Load Forecast Module, a Classifier Module and a Scheduler Module. These software modules run in the energy meter micro-controller. The Load Forecast module is responsible to forecast the load based on previous data. This module uses the power data stored by the energy meter, excluding the contribution of the smart plugs for the global power consumption. The forecast is performed using the averaged previous data for the same time frame and taking into account if it is a working day or weekend, since the load diagram varies significantly from working days to weekend. The forecast is performed with five minutes interval, despite data is being stored at each second.

The Classifier module (Figure 3) is responsible by assessing the time slots where the charge of the EV may occur and classify them as valid or invalid. This module will run when the EV is plugged in and based on the load and renewable generation forecasts, electricity price, contracted power and power draw by the vehicle will determine a set of valid time frames to charge. The load forecast for a given timeslot considers the past five identical timeslots (e.g. the load from the previous five days at 15:00 hours) and is calculated using Equation 1:

$$L_t = \sum_{n=1}^5 \alpha_n \cdot L_n \quad (1)$$

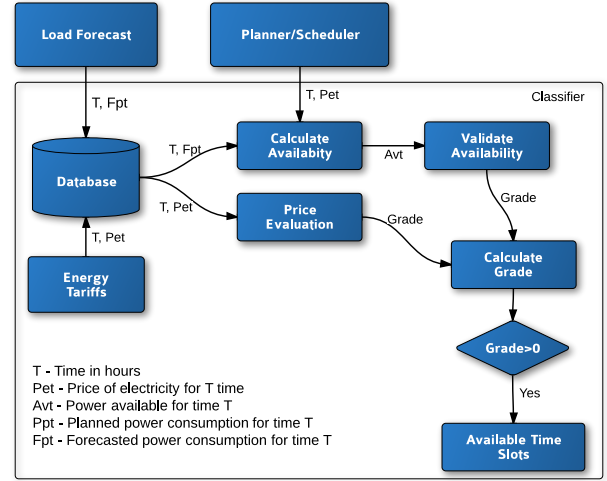


Fig. 3. Diagram for the classifier implemented in the SMARTplug system. The classifier determines the valid time slots to charge the EV based on the load forecast, electricity price and planned power consumption.

Where L_n is one of the past timeslots and α_n the weight factor considered for that timeslot. A given time slot is only valid if the contracted power is higher than the load forecast plus the power draw by the vehicle. The availability of a time slot is calculated using Equation 2:

$$A_{vt} = P_{cont} - (F_{pt} + SM) - P_{ch} \quad (2)$$

Where P_{cont} is the contracted power, F_{pt} is power consumption forecast for time T , P_{ch} is the power of the EV charger (3.6 kW for Level 2) and SM is a safety margin (0.2 kW). From Figure 3, in the validation of availability, depending on the ratio between A_{vt} and P_{ch} , a grade is assigned. The values for the grade were chosen arbitrarily to penalize time slots with high energy tariffs and demand forecast.

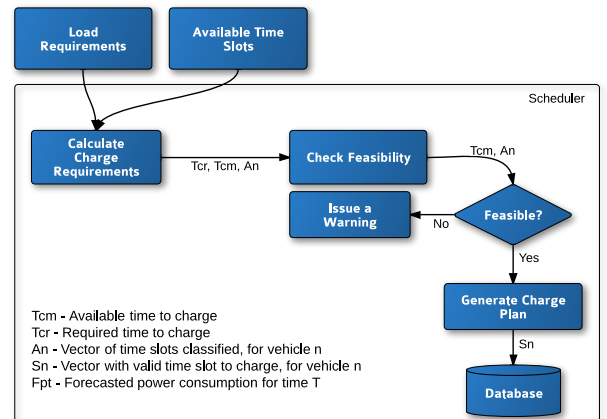


Fig. 4. Diagram for the scheduler implemented in the SMARTplug system. The scheduler generates a charge plan based on the available time slots and load requirements.

The Scheduler module (Figure 4) is responsible by the generation of a charging plan. After the validation of the time

slots, the planner will assign the best slot to charge the vehicle, based on load requirements (in this case the load is the EV). The load requirements are the capacity of the battery, the SoC of the battery when the vehicle is plugged in, the required SoC and the time of unplug. Based on these parameters the charging requirements are calculated using Equation 3:

$$T_{cr} = (B_{cap} - B_{cap} \cdot (SoC_{ini}/100))/P_{ch} \quad (3)$$

Where T_{cr} is the required time to charge in hours, SoC_{ini} is the initial SoC in % and B_{cap} in kWh is the useful battery capacity (on the Nissan Leaf from the 24 kWh only 20 kWh are useful). The feasibility is only validated if a set of available time slots required to charge the vehicle are less or equal than the ones available. If several sets of time slots are available to charge the vehicle, the chosen one will be the one with less impact in the load diagram and maximum RES contribution, based on the TSO forecast for the RES generation, in order to minimize the environmental impacts.

III. IMPACT ON THE LOAD DIAGRAM

To understand the extent in which the management of the additional load introduced by EVs could be controlled by a system with minimal intervention by the user, it is important to have detailed information regarding the energy consumption during a large period of time.

Figure 5 shows an extract from a load diagram, for a weekend and three working days, of a residence that was monitored. These load diagrams are only for the household loads, excluding EVs. By observing the load diagrams it is visible that the consumption is concentrated in specific points in time and is very similar from day to day. For a given residence the load diagram tends to be very stable for working days and weekends. Based on these facts and using consumption data gathered over time, the consumption for the next 12 hours can be predicted. Without access to this information it would be very difficult to the user to choose the ideal time to start charging the vehicle. The benefits of an automated system over the common approach, where the user is responsible for the process of start charging the vehicle, is that the system can choose the best time to charge the EV taking into account several variables.

To assess the impact that an EV can have in the energy and power consumption of a residence, the load profile during the charging cycle must be analyzed. Figure 6 presents the load profile of a Nissan Leaf for full charge and for a partial charge. The full charge absorbs around 21 kWh of energy from the grid at an approximately constant rate of 3.6 kW during a period of five and a half hours. The profile of a partial charge is identical to the one of a full charge, except in the duration. This partial charge has absorbed 5.5 kWh during one and a half hour. For an EV with an energy consumption of 150 Wh/km , a charge of 20 kWh will provide a range of about 130 km , while a charge of 6 kWh will be suitable for 40 km .

Figure 7 and Figure 8 present the impact of the additional load imposed by the EV in different scenarios, where the EV

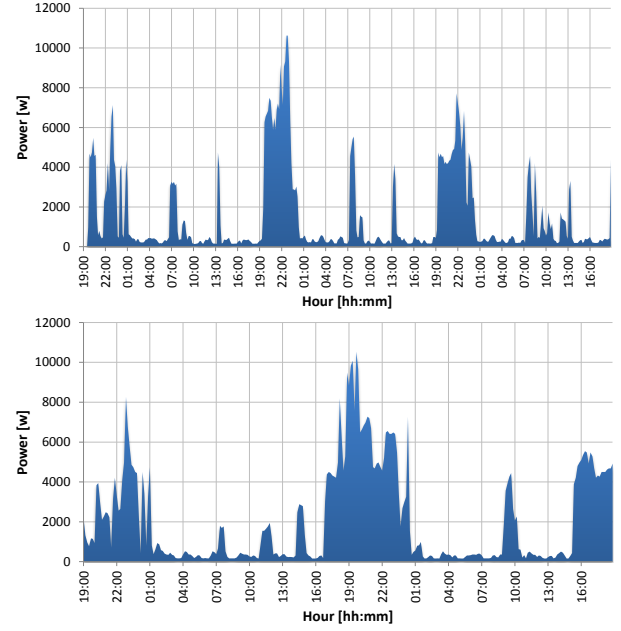


Fig. 5. Load diagram for three work days (top) and for a weekend (bottom) for a given residence.

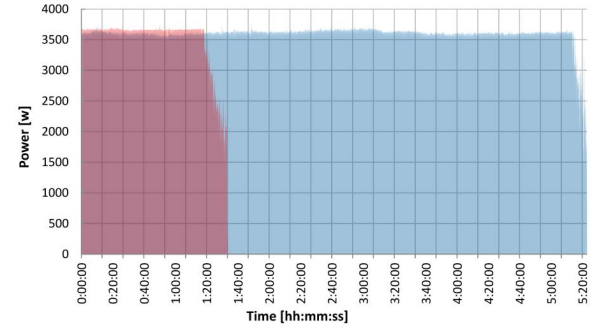


Fig. 6. Charge profile for the Nissan Leaf over a full charge cycle (top), with an energy consumption of 20 kWh over five and a half, and a partial charge cycle (bottom), with an energy consumption of 5.5 kWh over one and a half

is plugged at 19:00 and must be fully charged at 08:00. Such results are experimental data obtained with the current system implementation. The managed charge is based on the load forecast while the real load profile is presented for comparison. Figure 7 represents the impact of a partial unmanaged charge, where the vehicle starts charging when is plugged, and for a managed scenario, managed by the SMARTplug system.

Observing Figure 7, it is noticeable that the managed charge has a better performance than the unmanaged charge since it will occur in the valley of the load diagram that take place during the night, when the energy is cheaper. The managed charge also reduces the peak power required to charge the vehicle, since it only tries to charge it when the forecasted power consumption for the household, in a given time period, is minimum. Therefore, the system is able to reduce costs and power requirements and thus increasing the grid reliability. If

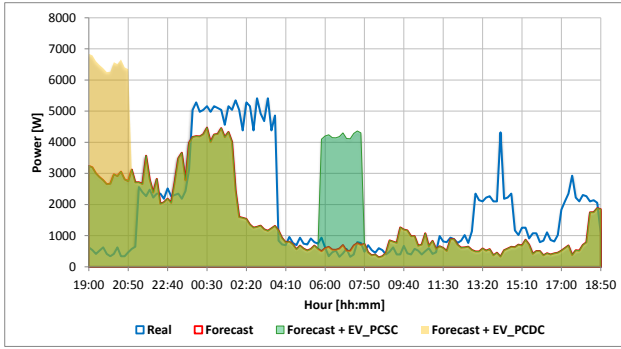


Fig. 7. Load diagram (real and forecast) for a household with an EV unmanaged (EV_PCDC) and managed (EV_PCSC) partial charge. The vehicle is plugged in at 19:00 hours and must be charged at 08:00. The charge takes two hours and consumes 7.2 kWh.

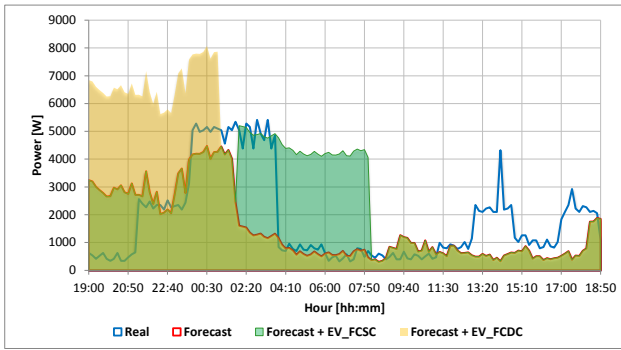


Fig. 8. Load diagram (real and forecast) for a household with an EV unmanaged (EV_PCDC) and managed (EV_PCSC) full charge. The vehicle is plugged in at 19:00 hours and must be charged at 08:00. The charge takes six hours and consumes around 21 kWh.

the vehicle is plugged in only at 23:00 hours the peak power will be much higher and the household protections could be tripped due to overload. The benefit of a managed charge is more visible for full charge cycles where a large amount of power is drawn over a long period of time (Figure 8). In such situation the system is also able to reduce the costs and power requirements, but with a higher impact due to the longer duration of the charging.

In this approach, a simple forecast algorithm was used and by observing the load diagram from Figure 7 it is noticeable that for a given time period the load forecast will not match the real load accurately. This happens for periods where the load variation for a given time period is not very constant during the past days. Upgrading it to consider the different types of loads found in a household and including a model based on their use could improve the load forecast, however this approach would require a more complex configuration of the system. If multiple EVs are charging at the same time, the algorithm takes into account the charging plan of the remaining (their load is considered in the load forecast) vehicles. The system will give priority to the vehicles with tighter deadlines to achieve a pre-determined battery SoC. If a given vehicle cannot meet the user requirements, the user

intervention is required to change the parameters.

IV. ENVIRONMENTAL IMPACTS

The main aim of the presented system is to ensure a flatter load diagram and to decrease the charging costs. However, a second objective is to maximize the use of energy in periods where the environmental impacts associated to the EV charging are lower (based on the RES generation forecast). The first priority is to select the period for charging the EV which ensures a minimum impact on the total required power, but when different periods are available to ensure it, the system selects the period with lower environmental impact.

The environmental impacts associated with the EV battery charging are directly related with the electricity generation. The electricity generation mix varies from region to region and in a daily and seasonal basis, due to the variation on the renewable generation resources. To assess these impacts the Portuguese electricity mix was considered, taking into account their daily variation during a year. The monthly impacts were assessed considering the days with the minimum and maximum share of RES for a given day in that month. This allows the evaluation of the system performance in extreme situations of the RES share.

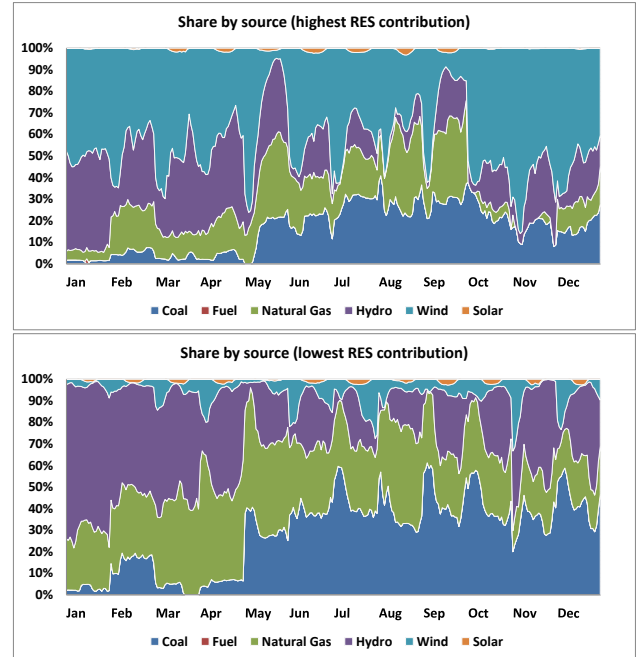


Fig. 9. Evolution of the contribution from the primary energy sources for the Portuguese electricity mix during 2011, considering the highest (top) and lowest (bottom) contribution from RES.

The impacts associated with electricity generation were calculated taking into account the emissions from Table I, which represent the life-cycle impacts of average European technologies, and the daily variation during a year for the several energy sources that contribute to the Portuguese electricity mix (Figures 9). Figure 10 represents the real RES generation and the forecast by the TSO for the same period.

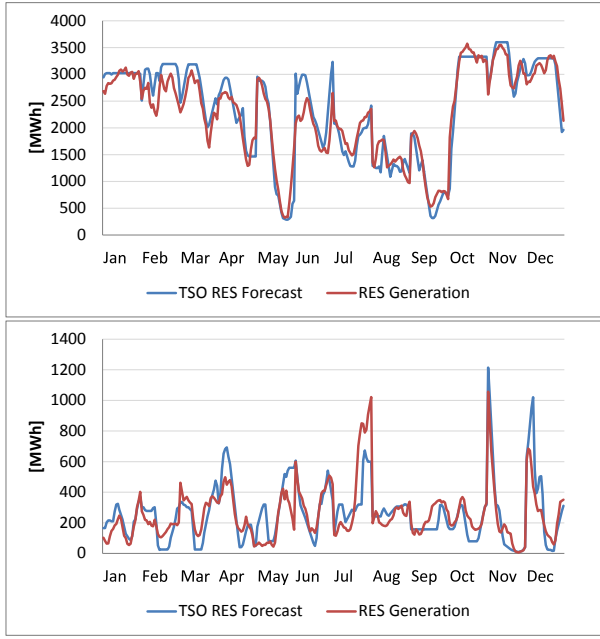


Fig. 10. RES electricity generation, both real and the forecast from the TSO, for the maximum (top) and minimum (bottom) share of RES in the Portuguese electricity mix.

The following impact categories from CML 2001 were assessed: Abiotic Depletion; Acidification; Eutrophication and Global Warming Potential. In terms of environmental impacts, Abiotic Depletion is associated with the depletion of non-renewable resources and their availability for future generations; Acidification estimates the potential contribution from SO_2 , NO_x , HCL , NH_3 and HF to the potential acid deposition (potential to form H^+ ions); Eutrophication estimates the potential to cause over-fertilization of water and soil, which can lead to an increase growth of biomass and GWP is the sum of emissions of the greenhouse gas (CO_2 , N_2O , CH_4 and Volatile Organic Compounds) multiplied by their respective GWP factors.

TABLE I
LIFE CYCLE ENVIRONMENTAL IMPACTS BY TYPE OF GENERATOR [10].

	Ab. Depletion [gSbe/kWh]	Acidification [gSO ₂ e/kWh]	Eutrophication [gPO ₄ ³⁻ e/kWh]	GW [gCO ₂ e/kWh]
Coal	7.8	2.8	2.3	1020
Wind	0.08	0.05	0.027	11.3
Hydro.	0.03	0.16	0.05	6.5
Solar PV	0.36	0.246	0.157	50.9
Nat. Gas	3.7	0.413	0.07	434
Diesel, Oil	5.9	19	0.57	911

The environmental impacts were calculated for the managed and unmanaged charge of the EV, both for a partial and full charge. The scenario where the RES generation forecast is taken into account for the attribution of charging slots was also considered. These results were calculated assuming a 90% efficiency for the electricity transport and distribution grid, and

a traveled distance of 40 km/day (15000 km/year) for an EV with an energy consumption of 150 Wh/km. The partial charge of the EV occurs on a daily basis and requires around two hours to charge 6 kWh, while the full charge occurs approximately two times a week and requires six hours to charge around 21 kWh.

This type of assessment allows the comparison between different charging strategies and to identify the strategy with the lower environmental impacts. The results considering the electricity mix with the highest share of RES sources are presented on Figure 11, while the results for the mix with the lowest share of RES sources are presented on Figure 12.

Observing Figures 7 and 8, for the load diagram impact, and Figure 11 and 12, for the environmental impacts, it is noticeable that a managed charge is beneficial by distributing the load diagram peaks along the day. A partial charge is also beneficial since it allows a broader period to be selected to charge the EV and thus reducing the load diagram peak. In terms of environmental impacts, a managed charge is also beneficial, when compared with an unmanaged charge, being the benefits higher if the RES forecast is taken into account, as it is ensured by this system. In this case, a partial charge presents more benefits than a full charge, being this type of managed charge more beneficial for a system with a large share from RES. The total impacts per year for each impact category are presented on Table II and III.

TABLE II
ENVIRONMENTAL IMPACTS, PER YEAR, FOR A MANAGED AND UNMANAGED CHARGE OF EV FOR THE PORTUGUESE ELECTRICITY MIX, WITH THE HIGHEST SHARES OF RES.

	Ab. Depletion [kgSbe]	Acidification [kgSO ₂ e]	Eutrophication [kgPO ₄ ³⁻ e]	GW [kgCO ₂ e]
FCDC	5.08	1.48	1.07	645.12
PCDC	5.38	1.56	1.14	639.38
FCSC	4.21	1.24	0.89	534.62
PCSC	4.63	1.34	0.96	549.27
FCSC+maxRES	4.21	1.24	0.89	534.62
PCSC+maxRES	4.01	1.16	0.82	475.59

TABLE III
ENVIRONMENTAL IMPACTS, PER YEAR, FOR A MANAGED AND UNMANAGED CHARGE OF EV FOR THE PORTUGUESE ELECTRICITY MIX, WITH THE LOWEST SHARES OF RES.

	Ab. Depletion [kgSbe]	Acidification [kgSO ₂ e]	Eutrophication [kgPO ₄ ³⁻ e]	GW [kgCO ₂ e]
FCDC	8.38	2.32	1.67	1057.97
PCDC	7.66	2.07	1.47	903.57
FCSC	9.74	2.77	2.03	1232.81
PCSC	9.49	2.69	1.96	1123.88
FCSC+maxRES	9.74	2.77	2.03	1232.81
PCSC+maxRES	9.89	2.81	2.05	1170.32

V. CONCLUSIONS

In the future EVs will have an active contribution in the electrical grid management, due to a significant penetration

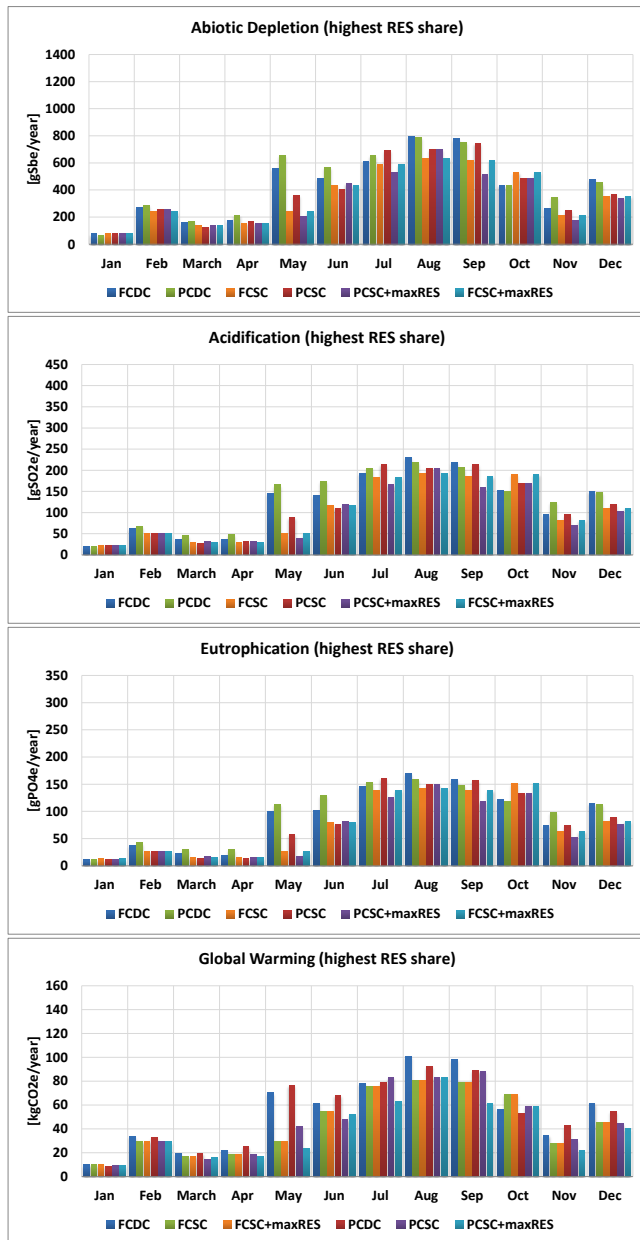


Fig. 11. Environmental impacts for each impact category for the Portuguese electricity mix, with the highest share of RES, for a year. The results are for a managed (FCSC and PCSC) and unmanaged (FCDC and PCDC), both for full and partial charges, respectively. The scenario where the managed charge takes into account the RES forecast is also considered (FCSC+maxRES and PCSC+maxRES), both for full and partial charges.

ratio, by being able to absorb and inject power in a smart grid environment). However, nowadays even with a low penetration ratio of EVs and with the smart grid in an embryonic stage it is already possible to develop solutions that can implement some concepts from the smart grid. The capacity to inject power into the grid will lead to additional cycling of the EV battery, and contributes to accelerate the battery aging, however this impact will depend on the frequency that the grid will require this service. Due to cheaper electronics,

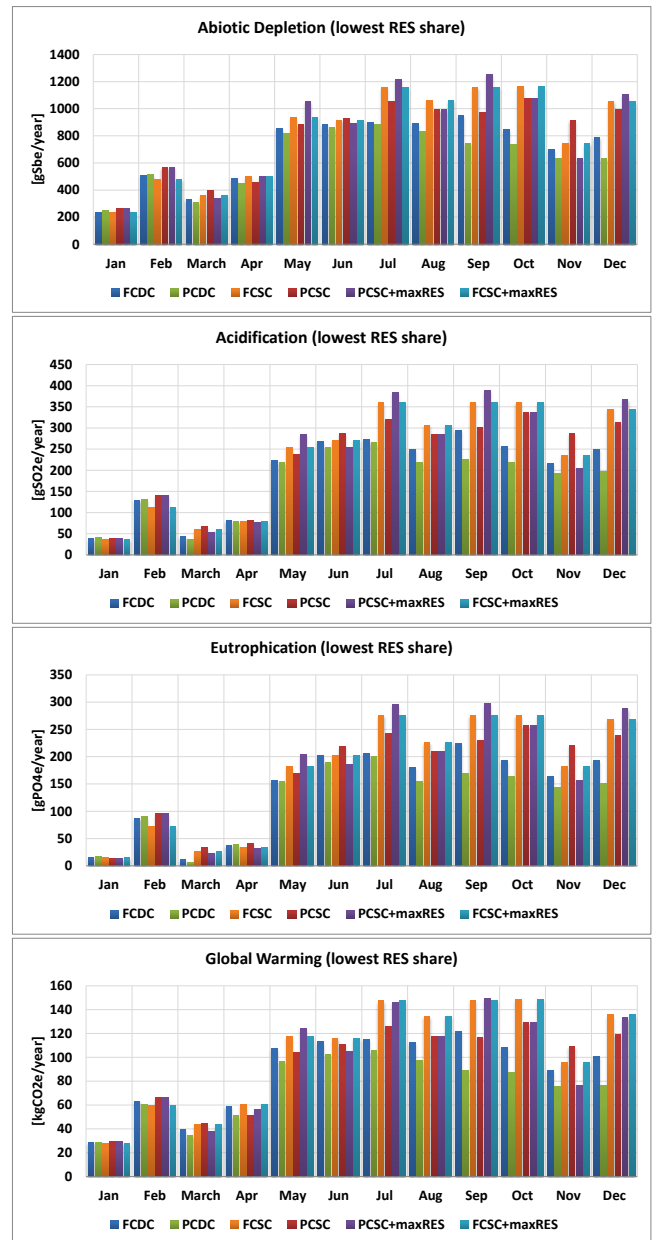


Fig. 12. Environmental impacts for each impact category for the Portuguese electricity mix, with the lowest share of RES, for a year. The results are for a managed (FCSC and PCSC) and unmanaged (FCDC and PCDC), both for full and partial charges, respectively. The scenario where the managed charge takes into account the RES forecast is also considered (FCSC+maxRES and PCSC+maxRES), both for full and partial charges.

standardization and mass use of communication infrastructures it is possible to develop a system than can be integrated in a smart grid, by implementing state of the art concepts without or with minimal intervention from the consumer, simply by updating the software in the device. By using a system similar to the described, the charging of an EV is straightforward and situations that can pose a risk to the household electrical system can be mitigated.

Several other approaches of charging systems to manage the

required power and costs were already proposed [11] [12] [13] [14] [15]. However, they are typically ensured by the design of new chargers and additional control infrastructure, which increases the costs and the complexity of the system. The system proposed in this paper is based on a simple controllable plug and a meter. Therefore, such system can already be easily used since it does not require any additional infrastructure and only uses data that is already available. Due to the simplicity of such system it has potential to be a very cheap solution with high reliability. The system is reliable in its operation, however if the energy use profile is changes suddenly the charge of the EV cannot be assured, since the charge scheduling is based in a forecast based on the energy use profile. This could be adjusted by increasing the safety margin, which in turn could increase periods where the EV could not be charged.

Currently, demand side management requires the active consumer involvement, which is not very effective. By relying on a system that only requires the consumer input to specify its preferences, it can be shown that the additional load due to the charge of EVs can be easily integrated in the daily load diagram of a household without contributing to increase the peak demand and ensuring the minimization of environmental impacts. A partial charge of the EV, in a daily basis, is preferred to a full charge two times a week, since it allows a larger margin for the system to schedule the EV charge. This allows not only the reduction the impact on the grid, in terms of peak power demand, but also contributes to a higher reduction in terms of environmental impacts. The system is also able to detected abnormal situations and notify the consumer (when it is not possible to meet the charge requirements) or act accordingly (when the EV is charging and an overload situation is imminent the charge is stopped).

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