Development of an Energy Management System for the Charge Scheduling of Plug-in Electric Vehicles

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Abstract. As the number of Plug-In Electric Vehicles continues to rise, existing electrical grids need to adapt to support the expected charging demand of such vehicles. Fortunately, a growing number of renewable energy sources are also being introduced in current electrical grids, reducing the dependency on fossil fuels. Leveraged by the self-consumption legislation in several countries, the introduction of renewable energy sources continue to happen well beyond the end of the feed-in tariff rates. However, due to their variable nature, renewable energy sources are frequently characterized as intermittent resources, which cause mismatches in the required equilibrium between production and demand. In this scenario, the role of end users is very important, since they are not only required to participate in energy generation - becoming the so-called prosumers – but also they should allow the adjustment of the consumption, according with the generation levels. Plug-In Electric Vehicles, due to their power requirements, just exacerbate this problem. Following our previous work concerning scheduling algorithms for self-consumption scenarios, in this paper we describe the implementation of an Energy Management System for the charge scheduling of Electric Vehicles. The proposed system considers several requirements, including electrical grid limitations, present time and subsequent tariff costs, actual and predicted renewable energy generation levels, and user preferences. It then runs an optimization algorithm that decides when the charging of such vehicles should happen and controls the power delivered to charge them, accordingly.

Keywords: Plug-in electric vehicles · Load scheduling

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1 Introduction

Electrical grids are undergoing a process of transformation that result, among others, from an increasing integration of renewable energy sources at the distribution level. In many countries, legislation nowadays allow end users/companies to produce electricity from renewable energy sources and consume it, or sell it, while they are still connected with the utility operator.

The introduction of such Distributed Generation (DG) sources (Shen 2012), however, requires the implementation of methods capable of ensuring the mandatory real time balance between consumption and production - a challenge magnified by the variable nature of renewable energy sources.

In this context, users play a critical role (Monteiro et al. 2014). In order to use the energy that is produced at a certain time instant, users need to allow the adjustment of the working periods of their electrical appliances. This can be done through a manual control of each equipment, machine or lighting system, or preferably through an Energy Management System (EMS) that automates the whole process. EMSs perform the control of electrical devices, reducing user intervention by running an optimization algorithm that decides when electrical devices should work. In order to do it, EMSs take into account several factors, including: (1) user restrictions, (2) generation levels, (3) tariff rates, (4) contracted power level and (5) electrical circuit limitations (Monteiro et al. 2014). Based on these parameters and restrictions, EMSs then run scheduling algorithms that identify solutions aiming to either minimize costs or maximize profits. While EMSs can potentially simplify power management, reducing the weight of individual on/off control of electrical devices, they are also a complex solution that require a combination of Information and Communication Technologies (ICT), Internet of Things (IoT), Human Computer Interaction (HCI) and Operational Research techniques.

At a certain level, Electric Vehicles (EVs) can be seen as another electrical load that require significant amounts of energy and power in the charging process. In the context of Smart Grids, the increasing capacities of their batteries also make them an ideal storage solution capable of accommodating the overproduction, whenever the power generated surpasses the consumption levels. Thus, even without considering reverse charging, EVs can not only be seen as a problem, but also, as part of the solution.

Since EV parking facilities will likely play an important role in the charging process, in this paper we focus in building an EMS for these infrastructures (see Fig. 1). Given the current legislation regarding self-consumption and the current perspectives about the introduction of renewable energy sources, in this paper we consider that the electrical grid of such park is, at the same time, connected to the utility grid and generating electricity for their own consumption. Thus the energy can either be bought from the utility company or sold.

For this type of scenario, in (Monteiro and Nunes 2015, Cruz and Monteiro 2017) we have defined and tested different algorithms for charge scheduling of EVs. Particularly in (Cruz and Monteiro 2017) the EV scheduling algorithm was adapted to consider different charging powers, as happens with EVs. Based on these improvements we have then tested the enhanced versions of the scheduling algorithms

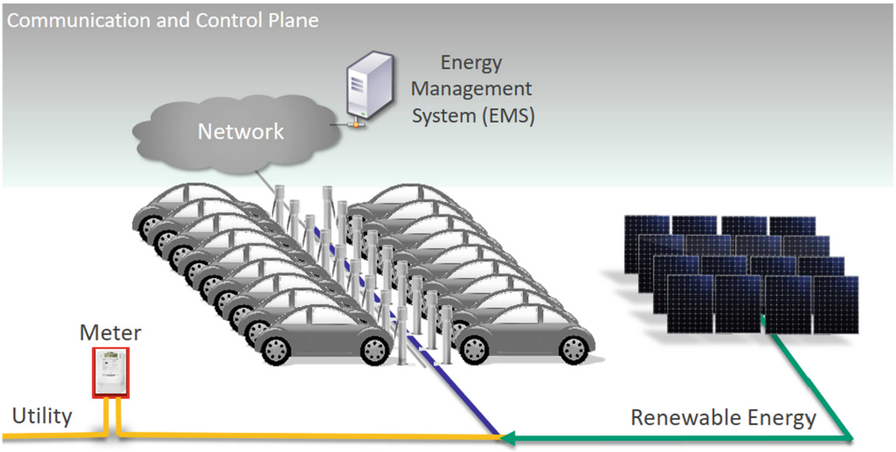


Fig. 1. Scenario considered in this paper.

considering real generation data and dynamic tariff values of several days in different months of the year, with very distinct generation conditions. In this paper we extend the work previously done, by describing the implementation of an EMS and Electric Vehicle Supply Equipment (EVSE) that use these algorithms to manage charging stations.

The rest of this paper has the following structure. Section 2 presents the current state of the art in terms of standards for EV charge control and algorithms for the charge scheduling of EVs. Section 3 presents the results of a survey that analyzed user preferences concerning the scheduling of electric vehicles. Section 4 presents the implemented elements comprising the EMS and EVSE. Section 5 concludes the paper, pointing out some future developments of this work.

2 State of the Art

2.1 Standards for EV Charge Control

Several standards have been defined for the interoperation between electric vehicles and electrical grids (Schwarzer and Ghorbani 2015). One of such standards is the International Electrotechnical Commission standard IEC-62196 that defines the conductive charging processes of electric vehicles. Particularly, the IEC International Standard 62196-1 (2014) defines the general requirements that apply to plugs, socket-outlets, vehicle connectors, vehicle inlets and cable assemblies for electric vehicles, incorporating control solutions and having a rated voltage not exceeding: (1) 690 V AC, 50–60 Hz, with a rated current not exceeding 250 A; or (2) 600 V DC, with a rated current not exceeding 400 A.

The international standard IEC 61851 defines conductive charging systems based on AC or DC, and defines the charging modes for electric vehicles and their respective EVSE. As defined in the IEC International Standard 61851-1 (2017) the defined modes are: Mode 1 - Slow charging through normal household outlets; Mode 2 - Slow charging through standard household outlets, but with a cable protection unit; Mode 3 - Slow or fast charging with a specific outlet, with protection and control functions; and Mode 4 - Quick Charging, using an external charger.

Signalling pins that allow status information to be conveyed between the EV and EVSEs have been defined in the standard SAE J1772-2001, and later on, included in both IEC 61851 and IEC 62196-2 standards. In addition to the power pins and Protective Earth, all types of IEC 62196-2 connectors have two additional pins: the Control Pilot (CP, pin 4) and the Proximity Pilot or Plug Presence (PP, pin 5). Together they allow a basic control and communication between the EV and the EVSE regarding the charging process. For instance, in Mode 3, EVSEs are able to inform EVs about the maximum current that they are allowed to get from the electrical grid, using a PWM signal in the CP.

Another standard that is currently under definition for the vehicle-to-grid communication interface (V2G CI) is ISO 15118. It complements the IEC 61851-1 standard, providing Internet Protocols (IP) bi-directional digital communications. It also defines the data and message format of the V2G CI. Thus, the aim of the standard is to establish a more advanced and autonomous charge control mechanism between EVs and charging infrastructures (Schmutzler et al. 2012; Käbisch et al. 2010). Currently, ISO 15118-1 (2013) standard concerning the general information and use case definition, ISO/IEC 15118-2 (2014) regarding network and application protocol requirements and ISO/IEC 15118-3 (2015) that includes the physical layer and data link layer requirements have already been issued as international standards. The rest of the list of ISO/IEC 15118 international standards, namely: 15118-4 (network and application protocol conformance test); 15118-5 (physical and data link layer conformance tests); 15118-6 (general information and use case definition for wireless communication); 15118-7 (Network and application protocol requirements for wireless communication); and 15118-8 (physical layer and data link layer requirements for wireless communication), are currently under definition.

While these standards support the communication between EVSEs and EVs, other mechanisms are needed to schedule the charging process of these vehicles. In the following we describe some of these solutions.

2.2 Algorithms for Charge Scheduling of Electric Vehicles

Given an EV parking facility, consisting of several EVSEs and/or plugs, which integrates renewable energy generation under a self-consumption scenario, several algorithms can be used to schedule their charging periods. Basically these algorithms can be classified into two types: predictive versus non-predictive solutions.

Predictive scheduling algorithms decide when loads should work taking into consideration future variables, like for instance the future (i.e. predicted) generation levels or the subsequent tariff rates. Using an objective function, optimization algorithms are used to either minimize costs, or maximize profits. Several predictive scheduling solutions can be used, as exemplified next.

The Earliest Departure First (EDF) (Chen et al. 2012) is an algorithm that schedules the charging of electric vehicles according with the associated time of departure. So

EVs that leave sooner, will have a higher priority. While EDF was adapted to EV scheduling in (Chen et al. 2012), the proposed EDF algorithm did not consider self-consumption scenarios and thus the variability of renewable sources could lead to the non-completions of the charging process, so penalties were considered when a request was not assured. Since the variability of the renewable energy sources does not fit well in strict models that assures all the energy that is requested by car owners, in (Monteiro and Nunes 2015) the algorithm was changed to consider two charging components, one mandatory and the other optional. Given the fact that EVs tend to have battery capacities well beyond the required for daily usage, the model considers that drivers will tend to allow their cars to serve as storage units whenever the generation levels surpass the consumption ones. Yet, this assumption was not validated. This last model, was called Adapted EDF (AEDF). AEDF was compared with other scheduling solutions (Monteiro and Nunes 2015), namely Linear Programming (LP), First Come First Served (FCFS) and with an algorithm that charges conversely in respect of tariff rates (so called gradual). Later in (Cruz and Monteiro 2017), the model was improved and further tested in different scenarios.

In terms of non-predictive solutions, one implementation that has gained some relevance is PowerMatcher. PowerMatcher combines power distribution systems with a communication protocol to create a unique and flexible Smart Grid. This technology allows the adjustment of the operation of loads according with the production from both renewable and conventional energy sources. It also applies demand and supply market laws. These algorithms were adapted to consider EV charging, as in (Bliek and Van Den Noort 2010) and (Kamphuis et al. 2013). Also, in (Kempker et al. 2015), a stochastic dynamic programming strategy is used to perform the load scheduling in PowerMatcher, with the objective of minimizing the total cost of charging EVs, within a given time interval. For this, an optimum control rule was used to determine the amount of energy that can be charged in a given period of time.

Among all the above explained solution only the proposed LP and AEDF algorithms perform a predictive type of scheduling. The results obtained in (Monteiro and Nunes 2015) demonstrate that these predictive algorithms are able to achieve better results when compared with non-predictive options, like the FCFS and Gradual model. Still, while LP has demonstrated in (Monteiro and Nunes 2015, Cruz and Monteiro 2017) to be able of achieve the best results, AEDF obtained similar results with much lower computational costs. Thus in the following we will select the AEDF algorithm as the optimization mechanism of the Energy Management System.

3 Evaluation of User Preferences in the Scheduling of Electric Vehicles

As already explained the AEDF model assumes that the vehicle owner will be available or willing to participate in demand response, by adjusting the charging level of the EV according with the generation levels. However this assumption was not previously validated. In order to assess it, we started by conducting a survey. In it, among other questions, we asked assessors about their availability in adjusting the charging level of their Electric Vehicle according with the level of power generated locally. The survey was made available online, resulting in a total of 364 assessments. Table 1 summarizes the main characteristics of the evaluation panel.

Table 1. Description of the evaluation panel in terms of: Gender; Education; Age group; Number of persons in the household; and Number of vehicles in the household

Gender	[%]
Female	50.6
Male	49.4

Education	[%]
Basic	0.3
Secondary	8.0
Bachelor	31.6
Master	23.8
Phd or above	36.3

Age	[%]
18 – 25	5.1
26 – 30	7.3
31 – 35	12.0
36 – 40	10.7
41 – 45	22.6
46 – 50	19.2
51 – 55	12.0
56 – 60	6.4
61 – 65	3.4
66 – 70	0.9
71 – 75	0.4

Persons in the household	[%]
1	13.6
2	27.1
3	28.8
4	26.6
5	3.6
6	0.3

Vehicles in the household	[%]
1	24.8
2	58.0
3	13.2
4	2.5
5	0.6
6	0.3
7	0.0
8	0.6

The large majority of assessors stated that they would be available to adjust the charging of their EV according with the generation levels (only 4.2% of assessors answered no). Among those that responded this question: (1) 57.5% answered that they would be available to do it, but just if the system would guaranty them a minimum level of charge, and thus autonomy; (2) 36.8% answered that they would be willing to charge with energy coming from renewable energy sources, regardless of the economic benefit they would get from it, while (3) 26.4% answered that they would be available to do it, if they could get some economic benefit from it; finally (4) 26.1% answered that they would be available to do it, but only if the system was automated, and thus not relying in their interaction.

When asked about the relevance of having a system in their homes capable of lowering the electricity costs by automatically managing the charging periods of their future electric vehicle(s) (according with the tariff rates, renewable energy generated, and/or avoiding to pay more for the contracted power), 73.2% of answered positively.

These results show that most of the persons consider it relevant to have a device that is capable of managing the charging process of their EVs, and to use them as storage units, as long as it respects some conditions like: minimum autonomy of the EV, economic benefit, and/or simplicity of usage.

4 Development of the Electric Vehicle Scheduling Device

Given the aforementioned results we now proceed to describe the implementation of the Energy Management System. We start by describing the renewable aware model for the scheduling of EVs, followed by the description of the implemented system.

4.1 Charge Scheduling Algorithm

The EMS schedules EV charging times in accordance with a model that was firstly proposed and described in (Monteiro and Nunes 2015). It considers that the total energy requested by each EV (E_{Tv}) can be obtained through two components, a Guaranteed Energy (E_{Gv}) part and Non-Guaranteed (E_{Nv}) one.

The Guaranteed Energy part reflects the minimum energy required by the user/owner to charge a specific EV, whose fulfilment until the end of the charging period, is mandatory. This energy in turn can be obtained from two power components, namely the utility grid (C_{vt}) or local renewable sources $\left(P_{gvt}\right)$.

As for the non-Guaranteed Energy component, it can only use power generated locally $\left(P_{nvt}\right)$ using renewable energy sources and therefore it completely depends in its availability. When there is no spare energy, the non-Guaranteed Energy component will not be fulfilled. However if, at any given instant, the power generated surpasses the Guaranteed Energy part, EVs will start to be used as storage units. This can be an advantage to parking facilities that, by this way, are able to avoid selling the energy at a very low rate (as for instance 0.045 € per kWh in Portugal), as long as they are able to sell it to car owners by any value higher than that. This would also result in an advantage to car owners since they would probably pay more at their own facilities if they buy it from the utility.

From the point of view of the electrical grid, the non-Guaranteed Energy component gives an additional degree of freedom to the system, introducing a flexibility in the charging process that aims to compensate the intermittent nature of renewable energy sources.

The total energy requested for an EV (E_{Tv}) is thus given by the sum of the two energy components, as shown in Eq. (1).

$$E_{Tv} = E_{Gv} + E_{Nv} \tag{1}$$

In (Cruz and Monteiro 2017), the AEDF algorithm was improved when compared with the one presented in (Monteiro and Nunes 2015). Not only allows charging of EV batteries with different power levels, but also accounts for the economic return obtained from selling the surplus photovoltaic production to the utility grid, in accordance with a self-consumption legislation. The algorithm aims at minimizing the cost of buying energy from the utility and maximize the profit that will be obtained from the energy regulator.

For each EV, starting with the ones that leave sooner, the algorithm selects as charging intervals, the subsequent periods of time that show lowest tariff costs. In addition, if there is local generation, the purchase cost and sale revenue of the renewable energy produced are compared, and the lowest cost (highest profit) is selected.

The EV allocation is done according to:

- For each non allocated EV, allocate renewable energy for the Guaranteed part (E_G) until exhaustion;

- For each non allocated EV, allocate power from the utility grid for the Guaranteed part (E_G) starting with the lowest available costs;
- For each non allocated EV, allocate renewable energy for the Non-Guaranteed part (E_N) until exhaustion.

Please see (Cruz and Monteiro 2017) for further details regarding the AEDF scheduling algorithm.

4.2 Implementation of the Energy Management System

Figure 2 shows the general architecture of the implemented energy management system, including the communication interfaces between several modules. The system is divided into four units, namely the Energy Management System (EMS), Human Machine Interfaces (HMI), Machine to Machine (M2M) and Operations Management System (OMS). Each of these units encompasses several modules responsible for a specific function.

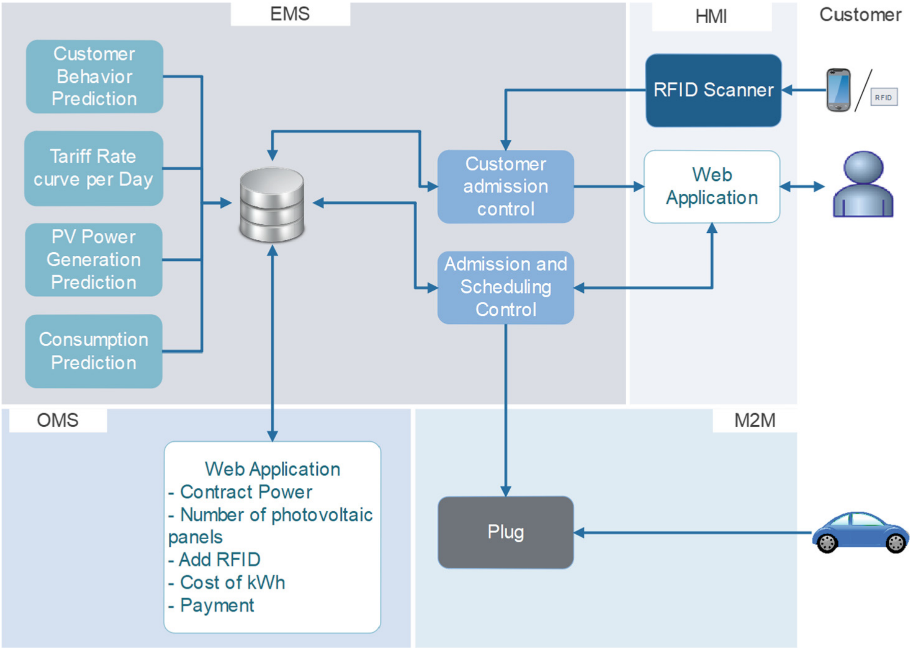
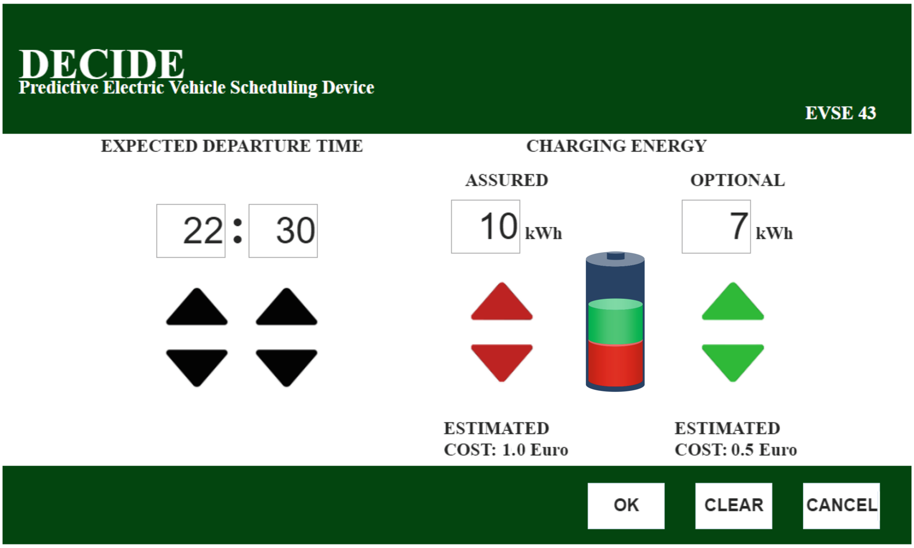


Fig. 2. System architecture of the energy management system.

When accessing the system for the first time, the user communicates with the EMS using an Web interface. An RFID card in then associated to his account. In the Web interface he will be able to insert the expected time of departure and the assured (Guaranteed) and optional (non-Guaranteed) charging levels, as shown in Fig. 3. After this initial configuration, the system will try to minimize repeated user intervention by learning from his daily routines. Still, subsequent changes to these values can always be made online, from any computer or smartphone.



EXPECTED DEPARTURE TIME 22 : 30

ASSURED 10 kWh

OPTIONAL 7 kWh

ESTIMATED COST: 1.0 Euro

ESTIMATED COST: 0.5 Euro

Fig. 3. User Interface for the selection of expected time of departure and charging values.

Figure 4 shows the sequence of messages for the setting up of the charging process. The EV charging process begins with Customer's authentication using the RFID card. The RFID scanner reads the card ID and requests the verification of the customer, to the Admission Control module. This module then checks if the user registration is valid, requesting the associated data from the database. After the successful client registration, the HMI unit requests the identification of an available socket, consulting the database. The user will then be informed about which plug he should connect his EV to. After connecting the EV to the selected plug, the HMI then powers it up.

When the user connects his vehicle to a type 2 socket for the first time, the EVSE Protocol Controller reads the maximum power that can be used to charge the associated EV, measuring the internal resistor of the cable. As this value will later be used by the scheduling algorithm, it is also stored in the database, as a feature of that particular vehicle of a certain user.

Figure 5 shows the EVSE that is being implemented, from the 3D design to its internal structure.

5 Conclusions and Future Work

In this article, we describe the development of an EMS and EVSE that implement the scheduling of electric vehicles in a charging facility/park. The implementation is based on an optimization model that was previously tested.

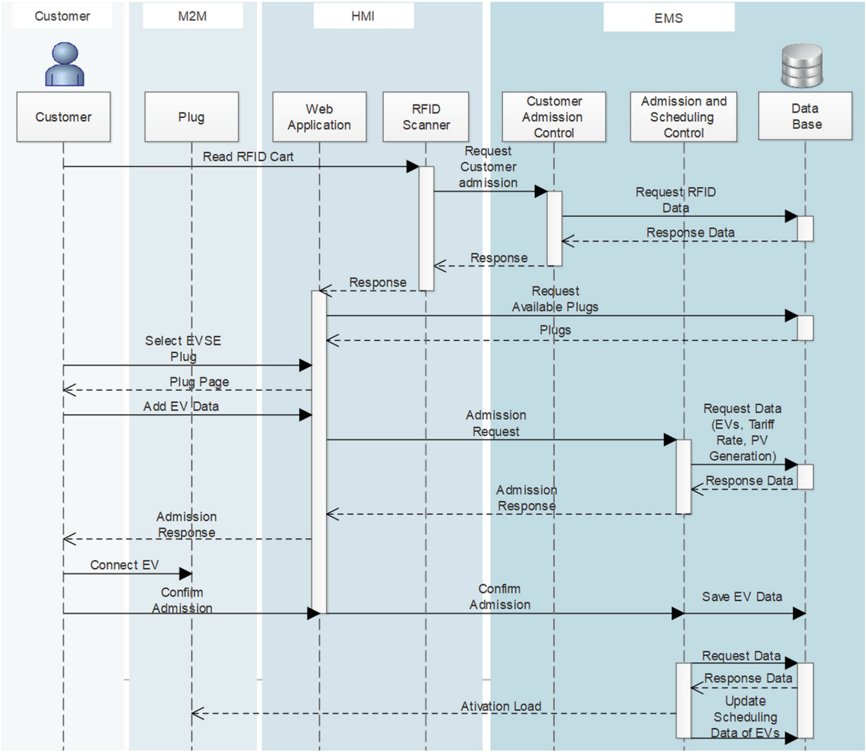


Fig. 4. Sequence diagram for the communication steps during the process of charge setup.

Fig. 5. 3D modeling of the EVSE (left and central images) and its current internal implementation (right side images).

The relevance of the proposed system, and developed model, was validated using a survey. In it, assessors considered it relevant to have a system like the one proposed in this paper, i.e. capable of managing the charging process of EVs and to use them as storage units. Other desirable features for the system include: charging to a minimum autonomy of the EV, economic benefit return, and/or simplicity of use.

The Energy Management System is already working and is able to control several sockets, as a result of user preferences. The EVSE shown in Fig. 5 is currently under deployment.

In terms of future developments the system needs to be fully integrated. In its final version, it will incorporate Low-Power Wide-Area Network (LPWAN) to enable long range communications, and machine learning solutions. Machine learning will enable the system to learn from user habits, reducing the need for repetitive user intervention - another requirement identified by assessors of the performed survey.

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