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Management Algorithms for Charging Electric Vehicles in Residential Buildings

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Algoritmos de Controlo para o Carregamento de Veículos Elétricos em Edifícios Residenciais

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Abstract

The transport electrification will play an important role in future smarter and more sustainable cities. Due to the increasing adoption of electric vehicles (EVs), if the charging cycles are not managed, a number of grid related issues, such as overload, could arise, which can lead to power outages. Thus, smarter charging strategies are required.

This dissertation presents smart charging management algorithm (SCMA) that simulates the charging of the EV according to the user's preferences, as well as the grid's requirements. Such algorithm allows further energy savings to the consumer, whilst benefiting the grid and the environment. It is considered that the residential dwelling is operating under time-varying electricity prices, that change on an hourly basis. This work assumes that electricity pricing variations, the load forecast and the renewable energy generation data are provided to the SCMA.

The SCMA was simulated under three objectives: to minimize the charging cost, minimize the environmental impact and to flatten the load profile. In order to do this, the algorithms either prioritize the time slots with the lowest electricity price, or the ones with higher RES share, or the ones with more available power, respectively. Then, the algorithms were tested for a series of case studies.

Lastly, the optimized charging scenarios were compared among them and to an unmanaged charging scenario. The SCMA successfully optimized the EV's charging cycles under any objective.

Keywords: electric vehicles, smart charging management algorithm, cost minimization, environmental impact, load profile flattening.

Resumo

A eletrificação do setor dos transportes irá desempenhar um papel fundamental no futuro de cidades mais inteligentes e mais sustentáveis. Devido à crescente adoção de veículos elétricos (EVs), se o carregamento não for controlado, poderão surgir eventuais problemas na rede elétrica, tal como sobretensões, levando a perdas de energia. Assim, torna-se necessário a criação de estratégias de carregamento mais inteligentes.

Esta dissertação apresenta um algoritmo inteligente de controlo de carregamento (SCMA) que simula o carregamento de um EV, numa residência, de acordo com as preferências do utilizador, bem como as da rede. Este algoritmo permite ao utilizador poupanças de energia e beneficiam, simultaneamente, a rede elétrica e o ambiente. Para o seu funcionamento, considera-se que a residência em causa tem uma tarifa energética variável no tempo, de hora em hora. Assume-se também que os dados da variação do preço da eletricidade, da previsão de procura e da geração energia renovável são comunicados ao SCMA.

O SCMA foi simulado de acordo com três objetivos: minimizar o custo de carregamento, minimizar o impacto ambiental e suavizar o diagrama de carga. Par tal, os algoritmos priorizam ou os intervalos de tempo com menor custo de eletricidade, aqueles com maior percentagem de energia renovável, ou ainda os que apresentem maior disponibilidade de potência. Depois, os algoritmos foram simulados para vários casos de estudo.

Por último, os cenários de carregamento otimizado foram comparados entre eles e com um caso de carregamento não otimizado. O SCMA foi bem sucedido na otimização do carregamento do EV sob todos os objetivos.

Palavras-chave: veículos elétricos, algoritmo inteligente de controlo de carregamento, minimização de custo, impacto ambiental, suavização de diagrama de carga.

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Acronyms

BEV	Battery Electric Vehicle
EMS	Energy Management System
EV	Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photovoltaics
RES	Renewable Energy Source
RTP	Real-Time Pricing
SCMA	Smart Charging Management Algorithm
SOC	State Of Charge
TOU	Time-Of-Use
V2G	Vehicle-to-Grid

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1 Introduction

1.1 Motivation

Electric vehicles (EVs) have become an important matter in the last decades, mainly because of its potential to reduce greenhouse gas (GHG) emissions, that continue to harm the environment [1]. The transportation sector alone, is responsible for 14% of greenhouse gas emissions which are involved in the burning of fossil fuels and about 95% of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel [2].

Substantial EV market penetration will likely unfold gradually over the next decades. This inevitability will impose a rather large additional load on the electrical grid, due to EVs' charging. Nowadays, with the low penetration rate of EVs, that additional load does not constitute an issue, but with subsequent EV deployment, it may pose a serious challenge to the electrical grid. The main issue is not the additional load itself, but the peak load that it may represent. Most EVs will be charged in a residential dwelling and will be plugged in to the electrical grid by the time the user arrives [3]. Given the fact that a large share of users is likely to arrive in the evening, which is a period of high demand, the simultaneous charging of EVs may lead to numerous issues, such as overloading the grid which can, consequently, cause power outages. So, if this is to happen, the electrical grid's reliability is put at risk and capacity generation investments may be necessary [4]. Moreover, to mitigate these problems, the EVs' charging cycles ought to be managed.

Therefore, this dissertation arises due to the need to avoid and mitigate the problems described above. The concept of smart 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 [5]. Besides, the energy storage capability of EVs makes them an attractive solution for the optimization under time-varying electricity prices. An EV can be considered as flexible load that can be charged throughout the day instead of following a strict charging schedule. Despite the benefits for the grid in terms of increased reliability, this service can also bring economic advantages to the users.

1.2 Objectives

The present dissertation is intended to develop smart management charging algorithms, using MATLAB, with the purpose of optimizing the EVs' charging in residential dwellings. Such algorithms must allow to conduct the EVs' charging under numerous criteria, both technical and economical, and according to the user's preferences, as well as the grid's. The main restrictions to take into account are the time of departure, the desired state-of-charge, the battery's capacity, the chargers' level of power, the RES forecast and the energy tariff, the contracted power of and the demand forecast of the household. The goals are to minimize the charging cost of the charging process, to minimize the environmental impact and to smoothen the load profile. Thus, benefitting the user, as well as the environment and the grid. A series of simulations are to be made, considering different approaches, to assess the algorithms' impact in each case.

1.3 Structure

The present dissertation is divided in 7 chapters. In the first chapter, a brief introduction is presented, with both the motivation and objectives that gave rise to this study.

Chapter 2 provides information about electric vehicles, describing the different topologies, its technology and presenting specifications of some of the most popular models, available for the mass market, from numerous car manufacturers. Next, the advantages and disadvantages - both technical and economical - of adopting an electricity fueled vehicle are assessed, alongside with its impact on the environment. This section ends with an analysis on the future growth of the deployment of electric vehicles.

Chapter 3 is focused on state of the art charging management strategies, that are currently being developed. Several approaches to this topic are briefly described and analyzed, as well as the achieved results. These techniques are grouped according to the objective and strategy used.

In chapter 4, the objectives and structure of the algorithms are presented. The proposed method is described step by step, together with a flowchart and the used variables and mathematical expressions, that ease the algorithms' comprehension.

Chapter 5 thoroughly describes the algorithms' operation, which were developed using MATLAB. The variations of the algorithms are demonstrated in a graphical manner, whether the user chooses to optimize the EV's charging or to charge the EV with no management. In order to demonstrate how the algorithm interacts with the user, a few examples of warnings, due to invalid or impossible inputs that prevent the algorithm's proper operation, as well as errors, are displayed. Moreover, two distinct examples of end results are presented.

In chapter 6, the algorithms are simulated for various scenarios, and the results are displayed and its impact is assessed. The different scenarios' results, with different objectives, are compared, to evaluate the impact on charging costs, RES (Renewable Energy Source) usage and on the load profile.

Lastly, in chapter 7, conclusions about the work developed in this dissertation are made and also some suggestions about future work and improvements.

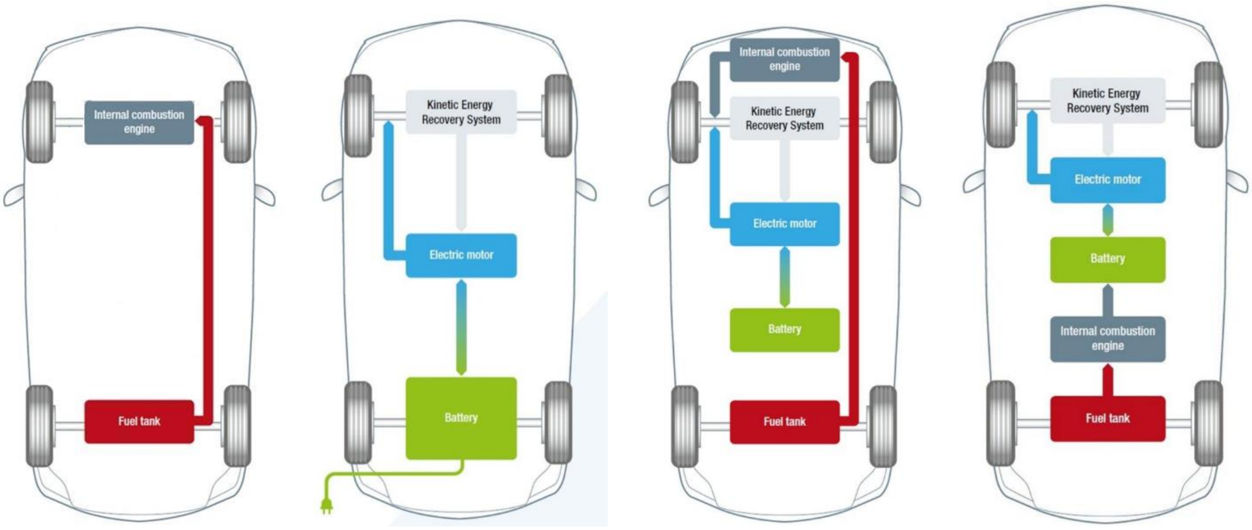
2 Electric Vehicles

Electric vehicles (EVs) can be classified in three categories:

- Hybrid Electric Vehicles (HEVs) (Figure 2.1 c)), which combine the benefits of an Internal Combustion Engine Vehicle (ICEV) (Figure 2.1 a)) and the benefits of an electric motor, complementing one another when required [6];

- Plug-In Hybrid Electric Vehicles (PHEVs) (Figure 2.1 d)), which are similar to the previous ones, but also include a small battery pack providing a range from 30 km to 80 km on all-electric mode. When the batteries have depleted, the drive system uses an ICE as a range extender. The batteries can be recharged by plugging the car into the grid, increasing fuel efficiency [6];

- Battery Electric Vehicles (BEVs) (Figure 2.1 b)), which operate in all-electric mode. This means that the vehicle is powered exclusively by one or more electric motors and includes a large battery pack, providing a range up to 450 km [6].



a) b) c) d)

Figure 2.1: Different vehicle architecture: a) ICEV; b) BEV; c) HEV or PHEV parallel hybrid; d) PHEV series.

Electricity as a fuel leads to more sustainable transportation, reducing CO_2 emissions, improving air quality, increasing energy efficiency and ultimately reducing oil dependency. Additionally, EVs can benefit from regenerative braking. This means that as the car brakes, kinetic energy is transferred from the wheels to the electric machine, therefore acting as a generator, producing electricity and sending it back to the battery pack. Such technology will contribute to the vehicle's overall efficiency [7].

The more commonly used electric motors in electric vehicles are the Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) [6]. The efficiency of an Internal Combustion Motor (ICE) is on average 28-30% whilst the efficiency of an electric motor can reach 85-95% [6]. One characteristic of electric motors is the ability to supply the maximum amount of torque over a large range of speed, eliminating the need for gear shifting in EVs and giving the vehicle a smoother acceleration and braking [8].

A PHEV typically requires a battery capacity of 8-16 kWh for a 40-80 km range, since it has an ICE to assist the vehicle operation. A BEV requires a battery capacity of 24 kWh for a 160 km range, which is by far lower than the range provided by a conventional ICEV. Nonetheless, it is sufficient for the daily commute. Some of the most popular BEVs' range and battery capacity are presented in Table 2.1. The range values marked with (^{1}) were measured according to the New European Driving Cycle (NEDC), which means, as some automobile manufacturers mention, that the vehicle's real range may be lower [6].

Table 2.1: EVs' range and battery *[9] [10] [11] [12] [13] [14]*.

	Range (km)	*Battery (kWh)*
Nissan Leaf	250^1	30
Renault Zoe	300	41
BMW i3	200	33
Kia Soul EV	212^1	27
Volkswagen e-Golf	190^1	24.2
Tesla Model S	865	100

Energy losses in EVs occur in three principal subsystems: the Energy Storage System (ESS), the fuel tank equivalent in an EV; the Powertrain (PT), the main components that generate power and deliver it to the wheels; the Power Electronics Module (PEM), responsible for motor control, charging and regenerative braking [6].

Several Life-Cycle Assessment (LCA) studies show that during the manufacturing phase of the vehicle, environmental impacts are similar for ICEVs and BEVs, without considering the battery production. The last one accounts for about 15 % of the total environmental impact caused the EV. The environmental impacts are dominated by the operation phase of the vehicles whether it is an EV or an ICEV that is being considered, being the last one with the higher environmental burden [6].

2.1. Benefits

Electric vehicles have a set of benefits over conventional ICEVs, such as:

- Fuel Cost: A full charge on an EV costs about a third when compared to petrol, for the same range [7];
- Maintenance Costs: The maintenance of an EV is simpler, since it does not have as much moving parts as an ICEV [7];
- Emissions: Full BEVs do not have any sort emissions associated with its operation [7];
- Noise Pollution: The electric motors used in EVs are practically silent, meaning it does not contribute to noise pollution [7];
- Tax rebates: There are other benefits of using an EV/PHEV like government subsidies to green vehicles, tax rebates, carbon taxes and more applied by several EU member states. These incentives were created for early adopters and are expected to end in the following years [6] [15].

In Portugal, BEVs do not have to pay vehicle registration taxes (ISV) and benefit from cheaper circulation taxes (IUC). As of 2017 the Portuguese Ministry of Environment stated that the buyer is entitled to a bonus of 2250 €, upon the presentation of a probative document of the BEV's purchase. This incentive is limited to the first 1000 buyers. Prior to that year, buyers had to give in an end-of-life vehicle for scrapping to obtain and incentive of the same amount [16]. Moreover, there is a right to VAT deduction in full, for expenses associated with acquisition, vehicle operation, maintenance, insurance, if the EV in question is considered to be a tourism oriented vehicle [17]. Also, EV owners get free and priority parking in some regions [18].

2.2. Disadvantages

EVs are an attractive solution, not only in environmental matters but also in economic issues. However, there are still some barriers towards their adoption, such as:

- Range: Due to the low energy density capability of batteries, vehicle range is usually limited to 100-150 km between charges, while conventional ICEVs, on the other hand can drive around 600 km on a full petrol tank [7];
- Upfront cost: Nowadays, the average cost of a medium-sized EV is about the double price

of a conventional car. The higher upfront cost for EVs is mainly due to the battery pack, currently with an estimated cost between 300 and 400 €/kWh [7] [19];

- Charging time: An EV can take up to 8 hours to fully charge while ICEVs take few minutes to refill the tank [7];
- Lack of charging stations: The number of charging stations is growing, but there are still few [7];
- Silent operation: EVs nearly silent operation may pose a safety issue to pedestrians and other road users [7];
- Battery durability: Like the majority of electronic devices that rely on batteries, its lifespan falls short of the expected for road transportation when compared to ICEVs'. Current lithium–ion batteries manufacturers assure a 70–80 % capacity after 8–10 years, which is practically the life cycle of a vehicle [1].

2.3. Importance

It is common knowledge that transportation is nowadays a petroleum-based human activity, which corresponds approximately to more than 21 % of the total energy usage. Moreover, the transportation sector is responsible for about 30 % of fossil fuel emissions in the EU, thus making it harder to satisfy stringent environmental regulations [6] [7].

The transportation sector needs to face major changes in order to reduce greenhouse gases (GHG) emissions, and by that improving air quality. Besides, the search for more efficient and environmental friendly vehicles will translate into significant savings in energy billing and taxes [8]. In Portugal, with modern EVs it is possible to drive 100 km with a cost of 1.5 €, depending on energy tariffs and whether the vehicle is charged by night or by day. Another advantage of charging the vehicle by night, is that in those periods the renewable energy source (RES) share is higher, thus helping to mitigate environmental impacts associated with the generation of electricity [20]. In Portugal, during the day (08:00h–22:00h) electricity costs 0,1942 €/kWh, while at night (22:00 h–08:00 h) it costs 0,1014 €/kWh, which translates to a 48 % reduction in electricity cost per year, by only charging the EV at night [8].

The electricity mix is related to the EV's environmental impact and as expected, charging the EV with an electricity mix with low GHG emissions reduces the overall life-cycle emissions [8]. With disregard for the electricity mix, the operation phase is the one responsible for the overall impacts, however considering an electricity mix with a large share of RES, it is the vehicle and battery production phase that accounts for most of the environmental impacts [8]. Another relevant aspect to take into consideration, is that the electricity mix is not constant during the year nor during the day [8].

For a mix were the main share of RES is hydro and wind such as Portugal, during winter months, charging at night will emit approximately less 20–50 % when compared with a charge during the day. The same cannot be stated for summer months, as charging during the day will emit approximately less 4-23 % when compared with a night charge [8].

2.4. Future Growth

Looking back a couple of years, EVs' (including BEVs and PHEVs) sales have increased by 70 % between 2014 and 2015, with over 550,000 being sold worldwide [21]. In Portugal, in the year 2016, 1970 EVs were sold, a 51 % increase when compared to the 1305 EVs sold in 2015 and represents 0,95 % of the total vehicles' sales in that year. Also, there has been a noticeable growth in PHEVs' sales from a share of 37 % of the total EVs' in 2015 sales, to 53 % share in 2016. According to Mobi.e, a Portuguese company in charge of the charging systems for electromobility, it is expected that the number of EVs (including mopeds, light, heavy, motorcycles, tricycles and quadricycles) reaches 5000 by the end of 2017 [22].

Although the incentives towards the adoption of EVs will decrease in some countries in the following years, BEVs' mass market will result in price reduction and will still compensate its purchase [6]. The main obstacle for the mass adoption of EVs has been the battery. Battery pack prices fell about 80 % from 2010 to 2016, about 940 €/kWh to 213 €/kWh as shown in Figure 2.2. Despite this price drop, battery costs continue to make EVs more expensive than ICEVs. However, due to mass production, the price per kWh is expected to decrease below 179 € by the end of the decade and put the battery pack prices below 94 €/kWh by 2030, according to Bloomberg New Energy Finance and also shown in Figure 2.2 [23]. Therefore, by 2020 onwards with the price reduction of EVs, due to advances in battery technology and mass production, the mass market buyers will be influenced by the lower total cost of ownership of EVs versus ICEVs at the time of buying a new vehicle [6]. Also with technological advances, faster charging will become possible, making transport electrification even more appealing.

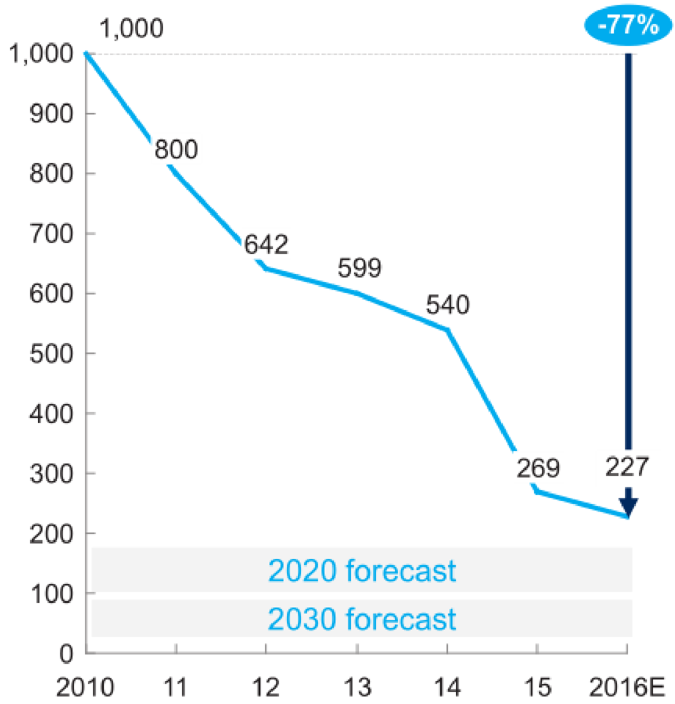


Figure 2.2: Average battery pack price and forecasts *[23]*.

The governments play an important role in accelerating the transition to clean and sustainable mobility through pioneering policies. Such policies can be the implementation of stronger fuel economy regulation, so that car manufacturers can be provided with incentives to invest in EV technology, thus helping with product diversity. Furthermore, providing for transparent and predictable fuel economy regulations in the near future will help manufacturers prepare to meet them.

Another example is restricting access to roadways for ICEVs, which is being done in California. Governments at the national, regional and local levels by adopting transport electrification themselves, can lead by example and even inspire other fleet operators to consider EVs. While some policies can have beneficial impact on EV deployment, a lack of policies or clear regulations can set back widespread adoption of EVs in many countries. The EV market is ready to expand aggressively, given proper consumer education and continued, robust government policies. According to the Electric Vehicles Initiative (EVI), EV sales for selected countries (EVI members) are shown in Figure 2.3 [18].

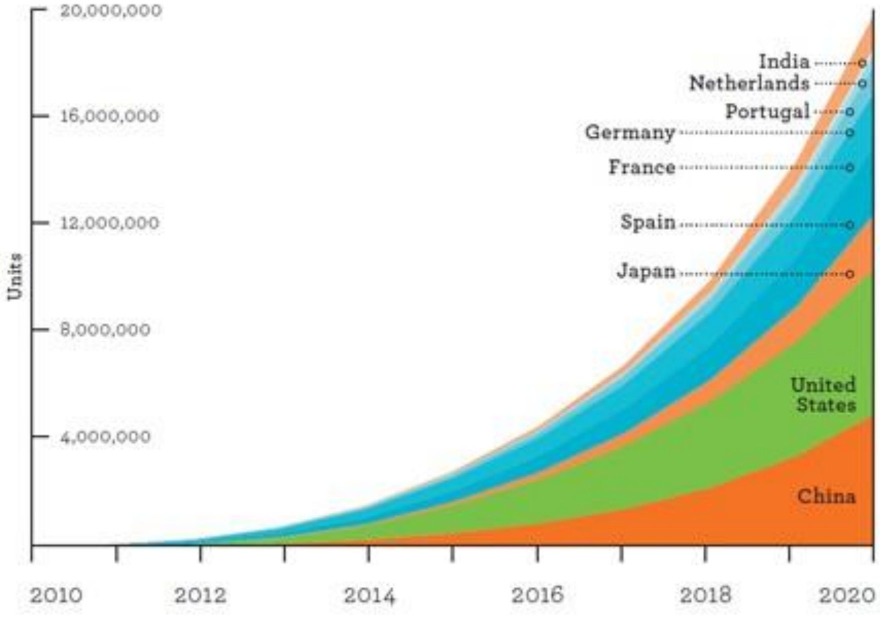


Figure 2.3: EV sales targets *[18]*.

3 Charging

In this chapter, several management charging strategies are analyzed, as well as their methodology and results.

3.1 Strategies and Objectives

Due to the increasing EV penetration, the unmanaged charging of EVs could lead to several problems related with the electrical grid, because the extra load introduced by EVs can create high peak loads, overloading the grid, which will increase power losses and shorten equipment lifetime [24] [25] [26]. Therefore, smart charging methods, to distribute the extra load introduced by EVs over a longer period of time, are needed. The introduction of EVs will also have an impact on the electricity bill and by designing proper SCMA, the negative effects caused by unmanaged EV charging can be mitigated. The main objectives that can be ensured by SCMA are to minimize the environmental impacts, increasing the grid reliability and avoid investments, and reduce the costs associated with the EV operation.

It is possible to avoid the overload of the electrical grid and therefore increase its reliability, through strategies such as valley-filling, which is the process of charging the EV in off-peak times, when demand is low, as shown in Figure 3.1. Distributing the EV charging loads over a longer period of time in each household will minimize demand peaks, which contributes to reducing the distribution and transmission losses and stress in the grid [26]. Such strategy can also prevent unnecessary grid investments, since expensive investments in generating capacity could be avoided by managing the additional loads [27].

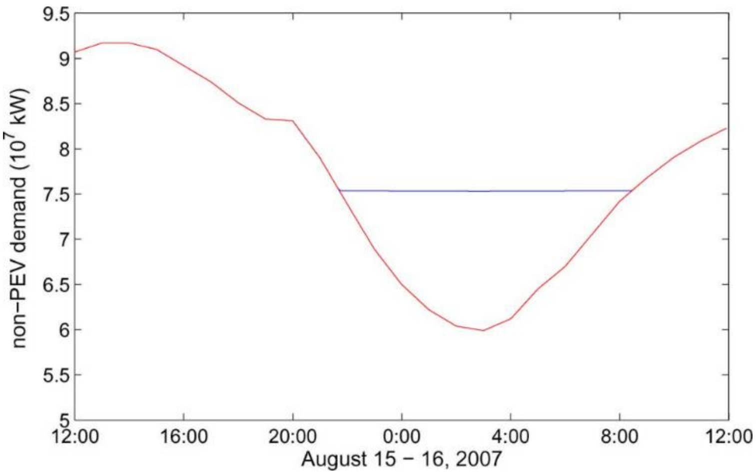


Figure 3.1: An ideal valley-filling profile *[28]*.

The environmental impacts associated with EVs can be minimized by concentrating the charging phase in periods with higher share of RES and thus minimizing GHG emissions [26]. The reduction of costs associated with vehicle operation is possible by scheduling the charging times to periods with lower electricity prices [25].

In the unmanaged charging scenario, there is no control or coordination, as the EV is charged at a fixed rate and starts upon plugging in the EV to the grid, in order to have it fully charged for the next departure. This can lead to additional load to existing peak loads like the ones in Figure 3.2, which shows a typical residential load profile for a Portuguese family of four.

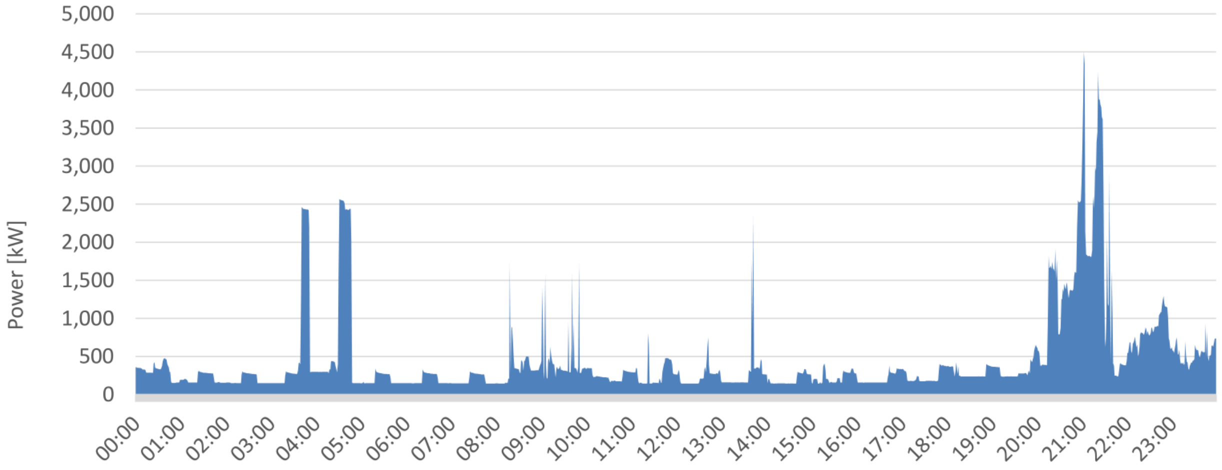


Figure 3.2: Typical load diagram for a household in a weekday *[29]*.

With unmanaged charging, it is likely to have a large number of EVs connected to the grid simultaneously, mostly in the evening, as Figure 3.3 suggests. If they are concentrated in a small region, the resulting spike in demand could blow the transformers feeding those households and wreak havoc on the distribution system [30] [31] [32].

These concerns lead to the development of smart charging strategies, being the charging process controlled by a device embedded in the vehicle or at the charging station. There are numerous strategies that can be implemented with the common objective of minimizing EV associated costs. Moreover, solutions aimed at minimizing costs for the user, often also end up in being beneficial for the stabilizing the grid. Some strategies are focused on the coordination of a small group or a large fleet of vehicles and such strategies can be divided in centralized and decentralized strategies [25] [28] [33] [34] [35].

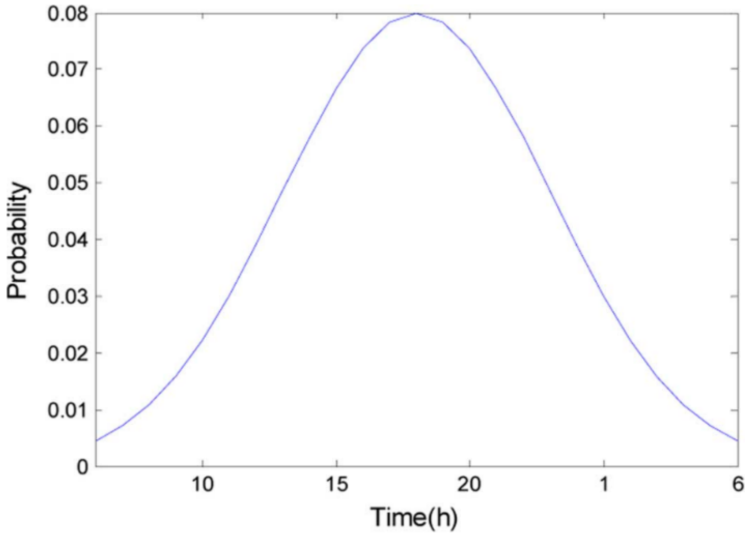


Figure 3.3: The distribution curve of the starting time of charging *[36]*.

Some strategies take into account Vehicle-to-Grid (V2G) strategies, which is when vehicle power is fed into the grid. The main objective is to improve grid operation and minimize costs, but with the current battery technology this option is not that viable, as the price by kWh is still high and batteries degrade at quite fast rate with normal operation. With the introduction of V2G, batteries would cycle even faster [25] [32] [37] [38] [39]. This work will be focused on local management strategies, without considering V2G.

3.2 Local Management Strategies

For the local management, some approaches are based on pricing strategies which serve as stimulation and guidance for power demand and consumption for customers. Customers will respond to variable electricity prices, actively adjusting charging rate and time periods [36]. These strategies are often based in either Time-Of-Use (TOU) pricing or in Real-Time Pricing (RTP).

With TOU, the electricity price is divided in two or three time blocks for 24h periods, based on typical demand (with higher prices during on-peak hours). These prices are set for a specific time period on an advance or forward basis, typically changing every year, allowing consumers to vary their demand usage in response to such prices and managing their electricity costs by shifting consumption to a lower cost period or reducing the overall consumption [40]. With RTP, prices are provided in real time or near real time. Electricity prices may change as often as hourly, meaning that consumers may receive notification of prices change on a day-ahead or hour-ahead basis. RTP is not yet in available in Portugal.

Pricing based algorithms are explored in references [24] [30] [36] [41] [1] [42]. In [36], a heuristic charging algorithm is implemented in response to TOU pricing with the objective of minimizing charging costs, considering the relation between the acceptable charging power of EV battery and the State Of Charge (SOC). The authors state that the proposed algorithm was effective in flattening the load profile and was able to minimize charging costs up to 51.52 %, if peak and valley time periods are partitioned appropriately.

In [1], it was formulated an optimal control algorithm, in order to schedule EV charging under RTP to minimize the users' electricity payments. The proposed charging model could be used to study charging patterns in a simulation environment and the optimal control algorithm can be embedded into a home Energy Management System (EMS) or a smart charger. When compared with uncontrolled charging, results showed that electricity costs and peak load could be reduced by 18.5 % and 31.2 %, respectively. Another RTP based study was proposed in [41], in which a heuristic algorithm was formulated, assuming a smart grid framework, to minimize EV charging costs while taking into account user's requirements of battery SOC. The proposed method was able to shift demand from on-peak hours to off-peak, hence reducing costs associated with the EV charging.

In [43], an algorithm based on monitoring of load changes to predict further load behavior was developed. The algorithm was implemented in the EMS of a smart microgrid and the result was a higher load factor and a reduced electricity bill, considering TOU pricing with 2 periods. In [3], a model for generating PHEV home charging patterns is presented, which combines PHEV usage with the users' electricity-dependent activities. Results show that if users only charge the PHEV at home, it will most likely occur in the evening and that would represent one third of the total expected load during peak time and about a fifth of the total daily electricity consumption. With this model, it was possible to simulate the expected residential load profile, making load shifting an easier task.

A local energy control strategy aimed at minimizing the peak load and flattening the global load profile is presented in [31]. This control method can be implemented with a device such as a Home Energy Control Box like the one used in the paper, or a Smart Charger/Plug. The first step of the local energy control strategy was to determine the optimal load profile which is based on the local base load and a fixed charger load. The developed control method was compared with an uncontrolled scenario. A 30 % EV penetration would lead to an almost 50 % increase in peak load, but the local control strategy would be able to reduce this peak to about 26 %.

In [44], an energy management strategy based on heuristic unidirectional offline algorithm was developed with the purpose of minimizing charging costs. The algorithm ensured a desirable SOC for the next departure, charging the EV at a variable power rate. The simulations were made on a database of 10000 real case studies for energy prices in France and in the US, being assumed that each household had only one vehicle and that the vehicle departs and arrives home once a day. The algorithm requires as input data the house's daily load profile, arrival and departure times, contracted power, initial and desired SOC, battery's rated capacity and desired charging power rate. Firstly, the algorithm detects the presence of the EV, and defines the period of time for charging. Then, it calculates the available power for charging, taking into account the contracted power and the charger's energy losses. Next, it classifies the electricity prices in ascending order and starts charging upon finding the lowest price. As the algorithm is running, it verifies if the current SOC exceeds the desired SOC, at each step. The EMS ensures that the voltage and charging current does not exceed the nominal values and also prevents power outages due to charging, as it adjusts the charging power rate. Results show that by applying the EMS, users can save up to 47.5 %.

Saving on the electricity bill may be the best incentive for users to adopt smart charging strategies, but from the grid point-of-view, other important aspect to consider is the integration of renewable energy. This matter is explored in [45], in which a smart charging algorithm is formulated, that not only minimizes charging costs, but also takes into account the renewable energy availability, for instance, from photovoltaic (PV). The algorithm optimizes the EV charging based on TOU prices as well as the RES availability and additionally prevents the battery from overcharging, extending its lifetime. The charging schedule is chosen by a programmable controller embedded in the household. Several input parameters are needed for the algorithm, including the battery specifications, arrival and departure time, as well as initial and final SOC. Then, the system automatically selects the best charging source for each charging interval, based on energy availability determined by a smart meter, and based on load profiles. The charging times were randomly chosen, with different initial and departure times throughout the day. Comparisons between un-optimized and optimized charging with and without PV were made and although charging costs are higher when RES is not available, results show that the overall cost is still lower when compared to an unmanaged charging. For charging a single EV the algorithm is able to achieve a maximum saving of 73.25 %, with an average saving of 22.09 %. From the simulation results, the authors conclude that their method can effectively take full advantage of renewable energy sources and successfully shifts demand from peak times to off-peak times, thus minimizing charging costs.

In [26], a system architecture is presented to dynamically control EV charging. The main objective of the system is to increase the load factor, through peak shaving, and by that reducing overall electricity costs with the introduction of an EV. The secondary objective is to maximize the energy use in periods with lower environmental impacts. The hardware is consisted of two devices, a smart plug and an energy meter, both with communication, data storage and local processing capabilities. The smart plug is intended to replace the standard plug used for charging the EV and the energy meter's purpose is to measure the global energy consumption in real-time. The software consists of three main modules, a load forecast module, a classifier module and a scheduler module. The load forecast module is responsible for forecasting the load based on previous data, the classifier determines the proper time slot for charging based on load forecast and the scheduler module is responsible to arrange a charging time table based on the available time slots. The algorithm, to be able to optimize the EV charging, requires as parameters the contracted power, vehicle charging power, energy tariff, required battery SOC, unplug time and renewable generation forecast. Two approaches were compared, one being to fully charge the EV and the other to partially charge the EV. Then, it was concluded that the benefits of fully charging the EV are more noticeable for mitigating the impact on the load profile. On the other hand, partially charging the EV is more effective when it comes to taking advantage of high RES contribution. The resultant EV charging scheduling is depicted in Figure 3.4.

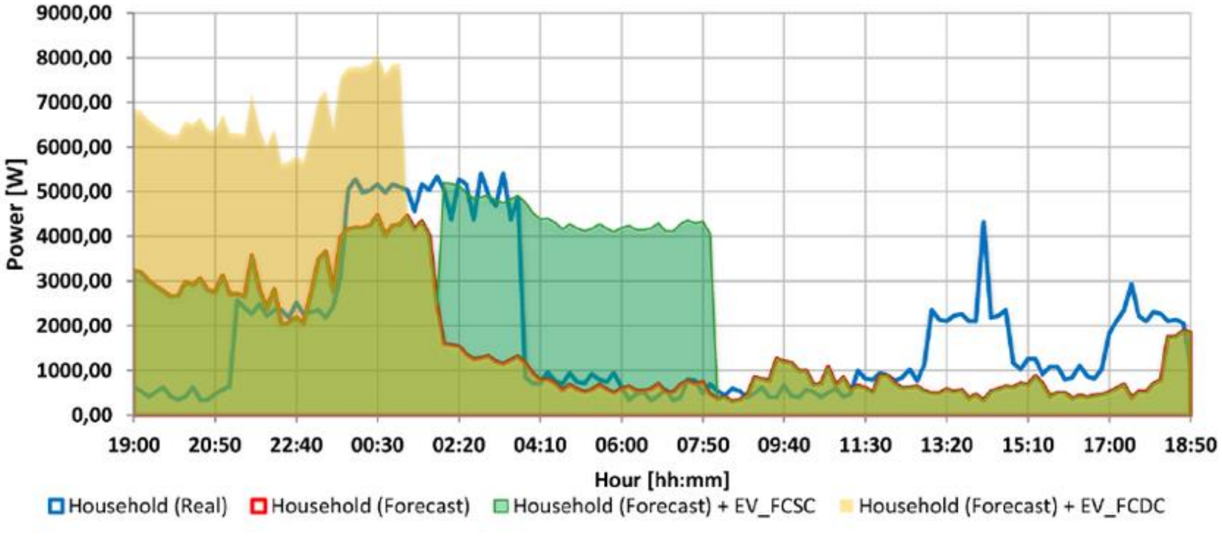


Figure 3.4: Load diagram (real and forecasted) for a household with an EV unmanaged (EV_FCDC) and managed (EV_FCSC) full charge *[26]*.

Therefore, SCMA are a potential candidate solution to shift charging demand based on the renewable energy production or to shift charging to off peak hours, decreasing energy bill and improving grid quality [33].

4 Objectives and structure of the algorithm

This chapter describes the objectives and structure of the proposed algorithm.

4.1 Objectives

The SCMA has four objectives:

1. Minimize the costs (EC) associated with the charging process, preferably charging in the lower electricity price slots;
2. Minimize environmental impacts (EI), by maximizing the use of available RES, preferably charging in periods with renewable energy generation surplus;
3. Smoothen the residential load profile (PI), resulting in a higher load factor, by charging during periods with lower energy consumptions;
4. Preferable charging with lower power (LP), if variable power charging is possible.

The first three objectives are alternatives and one must be selected for optimization. The fourth objective is complementary to the others, but objectives 1, 2 and 3 are priorities and objective 4 is implemented, only if it does not significantly worsen the main objectives' results.

The purpose of charging with lower power is to avoid damaging the battery and to improve the load factor. Charging at a higher rate causes additional stress on the battery, so the algorithm tries to charge at a lower rate to prevent additional cycling of the battery. However, charging with lower power will extend the duration of the charging, therefore requiring more time slots with less suitable values for the other objectives [46].

4.2 Structure

In order for the algorithm to perform effectively, it requires some necessary input restrictions, as presented in Table 4.1. Some are user's preferences, while others are residential and vehicle related specifications. These can be divided in variable and fixed restrictions, as some are likely to differ from one day to the next, while others may not suffer any modification once they are introduced for the first time. For example, the departure time and desired SOC are variables whose value is likely to change for each charging process. However, the EV's battery capacity and the chargers' level of power are not expected to change, as they are vehicle inherent specifications and the contracted power is rarely updated.

Lastly, there are grid related restrictions that are collected from real data, but for simulation purposes such restrictions also have to be gathered by the user. The demand forecast is essential to build the charging schedule and it is based on the previous data for the same time period. The renewable energy generation forecast data is provided by REN's Electricity Real Time Information website. Another required variable is the energy tariff, in order to know the electricity prices and it is provided by REN's Energy Market Information System website [47] [48].

For the demand forecast, the electricity consumption breakdown in EU households was used as reference and adapted to the Portuguese reality using the ownership rates of each appliance [49].

For the RES forecast data, the surplus of the renewable generation is considered. The results are obtained by the ratio between the sum of the renewable generation contributions - such as dams, run-of-the river hydroelectricity, hydropower, geothermal, wind, solar and wave power - and the sum of the consumption and pumping involved in the process. This means that values from 100% and above represent RES surplus.

In order to simulate a RTP tariff, the tariff data is obtained by the product between the electricity market price by the ratio between the average electricity market price in Portugal and the average electricity price for a Bi-Hourly rate tariff in Portugal [50].

Table 4.1: Input restrictions.

Restrictions		
Fixed	**Variable**	**Grid related**
Battery capacity ($C_{battery}$)	Departure time ($T_{departure}$)	Energy tariff (ET)
Contracted power ($P_{contracted}$)	Desired SOC (SOC_{final})	RES generation forecast (RES)
Level 1 charger ($P_{charger_1}$)		Power demand forecast (F_P)
Level 2 charger ($P_{charger_2}$)		

The design of the proposed algorithm is depicted in Figure 4.1. The variables and equations necessary for each step of the algorithm are presented in Table 4.2.

The algorithm is initialized and carries on after making sure the car is plugged in ($Connected = Yes$). The user is then asked if he wants to modify the fixed restrictions. If he selects to modify it, then the Boolean Mod is true and he may alter the restrictions' values, otherwise it goes straight to step **5**. In this step, a table $Data$ is created with the grid related variables that are read from a spreadsheet, including evenly spaced date and time slots between 00h00 of the day of arrival and 23h45 of the day of departure.

The simulations can be conducted with or without control strategies, so the user is asked if he wishes to use the SCMA, or to immediately start charging the EV (this case is discussed later). If the user does wish to use the SCMA, the Boolean $scma$ is true and in the next step the user introduces the departure time ($T_{departure}$) and the desired SOC (SOC_{final}). After the user's preferences are introduced, the algorithm calculates the required time to charge the EV (T_{req_i}), based on the battery capacity ($C_{battery}$), the power for each level of charging ($P_{charger_i}$) and the initial ($SOC_{initial}$) and final (SOC_{final}) SOC. Then, the algorithm assesses whether the previous calculated T_{req_i} is sufficient, based on $T_{departure}$ and the arrival time ($T_{arrival}$). If $T_{req_i}$is not sufficient for either of the chargers, the algorithm goes back to step **7**. If T_{req_i} is sufficient for one of the chargers, but not for the other, the latter is discarded, but the SCMA continues. When the charging time is not possible for either $P_{charger_i}$, the user must compromise and update $T_{departure}$ and/or SOC_{final}, to ensure a suitable T_{req_i}.

The next step creates another variable in the table $Data$ ($Data.Date$) with the possible time slots between $T_{arrival}$ and $T_{departure}$ minus the last possible slot, to make sure it does not exceed the time of departure. Also, the time slots are equally divided in 15 minutes' periods. From this step forward $Data_1$ and $Data_2$ are created from $Data$, with the purpose of managing the data for each level of charging, independently. Then, the algorithm calculates the available power (P_{a_i}) for each time slot, based on $P_{contracted}$, $Data_i.F_P$ and $P_{charger_i}$. A unity power factor is considered. The next step checks if every slot is available for charging and the ones that are not, are excluded from the original table ($Data_i$). With the possibility of too many time slots being discarded, the algorithm must check if T_{req_i} is still sufficient, by comparing its size with the size of $Data_i$, because each line of the table corresponds to a 15 minute duration. If T_{req_i} turns out to be shorter for one of the charging levels, then that charger is no longer considered as option. If this occurs for both $P_{charger_i}$, then the algorithm goes back to step **7**, and requests a modification of the user's preferences.

After that, the algorithms sort the time slots according to each objective, whether it is to minimize charging costs (EC), or to minimize impact on the consumption profile (PI), or to minimize the environmental impact (EI), for each charger. For minimizing energy costs (EC_i), the time slots' desired order is according to their corresponding electricity price in an ascending order. For minimizing the impact on the load profile (PI_i), the time slots are sorted according the respective availability (P_{a_i}) in a decreasing order. For minimizing the impact on the environment (EI_i), the time slots are sorted according to corresponding surplus of RES in a decreasing order.

Then, in the next step, the necessary time slots for charging, based on T_{req_i}, are selected for each objective and the previous tables are updated (EC_i, PI_i, EI_i). If by now, the charger to be used is not yet chosen, in the next step, the algorithm compares the cost of the charging for each of the tables and if the sum for $P_{charger_1}$does not differ too much (considering a margin $\varkappa$ in percentage) from the sum for $P_{charger_2}$, then $P_{charger_1}$ is the charger selected for charging.

At last, every data required to start charging is now gathered. In the next step, the algorithm checks if the current SOC is lower than the desired one and if it is, moves to the next step in which the EV is charged during the amount of time D (a 15 minute duration variable) and the SOC is updated. This process is repeated for the remaining time slots until the previous condition (step **17**) is no longer met. In this case, the algorithm goes to step **24**, meaning the charging is complete.

Going back to step **6**, in which the user is asked if he desires to use the SCMA, if the answer is negative, then the algorithm goes to step **20** and the user must only introduce the desired SOC (SOC_{final}). This decision may reflect the urgency to charge the EV as fast as possible, with the purpose of assuring a minimum SOC, that may be considered as a safety margin, in case he has the need to use the vehicle for an emergency and the EV's SOC is low. For instance, after charging the EV without the SCMA until the battery reaches 10 % above the minimum SOC, the user may restart the algorithm and choose to use the SCMA. Since the reason for not choosing to use the SCMA is to charge as fast as possible, only the Level 2 charger is considered. After inserting the desired SOC, the algorithm goes to step **21** to calculate the required time (T_{req}), similar to the one previously described. In the next step, the EV starts charging for the amount of time T_{req}, in 15 mintutes' intervals (D), also similar to the one previously described. The algorithm keeps cheking if there is any time left for charging and if there is, it goes back to step **22**, otherwise it goes onto the next step and the charging is considered complete.

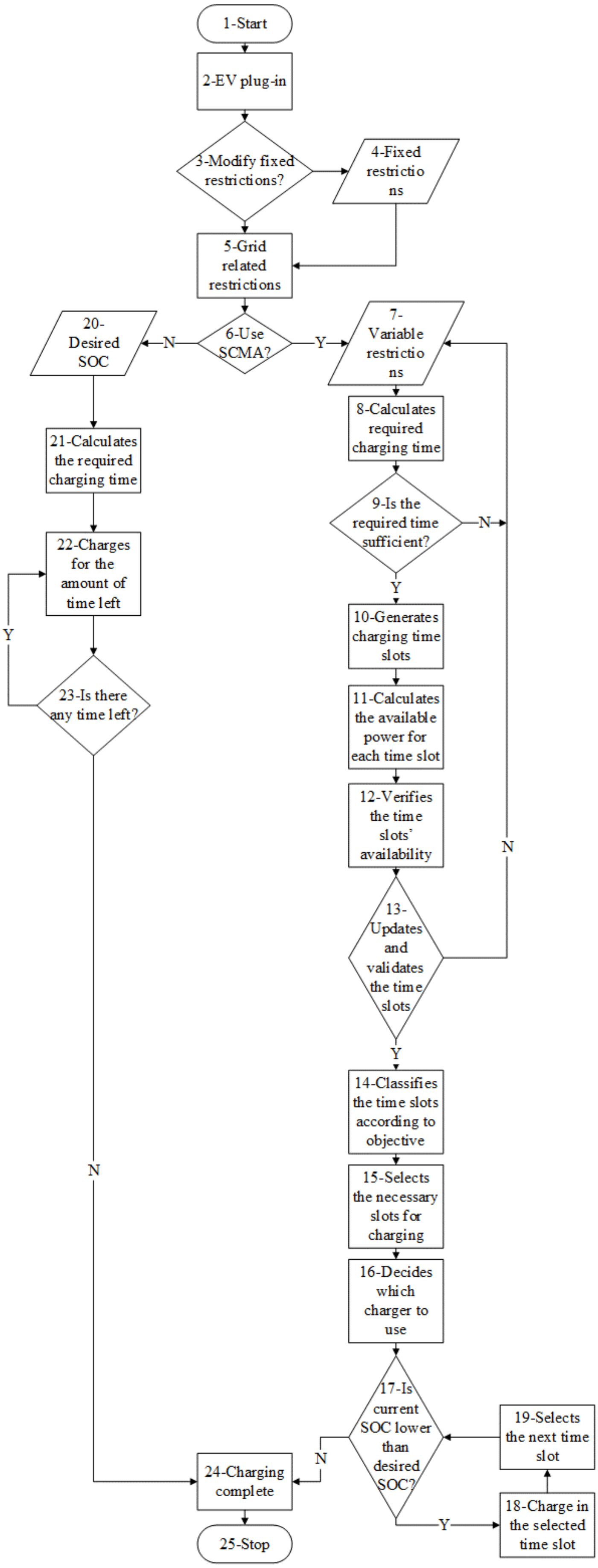


Figure 4.1: Flowchart of the algorithm.

Table 4.2: Variables and equations.

Step	Variables/Mathematical expression
1	N/A
2	$Connected$
3	Mod
4	$C_{battery} = C_{battery_{New}}$ $P_{charger_1} = P_{charger_{1_{New}}}$ $P_{charger_2} = P_{charger_{2_{New}}}$ $P_{contracted} = P_{contracted_{New}}$
5	$Data$ $Data.RES$ $Data.F_P$ $Data.ET$
6	$scma$
7	$T_{departure}$ SOC_{final}
8	$T_{req_i} = \frac{C_{battery} \times (\frac{SOC_{final} - SOC_{initial}}{100})}{P_{charger_i}}, i = 1, 2.$
9	$T_{req_i} \leq T_{departure} - T_{arrival}, i = 1, 2.$
10	$Data_i, i = 1, 2.$
11	$Data_i.P_{a_i}(t) = P_{contracted} - Data.F_P(t) - P_{charger_i}, i = 1, 2.$
12	$Data_i.P_{a_i}(t) > 0, i = 1, 2.$
13	$T_{req_i} > \sum_{t=1}^{M} Data_i.Date(t), i = 1, 2;$
14	$EC_i, i = 1, 2.$ $EI_i, i = 1, 2.$ $PI_i, i = 1, 2.$
15	$EC_i, i = 1, 2.$ (update) $EI_i, i = 1, 2.$ (update) $PI_i, i = 1, 2.$ (update)
16	$Sum_{O_i} = \sum_{j=1}^{N} O_i.ET, O = EC, PI, EI;\ i = 1, 2; j = 1, 2, 3, \ldots, N, j \in \mathbb{N}.$ $\frac{\lvert Sum_{O_1} - Sum_{O_2} \rvert}{Sum_{O_2}} \leq \varkappa$
17	$SOC(t) < SOC_{final}$
18	$SOC(t) = SOC(t-1) + \frac{P_{charger_i} \times D}{C_{battery}}, i = 1, 2.$
19	$t = t + 1$
20	SOC_{final}
21	$T_{req} = \frac{C_{battery} \times (\frac{SOC_{final} - SOC_{initial}}{100})}{P_{charger_2}}$
22	$SOC(t) = SOC(t-1) + \frac{P_{charger_2} \times D}{C_{battery}}$
23	$T_{req} < \sum D(t)$
24	$SOC(t) = SOC_{final}$
25	N/A

5 Algorithm’s Operation

The present chapter describes the algorithm’s operation and the way it interacts with the user. As was described in the previous chapter, the algorithm can be run with or without control strategies, though the first few steps are common for both approaches. The algorithm was developed using MATLAB and it is presented in the appendix A1.

5.1 Inputs

The algorithm starts by asking the user if the EV is connected, shown in Figure 5.1. Every time the user answers “No”, that same question box appears again. If the user selects to cancel, an error box like the one in Figure 5.2 is displayed and the algorithm stops running. If the answer is affirmative, the algorithm continues and the time of arrival is defined. This parameter ought to be the current date of the algorithm’s execution, but for simulation purposes, its value is defined and can be modified within the code.

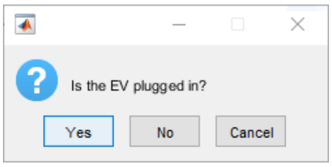
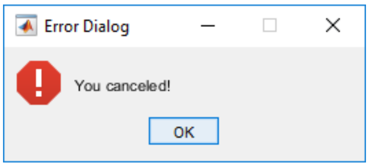

Is the EV plugged in?

Figure 5.1: EV plug-in question dialog box.



You canceled!

Figure 5.2: Error dialog box.

Next, a box like the one in Figure 5.3 appears for introducing the current SOC, in percentage. If the input is not a positive number lower than 100, a warning box is displayed like the one presented in Figure 5.4. Again, this is only required due to simulation purposes, because in a real case scenario, the charging system would be able to measure the initial SOC’s value without the user’s interaction.

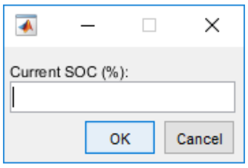
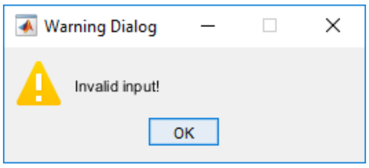

Current SOC (%):

Figure 5.3: Initial SOC input dialog box.



Invalid input!

Figure 5.4: Invalid input warning dialog box.

In the following step, the user is asked if he wants to modify fixed restrictions, such as the contracted power, the battery’s capacity and the chargers’ power, as depicted in Figure 5.5. If the user chooses not to modify any restriction, the algorithm loads the variables from the file ‘variables.m’. If this file does not exist, the algorithm stops running due to an error.

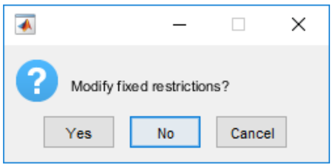

Modify fixed restrictions?

Figure 5.5: Fixed restrictions modification question dialog box.

If the user chooses to modify the restrictions, but does not intend to modify every single one, there is an option to type ‘dc’ (short for ‘do not change’), present in every dialog box meant for changing the variable’s value, like the one in Figure 5.6. Every time the algorithm changes a fixed variable, the previous value, in the file ‘variables.m’, is overwritten and updated with the new one. When the algorithm is being executed for the first time, the file does not exist, so the user must choose to modify the fixed restrictions, in order to create the file. A warning like the one in Figure 5.4 is displayed when the input for the new contracted power’s value is neither ‘dc’, nor does it correspond to any of the options. Additionally, a dialog box is displayed with the possible values for the contracted power, as exemplified in Figure 5.7. For the other three variables, a warning box is displayed when the input is neither ‘dc’, nor a positive number.

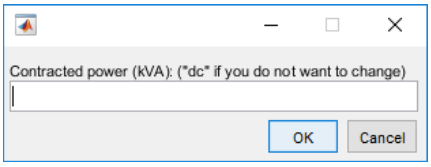

Contracted power (kVA): ("dc" if you do not want to change)

Figure 5.6: Contracted power modification input dialog box.

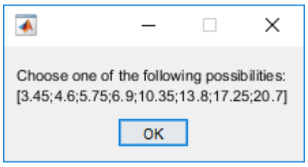

Choose one of the following possibilities:
[3.45;4.6;5.75;6.9;10.35;13.8;17.25;20.7]

Figure 5.7: Possible contracted power values.

Then, the grid related data, such as demand forecast, RES forecast and energy tariff data is imported from the spreadsheet file ‘Data_12_13_Jan_2016.xlsx’ or ‘Data_12_13_Jun_2016.xlsx’. After that, the user is given the option of using the SCMA or not, as presented in Figure 5.8, and from this point forward the algorithm will behave differently for each case.

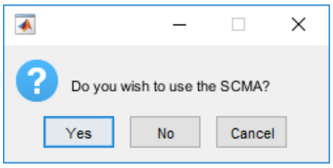

Do you wish to use the SCMA?

Figure 5.8: Charging approach question dialog box.

5.2 Charging Using the SCMA

If the user chooses to use the SCMA, then an objective must be selected from the menu, like the one presented in Figure 5.9.

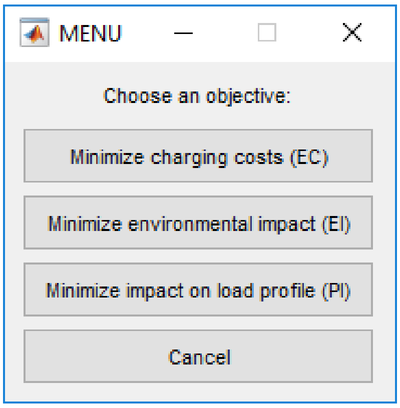
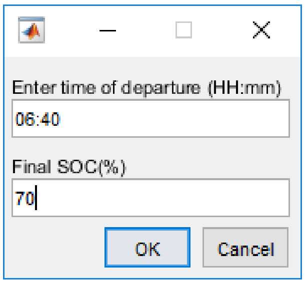


Figure 5.9: List objectives' menu.

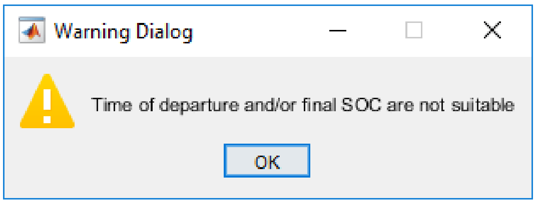
After that, the user must introduce both the required time of departure and the desired SOC in the respective input fields, as shown in Figure 5.10. If either the input for the arrival time is not valid, nor in the required format, or the input for the SOC is below the initial SOC, or over 100, a warning box, like the one in Figure 5.11, is displayed. If the warning persists, it might be advisable to choose a higher contracted power. After introducing suitable restriction inputs, an informative box, like the one presented in Figure 5.12, is displayed regarding the date and time of when the charging process will start and when it will be concluded. Then, the simulation of the charging process starts.



Enter time of departure (HH:mm)
06:40

Final SOC(%)
70

Figure 5.10: Time of departure and final SOC input dialog box.



Time of departure and/or final SOC are not suitable

Figure 5.11:Informative warning dialog box.

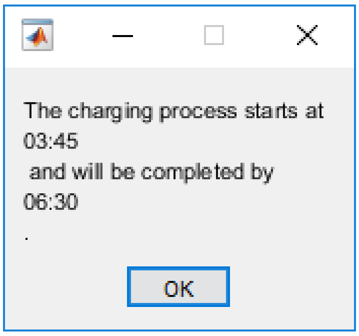

The charging process starts at
03:45
and will be completed by
06:30
.

Figure 5.12: Charging scheduling dialog box.

5.3 Charging Without the SCMA

When the user chooses not to use the SCMA, the only requirement that must be introduced is the desired SOC, as presented in Figure 5.13. If the input for the SOC is below the initial SOC, or over 100, a warning box is displayed. After introducing a suitable SOC, the algorithm starts charging at the time of arrival, continuously, for the required time.

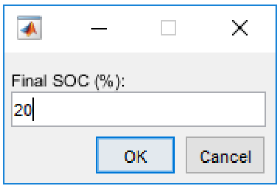

Final SOC (%): 20

Figure 5.13: Final SOC input dialog box.

5.4 Results

In both approaches, when the EV has finished charging, a dialog box informing that the EV has stopped being charged is displayed, as depicted Figure 5.14.

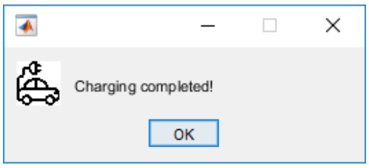

Charging completed!

Figure 5.14: Charging' completion dialog box.

Additionally, a plot is presented, representing the EV’s charging profile, showing the contracted power, the demand forecast and the total demand with the introduction of the EV’s load, where each step of the stairs represents a 15 minutes’ charging slot. The figure also presents information such as the final SOC, the charging’s energy consumption, its cost and the percentage of RES used in the charging. Examples of these are presented in Figure 5.15 and Figure 5.16.

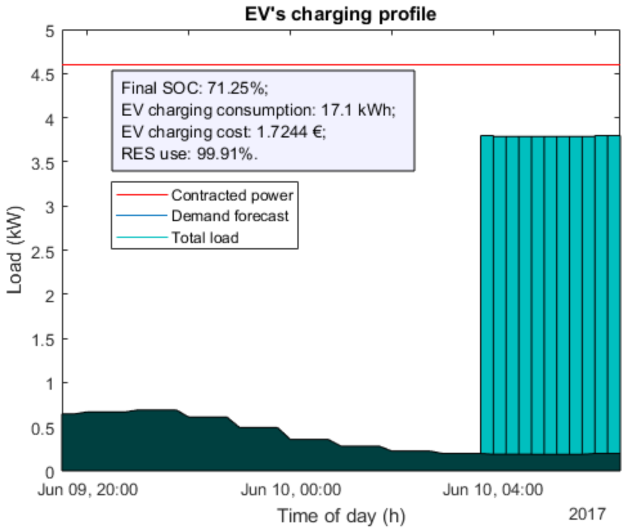


Figure 5.15: EV's charging profile with the use of the SCMA.

In both approaches, the algorithm avoids overcharging the vehicle, however, the final SOC may exceed the required value introduced by the user. This happens because the charging is made using 15 minutes time slots for simulation purposes, so it is likely not be so accurate.

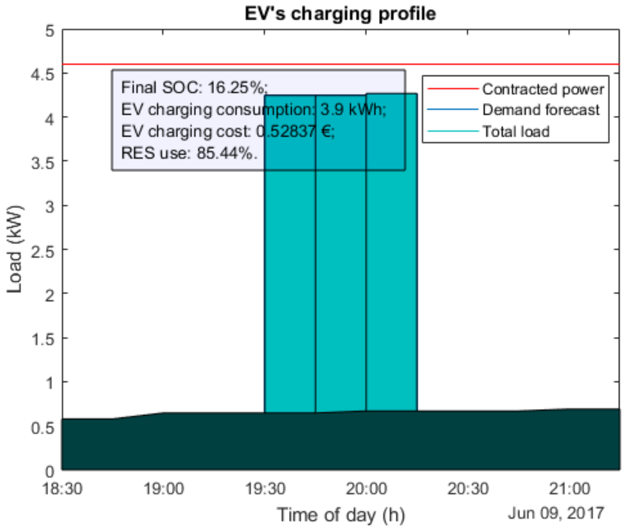


Figure 5.16: EV's charging profile without the use of the SCMA.

6 Results

6.1 Grid related data

In order to facilitate the simulation results' comprehension and assessment, a few diagrams regarding the used data, such as demand forecast, RES forecast and electricity prices throughout the days, are presented below. The demand forecast data, for work days and for weekends, is presented in Figure 6.1.

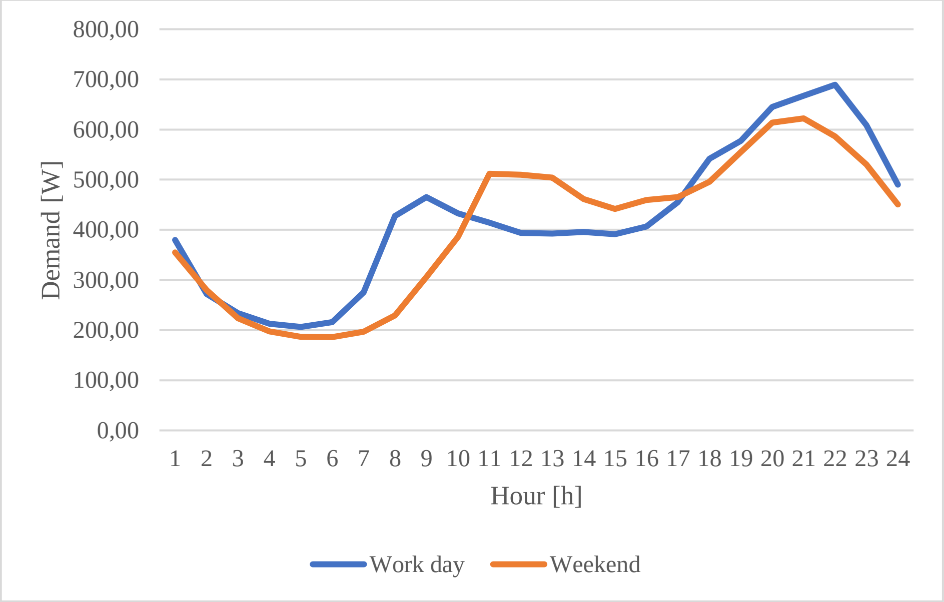


Figure 6.1: Load profile.

Two consecutive days in winter and in summer day were chosen for the simulations, January 12th and 13th 2016 and July 12th and 13th 2016. The purpose of choosing days from different seasons is to analyze the impact of the seasonal variation of RES generation and electricity prices. The RES share for each day is presented in Figure 6.2.

As can be seen, the RES share is more abundant in the winter, rather than in the summer. Also, the hourly price of electricity for each day is presented in Figure 6.3.

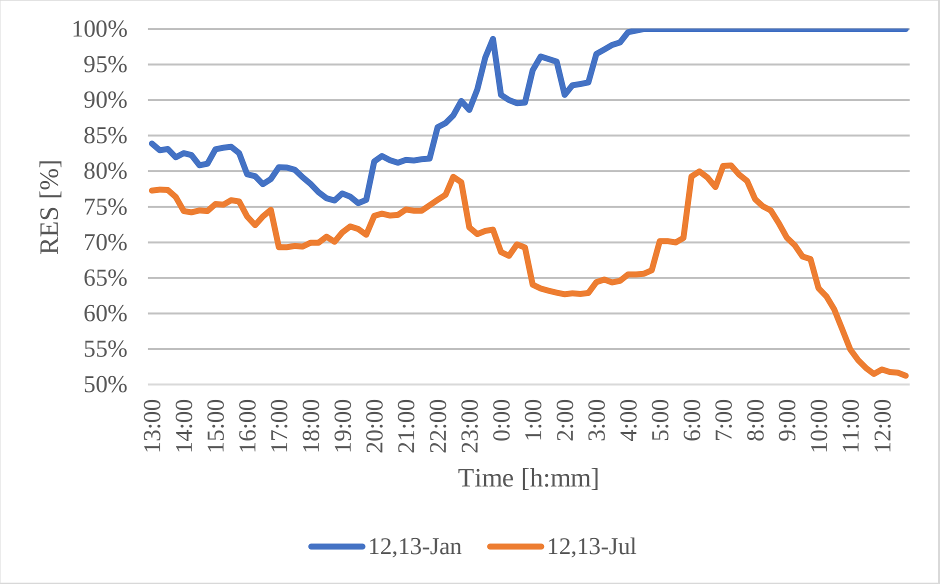


Figure 6.2: RES generation.

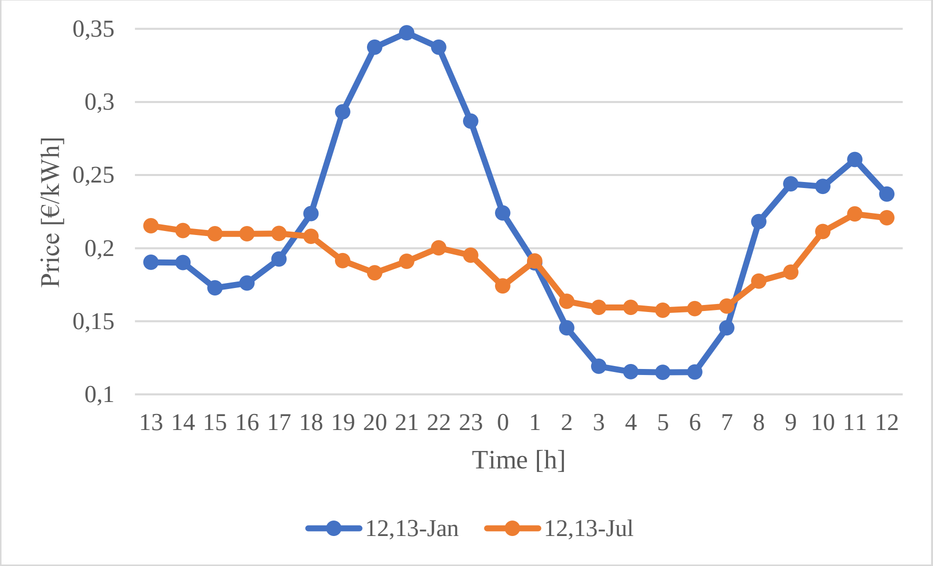


Figure 6.3: Electricity prices.

6.2 Simulation's results

6.2.1 Winter

For both days, the simulation was conducted for the same fixed variables, the same times of arrival and departure and the same initial and final SOC, presented in Table 6.1.

Table 6.1: List of parameters.

Contracted power	6.9 kVA
Battery capacity	24 kWh
Level 1 charger	1.4 kW
Level 2 charger	3.6 kW
Time of arrival	19:40
Time of departure	07:50
Initial SOC	40 %
Desired SOC	90%

Firstly, the algorithm was simulated for the winter day, for all possible objectives, including the one that does not use the SCMA. The simulation diagrams are displayed from Figure 6.4 through Figure 6.7. The achieved results and differences (considering the unmanaged case as baseline) regarding the charging costs and use of RES are presented in Table 6.2.

Table 6.2: Charging cost and RES use (winter).

Objective	**EV charging cost**		**RES use**	
	€	**Dif. (%)**	**%**	**Dif. (%)**
Charging costs	1.46	-64	97.97	+17
Environmental impact	1.84	-54	99.98	+20
Load diagram	1.47	-63	96.89	+16
Without SCMA	4.00	-	83.43	-

As expected, the case in which the algorithm’s objective is to minimize the charging costs, in Figure 6.4, is the one that has the lowest charging cost. The case whose objective is to maximize the use of RES, in Figure 6.5, is the one with the higher percentage of RES’s use, as predicted. Additionally, it can be seen in Figure 6.6 that the algorithm was able to minimize the impact on the load profile by assigning the time slots with lower demand for charging the EV. Lastly, the unmanaged case is presented in Figure 6.7 and it is clear the EV starts charging, continuously, from the time of arrival until it reaches the desired SOC. Thus, it can be concluded that the algorithms fulfilled the objectives’ demands.

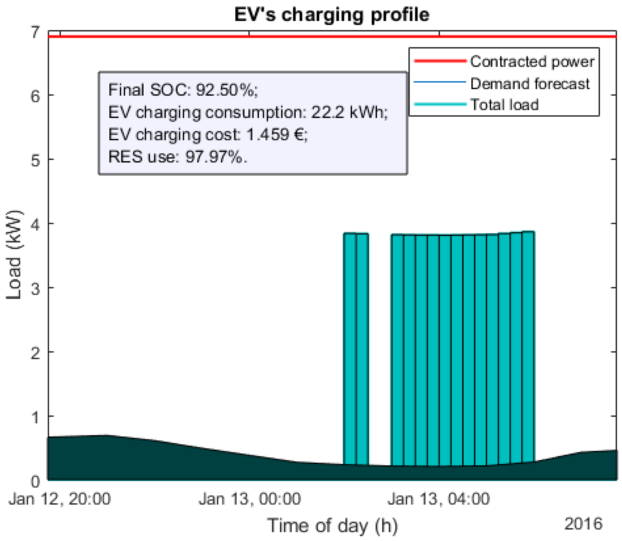


Figure 6.4: Charging while minimizing charging costs (winter).

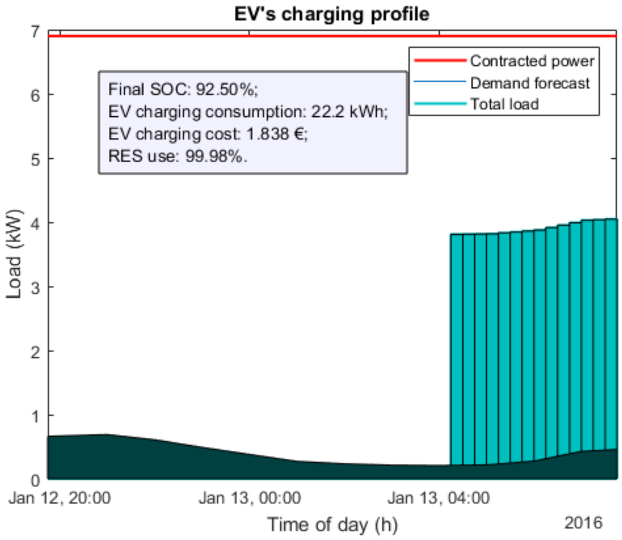


Figure 6.5: Charging while minimizing environmental impact (winter).

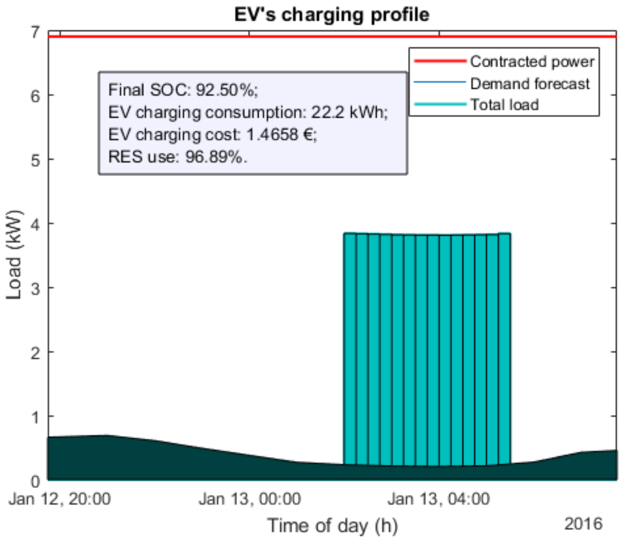


Figure 6.6: Charging while minimizing the impact on the load diagram (winter).

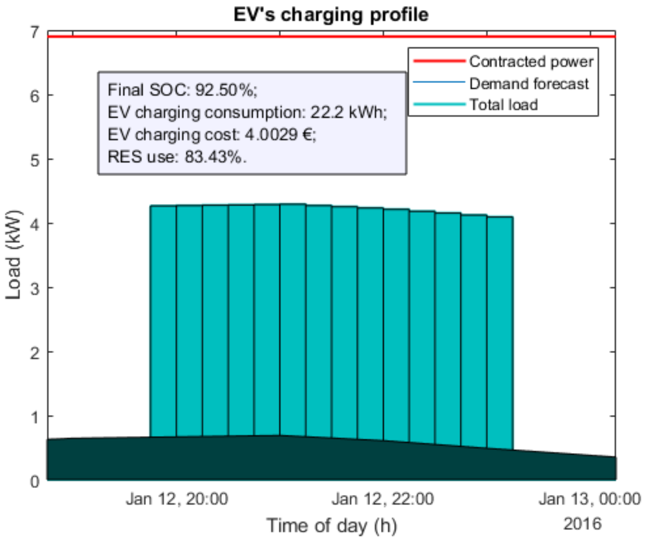


Figure 6.7: Charging without using the SCMA (winter).

Furthermore, when comparing the result of unmanaged charging with any of the other options' result, it is undoubtedly worse for both charging cost and RES's use. The RES share, when the objective is to minimize the environmental impact, is 20 % higher than the value achieved without using the SCMA. Even more noteworthy is the difference in charging costs between unmanaged and managed charging, because charging while minimizing the charging costs, ensures a 64 % lower cost than the unmanaged scenario.

Although there are three distinct objectives, it is noticeable that the results for both charging cost and use of RES are not strikingly different. This is not surprising, because the electricity price in the wholesale market tends to follow the variation of the RES generation during the day. The price of electricity does not vary as frequently as the RES generation, because the price's variation is hourly, while the RES generation varies every 15 minutes. Also, the price of electricity is usually lower in periods of lower demand, therefore also ensuring a high correlation between the objectives to minimize costs and the impact on the load diagram.

6.2.2 Summer

Afterwards, a similar simulation was conducted for the summer days. The simulation diagrams are displayed from Figure 6.8 through Figure 6.11. The achieved results and differences (considering the unmanaged case as baseline) regarding the charging costs and use of RES are presented in Table 6.3.

Table 6.3: Charging cost and RES use (summer).

Objective	**EV charging cost**		**RES use**	
	€	**Dif. (%)**	**%**	**Dif. (%)**
Charging costs	2.00	-18	66.22	-11
Environmental impact	2.30	-5	77.98	+4
Load diagram	2.00	-18	65.15	-13
Without SCMA	2.43	-	74.85	-

Needless to say, the algorithm successfully optimized the EV charging for every objective. Concerning the RES, the algorithm increased its usage by 4 %, when compared to the unmanaged EV charging. The difference between the two values is small, when compared with the results presented in Section 6.2.1 for the Winter. Such result was expected, since the RES generation variation is subtler in the summer than in the winter.

Regarding the charging costs, the SCMA managed to save up to 18 % when compared to the unmanaged scenario. This result, like the one aforementioned, is not as optimal as the result presented in Section 6.2.1. Again, this is justified by the lower variation of the RES generation, that leads also to a low variation in the price. This and the correlation between lower electricity prices and lower demand, also justify the fact that the price for charging while minimizing costs and the price for charging while minimizing the impact on the load profile are practically the same.

By observing Figure 6.2 and Figure 6.3, it is clear that there is a substantial reduction of RES share, when compared to the results presented in Section 6.2.1. This justifies the fact that the charging cost in all managed scenarios, for the summer days, is higher than the managed scenarios for the winter days. If the RES share is lower, the thermal power plants have to operate for longer periods, leading to a higher electricity price.

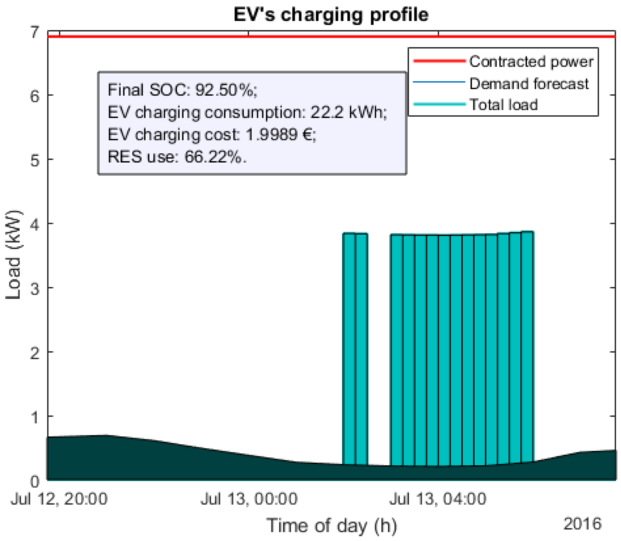


Figure 6.8: Charging while minimizing charging costs (summer).

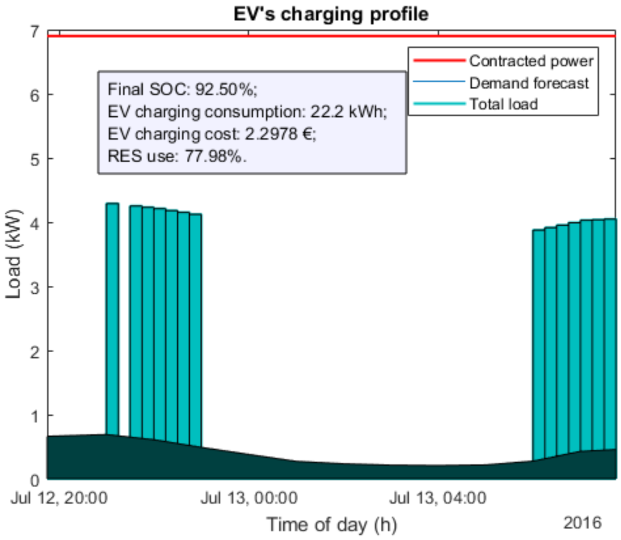


Figure 6.9: Charging while minimizing environmental impact (summer).

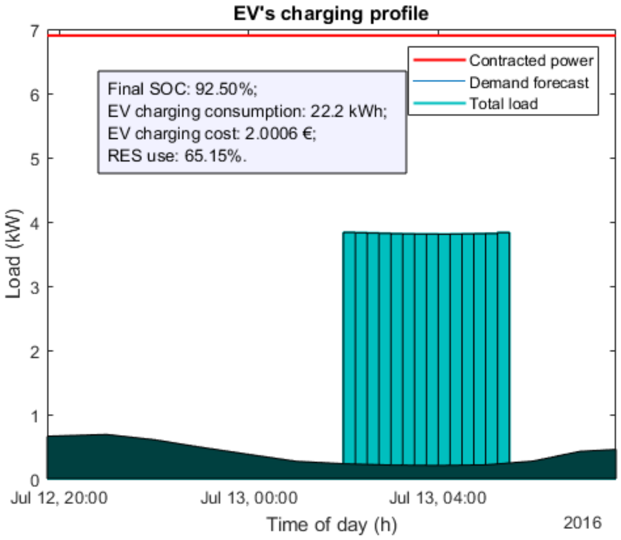


Figure 6.10: Charging while minimizing the impact on the load diagram (summer).

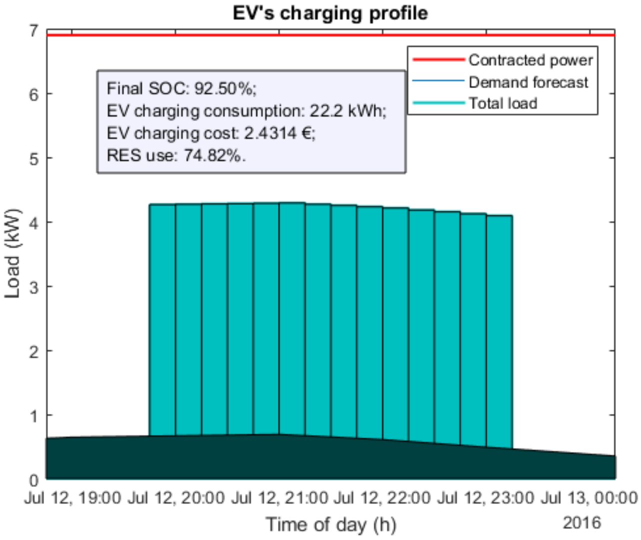


Figure 6.11: Charging without using the SCMA (summer).

6.2.3 Load Diagram

As presented in Chapter 4, the SCMA prevents that the contracted power is exceeded, so, to demonstrate it, a couple of modifications in the winter scenario were made, namely the charging interval, which was changed to a period of peak demand – from 16h00 to 00h30 – and the demand forecast was increased by 400 %, with the purpose of having a shorter margin between the demand forecast and the contracted power. The rest of the parameters, listed in Table 6.1, remain the same.

Figure 6.12 proves the algorithms' ability of effectively choosing the most suitable time slots for charging the EV, ensuring that the contracted power is not exceeded, thus avoiding triggering the dwelling's protection devices. Otherwise, if the user started charging the EV without using the SCMA, such consequences could not be averted, due to the lack of control.

For a scenario like this one, it becomes irrelevant under which objective the EV charging is simulated, since there are few possible time slots available for charging, meaning that the SCMA is not given any alternative for the charging period. As could be predicted, although it is an effective solution, it is not the most economical, as it constitutes the costliest charging simulation out of the four stated in 6.2.1.

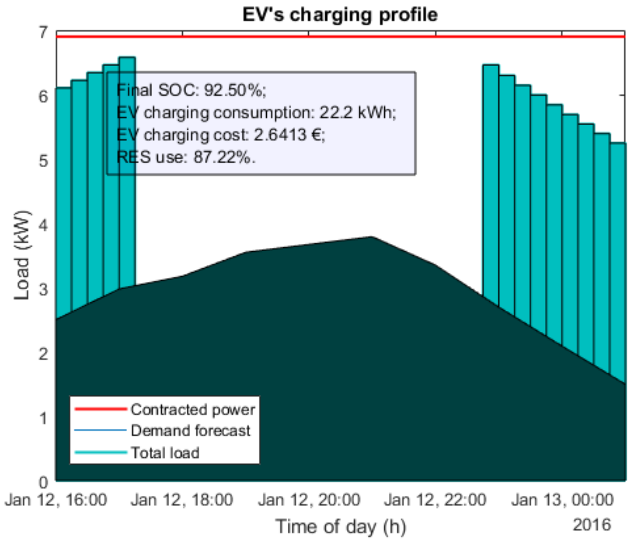


Figure 6.12: Algorithm's ability to avoid exceeding the contracted power (winter).

Another interesting approach, would be if the algorithm was forced to use a Level 1 charger, as in with a contracted power of 3.45 kVA. Such simulation was conducted and the result is depicted in Figure 6.13. Every parameter, but the charger, remained the same as in 6.2.1.

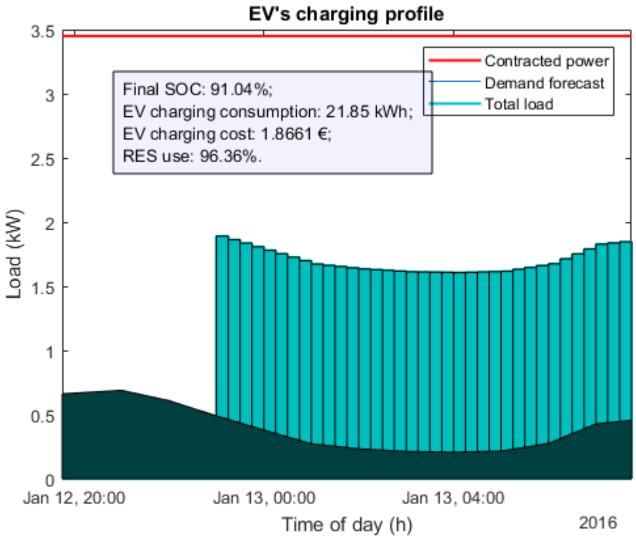


Figure 6.13: Charging using the Level 1 charger (winter).

The SCMA is able to recognize that there is no available power to use the Level 2 charger, thus choosing the Level 1 charger. Yet again, although this proves to be an effective solution, it is not the most preferable, since the charging cost is higher in comparison to any of the managed scenarios presented in Section 6.2.1. Even though the SCMA tries to choose the cheaper time slots for charging, inevitably, due to higher number of required time slots, the optimization is not as good as the one using the Level 2 charger that requires fewer time slots for charging. Additionally, the charging duration is 8 hours and 45 minutes, which is more than double when charging with the Level 2 charger, taking only 3 and half hours to charge the EV. Point being, that a difference of 5 hours and 15 minutes makes this approach way less desirable, if time is of the essence.

6.2.4 Strict Restrictions

Additionally, a similar scenario to the one presented in 6.2.1 was simulated, but the available time for charging was shortened to 5 and half hours. The results are displayed below from Figure 6.14 to Figure 6.16.

Results show that the lower the available time, the more irrelevant the objective becomes. The cost of charging is either the same, like in Figure 6.14 (minimizing charging costs) and in Figure 6.16 (minimizing the impact on the load diagram), or does not differ much from each other, like in Figure 6.15 (maximizing the RES use). Nevertheless, charging while maximizing the RES use is nearly 0.10 € costlier than the others. Needless to say, that the use of RES between results does not differ much as well, since the difference is approximately 1%.

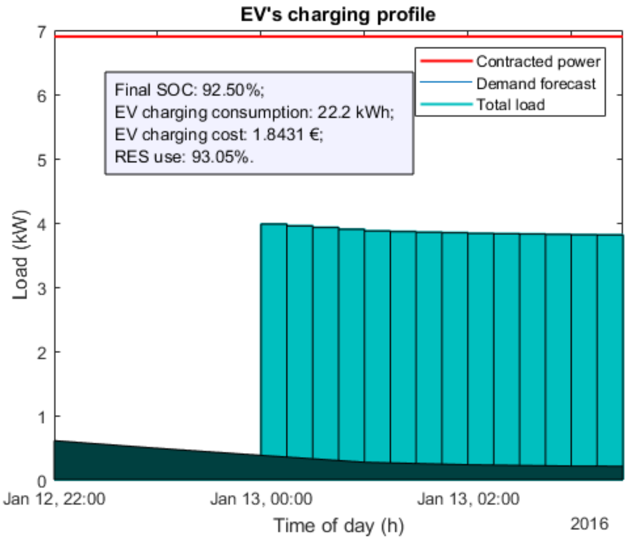


Figure 6.14: Charging while minimizing charging costs with less available time (winter).

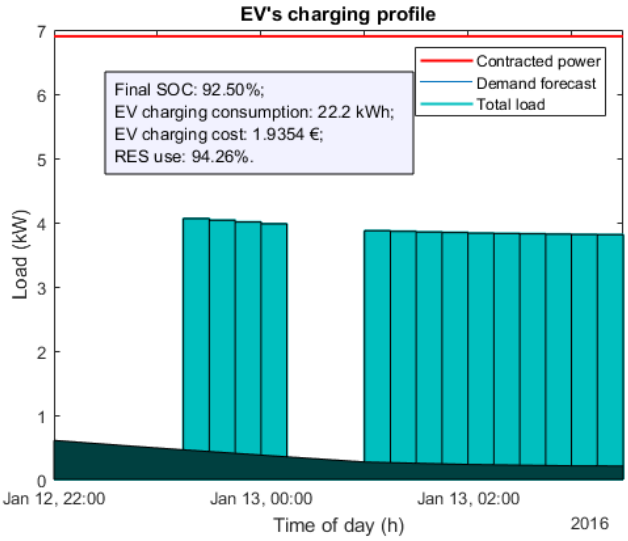


Figure 6.15: Charging while minimizing environmental impact, with less available time (winter).

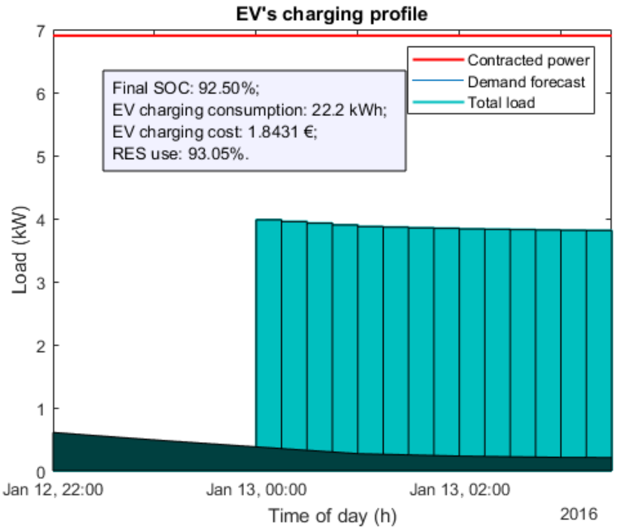


Figure 6.16: Charging while minimizing the impact on the load diagram, with less available time (winter).

7 Conclusions and Future Work

7.1 Conclusions

The inevitable penetration of EVs as the new era of clean transportation systems, represents one of the most promising pathways to reduced oil dependency and consequently fewer emissions of GHG and other pollutants. Another noteworthy benefit is that electricity as a fuel is a lot cheaper than conventional oil based fuels. However, the mass deployment of EVs brings a series of potential problems to the electrical grid, due to the additional load that they represent.

This dissertation worked towards the development of an algorithm that simulates the optimization of an EV's charging process, in a residential dwelling. The main goals were to minimize the overall charging cost, to minimize the environmental impact associated with the charging process and to minimize the impact on the household's load profile. In order to do this, the following assumptions were made: the house was equipped with only one EV; the EV arrives and leaves the house only once a day, the RES forecast, the demand forecast and the energy tariff data were provided to the household. Additional information had to be provided to the algorithm such as initial and final SOC, the chargers' level of power and the contracted power.

Initially, this dissertation started by assessing previous research related with management charging algorithms, analyzing various methodologies and strategies. When enough information was gathered, the algorithm's structure began to be outlined and perfected from then onwards. After the algorithm's structure was completed the actual charging algorithm started being developed, in MATLAB, alongside with gathering the grid related data.

Upon finishing the algorithm, it was then tested for several case studies. Firstly, the algorithm was simulated for a couple of summer days and for a couple of winter days, to assess the influence of RES in optimizing the EV's charging. After that, additional simulations were conducted to evaluate the algorithm's behavior when optimizing the EV's charging cycles under stricter restrictions, such as reduced time, charging at lower power, as well as testing its ability to prevent exceeding the household's contracted power.

The simulation-based analysis is dependent on the quality of dataset and the assumptions made about the research scenario. This work mostly employed real world data in particular for RES generation, as well as for price patterns.

The main conclusions of this dissertation are detailed as follows:

- To begin with, the algorithm developed in the course of this dissertation has proved its usefulness, by constituting an automated EV charging solution. This allows for an equally unpreoccupied alternative to plugging in the EV without any sort of management. Additionally, the proposed charging strategy is able to benefit the user, the environment and also the grid.
- The effectiveness of the proposed algorithm was demonstrated, as it was successful in fulfilling each objective for the selected case studies. The SCMA was able to gather and select the time slots with the lowest electricity price, when the objective was to minimize the charging cost, as well as when the objective was to minimize the environmental impacts, the algorithm was able to gather and select the time slots with the highest RES share and when the objective was to minimize the impact on the load profile, the algorithm managed to select the time slots with more available power. All the selected time slots were confined to the time interval between the arrival and departure times. Moreover, the SCMA made sure that the contracted power was not, in any circumstance, exceeded, thus preventing triggering the installation protections due to overload.
- The optimized charging results for the winter scenario, when compared to the standard EV charging, show better results than the optimized results for the summer scenario. Usually, the higher the RES share, the lower the electricity price. RES are more abundant in the winter than in the summer, hence the difference in the charging costs and RES usage.
- The differences between the results of managed and unmanaged charging are more noticeable for the winter scenario, compared to the differences registered in the summer scenario. A plausible explanation is the lower variation in electricity prices and RES generation, in the summer, when compared to the winter scenario.
- Charging the EV while minimizing charging costs or while minimizing the impact on the load profile becomes redundant, which is convenient. This is justified by the fact that the electricity price is usually lower in low demand periods.
- Economically speaking, the Level 2 charger is the one that allows for a cheaper charging cycle, compared to the Level 1 charger. Reason being, that the additional time slots required to charge the EV with the Level 1 charger have higher electricity prices, than the fewer time slots used with the Level 2 charger.

- Nowadays, with regards to the potential of minimizing the charging costs, this approach becomes less attractive, due to the bi-hourly tariff, which is widely adopted by users, since the SCMA would only have to offset the charging cycles to the period with the lower electricity price. This means that the charging process would start at a specific time of the day, every day, thus not requiring a smart charging strategy.

7.2 Future Work

The results achieved in this dissertation were coherent and the initial expectations were met, yet there is still room for possible improvements and variations that could be made.

For instance, a plausible extent to this work would be the possibility of coordinate charging of various EVs between different residential buildings. The additional control should avoid the simultaneous charging of EVs in a more effective way, thus contributing to peak load reduction, benefiting both the user and the grid.

Another interesting strategy that could implemented, would be V2G. With this possibility, the SCMA would be able to store energy in EV’s battery when the electricity prices are lower and sell that harnessed energy back to grid with a potential profit, thus providing added economic benefits to the user. Moreover, the stored energy could be used to power other domestic appliances, when the electricity prices are highest and the EV’s storage capability could even operate as an emergency power supply, in the event of power surge.

Furthermore, another interesting feature that could be added to this work, would be the integration of the SCMA with a household that is equipped with renewable energy generation devices, such as PV. That way, the algorithm would be able to manage the EV’s charging cycles with less dependency on the grid, and even reduce the charging costs involved in the charging process.

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Appendixes

A1 SCMA

1 - Start

```
clear,clc

[cdata,map] = imread('icon.png');
```

2 - EV Plug-in

```
while 1
    Connected = questdlg('Is the EV plugged in? ','','Yes','No','Cancel','Yes');
    switch Connected
        case 'Yes'
            fprintf('\nThe car is connected.\nYes.\n\n')
            break
        case 'No'
            continue
        case 'Cancel'
            uiwait(errordlg('You canceled!'))
            error('You canceled!')
    end
end

% Date and time of arrival:

% For simulation purposes, 9-06-2017 19:20 is the date and
% time of arrival chosen for simulation
Tarrival = datetime(2016,1,12,19,40,0);
%Tarrival = datetime(2017,6,10,4,0,0);
fprintf('Arrival time: %s\n\n',datestr(Tarrival))
%pause(1)

% The user is asked to input the current (initial) SOC
while 1
    SOCinitial = inputdlg('Current SOC (%): ','',1);
    if (isnan(str2double(SOCinitial{1})) == false) && (str2double(SOCinitial{1}) >= 0) &&
(str2double(SOCinitial{1}) < 100) % The SOC is expected to be positive and inferior that 100
        SOCinitial = str2double(SOCinitial{1});
        fprintf('The current SOC is %d%%.\n\n',SOCinitial)
        break
    else
        uiwait(warndlg('Invalid input!'))
        warning('Invalid input!')
    end
end
```

3 - Modify fixed restrictions?

```
wish = questdlg('Modify fixed restrictions?','','Yes','No','Cancel','No');
switch wish
    case 'Yes'
        Mod = true;     % Goes to step 4
        fprintf('Modify fixed restrictions?\nYes.\n\n')
    case 'No'
        Mod = false;    % Goes to step 5
        fprintf('Modify fixed restrictions?\nNo.\n\n')
    case 'Cancel'
        uiwait(errordlg('You canceled!'))
        error('You canceled!')
end
```

4 - Fixed restrictions

```
% Loads the variables restrictions
try
    load('variables.mat')
catch
    % If the algorithm is being run for the first time, the file does not
    % exist. This way, it is created.
    save('variables.mat')
end

if Mod == true
    % Vector containing the possible contracted power values for TOU tariff:
    contractedP = [3.45 4.6 5.75 6.9 10.35 13.8 17.25 20.7]'; % (kVA)

    % Contracted power
    while 1
        PcontractedNew = inputdlg('Contracted power (kVA): ("dc" if you do not want to
change)','',1);
        if strcmp(PcontractedNew,'dc') == 1 % Does not modify its value
            fprintf('Contracted power unchanged.\n')
            break
        else                                                      % If the input is not 'dc',
then it is expected to be a number
            equal = str2double(PcontractedNew{1}) == contractedP; % The input is converted to
double and assesses if it is possible
            if any(equal == true)
                Pcontracted = str2double(PcontractedNew{1});
                save('variables.mat','Pcontracted','-append');    % Writes to file
                fprintf('Contracted power: %g kVA\n',Pcontracted)
                break
            else
                uiwait(warndlg('Invalid input!'))
                warning('Invalid input!')
                str = {'Choose one of the following possibilities:', mat2str(contractedP)};
                uiwait(msgbox(str))
                disp(str(1))
                disp(str(2));
            end
        end
    end

    % Battery's capacity
    while 1
        CbatteryNew = inputdlg('Battery capacity (kWh): ("dc" if you do not want to
change)','',1);
        if strcmp(CbatteryNew,'dc') == 1 % Does not modify its value
            fprintf('Battery capacity unchanged.\n')
            break
        elseif (isnan(str2double(CbatteryNew{1})) == false) && (str2double(CbatteryNew{1}) > 0)
% If the input is not 'dc', then it is expected to be a number
            Cbattery = str2double(CbatteryNew{1});
% Checks if it is a positive number
            save('variables.mat','Cbattery','-append');   % Writes to file
            fprintf('Battery capacity: %g kWh.\n',Cbattery)
            break
        else
            uiwait(warndlg('Invalid input!'))
            warning('Invalid input!')
        end
    end

    % Carregador 1
    while 1
        Pcharger1New = inputdlg('Level 1 charger''s power (kW): ("dc" if you do not want to
change)','',1);
        if strcmp(Pcharger1New,'dc') == 1 % Does not modify its value
            fprintf('Level 1 charger unchanged.\n')
            break
        elseif (isnan(str2double(Pcharger1New{1})) == false) && (str2double(Pcharger1New{1}) >
0) % If the input is not 'dc', then it is expected to be a number
            Pcharger1 = str2double(Pcharger1New{1});
```

```
% Checks if it is a positive number
            save('variables.mat','Pcharger1','-append');  % Writes to file
            fprintf('Level 1 charger: %g kW.\n',Pcharger1)
            break
        else
            uiwait(warndlg('Invalid input!'))
            warning('Invalid input!')
        end
    end

    % Carregador 2
    while 1
        Pcharger2New = inputdlg('Level 2 charger''s power (kW): ("dc" if you do not want to
change)','',1);
        if strcmp(Pcharger2New,'dc') == 1 % Does not modify its value
            fprintf('Level 2 charger unchanged.\n\n')
            break
        elseif (isnan(str2double(Pcharger2New{1})) == false) && (str2double(Pcharger2New{1}) >
0) % If the input is not 'dc', then it is expected to be a number
            Pcharger2 = str2double(Pcharger2New{1});
% Checks if it is a positive number
            save('variables.mat','Pcharger2','-append');  % Writes to file
            fprintf('Level 2 charger: %g kW.\n\n',Pcharger2)
            break
        else
            uiwait(warndlg('Invalid input!'))
            warning('Invalid input!')
        end
    end
end

% Vector containing the chargers' values:
Pcharger = [Pcharger1 Pcharger2];
Pselect = 0; % Pselect will either be 1 or 2, depending on the decision
```

5 - Grid related restrictions

```
% Spreadsheet containing demand forecast, RES forecast, and tariff data
Data = readtable('Data_12_13_Jan_2016.xlsx');

fprintf('RES data imported.\n')
pause(1)
% Converting 24h value to 15min values------------------------------------>
format bank
% Converting demand forecast---------------------------------------------->

% Work days' demand for cast(kW)
Fp_wddummy = Data.Fp_wd/1000;
% Weekend's demand for cast(kW)
Fp_wedummy = Data.Fp_we/1000;

% Creating demand forecast vectors for 15min intervals
Data.Fp_wd = zeros(192,1);  % 192 is the number of 15 minute intervals in 48h
Data.Fp_we = zeros(192,1);

k = 1;
for i = 1:4:96
    v1 = linspace(Fp_wddummy(k),Fp_wddummy(k + 1),5);
    v2 = linspace(Fp_wedummy(k),Fp_wedummy(k + 1),5);
    g = 1;
    for j = i:i + 3
        Data.Fp_wd(j) = v1(g);
        Data.Fp_we(j) = v2(g);
        g = g + 1;
    end
    k = k + 1;
end

v1 = linspace(Fp_wddummy(24),Fp_wddummy(1),5);
v2 = linspace(Fp_wedummy(24),Fp_wedummy(1),5);
g = 1;
for j = 93:96
    Data.Fp_wd(j) = v1(g);
    Data.Fp_we(j) = v2(g);
    g = g + 1;
end

% Repeat the process for the next 24h (48)
Data.Fp_wd(97:end) = Data.Fp_wd(1:96);
Data.Fp_we(97:end) = Data.Fp_we(1:96);
% % higher consumption
% Data.Fp_wd = Data.Fp_wd * 5.5;
% Data.Fp_we = Data.Fp_we * 5.5;
% <----------------------------------------------Converting demand forecast

fprintf('Demand forecast data imported.\n')
```

```
pause(1)
% Converting the tariff---------------------------------------------------->

% Price in €/kWh for the day of arrival
Price_d1dummy = Data.Price_d1;
% Price in €/kWh for the day of departure
Price_d2dummy = Data.Price_d2;

% New variable to gather the electricity prices for 48h in 15 minute time
% slots
Data.ET = zeros(192,1);
k = 1;
for i = 1:4:96
    Data.ET(i:i + 3) = Price_d1dummy(k);
    Data.ET(96 + i:96 + i + 3) = Price_d2dummy(k);
    k = k + 1;
end
fprintf('Energy tariff data imported.\n')
% <---------------------------------------------------Converting the tariff
% <------------------------------------Converting 24h value to 15min values

% Updating the table Data
Data.Day = [];
Data.Time = [];
Data.Var5 = [];
Data.Hour = [];
Data.Price_d1 = [];
Data.Price_d2 = [];
Data = Data(:,[1,3,4,5,2]);
fprintf('Grid related restrictions imported.\n\n')
pause(1)
```

6 - SCMA?

```
scma = questdlg('Do you wish to use the SCMA?','','Yes','No','Cancel','Yes');
switch scma
    case 'Yes'
        fprintf('Do you wish to use the SCMA?\nYes.\n\n')
    case 'No'
        fprintf('Do you wish to use the SCMA?\nNo.\n\n')
    case 'Cancel'
        uiwait(errordlg('You canceled!'))
        error('You canceled!')
end

% If the user chooses to use the SCMA
if strcmp(scma,'Yes') == 1
    % The user chooses the objective
    obj = menu2('Choose an objective:','Minimize charging costs (EC)','Minimize environmental
impact (EI)','Minimize impact on load profile (PI)','Cancel');
    switch obj
        case 1
            fprintf('Which objective to use?\nMinimize charging costs (EC).\n\n')
        case 2
            fprintf('Which objective to use?\nMinimize environmental impact (EI).\n\n')
        case 3
            fprintf('Which objective to use?\nMinimize impact on load profile (PI).\n\n')
        case 4
            uiwait(errordlg('You canceled!'))
            error('You canceled!')
    end

    % 7 8 9 - The user is asked to introduce the variable restrictions

    [Tdeparture,SOCfinal,Treq1,Treq2,Pselect] =
restrictions(Cbattery,SOCinitial,Pcharger,Tarrival,Pselect);

    % 10 11 12 13
    [Data1,Data2,SOCfinal,Pselect,PlotData,Treq1,Treq2] =
timeslots(Cbattery,Data,Tarrival,Tdeparture,Pcharger,Pselect,Pcontracted,SOCinitial,SOCfinal,Tre
q1,Treq2);
```

14 - Classifies the timeslots according to objective

```
    if Pselect ~= 2
        EC1 = sortrows(Data1,'ET','ascend');
        EI1 = sortrows(Data1,'RES','descend');
        PI1 = sortrows(Data1,'Pa','descend');
    end

    if Pselect ~= 1
        EC2 = sortrows(Data2,'ET','ascend');
        EI2 = sortrows(Data2,'RES','descend');
```

```
        PI2 = sortrows(Data2,'Pa','descend');
    end
```

15 - Selects the necessary slots for charging

After sorting the tables, the slots which will not be used for charging are deleted

```
    if Pselect ~= 2
        for i = 1:size(Data1,1)
            duration = i * hours(0.25); % each line represents a 15 minute slot
            if duration >= Treq1
                break
            else
                continue
            end
        end
        % Deletes the unnecessary slots
        EC1(i + 1:end,:) = [];
        EI1(i + 1:end,:) = [];
        PI1(i + 1:end,:) = [];

        % Sorts the remaining slots in a chronological order
        EC1 = sortrows(EC1,'Date','ascend');
        EI1 = sortrows(EI1,'Date','ascend');
        PI1 = sortrows(PI1,'Date','ascend');
    end

    % The process is repeated
    if Pselect ~= 1
        for i = 1:size(Data2,1)
            duration = i * hours(0.25);
            if duration >= Treq2
                break
            else
                continue
            end
        end

        EC2(i + 1:end,:) = [];
        EI2(i + 1:end,:) = [];
        PI2(i + 1:end,:) = [];

        EC2 = sortrows(EC2,'Date','ascend');
        EI2 = sortrows(EI2,'Date','ascend');
        PI2 = sortrows(PI2,'Date','ascend');
    end
```

16 - Decides which charger to use

If the charger is not yet chosen, then this net step decides which one to use upon cost difference

```
    if Pselect == 0
        % Charging cost using the Level 1 charger (for each objective)
        SumEC1 = sum(EC1.ET);
        SumEI1 = sum(EI1.ET);
        SumPI1 = sum(PI1.ET);
        % Charging cost using the Level 2 charger (for each objective)
        SumEC2 = sum(EC2.ET);
        SumEI2 = sum(EI2.ET);
        SumPI2 = sum(PI2.ET);

        x = 1.2; % weight factor
        decision = abs(SumEC1-SumEC2)/SumEC2;

        if decision <= x
            Pselect = 1;
            fprintf('Level 1 charger is selected\n\n')
            pause(1)
        else
            Pselect = 2;
            fprintf('Level 2 charger is selected\n\n')
            pause(1)
        end
    end
```

17 18 19 - Charging process

```
    % Data assumirá a informação do objetivo e carregador escolhidos
    switch obj
        % EC (minimizing costs)
        case 1
            if Pselect == 1
```

```
                Data = EC1;
                fprintf('Chosen objective: EC\n\n')
            else
                Data = EC2;
                fprintf('Chosen objective: EC\n\n')
            end
            %EI (minimizing environmental impact)
        case 2
            if Pselect == 1
                Data = EI1;
                fprintf('Chosen objective: EI\n\n')
            else
                Data = EI2;
                fprintf('Chosen objective: EI\n\n')
            end
            %EI (minimizing profile impact)
        case 3
            if Pselect == 1
                Data = PI1;
                fprintf('Chosen objective: PI\n\n')
            else
                Data = PI2;
                fprintf('Chosen objective: PI\n\n')
            end
    end

    date = [Data.Date; Data.Date(end) + minutes(15)];
    date = datestr(date);
    str = {'The charging process starts at ',date(1,13:17),' and will be completed by
',date(end,13:17),'.'};
    uiwait(msgbox(str))
    fprintf('The charging process starts at %s and will be completed by
%s.\n\n',date(1,13:17),date(end,13:17))

    %   Charging
    i = 1;  % time slot index
    SOC = SOCinitial;
    for k = 1:size(Data,1)
        if (SOC < SOCfinal) && (SOC + 100 * Pcharger(Pselect) * 0.25 / Cbattery <= 100)
            SOC = SOC + 100 * Pcharger(Pselect) * 0.25 / Cbattery;
            fprintf('Charging in the timeslot: %s\nSOC = %g %%\n\n',datestr(Data.Date(i)),SOC)
            i = i + 1;
            pause(1)
        end
    end


    % Final SOC
    SOCfinal = SOC;
    fprintf('Final SOC: %.2f%%;\n',SOCfinal)

    % Consumption
    Consump = (SOCfinal / 100) * Cbattery;
    fprintf('EV charging consumption: %.2f kWh;\n',Consump)

    % EV charging cost
    Cost = sum(Data.ET(1:end)) * Pcharger(Pselect) * .25;
    fprintf('EV charging cost: %.3f €;\n',Cost)

    % RES
    RES = mean(Data.RES)*100;%sum(ismember(Data.RES,1))/(numel(Data.RES))*100;
    fprintf('RES use: %.2f%%.\n\n',RES)

    % Plot
    if size(PlotData,2) == 3
        if Pselect == 1
            PlotData(:,3) = []; % deletes Pa for Level 2 charger
        elseif Pselect == 2
            PlotData = PlotData(:,[1 3]); % deletes Pa for Level 1 charger
        end
    end
    x = table2array(PlotData(:,1));
    y1 = Pcontracted - table2array(PlotData(:,2)) - Pcharger(Pselect);
    idx = ismember(PlotData.Date,Data.Date);
    y2 = zeros(height(PlotData),1);
    for j = 1:length(y2)
        if idx(j) == 1
            y2(j) = Pcharger(Pselect) + y1(j);
        end
    end
    h = figure(2);
    plot([x(1) x(end)],[Pcontracted Pcontracted],'r','LineWidth',1.5);
    dim = [0.2 0.55 0.3 0.3];
    str1 = ['Final SOC: ' num2str(SOCfinal,'%.2f') '%;'];
    str2 = ['EV charging consumption: ' num2str(Consump) ' kWh;'];
    str3 = ['EV charging cost: ' num2str(Cost) ' €;'];
    str4 = ['RES use: ' num2str(RES,'%.2f') '%.'];
    str = {str1 str2 str3 str4};
```

```
annotation('textbox',dim,'String',str,'FitBoxToText','on','BackgroundColor','blue','FaceAlpha',0
.05)
    hold on
    s = stairs(x,y2);
    fillstairs(x',y2',zeros(1,size(PlotData,1)),h);
    a = area(x,y1);
    a.FaceColor = [0 0.25 0.25];
    xlim([x(1) x(end)])
    title('EV''s charging profile')
    xlabel('Time of day (h)')
    ylabel('Load (kW)')
    legend('Contracted power','Demand forecast','Total load');
    hold off
else   % If the user chooses not to use the SCMA
    Pselect = 2;    % Level 2 charger selected
```

20 - Desired SOC

```
    while 1
        SOCfinal = inputdlg('Final SOC (%):','',1);
        if (isnan(str2double(SOCfinal{1})) == false) && (str2double(SOCfinal{1}) > SOCinitial)
&& (str2double(SOCfinal{1}) <= 100) % SOCfinal must be a positive number between SOCinitial and
100
            SOCfinal = str2double(SOCfinal);
            break
        else
            uiwait(warndlg('Invalid input!'))
        end
    end
```

21 - Calculates the required charging time

```
    Treq = hours(Cbattery*((SOCfinal-SOCinitial)/100)/Pcharger(2));
```

22 & 23 - Charges for the required time and checking if there is any left

```
    % Time interval between arrival time and 14 minutes passed from that
    % time. This is useful to know which 15 minutes interval, from that
    % time on, is closest.
    Tinterval = (Tarrival:minutes(1):Tarrival+minutes(14))';

    % Data.Date is a datetime variable with the day of arrival until the
    % day of departure in 15 minutes' timeslots, from 00h00 23h45 of the
    % next day

    % Checks which indexes between Data.Date and Tinterval are equal:
    idx = find(ismember(Data.Date,Tinterval,'rows'));

    %   Charging
    i = 0; % For knowing how many slots are necessary for charging
    SOC = SOCinitial;
    D = hours(0); % Duration of the charging in hours
    while (Treq > D) && (SOC + 100 * Pcharger(Pselect) * 0.25 / Cbattery <= 100)
        % Charges in 15 minutes' time slots
        SOC = SOC + 100 * Pcharger(Pselect) * .25 / Cbattery;
        fprintf('Charging in the timeslot: %s\nindex: %d\nSOC = %g
%%\n\n',datestr(Data.Date(idx+i)),idx+i,SOC)
        D = D + hours(.25); % Each timeslot represents a 15 minute duration
        i = i + 1;
        pause(1)
    end

    % When added to i, represents he last charging timeslot
    i = i - 1;

    % Final SOC
    SOCfinal = SOC;
    if SOCfinal > 100
        SOCfinal = 100;
    end
    fprintf('Final SOC: %.2f%%;\n',SOCfinal)

    % Consumption
    Consump = (SOCfinal / 100) * Cbattery;
    fprintf('EV charging consumption: %.2f kWh;\n',Consump)

    % EV charging cost
    Cost = sum(Data.ET(idx:idx + i)) * Pcharger(Pselect) * .25;
    fprintf('EV charging cost: %.3f €;\n',Cost)
```

```
    % RES
    RES = mean(Data.RES(idx:idx + i))*100;%sum(ismember(Data.RES(idx:idx +
i),1))/(numel(Data.RES(idx:idx + i)))*100;
    fprintf('RES use: %.2f %%.\n\n',RES)

    % Plot
    g = 4;
    Fp = zeros(i + 2 + 8,1);    % (i + 2) -> number of slots used for charging;
                                % 8 -> Number of slots equivalent to 2h (1h prior to charging
and another after)
    for t = 1:4
        if isweekend(Data.Date(idx - g)) == 0
            Fp(t) = Data.Fp_wd(idx - g);
        elseif isweekend(Data.Date(idx - g)) == 1
            Fp(t) = Data.Fp_we(idx - g);
        end
        g = g - 1;
    end

    for t = 5:size(Fp)
        if isweekend(Data.Date(idx + g)) == 0
            Fp(t) = Data.Fp_wd(idx + g);
        elseif isweekend(Data.Date(idx + g)) == 1
            Fp(t) = Data.Fp_we(idx + g);
        end
        g = g + 1;
    end
    x = Data.Date(idx-4:idx + i + 1 + 4);
    y1 = Fp;
    y2 = [zeros(4,1); Fp(5:end-5) + Pcharger(Pselect); zeros(5,1)];
    h = figure(1);
    plot([x(1) x(end)],[Pcontracted Pcontracted],'r','LineWidth',1.5)
    dim = [0.2 0.55 0.3 0.3];
    str1 = ['Final SOC: ' num2str(SOCfinal,'%.2f') '%;'];
    str2 = ['EV charging consumption: ' num2str(Consump) ' kWh;'];
    str3 = ['EV charging cost: ' num2str(Cost) ' €;'];
    str4 = ['RES use: ' num2str(RES,'%.2f') '%.'];
    str = {str1 str2 str3 str4};

annotation('textbox',dim,'String',str,'FitBoxToText','on','BackgroundColor','blue','FaceAlpha',0
.05)
    hold on
    s = stairs(x,y2);
    fillstairs(x',y2',zeros(1,size(x,1)),h);
    a = area(x,y1);
    a.FaceColor = [0 0.25 0.25];
    xlim([x(1) x(end)])
    title('EV''s charging profile')
    xlabel('Time of day (h)')
    ylabel('Load (kW)')
    legend('Contracted power','Demand forecast','Total load');
    hold off
end
```

24 - Charging complete

```
uiwait(msgbox('Charging completed!','','custom',cdata,map));
fprintf('Charging completed!\n')

% Deletes unnecessary variables
clearvars -except Cbattery Connected Consump Cost Data decision EC1 EC2 EI1 EI2 Mod obj
Pcharger1 Pcharger2 Pcontracted PI1 PI2 PlotData Pselect RES SCMA SOCfinal SOCinitial Tarrival
Tdeparture Tinterval Treq Treq1 Treq2 x
```

Functions--

```
% Function steps 7 8 9
function [Tdeparture,SOCfinal,Treq1,Treq2,Pselect] =
restrictions(Cbattery,SOCinitial,Pcharger,Tarrival,Pselect)
% This piece of code only runs if the user chooses to use the SCMA. The
% user is asked to introduce the desired SOC and the time of departure
```

7 - Variable restrictions

```
% For simulation purposes, 10-06-2017 06:40 is the date and
% time of departure chosen for simulation
while 1
    VarRes = inputdlg({'Enter time of departure (HH:mm)','Final SOC(%)'},'',1);
    timechar = VarRes{1};
```

```
    if (size(timechar,2) ~= 5) || (str2num(timechar(1:2)) > 23) || (str2num(timechar(1:2)) < 0)
|| (str2num(timechar(4:5)) > 59) || (str2num(timechar(4:5)) < 0) || (strcmp(timechar(3),':') ==
false) %#ok<ST2NM>
        uiwait(warndlg('Invalid input!'))
    elseif (isnan(str2double(VarRes{2})) == false) && (str2double(VarRes{2}) > SOCinitial) &&
(str2double(VarRes{2}) <= 100) % The SOC is expected to be positive and inferior that 100
        timedate = datetime(VarRes{1},'InputFormat','HH:mm');
        if hour(timedate) > hour(Tarrival) % If it is the same day
            Tdeparture = Tarrival;
            Tdeparture.Hour = timedate.Hour;
            Tdeparture.Minute = timedate.Minute;
            break
        elseif hour(timedate) <= hour(Tarrival) % If it is the next day
            Tdeparture = Tarrival;
            Tdeparture.Day = day(Tarrival + caldays(1));
            Tdeparture.Hour = timedate.Hour;
            Tdeparture.Minute = timedate.Minute;
            break
        else
            warning('Invalid input!')
            uiwait(warndlg('Invalid input!'))
        end
    else
        warning('Invalid input')
        uiwait(warndlg('Invalid input'))
    end
end
SOCfinal = str2double(VarRes{2});
fprintf('Enter time of departure (HH:mm): %s;\nFinal SOC(%%): %d%%.\n\n',Tdeparture,SOCfinal)
```

8 - Calculates the required charging time

```
% Required charging duration for Level 1 charger
Treq1 = hours(Cbattery*((SOCfinal-SOCinitial)/100)/Pcharger(1));
% Required charging duration for Level 2 charger
Treq2 = hours(Cbattery*((SOCfinal-SOCinitial)/100)/Pcharger(2));

% Tavail is the available time in hours between the arrival and departure
% times
Tavail = Tdeparture - hours(.25) - Tarrival;
```

9 - Is Treq sufficient?

```
% Checks if both Treq1 or Treq2 are possible and if they are not, the
% user is asked to introduce the variable restrictions again until at
% least one of them is possible
while (Treq1 > Tavail) && (Treq2 > Tavail)
    [Tdeparture,SOCfinal,Treq1,Treq2,Pselect] =
restrictions(Cbattery,SOCinitial,Pcharger,Tarrival,Pselect);
end

% If Treq1 is not possible, then the Pcharger1 is discarded
if Treq1 > Tavail
    Pselect = 2;
    fprintf('Level 2 charger is selected\n\n')
end

% If Treq2 is not possible, then the Pcharger2 is discarded
if Treq2 > Tavail
    Pselect = 1;
    fprintf('Level 1 charger is selected\n\n')
end
end

% Funtion steps 10 11 12 13
function [Data1,Data2,SOCfinal,Pselect,PlotData,Treq1,Treq2] =
timeslots(Cbattery,Data,Tarrival,Tdeparture,Pcharger,Pselect,Pcontracted,SOCinitial,SOCfinal,Tre
q1,Treq2)
```

10 - Generates charging time slots

```
% Time interval between arrival and departure times minute by minute.
Tinterval = (Tarrival:minutes(1):(Tdeparture))';

% Data.Date is a datetime variable with the day of arrival until the
% day of departure in 15 minutes' timeslots, from 00h00 23h45 of the
% next day

% Checks which indexes between Data.Date and Tinterval are equal:
idx = ismember(Data.Date,Tinterval,'rows');
```

```
% Data is updated with the possible timeslots between arrival and departure
% in 15 minute slots
Data = Data(idx,:);

% Copies Data to tables Data1 and Data2 (for each charger)
Data1 = Data;
Data2 = Data;

% Create a table with the power availability for charging since the time of
% arrival to the time of departure in 15 minute time slots (for each
% charger)
```

11 - Calculates the available power for each time slot

```
% If the Level 1 charger has not been discarded yet
if Pselect ~= 2
    Data1.Pa = zeros(size(Data1,1),1);
    for i = 1:size(Data1,1)
        % If it is a work day
        if isweekend(Data1.Date(i)) == 0
            Data1.Pa(i) = Pcontracted - Data1.Fp_wd(i) - Pcharger(1);
            % If it is a weekend day
        elseif isweekend(Data1.Date(i)) == 1
            Data1.Pa(i) = Pcontracted - Data1.Fp_we(i) - Pcharger(1);
        end
    end
end

% If the Level 2 charger has not been discarded yet
if Pselect ~= 1
    Data2.Pa = zeros(size(Data2,1),1);
    for i = 1:size(Data2,1)
        % If it is a work day
        if isweekend(Data2.Date(i)) == 0
            Data2.Pa(i) = Pcontracted - Data2.Fp_wd(i) - Pcharger(2);
            % If it is a weekend day
        elseif isweekend(Data2.Date(i)) == 1
            Data2.Pa(i) = Pcontracted - Data2.Fp_we(i) - Pcharger(2);
        end
    end
end

% Creating variable w/ time and demand availability for plotting results
PlotData = array2table(Data.Date,'VariableNames',{'Date'});
if Pselect ~= 2
    PlotData.Pa1 = Data1.Pa;
end
if Pselect ~= 1
    PlotData.Pa2 = Data2.Pa;
end

% The last time slot is unsuitable for charging because it may exceed the
% time of departure. Hence, it is discarded
if isempty(Data1) == 0
    Data1(end,:) = [];
end

if isempty(Data2) == 0
    Data2(end,:) = [];
end
```

12 - Verifies the times slots' availability & 13 - Updates and validates the time slots

12 - Create vector with the indexes of time slots that are not available for charging 13 - Deletes the time slots that are not available for charging (for each charger)

```
if Pselect ~= 2
    avail1 = Data1.Pa <= 0;
    Data1(avail1,:) = [];
    if isempty(Data1)
        Pselect = 2;
    end
end

if Pselect ~= 1
    avail2 = Data2.Pa <= 0;
    Data2(avail2,:) = [];
    if isempty(Data2)
        Pselect = 1;
    end
end

% Available time for charging (for each charger)
```

```
% Each line represents a 15 minute time slot. The available time is the
% product of the number of lines for a 15 minute duration (in hours)
Tavail1 = size(Data1,1) * hours(0.25);
Tavail2 = size(Data2,1) * hours(0.25);

% If there is available time for charging for the Level 1 charger and not
% for the Level 2 charger
if Treq1 >= Tavail1 && Treq2 < Tavail2
    Pselect = 2;
    fprintf('Level 2 charger is selected\n\n')
    %pause(1)
end

% If there is available time for charging for the Level 2 charger and not
% for the Level 1 charger
if Treq2 >= Tavail2 && Treq1 < Tavail1
    Pselect = 1;
    fprintf('Level 1 charger is selected\n\n')
    %pause(1)
end

% If the available time for charging is not enough for both chargers
% The case in which there is no available time for either charger -> Step
% 13
while (Treq1 > Tavail1) && (Treq2 > Tavail2)
    Pselect = 0;
    uiwait(warndlg('Time of departure and/or final SOC are not suitable'))
    [Tdeparture,SOCfinal,Treq1,Treq2,Pselect] =
restrictions(Cbattery,SOCinitial,Pcharger,Tarrival,Pselect);
    [Data1,Data2,SOCfinal,Pselect,PlotData,Treq1,Treq2] =
timeslots(Cbattery,Data,Tarrival,Tdeparture,Pcharger,Pselect,Pcontracted,SOCinitial,SOCfinal,Tre
q1,Treq2);
end
end

% fillstairs
function fillstairs(X, Y1, Y2, h)
% - Method which draws two stair-functions and fills the area between them
% - Created by Florian Krause on 2016-01-25 (V1.0)
% - Use it as you like.

% Create "Stairs-Function"
Xi = [X(sort([1:length(X), 2:length(X)])), X(end)+(X(end)-X(end-1))];
Y1i = [Y1(sort([1:length(X), 1:length(X)]))]; %#ok<*NBRAK>
Y2i = [Y2(sort([1:length(X), 1:length(X)]))];

% Plot Stairs
figure(h)
plot(Xi, Y1i,'LineWidth',1.5,'Color',[0 0.75 0.75]);
hold on;
plot(Xi, Y2i,'LineWidth',1.5,'Color',[0 0.75 0.75]);

% Fill Stairs
for i = 1:2:length(Xi)
    if ( Y1i(i) > Y2i(i) )      % Upper
        xx = [Xi(i:i+1), fliplr(Xi(i:i+1))];
        yy = [Y1i(i:i+1), fliplr(Y2i(i:i+1))];
        fill(xx, yy, [0 0.75 0.75])%, 'FaceAlpha',0.2);
    elseif ( Y2i(i) > Y1i(i) )  % Lower
        xx = [Xi(i:i+1), fliplr(Xi(i:i+1))];
        yy = [Y1i(i:i+1), fliplr(Y2i(i:i+1))];
        fill(xx, yy, [0 0.75 0.75])%, 'FaceAlpha',0.2);
    else                        % Identical
        % do nothing
    end
end

% Draw Lines Again
hold on;
plot(Xi, Y1i, 'k');
hold on;
plot(Xi, Y2i, 'k');
end
```

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