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An innovative system for electrical vehicular charging in urban zone : conception, dimensioning, and performance evaluation

Mario Alberto Alvarado Ruiz

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Stratégies de recharge pour véhicules électriques connectés à un réseau public d'éclairage

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Charging strategies for electric vehicles connected to street lighting networks

Abstract:

In order to reduce the impact of global warming, the European Commission has decided in the continuation of the Kyoto protocol to reduce drastically greenhouse gas emissions. In this matter, the progressive replacement of thermal vehicles by electric ones is considered as a key objective. For that purpose, several prerequisites must be considered for the rapid deployment of Electrical Vehicles (EV) in the European market. The first of these prerequisites consists in the design of a new generation of batteries with higher energy efficiency, larger capacity and improved robustness. The second one is the design and rapid deployment of cost effective charging infrastructures. At last, the emergence of European standards in all these matters is an imperious necessity for the viability of the EVs European market. This thesis is mainly focused on the second of these three prerequisites. It is widely admitted that in the short term, EVs usage will be essentially limited to urban areas before being extended to the whole territory. As it is considered by the French National TELEWATT research project to which we have contributed, street lighting networks can be used judiciously to deploy in the short term low cost charging infrastructures. The basic principle of this project consists in coupling to each street light one or two EV's charging stations if one or two parking spots are located nearby. Various electrical constraints specified in the TELEWATT project must be satisfied to enable EVs' charging without degrading the quality of the lighting system. In this thesis, we begin to demonstrate the feasibility of such an operation. For that purpose, we have developed a simulator enabling to depict the dynamic behavior of the global system. The strength and originality of this simulator resides in its capacity to determine in real-time and with the necessary precision if an EV can effectively be connected to a charging station. The response to this question depends on static and dynamic characteristics of the street lighting network and on the state of charge of the batteries of both the connected and candidate EVs. The dynamism of the charging process of each EV strongly depends on the instantaneous power consumed by the global infrastructure. The second original result of this thesis consists in the design of scheduling policies to activate the various charging stations. Our objective is to propose via these scheduling policies, various types of guaranteed Quality of Service (QoS) to the end-users. Such guarantees can be declined for instance in terms of expected state of charge for a given parking term.

Keywords: Smart Charging, Electric Vehicles, Street Lighting Networks, Energy Management.

Stratégies de recharge pour véhicules électriques connectés à un réseau public d'éclairage

Résumé :

De façon à réduire l'impact du réchauffement climatique, la Commission Européenne a décidé dans le prolongement du protocole de Kyoto de réduire drastiquement les émissions de gaz à effet de serre. En la matière, le remplacement progressif des véhicules thermiques par des véhicules électriques est considéré comme un objectif clé. Dans ce but, plusieurs prérequis doivent être pris en compte pour le déploiement rapide des véhicules électriques sur le marché européen. Le premier de ces prérequis consiste en la conception d'une nouvelle génération de batteries avec une efficacité énergétique accrue, une plus grande capacité et une robustesse améliorée. Le second prérequis est la conception et le déploiement rapide et économique d'infrastructures de recharge. Enfin, l'émergence de normes européennes dans tous ces domaines est une impérieuse nécessité pour la viabilité économique du marché européen des véhicules électriques. Cette thèse se focalise essentiellement sur le second de ces trois prérequis. Il est largement admis qu'à court terme, l'usage des véhicules électriques sera essentiellement limité aux zones urbaines avant d'être étendu à tout le territoire. Tel que cela est pris en compte par le projet de recherche national TELEWATT dans lequel nous avons été impliqués, les réseaux d'éclairage publics en zones urbaines peuvent être utilisés judicieusement pour déployer à court terme des infrastructures de recharge bon marché. Le principe de base de ce projet consiste à connecter à chaque candélabre une ou deux stations de recharge pour véhicule électrique si une ou deux places de parking sont disponibles dans l'environnement proche. Diverses contraintes électriques spécifiées dans le projet TELEWATT doivent être satisfaites pour permettre la recharge de véhicules électriques sans perturber la qualité de l'éclairage. Dans cette thèse, nous commençons par démontrer la faisabilité d'une telle opération. Pour cela, nous avons développé un simulateur permettant de décrire le comportement dynamique du système global. La force et l'originalité de ce simulateur réside dans sa capacité à déterminer en temps-réel et avec la précision nécessaire si un véhicule électrique peut effectivement être connecté à une borne. La réponse à cette question dépend des caractéristiques statiques et dynamiques du réseau d'éclairage et de l'état de charge des véhicules déjà connectés comme des véhicules candidats. La dynamique du processus de recharge de chaque véhicule électrique dépend fortement de la puissance instantanée consommée par l'infrastructure globale. Le second objectif original de cette thèse consiste en la conception de politiques d'ordonnancement d'activation des diverses bornes de recharge. Notre objectif est de proposer, via ces politiques d'ordonnancement, divers types de qualité de service (QoS) garanties aux usagers. De telles garanties peuvent par exemple se décliner en termes d'état de charge attendu pour une certaine durée de stationnement.

Mots clés : Rechargement Electrique Intelligent; Véhicules Electriques; Réseaux d'Eclairage Publique, Gestion de l'Energie.

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List of Acronyms

ABM	Activity Based Model
ADEME	Agence de l'Environnement et de la Maîtrise de l'Energie
BMS	Battery Management System
BSS	Battery Swapping Station
CCF	Closest Charger First
CCM	Central Control Manager
CCS	Combined Charging System
CFCFS	Conservative First Come First Served
CHAdEMO	Charge de Move
ChP	Charging Point
CoTaSch	Conservative Task Scheduling Approach
CSO	Charging Service Operator
DoD	Depth of Discharge
DSO	Distribution System Operator
EDF	Earliest Deadline First
EM	Electric Motor
e-MSP	e-Mobility Service Provider
ESR	Electricity Supply Retailer
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipments
ExpTiEoC	Expected Time to End of Charge
FCF	Farthest Charger First
FCFS	First Come First Served
FlexTaSch	Flexible Task Scheduling Approach
HESF	Highest Energy Shortfall First
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICV	Internal Combustion Vehicle
IEC	International Electrotechnical Commission
LESF	Lowest Energy Shortfall First

LHS	Lamp Heating Stage
LLF	Least Laxity First
LV	Low Voltage
MSoCW	Minimum State of Charge Warranty
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Communications
PLS	Public Lighting System
PNO	Private Network Operator
PTA	Processor Time Allocation
QoS	Quality of Service
RCS	Random Charger Selection
RES	Renewable Energy Sources
SAE	Society for Automotive Engineers
SoC	State of Charge
SoH	State of Health
TMS	Thermal Management System
TSO	Transmission System Operator
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2V	Vehicle to Vehicle
WPT	Wireless Power Transfer
VE	Véhicule Electrique
EAVE	Equipement d'Approvisionnement des Véhicules Electriques
ARP	Allocation des Ressources du Processeur
REEP	Réseau Electrique d'Eclairage Public

Introduction

1.1 Motivation, Objectives and Thesis Outline

Massive industrial and agricultural activities have generated during these last decades carbon emissions that are considered nowadays as a real risk for the future of our planet. In this context, the major and always growing concern over climate change has recognized the reduction of carbon emissions as the most important alternative to prevent an irreversible increase of the temperatures. Many governments have set ambitious goals for the next years in order to reduce greenhouse gas emissions, to improve air quality in urban areas and to reduce our dependence on fossil fuels [18, 36, 58, 73]. Thus, the European Union (EU) aims to reduce greenhouse gas emissions from the year 1990 to the year 2020 by 20%. In parallel, the EU also wants to increase in the same proportion the energy obtained from Renewable Energy Sources (RES) [3]. Aligned with these objectives, the integration of EVs into the automobile market and the electric grid is of a great interest. At the date of publication of this manuscript, the installed capacity for energy production and distribution is still sufficient to absorb the demand of energy from the limited number of EVs charging stations, which is directly related to the very limited number of operational EVs. However, it is noticeable the interest and investment of all major car manufacturers to produce electric models for the market in all developed countries. It is then clear that it will become rapidly necessary to foresee an upgrade of the electrical grid to support this new energy demand. In this matter, the introduction at a large scale of RES in order to progressively substitute the proportion of the energy mix produced by traditional power plants seems irreversible.

Electro mobility (or e-mobility) is the key technology required to provide an alternative to fossil energy sources and in consequence reduce carbon emissions in the long term [75]. It is characterized by a diversified set of technological solutions which enable the deployment of affordable and efficient batteries and power trains for the electric propulsion of full electric and hybrid vehicles. However, it is still difficult to foresee the speed at which EVs models will progressively flood the car market. Major information technology research and advisory companies such as Gartner, Ernst and Young or Deloitte are trying to predict how and when such a technological revolution will occur. There are different challenges to overcome, from the point of view of the distribution network as well as from the final user perspective. We can predict that the massive deployment of EVs charging infrastructures in parallel to the requirements of domestic appliances will necessitate a redesign

of the power distribution network. The analysis of this redesign is out of the scope of this thesis.

Several factors must be considered to evaluate the speed at which EVs should replace existing combustion vehicles in developed countries:

1. **The cost of EVs:** According to an economic analysis of the French EV market [69], since the year 2013, thanks to different tax credits and incentives from government agencies, the acquisition price of an EV is getting closer and in some cases overtaking the price of its thermic version. For instance, the Smart Fortwo Electric Drive is available from 12500 euros compared to the 13500 euros of its thermic version, the Smart Fortwo Essence.
2. **Technological constraints inherent to battery technology:** Existing batteries are characterized by two major drawbacks. First, their capacity remains limited, this capacity being directly linked to the weight of the battery itself. At the date of publication of this manuscript, the batteries installed in the vehicles of the upper category enable ranges of the order of 200 kilometers and up to 420 kilometers [23]. This is a priori less than the achievable range offered by thermic vehicles, but this gap tends to decrease year after year thanks to the development of a new generation of battery's charging technology (such as induction-based recharging techniques). Second, the speed at which a battery can be charged is a real constraint for the end-users. As an indication, a full charge from empty can take up to 8 hours charging at 3.3 kW. This is clearly a strong commercial constraint that will limit for the very next years the usage of low and medium class EVs to urban moves. Meanwhile, like regular advances are observed in terms of battery capacity, advances are also expected in terms of charging speed and the installation of high speed charging stations, which are at the present time quite limited.
3. **The very limited coverage of the existing charging infrastructures:** Deploying EV charging infrastructures is costly since it necessitates in most cases heavy civil engineering. Before such infrastructures are deployed at a large scale, EVs will probably be used by most of the drivers mainly in urban areas. Most of the car manufacturers also promote the installation of private charging stations in the garage of EV owners. Intercity journeys with EVs will probably remain for a few years the privilege of wealthy customers with access to EVs with high energy capacity until high speed charging stations are deployed in motorway corridors connecting major cities.
4. **The anxiety of EV drivers:** Today, since the number of existing public charging stations remains focused in the hyper center of the cities, EV drivers may apprehend to do not have enough capacity in their battery to join their destination. In other terms, the "out of gas anxiety" sometimes mentioned in the literature could probably play as a brake to the rapid deployment of EVs on the market, and more specifically, on the interurban market. The technological constraints inherent to this anxiety will be particularly investigated in this thesis. Beyond the analysis that will be provided in this manuscript, the Federal Department of Transportation of the United States considers that a huge market will emerge in the very next years in matter of cartographic tools. Such tools are supposed to reduce the "out of gas anxiety" of EV drivers by including the geographical position of the available public charging stations along the journey submitted by the driver before his departure.

In France, more than 2 million of EVs are expected for the year 2020 [41]. Without the proper infrastructure to provide charging services, the growth of the EV's market could be at

risk. Charging infrastructures for EVs include a set of elements known as Electric Vehicle Supply Equipments (EVSE) such as connectors, conductors and other equipment associated to the charging stations.

In recent years, the infrastructures deployed for EV charging have significantly evolved, proposing new approaches and pushing researchers to find new solutions for reducing the time of charge or to improve the charging mechanisms which could benefit from the inclusion of energy from RES into the grid. Wired charging has evolved from slow and risky connections on household plugs, to fast charging stations and secure connections at public and private charging stations for the convenience of the users. Nevertheless, some issues still need to be solved. Thus, the standardization at a European and at an international scale of the supply equipment is of key importance for the viability of EVs' market. Last but not least, the problem of choice of the optimal locations to install new charging stations is quite complex since it is both subject to technical and economic constraints.

Different approaches have come to the US market relying on the Battery Swapping Station (BSS) concept. BSS consists in replacing low charged batteries with fully charged batteries at a specially designed swapping station in a few of minutes [4,24]. However, this approach needs to be revisited along with its business model in order to be fully and successfully exploited. The failure of the Better Place pre-commercial experiment has outlined the limits of this approach [15]. On the other hand, Wireless Power Transfer (WPT) is another promising charging concept that has gained a lot of attention in recent years from researchers and charging equipment manufacturers as well. The WPT concept aims to reduce the security issues inherent to wired charging. It has been shown that it is possible to proceed to the charging of the batteries of moving EVs by means of the installation of inductive loops in the road surface itself. Such an alternative approach could solve de facto the problem of the achievable range of next generation EVs. At the date of publication of this manuscript, the massive deployment of such inductive loops in the road surface still depends on improving the efficiency of the charging infrastructure at a reasonable cost.

The most urgent need in all EV markets is the financing for the rapid deployment of charging infrastructures [20]. The installation costs of EVSE could be very high, especially when the electrical network (the transformer and/or the distribution cables) must be upgraded or when civil engineering work is required. If it is not planned carefully, the charging infrastructure may be over-estimated for the actual needs of the market and lead to unused assets. For this reason, in a public context, the deployment of EVSE should not target the simple maximization of the number of charging spots, but rather the optimization of the combination of the various CAPEX/OPEX costs that best satisfy the CSO business models.

The rapid deployment of charging stations in urban areas is not only important to reduce drivers range anxiety but, it constitutes a real challenge as well. In this thesis, we present an innovative approach consisting in reusing existing PLS electrical network (also referred as Street Lighting Networks) for EV charging. In this architecture, the primary service provided by the PLS is the lighting of the streets. However, during the day when the lamps are inactive, the available power provided by the transformer serving the considered charging infrastructure can be potentially used to feed EV's charging stations. To the best of our knowledge, two testbeds of that type are currently under validation in the cities of Aix-en-Provence in France [70], and in the city of Munich in Germany [11], [1]. Two main advantages characterize these two approaches:

- Charging infrastructures can be deployed rapidly (a few weeks instead of a few months)

without costly civil engineering and without requiring an upgrade of the street lighting network. The main constraint that must be satisfied is the proximity of the parking spots with the lighting poles. It is also necessary to guarantee by means of preliminary power computations that the number of simultaneous active charging stations remains compatible with the power provided by the transformer. In this matter, two regimes must be distinguished: day and night power consumption profile. At evidence, the potential number of simultaneous active charging stations is lower at night than during the day.

- It appears that for most of the existing street lighting networks, a fraction of the unused power of the transformer can benefit the charging stations. In the remaining of this thesis, we shall assume that the installed capacity of the transformer is sufficient to cover the power demand when all the street lights are active. We know that this assumption is realistic in reference to the characteristics of existing street lighting infrastructures. In this matter, safety margins are considered by the professionals of street lighting networks in order to guarantee the stability and the quality of the lighting system.

To the best of our knowledge, the way most of the street lighting network operators manage the available power of their infrastructures is, in most cases, based on relatively rough calculations. In this matter, the French company Citelum, with which a fraction of the work presented in this thesis has been achieved, can be considered as a leader. The aim of this thesis is to contribute to the research of new EV charging infrastructures that could be rapidly deployed at low CAPEX/OPEX costs thanks to the usage of existing street lighting networks. More precisely, we have contributed within the Computer Science and Networks Department of Telecom ParisTech to the specification of original numerical analysis techniques that enable a very precise real-time evaluation of the instantaneous available power at any point of a street lighting network equipped with charging stations. A fraction of the assumptions considered in this thesis have been inspired from the TELEWATT research project. This project involving Telecom ParisTech, was placed under the supervision of the French company Citelum. It has been supported by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME), a subsidiary of the French Ministry of Industry. The objectives of the TELEWATT project are broader than the technical investigations carried out along this PhD thesis. The intelligence to manage the instantaneous available power at any point of the infrastructure is supposed to be located at the control management of the transformer. The description of the network protocol enabling the real-time dialogue between any charging station and any lighting point with the cabinet is out of the scope of this thesis. In summary, this thesis has three objectives:

- Our first objective is to build a simulation tool that is generic in the sense it can be applied to various configurations (single phase or three-phases infrastructures). The numerical results provided by our simulator must be in accordance with real measurements achieved on a real network. For that purpose, multiple scenarios have been considered in the context of the TELEWATT project. Disregarding the considered configuration of the electrical network, a constant quality of the lighting service is expected at night. Our software tool must be sufficiently generic to be applicable to a large number of network configurations. Each of these configurations may require different safety margins of the electrical characteristics of the system in order to guarantee a constant quality of the lighting service. Our tool must be sufficiently generic to be applicable to network conditions requiring different safety margins. These safety margins may vary according to the manufacturer of the street lighting network

and to the manufacturer of the charging stations.

- Our second objective is to make our tool exploitable in an operational environment. In operational environment, random events corresponding to the connection or to the disconnection of an **EV** necessitates that the intelligence of the system implemented at the cabinet can respond in real-time to any connection request.
- Our third objective is to prove the feasibility of the charging model proposed by the TELEWATT project and to design an innovative scheduling charging strategy that could provide a form of guaranteed **QoS** to the drivers. To the best of our knowledge, at the date of publication of this manuscript, the charging strategies available on the literature are mostly targeted to dedicated charging infrastructures and fleet charging. For the first case, all available resources of the network are exclusively designated for **EV** charging. While for fleet charging it is possible to know in advance the energy requirements of the vehicles. Our objective is to provide a minimum amount of energy to the user, which is the equivalent of a home to work traveling distance helping the **EV** drivers to reduce their range anxiety.

1.2 Contributions of this Thesis

The contributions of this PhD thesis are summarized below:

- We have developed an original simulation tool enabling to emulate the performance of a common **PLS** electrical charging infrastructure. The originality of this tool is its capacity to deal with complex configurations with response times below the second of computation. For that purpose, we represent any charging infrastructure configuration as a directed graph. By applying some graph theory concepts to circuits theory, we are able to compute the voltage and current values at any dipole of the electrical network in real time. In the considered graph, each charging station is represented as a variable resistor. The value of this resistor has to be recomputed dynamically in order to maintain constant the delivered power to the connected **EV** as other **EVs** arrive or leave the charging station.
- Through various simulations scenarios, we have investigated charging infrastructures inspired by those considered in the French TELEWATT research project. We show via our numerical results that random connections and disconnections of **EVs** are feasible without putting at risk the normal operation of a **PLS** electrical network. In a first step, an original charging strategy is proposed to guarantee an immediate charging to the **EVs** without disrupting the lighting service. In a second step, we investigate the performance of a set of on-line scheduling strategies proposed in the Processor Time Allocation (**PTA**) literature [71] adapting them to our research environment. These scheduling strategies enable a greater flexibility in the management of the charging process. We show how they enable a better use of the available resources extending the charging services to more users, which can be evaluated in terms of the acceptance connection ratio. Finally, we propose an original charging strategy that is oriented towards a form of **QoS** service guarantee. The originality of the considered simulated scenarios relies on their proximity with real life conditions.
- The analysis of various scheduling strategies under typical operational constraints has allowed us to evaluate the performance of **PLS** electrical network under various charging requests scenarios. These strategies consider the charging requests sequentially according

to their instant of occurrence. In other terms, our algorithms react to random events corresponding to the arrival or to the departure of an EV at any of the charging points of the infrastructure. Such a constraint was a prerequisite since the finality of this work is to be applied to a real testbed in the context of the TELEWATT project.

1.3 Thesis Outline

This dissertation is organized in 7 chapters. In Chapter 2 we briefly describe the currently available powertrain architectures and the most important elements of the supply equipment installed at charging stations. In Chapter 3 we describe the methodology used for developing the simulation tool used in this research project. Chapter 4 presents a conservative approach for the management of the charging process of the vehicles. In this chapter we present a conservative on-line scheduling strategy, which aims to prove the feasibility of the charging model proposed by TELEWATT. We introduce a set of metrics used for evaluating the performance of the scheduling strategies presented in this work. In Chapter 5 we present a set of on-line scheduling strategies adapted to our research environment considering now a more flexible approach for the management of the charging process of the vehicles. Followed by Chapter 6, where we present our original scheduling strategy oriented towards the QoS proposed to the user. Finally, Chapter 7 concludes this manuscript and provides a few perspectives in the continuation of this thesis.

1.4 Publications

This dissertation consists of an overview of the following conference publications:

1. Ruiz, M.A.; Abdallah, F.A.; Gagnaire, M.; Lascaux, Y. "TeleWatt: An Innovative Electric Vehicle Charging Infrastructure over Public Lighting Systems" *Connected Vehicles and Expo (ICCVE), 2013 IEEE International Conference on*, pp. 741,746, 2-6 Dec. 2013.
2. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Improving Energy Distribution for EV Charging over Public Lighting Systems" *IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Vienna, Austria, Nov. 2014. Best Paper Award Finalist.
3. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "On-line Scheduling Policies for Electric Vehicle Charging over Public Lighting Systems". *2014 IEEE International Electric Vehicle Conference (IEVC)*, Florence, Italy, Dec. 2014.
4. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Minimum Driving Distance Warranty for EV Charging over Public Lighting Systems". *2015 IEEE International Conference on Computer as a Tool (EUROCON)*, Salamanca, Spain, Sep. 2015.

A journal paper submitted for publication at the IEEE Transactions on Intelligent Transportation Systems and Intelligent Transportation Systems Magazine ICCVE special issue.

1. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Conservative Vs Flexible Scheduling Approaches for Charging EVs over the Public Lighting Network". *IEEE Transactions on Intelligent Transportation Systems and Intelligent Transportation Systems Magazine*. Jul. 2015. Submitted for publication.

Part I

**Electric Vehicle Charging
Infrastructures**

Electric Vehicles and Charging Infrastructures

Contents

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2.1 Introduction

This chapter presents a brief introduction to the different types of electric vehicles and their principal components. We provide a brief state of the art of the batteries used in automotive applications and the standards developed in recent years for the EV supply equipment. Such standards have particularly addressed the plugs and connectors linking an electrical vehicle to a charging station, as well as the charging modes. An essential element of this thesis is the PLS electrical network. Thus, not only this particular grid is presented, but the electricity and e-Mobility markets as well.

2.2 Electric Vehicles

Electric vehicles have been investigated by the automotive industry as soon as the years 1830s when it was first developed [64]. Despite the improvements done in their battery technology and low maintenance costs between 1910 and 1925 [43], Internal Combustion Engine Vehicles (ICEVs) took a significant market advantage thanks to the improvement achieved in terms of driving range and maximum speed.

A renewed interest in developing EVs between the years 1960s and the years 1970s has aimed to reduce the dependence on fossil fuels due to the rising oil prices. In this context, EV mass production really started in the late 1990s and more successfully throughout the years 2000s. It was in the 1990s that the first EV was launched in the US by General Motors known as the GM EV 1 [56]. It was followed by other automakers with more successful models, like the Nissan Leaf [6] or the Tesla Model S. The EV industry has started to emerge once again, favored by different economic and environmental factors, such as international policies aiming at the reduction of CO_2 emissions [73]. In parallel, renewable resources have emerged and enabled a reduction of fossil fuel's dependence.

There are four major components in the architecture of an EV, the drive train system, the battery pack, the charger and the charging inlet. In the following section we will briefly describe each one of these components.

2.2.1 Electric Vehicle Drive System Architectures

The drive train system is the group of components that couple the energy source to the driving wheels which transform it into mechanical power. The basic drive train system of an EV is composed by a battery connected to a motor driver in series with an Electric Motor (EM), a mechanical coupling and the transmission system. There are two main electric vehicle architectures according to the adopted drive train system: Battery Electric Vehicles (BEV) or hereby simply referred as Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV). EVs are exclusively powered with electricity, while Hybrid Electric Vehicles (HEVs) combine the traditional Internal Combustion Engine (ICE) and the advantages of an EM. Vehicles that cannot be plugged externally to charge their batteries are simply referred as HEVs. An HEV can only be charged by means of its engine and its regenerative braking system. On the other hand, when they can additionally charge their batteries from the grid they are referred as PHEVs [61]. When the first PHEVs appeared, the

addition of an EM to the ICE was only conceived to help the ICE to propel the vehicle. Reducing the fuel consumption was considered as a second order service. However, in recent years the roles have changed and it is now the ICE that is considered as an auxiliary motor of the EM. Its main purpose is to improve the performance of the vehicle, by increasing its driving range and supplying sufficient torque when it is required.

While the EV drive system is realized only by a motor driver and an EM, HEVs have at least two traction sources, both mechanical and electrical. This dual traction source enables the usage of smaller engines. Additionally, HEVs have at least two power sources, where one of them must be electric. Depending on the combination of the electric and mechanical traction that constitute the drive system of the vehicle and the interconnection of its components, HEVs can be divided into three configurations described in Figure 2.1 [43, 76].

- **Series:**

The electric traction system and the ICE operate in a series connection. The ICE generates the electric power for recharging the battery when it is coupled with a generator, then the battery supplies energy to an electric motor drive that transfers power to wheels.

- **Parallel:**

As its name indicates, the electric motor operates in parallel with the ICE. In this configuration the ICE supports the electric traction when higher power is needed on the wheels. A relatively smaller battery capacity is required compared to the series configuration, resulting in a lighter mass of the drive train.

- **Parallel-series combined hybrid:**

This configuration requires an additional mechanical unit placed between the electric motor and the generator. This allows the vehicle to operate in both, series or parallel configuration, which helps to run the vehicle in an optimal way by using only the EV or the ICE and the EM together depending on the driving conditions.

2.2.2 Batteries for Electric Vehicles

In recent years the commercialization of EVs has been subjected by two central issues. The first one is the limited range of the vehicle, that is related to the high cost of the batteries. The second one is more associated to the refueling process, which is not yet as easy and fast as the ICEV. The charging process for an empty battery could potentially take a long time, added to the scarcity of available charging points. Regarding the range of the vehicles, the research on high voltage batteries used in automotive applications have focused in the last years on increasing the energy density of the batteries. At the same time, reducing the cost of the battery pack and improving the charging process has remain a constant target. In spite of these efforts, the achievable range of EVs has remained limited around 200 kilometers.

The performance of a battery is highly influenced by different factors, such as the state of charge (SoC), the "state of health" of the battery related to its aging, the temperature of the battery, the environment as well as the load profile and the adopted charging algorithm. The price of the battery packs used on EVs and PHEVs is relatively high compared to the price of the whole car. It depends on the number of cells connected within the battery itself, the nature of the electrolyte and the necessary protection circuits. It must be noticed that depending on the

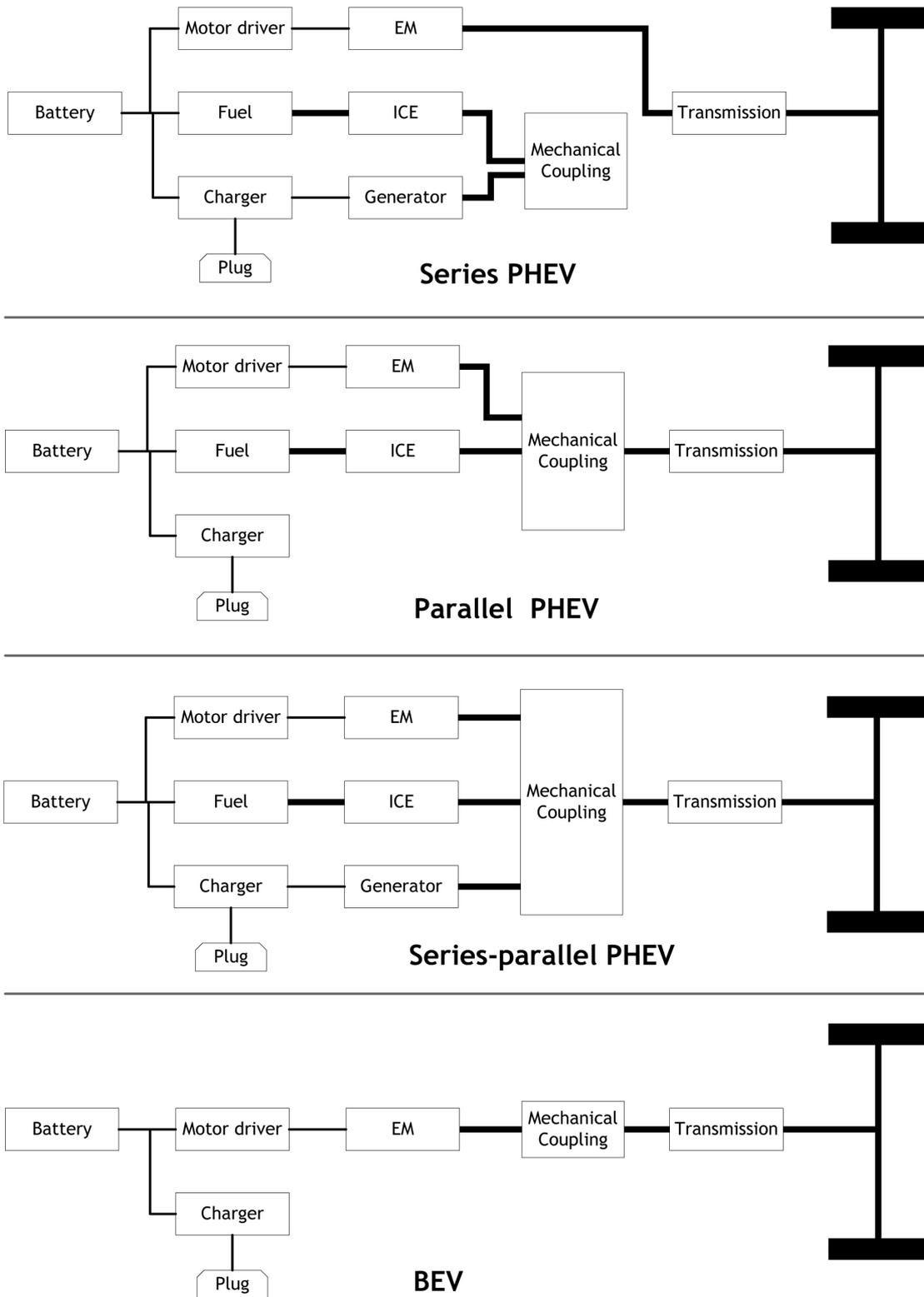


Figure 2.1 – EV and PHEV system as presented in [43].

user habits and the implemented charging algorithm, the life cycle of a battery can be affected, and as a consequence, the cost of the battery pack too. Longer life cycles of the battery pack will be more cost-effective. In the following section we briefly describe the terms and components of the batteries used in automotive applications.

Basic Terms for Battery Performance

In this section, we briefly present the terminology used for describing the different components and stages of a battery.

- **Cell, Module and Pack:**

A pack of batteries is a group of modules placed in a single container for better thermal management. Each module is a cluster of cells, which are at the same time independent batteries, with two current leads and separate compartment holding electrodes. An EV can have one or more battery packs placed at different locations in the vehicle.

- **Energy Density or Specific Energy:**

It is the amount of available energy from a fully charged battery per unit. When it is based on volume, the term energy density is used and expressed in Wh/L. It is referred as specific energy when the available energy is expressed in terms of weight, as Wh/kg, which is a more suitable factor than volume for EVs and PHEV.

- **C-Rate :**

C-Rate represents the amount of current used for charging the battery and it represents the charge rate equal to the capacity of the battery in one hour. So, for a 10 Ah battery, C corresponds to the charge or discharge of a battery at 10 A for one hour. This term should not be confused with the charge rate of the EV.

- **Charge Rate:**

It is the power that is constantly delivered by the charger to the battery. It sometimes can be referred as charging capacity. The charging capacity is determined by the type of charging connector and the available power at the charger. The effective charge rate provided to the battery depends on the link between the EV and the charging point with the lowest resistance. This means that if the battery pack demands a higher power to the charger than the actual available power or the maximum rate supported by the connector, the link with the lowest resistance is the one that will define the charge rate of the connection.

- **State of Charge (SoC):**

It is a term which refers to the percentage of remaining energy available in the battery [68]. The estimation of the SoC of a battery at instant t is given by Equation 2.1.

$$SoC(t) = \frac{c(t)}{C} \times 100 \quad (2.1)$$

where C represents the rated capacity of the battery and c the remaining capacity on the battery.

- **Depth of Discharge (DoD):**

It indicates the percentage of the total battery capacity that has been discharged as presented in Equation 2.2.

$$DoD = 1 - SoC \quad (2.2)$$

- **State of Health (SoH):**

It is usually used as a parameter to indicate the degree of performance of a battery in order to estimate its remaining life duration. The SoH value refers to the maximum charge capacity of an aged battery compared to the maximum charge capacity when the battery was brand new.

$$SoH = \frac{E_{Ca}}{E_{Cn}} \quad (2.3)$$

where E_{Cn} represents the rated energy capacity and E_{Ca} is the energy capacity of the aged battery.

- **Battery Life Cycle:**

It is a parameter that defines the operating life of the battery. It is formally referred as the number of discharge-charge cycles that the battery is capable to handle at a specific DoD before it can no longer meet any specific performance criteria. The safety, durability and performance of batteries are highly dependent on the way they are charged. This includes, the charge or discharge rates, as well as the temperature fluctuations of the battery and the charging algorithm. The life cycle of the battery becomes shorter as the DoD goes higher. In general, batteries typically suffer the loss of nearly 20% of their initial capacity after about 100 to 2000 full cycles. Fully charging or discharging the battery can accelerate the degradation of its life cycle. By reducing the SoC, complete discharges and overcharges of the battery pack are avoided since both of these operations drastically reduces the battery lifetime.

Chemical Process Inside a Battery

There are different chemistries proposed as the energy source to power EVs in the last years. Batteries are composed by a positive electrode with a higher potential and a negative electrode with an ion conductive electrolyte with a lower potential. During charging, the negative electrode is the cathode where the oxidation reaction occurs. The reduction reaction occurs at the positive electrode (the anode). There is a separator which serves as a reservoir for extra electrolyte that helps to prevent shortage due to the formation of residues, such as Li-dendrite in Li-ion batteries. In recent years, various battery chemistries have been proposed as the energy source to power electrical vehicles, each one with its own advantages and disadvantages.

- **Nickel Cadmium (Ni-Cd):**

This kind of batteries benefit from a mature technology, however its specific energy is quite low for vehicle applications. They are typically used when long life at reasonable cost is required, however its chemical composition implies some environmental concerns due to the toxic metals it contains.

- **Nickel-Metal Hydride (NiMH):**

This type of batteries can store more energy than Ni-Cd batteries, but at the cost of a

reduced cycle life. Its specific energy is in the range of 75-100 Wh/kg that makes it suitable for EV and PHEV applications.

- **Lithium-Ion (Li-Ion)**

Li-Ion batteries have an exceptional performance for EVs and PHEVs thanks to its high specific energy (100-140 kWh/kg). A Li-Ion battery of 20 kWh weighs about 160 kg, which is lighter than the Ni-MH batteries which weigh between 275 and 300 kg for the same application. This type of battery has a great potential for technological improvements and the absence of memory effect, which noticeably helps to extend the life cycle of the batteries when they are managed in proper conditions. Compared to Ni-Cd batteries, Li-Ion batteries are composed of environmental friendly materials. However its weak point is its safety, as over charging the battery could potentially cause explosions by overheating the battery pack. This issue has been handled by Lithium Iron Phosphate batteries ($LiFePO_4$), which have managed to reduce the flammability risk. It must be noted, that Li-Ion batteries do not need to be fully charged to properly operate, and it is actually avoided as high voltages could stress the battery. Another important drawback for this type of batteries is the cost which is still high. Finally, the cycle life of a Li-Ion battery is between 4000 and 7000 cycles.

- **Lithium Polymer (Li-Po)**

These solid state type batteries have the same energy density as the Li-ion batteries but at a lower cost. Li-Po batteries could eliminate the need of ultra-capacitors in the future, due to their outstanding performance in charging time and the flexibility of their design. Batteries of that type can reach over 90% of this capacity in only a couple of minutes. As Li-Ion batteries, the materials within the battery do not leak out even in the case of an accident.

Battery Model

Modeling the behavior of a battery is necessary to estimate its SoC and its SoH. The knowledge of the SoC and of the SoH is necessary for modeling its Battery Management System (BMS). that can itself be used to optimize the battery's efficiency. Several battery models are mentioned in the literature [33, 43, 64, 76]. Depending on the environment of its utilization, a given model can be more or less efficient. The availability of reliable simulation or modeling tools strongly conditions the evaluation of this efficiency. Ideally, the model of a battery should be the simplest as possible ignoring the internal parameters, the battery behavior being assimilated to a simple voltage source. More elaborated models, like the electro-chemical one relies on a detailed analysis of the electro-chemical reactions inside the electrolyte. Such models are used in practice only during the design stage of the battery (before its commercialization). However, when the integration, optimization, control and interconnection of EVs to the grid is studied, more generic models are considered. These models provide more interesting details through the specifications and dynamics of the battery (such as the voltage, current, size and temperature) than its chemical characteristics. In this case, two variants are provided in the literature.

- A linear model that considers an ideal battery behavior with open circuit voltage E_o and an equivalent resistance in series R_s . The open circuit voltage refers to the difference of the electrical potential between two terminals of a battery in the absence of a connected load [40]. This model does not consider the varying characteristics of the internal impedance of the battery. It can be implemented over generic simulation environments such as Matlab.

- If more details of the components are necessary, so as to generate the equivalent circuits and to test them with simulation software like PSpice, then the Thevenin model should be preferred. This model, in its most basic form uses a resistor and an RC parallel network in series. It assumes that the open circuit voltage is constant and it allows to predict the battery response at a particular SoC. This model does not allow capturing steady state voltage variations or runtime information.

For modeling purposes, we have adopted in this thesis a linear model to represent the battery of a vehicle in our simulation environment.

Battery Management System (BMS)

The BMS is a multi-level control and power system composed of a combination of sensors, controllers and additional hardware that takes care of all or some of the aspects affecting batteries. Such control is possible thanks to different software algorithms designed to control the charging process of the battery. To do so, the BMS establishes the maximum charge or discharge currents, estimates the SoC and the SoH of the battery pack so as to keep track of its progress and if needed, regulates the temperature of the battery to improve its charging process. The charging process of an EV is mainly determined by the properties of its battery pack. As previously stated, Li-Ion batteries are more commonly used. There are three charging methods that can be used on this type of batteries which are described next.

- **Constant Voltage (CV):**

This method is suitable for all kind of batteries and it is the simplest charging scheme available. For this method, the battery is charged at a constant voltage, while the charging current of the battery varies through the charging process. The current intensity can be high during the initial stage when the battery begins to charge. This intensity decreases to zero until the battery is fully charged. Constant Voltage is not available for most residential and parking infrastructures, as it requires very high power in the early stage of charging. Such voltages could induce operational risks.

- **Constant Current (CC):**

This method controls the charging voltage applied to the battery so as to maintain a constant current. This induces a linear increase of the SoC of the battery. In this case, it is a combination of parameters such as an increment on the temperature, or of the voltage, or simply after a defined period of time that the BMS determines that a charge is completed.

- **Constant Current - Constant voltage (CC-CV)**

This is a combination of the two methods previously described and it is the most widely used method for charging Li-ion batteries [32, 50]. Three steps are identified during a charging process as it is illustrated in Figure 2.2. During the first step, the battery is pre-charged at a low constant current, normally around 0.1 C rate units. At the second step, the charging current is maintained constant until a certain threshold is reached by the SoC, this normally happens when the voltage of the cell reaches the battery terminal voltage V_{BAT} , which is typically 4.2V. At this point, the third step begins, the voltage being kept constant (CV), until the current exponentially decays and reaches typically one-tenth of the fast charge current I_{END} . Approximately 70% of the total charge is delivered during the CC step and the rest is completed during the CV step.

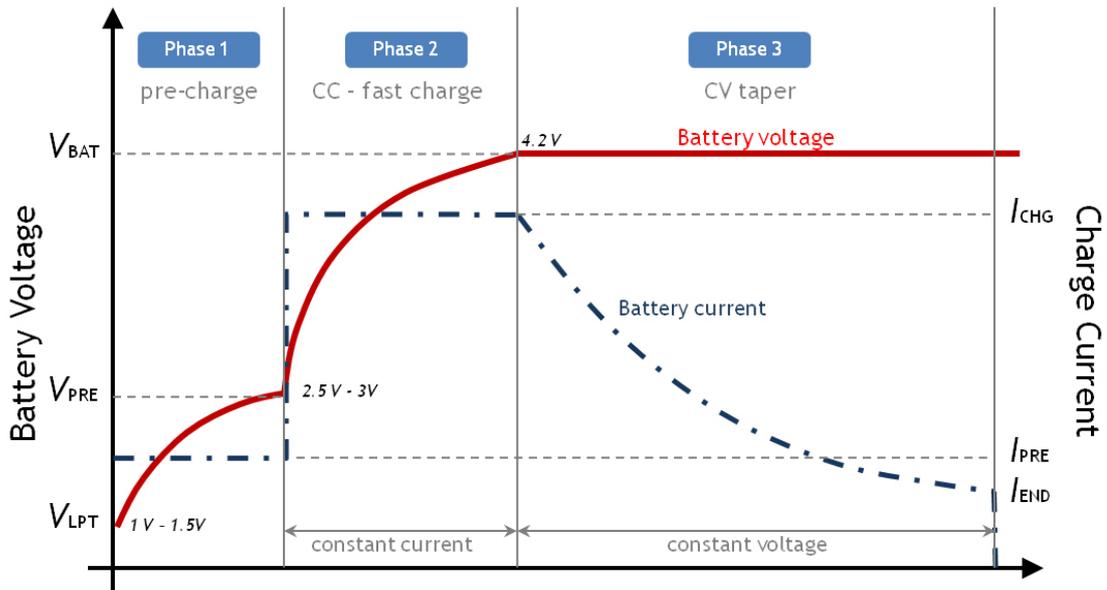


Figure 2.2 – Typical Li-ion battery charging profile according to [43] and [62].

An important advantage of this charging technique is its simplicity, that can be achieved by means of simple circuits while maintaining the cost of the charger admissible by the end-users.. Nevertheless, the performance of the CC-CV technique can still be improved [50].

There are different methods used by the BMS to stop charging a battery. They are based on different parameters, such as the considered instant, the measured temperature, or the voltage and current values. Depending on the selected parameter by the BMS once that one reaches its limit, the charging process ends in inducing a voltage decreasing..

2.2.3 Drivers Anxiety

As mentioned previously, one of the most important concerns of EV drivers is the range their vehicle can effectively reach before needing a recharge. In this matter, the lack of reliable information provided in real-time to the driver is at the origin of what we qualify of "drivers anxiety". This anxiety is first due to the current low density of charging infrastructures in urban areas. This scarcity of charging stations is even more noticeable in areas with low population density. A real-time estimation of the reachability of the available charging stations close to the instantaneous position of an EV is a complex operation. It assumes first that it is possible to convert the current SoC of the EV into a number of achievable kilometers [38]. Such a conversion depends on numerous parameters such as the dynamics of the discharge of the battery and on the availability of a 3-D cartography of the considered environment. As it has been mentioned in the previous sections, the energy efficiency between the electrical part and the mechanical part of an EV via the power train is very complex to model. In addition, information such as the effective weight and SoH [39] of the vehicle are also necessary. At last, the driver's behavior has also a strong impact on the energy consumption of his vehicle [42].

Thermal Management System (TMS)

The purpose of this system is to extend the life cycle of the battery pack in protecting it from overheating. In the case of NiMH batteries, a simple forced-air cooling system is adopted. However, the Li-Ion batteries used in EVs requires a more sophisticated liquid cooling system. The TMS is not only in charged of maintaining the temperature of different components at a certain interval, but to maintain a comfort temperature for the passengers inside the vehicle. This includes the ventilation and air conditioning system (HVAC) and a set of cooling and heating systems dedicated for the components of the vehicle.

The power train components of an EV contribute directly to the increment of the temperature in all the other components that can potentially lead to an overheating. The TMS aims to ensure that the threshold temperatures of different components are not exceeded, particularly the temperature of the battery that has tighter limits than the other components. The energy consumption of the TMS depends on the powertrain losses that themselves change with temperature. Temperature is controlled by the TMS [39]. Additionally, the TMS regulates the consumption of the components that are controlled by the environmental temperature. The HVAC loads may contribute to the energy consumption of the vehicle.

2.3 Electric Vehicle Supply Equipment

In recent years, the EV market has been subject to a continuous growth that is expected to increase for the years to come. Although it is expected that most drivers will charge mainly at their homes or at chargers provided at work, the need for public charging infrastructures should be considered as must for the expansion of the EV market. WPT or wireless charging, is today considered as a promising option for the years to come. It is gaining the attention of researchers who have already obtained significant advances in this matter. Several testbeds have proven WPT feasibility. Nevertheless, conductive charging remains as the most extended charging infrastructure nowadays with two main paths, AC and DC charging.

For historical reasons, AC charging was the first to be adopted and developed, as EVs were often charged from regular household sockets. Nevertheless, the maximum power was limited, which lead to long charging sessions and dangerous charging conditions for the final user. As a consequence, the automobile and electronic industry started to develop different plugs and sockets and a set of standards that could allow this inter-operability. In recent years, standardization efforts for the EVSE have been intensified from different organizations such as the International Electrotechnical Commission (IEC) and the Society for Automotive Engineers (SAE) in the United States. In the United States, the SAE J1772 standard specifies the EV conductive charging requirements. Its European counterpart is the IEC 61851-1 standard. Both standards define the operational and functional requirements for the charging infrastructure.

2.3.1 Charging Connectors

The IEC 62196 standard defines plugs, socket outlets, vehicle connectors and vehicle inlets. It is considered as a plug when it refers to the supply side, and as the vehicle inlet or vehicle connector when it refers to the vehicle side. The plug type refers to the specifications needed for the design

and manufacturing of the plug with which an EV connects to the charging equipment. At the date of publication of this manuscript, three plug designs are officially recognized for Mode 3 charging. These designs are designated as Type 1, Type 2, and Type 3. In accordance with the IEC standard 62196-1, the terms "sockets" and "plugs" are used for the supply-side. The terms "vehicle inlet" and "vehicle connector" are used for the vehicle-side.

The IEC 62196-2 standard specifies three physical plug designs, referred as "types". A slightly difference in the terminology refers to these types as "levels" on the SAE J1772 standard, but they are virtually the same [64]. In the 2003 version of the IEC 62196 standard, only the technical and safety requirements were specified, which was completed by the plug design specified in the 2011 version.

The first connector standards were only suited for low power levels, as EVs were mainly connected to regular household sockets. However, as the new generation of EVs require higher power levels for faster charging, several improvements have been achieved on the design of plugs and connectors. In practice, the sockets and plugs have been developed before any standard has been defined. We describe in this section the types of connectors available today on the market.

- **Type 1: The Yazaki connector**

This connector was approved by the SAE as the new J1772 connector standard which enables charging at 120 V or 200 V. It consists of two power pins, one ground pin and two additional pins for safety and communication features [10]. It is defined as a vehicle-side connector which requires a corresponding inlet. This connector is primarily used at charging stations which have fixed cables, as part of the infrastructure. Its vehicle inlet and connector were developed by the Japanese manufacturer of power network equipment Yazaki from where it gets its name. It was primarily embraced at the American and Japanese EV market.

- **Type 2: The Mennekes connector**

This plug is commonly referred as type 2 according to the IEC nomenclature as well as Mennekes plug. This name refers to the German manufacturer (Mennekes Ekektrotechnik) at the origin of the design of this plug. Due to the differences in the European power grids, such as the availability of three-phase power at households, the specifications of the Yazaki plug were considered insufficient. European manufacturers needed a plug which could handle semi-fast charging and three-phase power. These requirements are achieved by this new connector. It is used on loose cables which on the charger side can handle three-phase power connections while on the car side require a plug that matches the vehicle inlet. Type 2 plugs are rated for higher power levels than Type 1 plugs. The Mennekes plug has been adopted by the Association of German Car makers in 2010. It has also been adopted in 2013 by the European Commission as the European standard for AC Charging [27]. This plug is not compatible with the U.S. Type 1 plug.

- **Type 3: the Scame connector**

A group of French and Italian electrical equipment manufacturers, headed by the Scame Italian company, rejected the Mennekes plug. Because of an electro technical safety issue. As a consequence, the electrical equipment manufacturers members of the EV Plug Alliance proposed their own connector.

DC Charging

The standardization of DC charging followed a different path from the standardization process of AC charging. For DC charging, the definition of a standard happened before the installation of any equipment. However, the early standard has been challenged by alternative proposals from a consortium of different firms.

- **CHAdEMO**

In 2010, the Japanese power company TEPCO set up the Charge de Move (**CHAdEMO**) association, that includes different Japanese car manufacturers and electric utilities. Along with the Japan Automotive Research Institute, they designed a connector that can handle high voltages (300-600 V) and high current levels (up to 400 A). Due to the diameter of the copper wire of the cables to support such current intensities, it was decided to use a fixed cable on the supply side. At the vehicle side, **CHAdEMO** inlets have been progressively installed in Japanese vehicles. This massive implementation helped to position **CHAdEMO** as the DC fast charging standard. For this reason, the **CHAdEMO** design was recognized by the IEC 62196 standard. This standard needs however an exclusive vehicle inlet for DC charging. This can be considered as a drawback, since it will always be necessary to have a separate inlet for AC charging.

- **Combo or Combined Charging System (CCS)**

Announced in 2012, the Combo connector consists in a combination of AC and DC connectors. It prescribes fixed cables on the charging station. The Combo connector has been proposed by German car manufacturers. It considers two variants. The first variant is a combination of the Yazaki AC design with additional pins for DC charging. The second variant considers the Mannekes design. The European Commission defined the Combined Charging System (**CCS**) connector as the DC charging standard in Europe from 2014 [28]. However, it will take some time to replace the **CHAdEMO** stations previously deployed, leaving at least two DC connector standards in Europe in the years to come.

- **Tesla supercharger**

This is a proprietary DC fast charging delivering up to 120kW enabling long distance travel for the Tesla Model S, which is currently the only **EV** capable of charging at this rate. The supercharger is capable of delivering up to 50% of the 85 kWh battery in about 20 minutes, equivalent to 170 miles of range.

2.4 Charging Modes

The **IEC** defines four different charging modes according to the complexity of the system and the charging speed. A charging mode refers to the power level that rates a charger and its connectors. It also specifies the safety and control features that guarantee the safety and efficiency of a charging [10, 43, 64].

- **Mode1**

It is the simplest and most direct connection between the grid and the vehicle. It uses a standard non dedicated socket outlet at 16 A for single or three-phase infrastructures. It provides basic charging capabilities for domestic use, limiting its power at 3.3 kW for a single

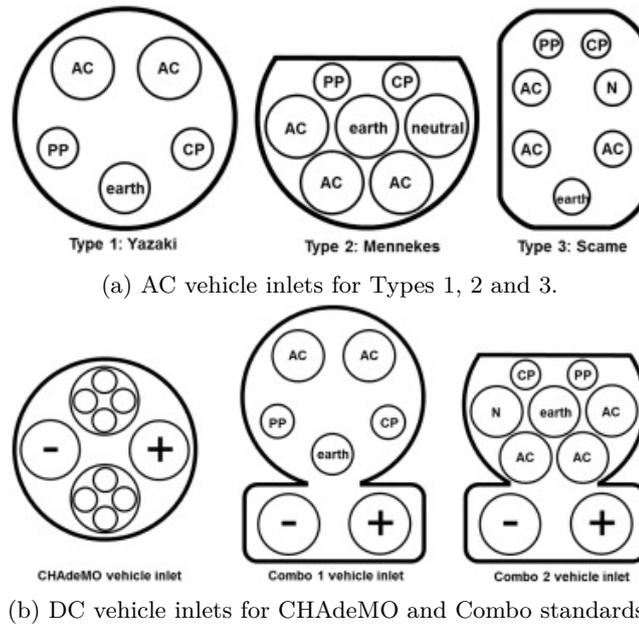


Figure 2.3 – AC and DC power plugs available. Figure taken from [28].

phase connection. However, this mode is currently prohibited in the U.S. due to the risk of overheating that it represents. Indeed, as the only protection against electric shock relies on differential breakers implemented either in the cable or in the charging infrastructure. Since the standard household sockets are available almost everywhere and the charging time is relatively long, this mode is more suitable for overnight charging.

- **Mode 2**

This is the default mode for new EVs in the U.S. and Japan, where the J1772 plug is used on the EV side. As in mode 1, a direct connection is established between the vehicle and the grid. Unlike mode 1, mode 2 uses a charging cable including a protective device that consists in a control pilot pin. The control pin allows to detect possible current-leakage and indicates the maximum charge current that can be supported. In order to avoid any risks of overheating of the electrical installation, a power limit is considered. Meanwhile, current intensities of 16 A or 32 A are admissible in the charger.

- **Mode 3**

This mode enables fast charging on an AC connection, which can go up to 55 kW. For that purpose, a dedicated EVSE is required for charge monitoring through a dedicated cable. This mode is safer than modes 1 or 2, as it allows a continuous communication between the vehicle and the charging station. The pilot wire not only indicates the maximum charge level, but it confirms to the charging station that the connection is secured and that the vehicles is ready for charging. The pilot wire also confirms the interruption of the charge if a disconnection is detected.

- **Mode 4**

An indirect connection between the vehicle and the grid through an external charger is performed. For monitoring the charging process, mode 4 requires a bidirectional communication over the pilot of a dedicated wire. This mode enables fast charging using DC and

higher voltages that would enable long-distance travels since the charging time is considerably reduced. The maximum current specified is 400 A. This mode is therefore preferred by dedicated charging stations due to its installation requirements and safety issues.

- Wireless Charging

WPT for **EV** charging is defined as the transmission of electrical power from the grid to the vehicle without the use of physical connectors. In recent years, it has gained considerable interest from different car makers and electric equipment manufacturers. **WPT** proposes an alternative solution for **EV** charging that could help to eliminate the risks and drawbacks related to wired charging.

Based on Faraday's law of induction and Ampere's circuital law, Inductive Power Transfer (IPT) systems are composed by a transmitting coil that induces an electric field into a receiving coil. Some initial configurations of IPT systems used an inductor in series with the coil. An analogy can be made between such a configuration with a loosely coupled transformer [64]. For **WPT**, a high frequency inverter converts low frequency utility power to high frequency AC power. The resonance electromagnetic field generated in the transmitting resonator transfers power to the receiving resonator, where finally the received power at the secondary resonator is rectified to charge the battery pack.

Based on power transfer dynamics, two methods can be considered: stationary wireless charging and dynamic wireless charging. For stationary charging, drivers only need to align the vehicle with the charger when parking and then leave it for charging. On the other hand, dynamic charging could power the vehicle when it is in movement using the infrastructure deployed over the roads. Dynamic **WPT** would enable potentially unlimited range for EVs. Additionally, dynamic charging considers two approaches based on the design of the transmitter array. The first one considers a single transmitter track, composed of a long transmitter connected to a power source and a considerably smaller receiver. For the second approach, multiple coils are connected to high frequency power sources.

The most important challenges of **WPT** are to make this technology efficient and effective at a reasonable cost. For that purpose, the power transfer efficiency at high transfer range must be improved. Power losses must also be reduced. Finally, misalignment between the vehicle and the induction loop must accept a greater tolerance than it is today the case in current experimentations. Such an increase in tolerance requires an important investment in the management system and in the communication between the vehicle and the infrastructure. If these issues can be solved, **WPT** has the potential of simplifying the charging process, and as a consequence, to make **EV** charging more convenient for the final user. This solution could help to increase the driving range of the vehicles and reduce the size of the batteries. The anxiety of **EV** drivers mentioned previously could become in the long term de facto obsolete thanks to this last prospective **WPT** alternative.

2.4.1 Charging Schemes

The flow of energy between the **EV** and the **EVSE** can be in both directions depending on the needs of the vehicles or the grid. Vehicle to Grid (**V2G**) and Vehicle to Vehicle (**V2V**) schemes are still under continuous improvement and study by research teams around the globe.

- **Grid-to-Vehicle (G2V)**

The vehicle is connected to the grid and the charge rate is controlled by the grid, either locally or remotely. Controlling the charge of the vehicles by the grid enables a better management of the grid infrastructure and the possibility to take advantage of low cost energy during low activity periods.

- **Vehicle to Grid (V2G)**

This method allows vehicles to feed power back directly to the grid. In order to perform such an operation, a constant communication between the grid and the vehicle in both ways is necessary. This technology has been tested for providing different ancillary services to the grid, such as frequency control, energy balance and to ease the integration of renewable energies into the grid when they are available.

In this case, EVs are not only able to vary charging power, but also to inject power back into the grid, which can be beneficial for the utilities and the grid. A variant of V2G known as Vehicle to Home (V2H) consists in injecting power from the the batteries of EVs to the household. Such an operation is particularly useful when the price of electricity delivered by the grid is at the highest. V2H can also be considered as a backup energy source in case of natural disaster (an earthquake for instance) imposing a disconnection of the homes from the grid. Despite the current research status on V2G, its deployment in the electric network is not expected to be widespread in the near future without the proper economic model. The recent climatic disasters that occurred these recent years in Japan have been a strong incentive for V2H deployment in this country.

- **Vehicle-to-Vehicle (V2V)**

This is an innovative energy exchange presented by authors in [25]. This method allows to exchange energy between two vehicles connected to the same charging station. This scheme helps to significantly reduce the impact of the charging process on the electric grid during the day. Additionally, it could help EV users to buy energy directly from other EVs connected to the charging station instead of buying it directly from the grid. Added to the technical aspects that should be solved, the V2V business model should be investigated into more details before considering its effective implementation.

Communication Between the Vehicle and the Grid

The IEC 62196 standard considers only a limited communication between the vehicle and the grid. It only takes into account the physical and signaling interoperability from the hardware point of view. This means that only the connector compatibility and the signaling messages associated to each pin of the connectors are covered by this standard.

The signaling between the EVSE and the EV is done using a 1 kHz Pulse Width Modulation (PWM) signal, which indicates the current capabilities of the charger. On the one hand, EVs can use the control pin to send state information to the EVSE. The EV communicates to the EVSE the state of the charging process depending on the voltage levels. On the other hand, the voltage levels at the control pin indicate when the EV is connected and charging, or connected and not charging, when ventilation is required or simply when the EV is connected and the cable is unpowered. The proximity pin and the protected earth pin indicate the maximum current intensity and the cross section of the copper cable.

For more sophisticated applications, such as identification, payment and value added services, a more efficient protocol is required. For that purpose, a collective group was created between ISO and IEC in 2009 called IEC 15118. It uses a set of layer protocols that allow EVs to communicate to EVSE. It is based on a Power Line Communication protocol (PLC) over the pilot wire of the charger. The application layer is based on XML. Authentication is based on the use of certificates.

The drawback of the IEC 15118 standard is the lack of considerations for the communication between the EVSE and the back office. Two protocols have been proposed to cover this issue, the Open Charge Point Protocol (OCCP) and the IEEE P2030.2. The OCCP protocol proposes an open and free standard to facilitate the roaming between operators of public charge poles [37]. Similarly, the standard IEEE P2030 which currently holds a draft status, provides the guidelines for smart grid interoperability between end-use applications and the electric power system [45]. It is mainly addressed to the transportation providers, infrastructure developers and end-users of EVs serving as a guideline in applications for road-based personal and mass transportation.

2.4.2 Charging Locations

There are different charging architectures according to the location of the charging infrastructure and the provided services. Some of the most common locations are the following:

- **Residential:**

For historical reasons, private homes are at the date of publication of this manuscript the most popular charging location. Depending on the type of residence, a charging spot dedicated to private usage could be installed in the garage or at a private parking place. Each charging station operates autonomously. It is considered by authors in [36] that the driver's household will be the most common location for EV charging in the future.

- **Public and private parking area:**

This charging location is dedicated to users in private parking areas. The set of charging points is clustered thanks to a controller which is in charge of the energy management, authentication and billing. Depending on the financial model, the access could be either free or paid for users, as well as available for any EV driver or reserved for a particular set of users. This location is particularly suitable for charging fleets of vehicles.

- **Service stations:**

These are dedicated locations for EV charging equipped in some cases for fast charging. In recent years, some test locations have appeared. It is expected that this architecture will be mostly available in highways to support inter-city trips. With a charging window of 30 minutes, EV drivers could have one or several breaks along their trips. The most well known case is the Tesla's fast charging corridor deployed across the US [13].

2.4.3 Charging Architectures

Instead of defining a charging architecture by its location, we consider a different approach where we classify charging stations according to the way that the EVSE is used. Thus, we find two categories of EV charging architecture: dedicated and shared infrastructures.

Dedicated infrastructure the EVSE is exclusively deployed for EV charging and it is the only service proposed. Fast charging stations, car parks locations, EVs fleet charging stations or battery switch stations [17,57,77] are some of the charging locations that fit into this group. In this type of architecture, the charging stations are directly connected to an electrical supply. However, its main drawback is the considerable investment for installing and reinforcing the electric network. If a dedicated infrastructure is not judiciously dimensioned, EVSE can be oversized for the actual demand of energy.

Shared infrastructure provide EV charging services at the same time that other electrical services. Residential charging stations could be considered a typical example of this architecture, where the charging station is added to the residential electric network. When an EV is charging at its household, it is considered as a new load connected to the grid. As the number of EVs in the market increases, shared charging architectures will have to be upgraded to successfully supply the energy demand. For this, a smart control of the fluctuant available power is required.

2.5 E-Mobility Market

The existing electricity market is the foundation of the EV charging market. In this work, we consider as point of departure the generic electricity market proposed in [72]. In this section we present the actors involved and their respective role in the EV charging model considered for this thesis.

- **Electricity Supply Retailer (ESR)** It is the entity that holds the license to sell electricity produced by themselves or to purchase is on the electricity markets.
- **Transmission System Operator (TSO)** It is responsible for operating the transmission grid in a defined geographical area.
- **Distribution System Operator (DSO)** It is responsible for connecting the loads to the electric system. It must maintain the network safe and reliable to properly serve all the customers. It must ensure system stability and security of supply as well as certain flexibility for congestion management.
- **Charging Station Equipment Owner** It is an entity that owns the charging station which could be for example a municipality or parking lot owner. In some cases, the equipment owner could be the operator of the charging station.
- **Charging Service Operator (CSO)** It is a party in charge of the operation and management of the charging infrastructure that proposes charging services to EV drivers. This party normally has a contract with the DSO for the use of the grid system and eventually another contract with the ESR for its electricity consumption. It covers the technical and commercial aspects of operating the infrastructure, such as the maintenance of the EVSE and acquisition of electricity from the electricity market.
- **e-Mobility Service Provider (e-MSP)** It is an entity that sells charging services to E-mobility customers. It could provide access to charging infrastructures operated by different CSOs thanks to electricity roaming contracts.

- **Central Control Manager** It is a party responsible of the proper management the loads connected. It communicates constantly with the sensors connected at the loads, analyzes the collected data and performs the necessary adjustments to maintain the grid operating properly. It can notify to the **DSO** when a load presents some problems, so they it can be fixed.
- **Public Lighting Service Operator** This entity is in charge of the management, operation and maintenance of the **PLS** electrical network. It regulates the intensity of the lighting according to the time of the day for the comfort of the users.
- **Metering Network** It is a network of sensors connected to the different loads of the electrical network. Each sensor monitors the electric consumption of every single node of the grid. The group of sensors are constantly exchanging information in real-time with the **CCM** or directly to the **DSO** through a reliable bidirectional communication network.
- **Flexibility Operator** It is a bridge between the **DSO** and the electricity market. It is a party that aggregates load flexibility from different users and trades it with the **TSO** or the **DSO** in order to provide ancillary services. It may eventually be directly concerned for trading **V2G** services with the **DSO**.

2.5.1 EV Charging Over the Public Lighting System (PLS)

TeleWatt is a national project supported by the French National Environmental and Energy Agency agency -**ADEME**, a subsidiary of the French Ministry of Industry. The main objective of this project is to provide public **EV** charging services through existing **PLS** infrastructure. In this thesis, we have taken this idea as the base for our research project, where we have to prove in first place that it is feasible and then to guarantee the proper distribution of energy through the network.

The architecture proposed in this work does not consider massive changes or upgrades on the electrical network already deployed by the **PLS**. This novel **EV** charging infrastructure proposes the use of a specially designed vehicle charger, which is attached to a common lamp pole of the **PLS**. By doing this, the installation costs of the chargers could be significantly reduced. By doing this, the role of the **PLS** operator is transformed and now it is not only **CSO**, which could potentially and eventually become a new player in the market as an **e-MSP**.

2.5.2 Integration of the e-Mobility Market, the Electricity Market and the PLS

The e-mobility market is naturally related to the electricity market. In recent years, some new actors have appeared and some other have added new functions to their roles. Authors in [72] present a generic model of the electric market and the relations that exist between the actors of the electricity market and the e-Mobility customers when it charges at a public location. Inspired on this model, Figure 2.4 shows how the **EV** charging architecture proposed for this thesis and shows how it could be positioned within the current electricity market.

The model presented in Figure 2.4 considers that the public charging station deployed are independent from the **DSO** regulated grid business. This means that different actors can build

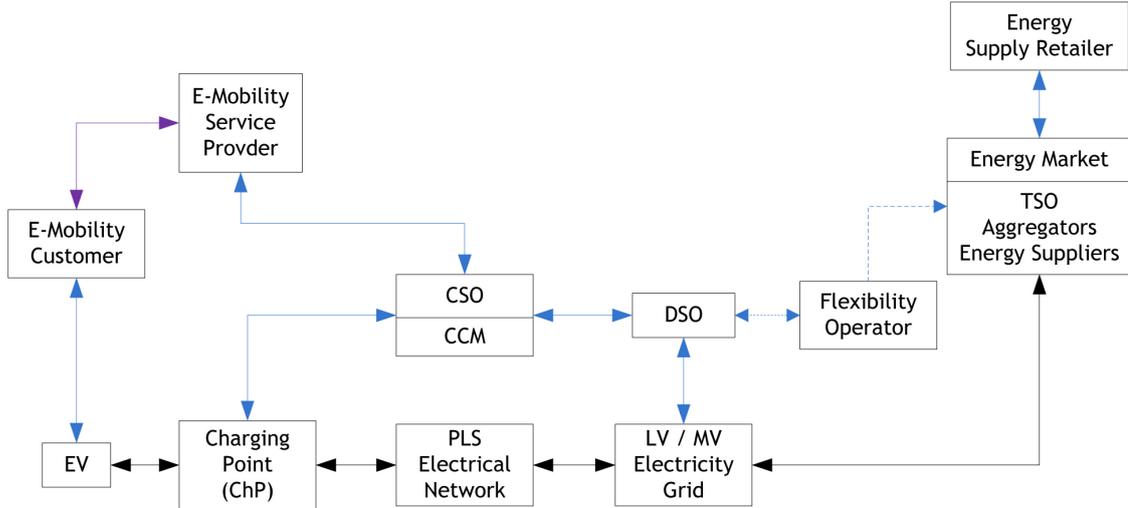


Figure 2.4 – E-Mobility market and the PLS grid added to the electricity market model.

and develop their charging infrastructure in the same geographical area. The black arrows in the graph indicate the physical connection between different actors. As previously mentioned, the charging stations or charging points (ChP) are directly connected to the PLS electrical network, which is linked to the Low Voltage (LV) electricity grid. We consider that the PLS depends is directly associated with the DSO, which buys the electricity at the energy market based on the energy consumption forecasted for the PLS and EV charging.

In the model here proposed, the CSO deploys a metering network through the grid which allows to collect data from all the loads connected. The CCM of the CSO uses the collected data for controlling the charging process of the EVs, the intensity of the lighting and to provide the e-MSP the information required for billing the customers. The CSO must be able to provide a connection to the network to any e-Mobility service provider interested on developing e-Mobility services to its customers.

The customer has a contract with the e-MSP which could eventually provide access to charging stations operated by different CSOs. In our model, a user contacts its e-MSP through its smartphone when it needs to charge its EV. The e-MSP contacts one or several CSO depending on its roaming agreements and depending on the availability of the charging stations. Only one e-MSP is considered at this stage of the project. We assume that the user sends different parameters to the e-MSP which allows the CSO to decide if the EV can be charged or not. When the e-MSP requests a new charging process to the CSO, the CSO can estimate if the EV can be accepted for charging, depending on the number of chargers and the power available at a given charging station and the energy requested by the EV. The CSO sends the availability of charging stations to the e-MSP which are forwarded to the user. When the user connects to a charger, the CCM is in control of the charging operation and collects the information needed for billing the operation.

2.6 The PLS Electrical Network

Although the PLS electrical network could be considered as an extension of the LV electricity grid, its operation is slightly different. It presents a well define operational schedule and under normal

Stage	Description
Daylight	It starts at dawn All street lamps are off
Lamp Heating Stage (LHS)	Starts at dusk and lamps are turned on Lamps increase their power consumption over their nominal power
Early Night	It starts when the LHS is over Lamps operate at nominal power to provide high lighting intensity on the streets
Late Night	Intensity of the lights is reduced and lamps can operate under their nominal power Takes place when the affluence of people on the streets is reduced and lower intensity of lighting is demanded Helps to reduce operational costs and save energy as proposed by [48]
Early Morning	It starts when the affluence of people and vehicles on streets increases and the intensity of lighting needs to be increased again Lamps operate at their nominal power This stage lasts until dawn

Table 2.1 – Definition of each stage present on the PLS through the day.

conditions, a regular power consumption from the loads connected. This particular electrical network is normally dedicated to provide exclusively street lighting services, however, in this thesis we explore the possibility to connect one or several charging stations. To achieve this, we must know its components and understand how it operates and the necessary constraints for an optimal performance.

In this section we briefly describe the components of the PLS electrical network considered in this thesis and the operational conditions and constraints taken into account.

2.6.1 PLS Power Consumption Profile

The availability and amount of power used for EV charging over the PLS depends on its scheduled power consumption. This means, how much power is demanded for street lighting at the different times of the day, which eventually defines the available power for EV charging. The lighting schedule of the PLS is divided in different stages which define how the intensity of the lighting will be increased or decreased. The stages of the PLS are presented in Table 2.1.

During the *Daylight Stage*, all the P_{av} can be used to charge the EVs. However, as soon as the *Lamp Heating Stage (LHS)* starts, due to the increase on the power demanded by the lamps at this stage, all the EV charging processes in course must be interrupted. As soon as the LHS ends and the *Early Night Stage* begins, the available power for EV charging could support one or several connections at the same time. However, in most cases it will not be the same number of vehicles that were previously connected during the daylight stage. Therefore, it is necessary to implement the remaining power in the most efficient way, so the EVs previously connected could resume their charging process.

2.6.2 Electric Operational Constraints

The PLS electric network is based on a simplified LV public distribution feeder used within the PLS in France. This network operates at a nominal voltage of 230/400V with a tolerance of $\pm 10\%$. The topology of the network used for the test bed is composed by a supplying feeder with 90 lamps deployed through 3 km of 3-phase and one neutral copper main cables, which are connected to a transformer (also designated by electric cabinet). The input voltage considered V_{input} is 322V or $227.69V_{rms}$. In the model here presented, the power capacity of the source T_{Pc} 2.4 is equal to the size of the transformer (T_s) multiplied by the input voltage (V_i) which is expressed in rms values:

$$T_{Pc} = T_s \times V_i \quad (2.4)$$

The size of the transformers could change depending on the number of loads connected and the geographical area that has to be served. According to the PLS operator in France [2], the common values for the current at the transformer in France are 16 A, 32 A, 64 A and 128 A in new networks. However, the most common value installed is 64 A, which gives us a total available power for feeding the street lamps of 14.5 kVA and a maximum voltage drop allowed at any point of the network of 204.92V. For modeling purposes, only one lamp is connected to a light pole, with a nominal power consumed by the lamp of 145 W. In order to balance the loads through the feeder, the street lamps are equally distributed through the 3 phases of the transformer and separated 33m one from each other.

2.6.3 EV Charging Point Specifications

It is assumed that the chargers work exclusively in AC and therefore no fast charging is considered. The three charging rates proposed at the charger are the following: 1.4 kW, 3.3 kW and 7 kW. It must be noticed that the power delivered by the charger could vary during the recharge. Specifications for the network model components were supplied by [2].

It is considered that only one charger could be attached to a lamp. In order to evaluate the effects of a particular location of the charger on the network, different network configurations are considered for the placement of the charging stations according to their distance from the cabinet in charge of their energy feeding.

2.7 Conclusion

In this chapter we have presented a brief introduction to the EV's market and to the various actors involved in the research, development and deployment of EV charging infrastructures. We introduced the different types of electric vehicles available in the market and the components of their architectures. Additionally, we have presented a short summary of the batteries used for automotive applications. This includes considerations about the chemistry of the electrolytes used in the batteries and the adopted charging algorithms. The electrical characteristics of the charging procedures and in fine, the specification and standardization of the connectors enabling to connect an EV to a charging station have been described. The basic principle of the charging

algorithms has been discussed. Globally, this chapter has provided a brief introduction to the electricity and e-Mobility market models considered for this thesis. The **PLS** market model has been discussed since it is a key element for the charging architectures considered in this thesis. In the following chapter, we present the method used for simulating the realistic operation of **PLS** electrical networks.

Development of Simulation Tools

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3.1 Introduction

In previous chapters we introduced the elements that constitute the **EVSE** and the **PLS** electrical network in the architecture proposed for **EV** charging over the **PLS** network. For testing the feasibility of such architecture, we had to create a computational model that could allow us to reproduce the conditions of any topology available for the **PLS** network, independently of its size or configuration. Therefore, we developed a simulator on **C#** language to emulate the operation of the **PLS** electrical network and how its operation could be affected by the addition of an **EVSE** to provide **EV** charging services and the new loads added to the grid.

The first step was to take the network information provided from the **CSO** and translate it into a graphical representation of the **PLS** network to replicate the relationships of currents and voltages through the network. By implementing the technique proposed by [59], it is possible to generate a set of matrices that define the relation between voltage and current for all the devices of the topology, which make possible to apply the Kirchhoff's laws and obtain the current and voltage at any point of the network [74].

In this chapter we present the developed tools for simulating the **PLS** network and the numeric methods used to calculate the voltage drop and current at every point of the grid. This allowed us to simulate the addition of **EV** chargers to the **PLS** electrical network and test the feasibility of connecting an **EV** to the architecture proposed.

3.2 Modeling of the **PLS** Electrical Network

An electrical network model is defined as the representation of the electrical power system, which is an assemblage of different devices and components interconnected electrically. Each electrical network is different, either by its size, the number of components or its configuration. Therefore, it is of our particular interest to reproduce any possible topology of the **PLS** in the closest possible way to real life conditions.

The model that we propose in this thesis does not consider any major upgrades to the current **PLS**, as the **EV** chargers proposed do not require a significant modification on its electrical network. As the first step of our model, we have to reproduce the **PLS** electrical network via simulation. We must verify that the voltage and current values measurements at each point of the simulated model match the actual values obtained in real life.

Representation of the **PLS** Electrical Network

The **DSO** in charge of the operation of the **PLS** has a database with all the information from all the components of its electric network. Such database includes the geographical position of each connected device. Thus, it is possible to know where different transformers and lamps are located, as well as the phase of the transformer where a given lamp is connected. However, for modeling purposes the topology of the network should be translated into an electric diagram as to generate the equations which represent the interaction between all the elements of the electrical network. With this information, it is possible to estimate the voltage and current at every point of the grid.

For this thesis, the PLS operator in France [2] provided us an electrical diagram as an example of the base topology of the PLS which we use as the point of departure for our testbed. The full diagram of the PLS electrical network is available in Appendix A.1. However, in Figure 3.1 we show a section of the full electrical diagram, which allows us to display more in detail its components. We can observe how the transformer is modeled as three power sources where the lamps are connected. The elemental characteristics of the network components are displayed on the diagram, which are based on real-life devices.

In order to build our test-bed, an idealized electrical representation of each component was provided by the DSO. Figure 3.2 displays more in detail how a lamp, the transmission cables or an EV charger are electrically modeled. Which in the case of the charger is simply modeled as a resistor connected in parallel to a lamp. For modeling purposes, an EV charger of 3.3k W is represented by a resistor of 16 Ω . Nevertheless, as we will explain later on this chapter, the value of the resistor should eventually be adjusted to simulate different charge rates proposed by the CSO. It should be noted that the equivalent circuits for the lamps and cables were provided by the DSO according to real-life characteristics of these elements.

Construction of a Generic Topology of the PLS

The electric diagram in Figure A.1 is only a visual representation of a specific network topology. In this case, it corresponds to the PLS electrical network considered for building our test-bed. To be capable of simulating the behavior of the elements on the PLS, we need to conceive a tool that could automatically build the equivalent circuit of any PLS configuration. Once the equivalent circuit is generated, it is possible to know how the loads are interconnected and how they interact with the rest of the components in the network.

The first step for building our testbed simulator is to replicate the topology of the network from the data provided by the DSO. We assume that the information available at the DSO's database includes the geographical position of the transformer, of every lamp and every EV charger connected to the network. Most importantly, the cable's distance between the transformer and the lamp are provided, as well as the phase at which the load is connected. This information allows us to generate the full topology of the network by means of a graph made of branches and nodes which represents all the components of the PLS. For modeling purposes, all the elements connected to the transformer should be considered when the topology is generated, even if a given element is turned on or off when the topology is created. By doing this, the size of the topology will always remain constant, unless a new lamp or an EV charger is physically added to the network. Once the graph of the network is generated, it is possible to combine the characteristics of all the elements of the circuit with the well known Kirchhoff laws [74], in order to obtain the voltages and currents at every location in a circuit following the method proposed by [60].

3.3 Graph Theory Applied to the Design of Electric Circuits

It is well known the importance of Kirchhoff's laws in circuit design for power systems. However, in order to apply such laws, the information available from the network configuration should be

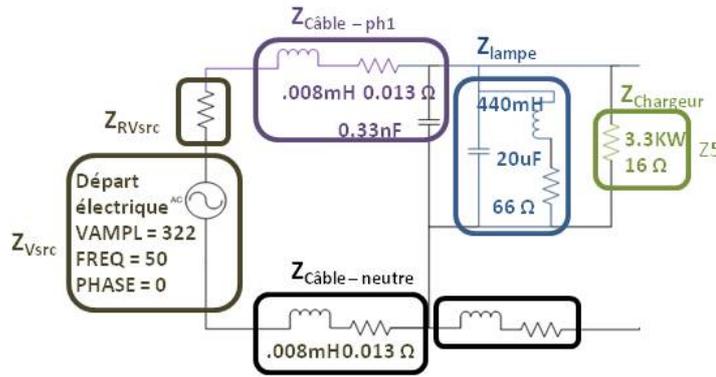


Figure 3.2 – Values considered for the electric circuits of the network.

interpreted first into an algebraic language. This can be achieved by means of the well known graph theory, which allows us to represent the topology of the electrical network as a graph. Afterwards, a set of equations defines the interaction of all the interconnected elements of the circuit.

Generating the Topology of the Electrical Network

Graph theory tell us that the topology of a given circuit can be represented as a graph constituted by a set of nodes interconnected by another set of branches that indicate an electrical connection between them [5]. For building the PLS topology in our test-bed, the transformer is taken as the point of departure of the topology. It is represented as three power sources connected to a common neutral. Each lamp is represented by a new branch, and the branches are added one by one to the graph. The first node of a branch's lamp is connected to the last element connected to the common neutral, while the second node of the branch is linked to the last node connected on the same phase of the transformer. Lamps are added from the closest to the furthest distance from the transformer.

For the construction of the circuit graph all the details of the circuit elements are not considered, leaving only the topological information about the circuit. Within a graph two topological groups are found, links and tree branches. Tree branches constitute a subset of the branches such that when they are connected, they do not form any closed path or loop. While the links close a loop when they are connected into the graph. Using the method proposed in [59], it is possible to separate the branches into tree branches and links from the generated topology. Once they are separated, it is possible to identify all the loops of the topology as well as the branches that belong to each one of the loops.

When all the loops on the topology have been identified, is possible to build an incidence matrix between the branches and the loops. This matrix is called matrix C and has a size $n \times m$. Where n is the number of branches and m is the number of loops, this makes it possible to identify to which loop a branch belongs to. As the configuration of the network does not change unless a new lamp is added, the size of the topology and therefore the number of branches will not change when the elements of the network are turned on or off or when an EV starts charging. Thus, the size of the matrix will remain the same.

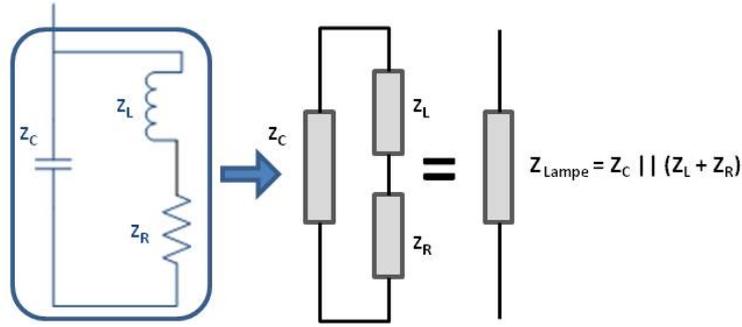


Figure 3.3 – Representation of electric circuits as impedances.

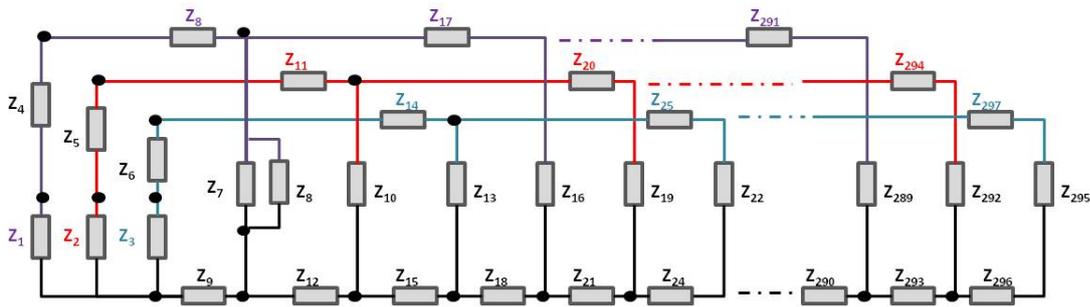


Figure 3.4 – Representation of the electric network in terms of their equivalent impedances.

$$C = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,m} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n,1} & c_{n,2} & \cdots & c_{n,m} \end{bmatrix}$$

Once all the elements have been added and the graph is built up, the branches can display the equivalent impedance values of the elements connected between two nodes. Each branch at the graph contains only one impedance value, independently of the number of electric circuits placed at the same branch. The impedance of each branch contains a real part, which corresponds to the resistive elements of the connected components and an imaginary part, which corresponds to the reactive elements, such as capacitors and coils present on the circuits connected.

In Figure 3.3 we can observe how all the electric components that constitute a lamp on the PLS network can be reduced to a single equivalent impedance value, which helps us simplify the voltage and current computations. Following the same logic for all the branches on the topology, Figure 3.4 presents a condensed version of the topology obtained from the electric circuit A.1.

The electrical information of each component, allows us to build a second matrix which contains the impedance values for each branch of the topology. This matrix is referred as matrix Z_{bb} . It has a size $n \times n$ where n is the number of branches on the graph. The elements on the diagonal of the matrix contain the impedance value Z_i of each branch on the topology and the value of the elements outside the diagonal is equal to zero. As for the matrix C , while the impedance values can change through the simulation, the size of the matrix remains constant. This happens for instance when an EV starts or stops charging.

$$Z_{bb} = \begin{bmatrix} Z_1 & 0 & \cdots & 0 \\ 0 & Z_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_n \end{bmatrix}$$

3.4 Voltage and Current Computation of the Loads

Kirchhoff's voltage law and Kirchhoff's current law, referred as KVL and KCL respectively, represent the key point to understand the interdependence of all the elements of a power system, as voltages and currents through the circuit must obey both laws. KVL states that when voltages are added up around any closed loop in a circuit, the sum must be equal to zero. On the other hand, KCL states that the currents leaving and entering any node in a circuit must add up to zero.

Kirchhoff's laws are usually applied to complex circuits with many connections, as they allow to determine the voltages and currents in every circuit branch from a set of independent equations normally arranged in a matrix. We previously presented how matrices Z_{bb} and C are generated. These two matrices allow us to build the relationship between branches and loops with its impedance values, needed to implement the Kirchhoff's laws in a third matrix referred as Z_{loop} matrix.

Z_{loop} is a square matrix, invertible and of size $m \times m$, where m is the number of loops found in the topology. It contains the sum of the impedances of each loop found in the network's topology. It is obtained by multiplying matrices Z_{bb} , C and its transposed matrix C^t . The KVL loop equations obtained is assured to be independent, as there are no loop equations that can be obtained by a combination of the other loops.

$$\begin{aligned} Z_{loop} &= C^t \times Z_{bb} \times C \\ &= \begin{bmatrix} c_{1,1}^t & c_{1,2}^t & \cdots & c_{1,n}^t \\ c_{2,1}^t & c_{2,2}^t & \cdots & c_{2,n}^t \\ \vdots & \vdots & \ddots & \vdots \\ c_{m,1}^t & c_{m,2}^t & \cdots & c_{m,n}^t \end{bmatrix} \times \begin{bmatrix} Z_1 & 0 & \cdots & 0 \\ 0 & Z_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_n \end{bmatrix} \times \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,m} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n,1} & c_{n,2} & \cdots & c_{n,m} \end{bmatrix} \end{aligned}$$

Finally, matrices U and I of size $m \times 1$ help us calculate the voltage and current for each loop and eventually at each branch of the topology.

3.4.1 Branch's Voltage and Current Computation

As the voltage value for the power source is available, it is possible to use this information combined with the Z_{loop} matrix in order to calculate the sum of the voltage for each loop, which will be given by matrix U . Before calculating the voltage drop at each branch, the current I must be calculated first by using the Ohm's law basis.

For this, let us consider:

$$\underline{I} = (i_0, \dots, i_{n-1}) \text{ where } i_j \text{ is the current in each loop.}$$

And

$$\underline{U} = (u_0, \dots, u_{n-1}) \text{ where } u_j \text{ is the voltage drop in each loop.}$$

We have then:

$$\underline{U} = \underline{Z}_{loop} \times \underline{I} \Rightarrow \underline{I} = \underline{Z}_{loop}^{-1} \times \underline{U}$$

The current vector \underline{I} is calculated from the product of the inverted matrix of Z_{loop} and the voltage vector \underline{U} . Being \underline{I} , the voltage drop at the branch j equal to $u_j = Z_j i_j$.

Dynamic Processing of Changes on the Electrical Network

Each time that an **EV** is connected or disconnected from an **EV** charger, it causes a change in the voltage levels registered on the entire electrical network and not only where the charger is located. The scope of dynamic processing the information provided by the electric network is to guarantee the proper management of each one of the chargers deployed over the network. This should allow us to provide a constant charge rate to the vehicles connected without causing any disruption on the **PLS**.

In order to consider that a given charger can work properly, two conditions must be guaranteed: in first place, the consumed power by all the components and devices connected to a given transformer should not exceed its power capacity. In second place, the addition of a new load to the network should not cause that the voltage drops under the minimum threshold defined by the **DSO**. This last condition is essential to properly operate the street lighting service, which will remain the primary service on the **EV** charging architecture proposed in this thesis.

Before a new connection takes place, the **CCM** should verify if the selected charger can actually support the new load by respecting the previous stated conditions. For this, the new connection is simulated and if the constraints of the network are respected, the charger can actually accept and charge the new arriving **EV**.

Adjustment on Resistor Value

We consider for our test-bed model that an **EV** charger must provide a constant power to the connected **EVs**. This is only possible if the charger is modeled as a variable resistor. Modeling the charger as a resistor eliminates any phase shift between the voltage and the current. It must be considered that in power systems, at times of high electric demand and therefore high current flow, the voltage drop along the transmission line increases. This means that the voltage drops more rapidly as the distance increases. For this reason, the value of the resistor will depend on different factors: the location over the feeder, the other loads connected to the network and the value of the charge rate requested.

If an **EV** charger was represented by a resistor with a fixed value, it will be more dependent on the other loads connected to the grid. This means, that when another **EV** starts or stops charging, it will cause a variation on the voltage at all the points of the network. However, the voltage drop

will change differently at each branch. As a consequence, the power originally delivered by the charger would change and it would produce a different charge rate from the expected constant power P_c . By using a variable resistor, its value can be adjusted by the CCM in order to provide the proper expected charge rate despite the variations on the network.

To calculate the value of the resistor R_i that provides the power P_c at the charger, let us consider:

$$P_c = V_i I_i \cos(\phi) \quad (3.1)$$

with $\cos(\phi) = 1$

We have the relation:

$$V_i = I_i R \quad (3.2)$$

Which can be expressed like:

$$P_c = \frac{V_i^2}{R_{i+1}} \quad (3.3)$$

In consequence

$$R_{i+1} = \frac{V_i^2}{P_c} \quad (3.4)$$

Where V_i corresponds to the voltage drop at the charger and I_i is the current that runs through the charger. The difference of potential at a charger with no connected EVs is denoted by V_0 and the real consumed power is referred as P_c .

The approximate value of the resistor is obtained by means of Equation 3.4. However, as voltage and current values change along the network when the resistor value is adjusted, it is required an iterative process to finally obtain the desired value at all the chargers simultaneously. This guarantees that the proper charge rate will be provided at every active charger. The following algorithm proposes an iterative process implemented by the CCM to find the resistor's value that approaches the requested charge rate.

Algorithm 1 : Estimation of the value for Ri

Data : V_i, I_i, P_c

Result : Estimation of the value needed for R to consume the power P_c .

for i from 0 to ∞ **do**

$$R_{i+1} = \frac{V_i^2}{P_c};$$

Compute $Z_{loop}^{-1}(R_{i+1});$

I_{i+1} calculated from $Z_{loop}^{-1}(R_{i+1});$

V_{i+1} calculated from $Z_{loop}^{-1}(R_{i+1});$

if $P_c - R_{i+1} I_{i+1}^2 < \varepsilon$ **then**

$R = R_{i+1};$

break;

end

end

At the first iteration of the algorithm, the value for the resistor $R_1 = \frac{V_0^2}{P_c}$ is calculated in order to consume the power P_c for a voltage V_0 . When an EV is connected, there will be a voltage drop at the charger and the power provided by R_1 will be under the desired value for P_c . To rectify this

effect, the value of the resistor R must be reduced at every iteration and the value of the voltage must be calculated again. Which means, computing the value of the Z_{loop}^{-1} matrix one more time. All these computations must be done until the proper value of the resistor R is reached and the consumed power at the charger approaches the expected charge rate at the charger P_c . A key process in the iteration is the computation of the matrix Z_{loop}^{-1} , which has to be performed really fast to be capable of offering the EV charging service in real-time. Details are given in the next section.

3.5 Power Computation in Real Time

In the previous section we demonstrated how graph theory can be applied to electrical circuit theory. A set of matrices containing the information about the electrical network and how their components are interconnected. Among this set of matrices, the matrix Z_{loop} contains the sum of all impedance values for each loop found in the topology. As the voltage of the source is known, it is possible to apply the well known Ohm's law to obtain the current and voltage values for each branch of the topology. For this, we need to obtain the matrix Z_{loop}^{-1} , which can be done through different methods. In this section we present two methods used for matrix inversion in our simulator and their performance in terms of time of execution, which is an important issue, as the computation should allow the CCM to provide a real-time service to its users. All our simulations were performed in a computer with the following characteristics: an Intel Core2 Duo CPU processor @ 3.6 Ghz, 8 Gb or RAM and Windows Vista Professional of 64 bits.

Cramer's Rule or Cofactor's Method

Cramer's rule expresses the solution in terms of determinants of the coefficient matrix and the matrices obtained from it. Despite it is considered an inefficient method for large matrices, this method was selected because of its simplicity to be implemented and to serve as the worst case scenario to be taken as a reference.

Let $A = (a_{i,j})$ be a square matrix of size $n \times n$ that has to be inverted. The coefficient $C'_{i,j}$ of an entry $a_{i,j}$ of the matrix A can be obtained as follows:

Being

$$C'_{i,j} = (-1)^{i+j} M_{i,j}$$

Where $M_{i,j}$ is defined as the determinant of the resulting square submatrix after eliminating the row i and column j from A [26]. Consider C' the coefficient matrix of A

$$C = \begin{bmatrix} C'_{1,1} & C'_{1,2} & \cdots & C'_{1,n} \\ C'_{2,1} & C'_{2,2} & \cdots & C'_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C'_{n,1} & C'_{n,2} & \cdots & C'_{n,n} \end{bmatrix}$$

where $adj(A)$ denotes the adjugate matrix of A which is the transposed matrix of the coefficient

matrix C' .

$$\text{adj}(A) = C'^t = \begin{bmatrix} C'_{1,1} & C'_{2,1} & \cdots & C'_{n,1} \\ C'_{1,2} & C'_{2,2} & \cdots & C'_{n,2} \\ \vdots & \vdots & \ddots & \vdots \\ C'_{1,n} & C'_{2,n} & \cdots & C'_{n,n} \end{bmatrix}$$

It is then possible to obtain the inverse of A from the following equation:

$$A^{-1} = \frac{1}{\det(A)} (\text{adj}A) = \frac{1}{\det(A)} \begin{bmatrix} C'_{1,1} & C'_{2,1} & \cdots & C'_{n,1} \\ C'_{1,2} & C'_{2,2} & \cdots & C'_{n,2} \\ \vdots & \vdots & \ddots & \vdots \\ C'_{1,n} & C'_{2,n} & \cdots & C'_{n,n} \end{bmatrix}$$

Results by the Cramer's Rule Method

The complexity of computing the determinant of matrix Z_{loop} is equal to $O(n!)$. Such complexity becomes an essential factor for this method performance. The topology of the tested network considers in a first stage only a transformer with 30 lamps connected and balanced over the three phases of the transformer. Results obtained by the [DSO](#) via PSpice were compared to our results obtained using the Cramer's rule method for the inversion of the Z_{loop} matrix. The voltage and current values obtained in our simulation were validated. However, as expected, the total time required for computing the matrix Z_{loop}^{-1} was too long. It took a total of **9.75 minutes** or **585 seconds**. Despite the accuracy of the results, the time of calculation is not suitable for implementation on a real-time system, specially when the same computation would constantly be called to adjust the value of the resistor on every charger. Thus, another solution with a faster time of computation had to be found.

Gauss-Jordan Method

The second method was selected for its simple implementation and its improvement in terms of performance. This method allows us to inverse a square matrix $A = (a_{i,j})$ of size $n \times n$, by generating an augmented matrix that contains the matrix A and the identity matrix I_n of the same size that A [52] [63].

Let us have:

$$(A|I_n) = \left(\begin{array}{cccc|cccc} a_{1,1} & a_{1,2} & \cdots & a_{1,n} & 1 & 0 & \cdots & 0 \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} & 0 & 0 & \cdots & 1 \end{array} \right)$$

The goal is to transform the matrix $(A|I_n)$ into $(I_n|A^{-1})$ by a set of operations applied to the rows of the $(A|I_n)$ system.

The Gauss-Jordan algorithm is described next:

Where l_i^k is the row i of the matrix $(A|I_n)$ at the iteration k
 $A_{i,j}^k$ the scalar $a_{i,j}$ of matrix A at the iteration k

Algorithm 2 : Gauss-Jordan Elimination**Data :** The augmented matrix $(A|I_n)$ of size $n \times 2n$ **Result :** The inverse matrix $(I_n|A^{-1})$.

```

for  $k$  from 1 to  $n$  do
  pivot =  $A_{k,k}$ ;
  if  $pivot = 0$  then
    for  $i$  from  $k$  to  $n$  do
      if  $A_{i,k} \neq 0$  then
        |  $l_i \leftrightarrow l_k$ 
      end
    end
  else
     $\alpha = \frac{1}{pivot}$ ;
     $l_k \leftarrow l_k \times \alpha$ ;
    for  $i$  from 1 to  $n$  do
      if  $i \neq k$  then
        |  $l_i \leftarrow l_i - A_{i,k} \times l_k$ 
      end
    end
  end
end

```

 i = the row number of matrix $(A|I_n)$ k = the number of columns of matrix A n = the number of rows of matrix A

3.5.1 Gauss-Jordan Results

The complexity of Gauss-Jordan method is of order n^3 , where n is the size of the matrix to inverse. In our simulator, the Gauss-Jordan algorithm was tested to compute the inverse of Z_{loop} on the same test topology of 30 lamps and 3 chargers. With this algorithm, the total time needed for the matrix Z_{loop}^{-1} was reduced to **0.215 seconds**, which is **1465** times faster than the Cramer's rule method.

Results were compared against those obtained with the Cramer's rule method. As they were accurate, the second stage was to test the network with all the lamps turned on and only the closest **EV** charger from the transformer turned on with an available charge rate of 3.3 kW. This results matched once again the results obtained via PSpice by the **DSO** and the simulator was validated for experimentation considering this method for the calculation of the resistor R .

3.6 Summary

In this chapter we have presented the methodology used for modeling the **PLS** electrical network from the information provided by the **DSO**. In order to properly manage the grid and all the elements connected to it, we need to know the voltage and current values at every point of the

grid in real-time. Therefore, the electrical network must be expressed in algebraic terms before being able to implement any circuit's theory. To achieve this, we have implemented a method to build a graph that reflects the topology of the electrical network and all its components. From the generated topology, we adapted an algorithm found on the literature to generate a group of matrices that show the relation and interconnection of all the elements connected following the Kirchhoff's voltage and current laws.

The architecture proposed for EV charging considers that a charging station will be attached to a given lamp of the grid. In the electrical model, the charger is represented as a simple resistor. The value of this resistor must be calculated in order to obtain a value equivalent to the charge rate provided to a given EV. In this chapter we have presented an iterative algorithm to balance the value of the resistor according to the changes on the network. For this, it is necessary to constantly compute the voltage and current values of every point of the topology. In order to achieve this, we need to calculate the inverse of a matrix which allows us to use the well known Ohm's law and obtained the required values.

For this purpose, we have evaluated two methods to compute the inverse of a matrix. The first one, known as Cramer's rule method allowed us to validate the model conceived for simulating the electric network. Nevertheless, its performance in terms of time of execution was quite deficient for the actual needs of the CCM. The second one was the Gauss-Jordan algorithm, which computation time presented was significantly improved. This allowed us to obtain the required values of the grid in real-time and pass to the next stage of this thesis.

Part II

Smart Charging Strategies

Conservative Strategies for Electric Vehicle Charging

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4.1 Introduction

The first part of this thesis is dedicated to present the context of the **EV** market and the charging infrastructure available for its current and future deployment. As previously presented, this work aims to provide a short term solution to extend the charging infrastructure in urban areas at a low cost of investment. This should be possible if the integration of the **EV** charging services to the **PLS** is feasible. In order to prove the feasibility of the proposed solution, we have developed a testbed that could help us simulate the behavior of the electric network as mentioned in chapter 3.

The second part of this thesis is dedicated to present the experimental deployment of the proposed **EV** charging infrastructure. By means of the electric network simulator that we have built, a set of different scenarios were considered in order to verify the feasibility of adding **EV** charging services to the **PLS** under different circumstances. In a first attempt, a conservative approach referred as **CoTaSch** is conceived to secure that the **EVs** will be capable of charging before its arrival to the **ChP** without disrupting the lighting services. Therefore, the main scope at this stage of the project is only to demonstrate if the integration of **EVSE** to the **PLS** infrastructure to provide **EV** charging services is feasible.

In this chapter we present the conditions required for the proper operation of the PLS. For the CoTaSch approach, only one charging strategy is implemented based on the order of arrival of the EVs, which is referred as CFCFS. A set of evaluation scenarios that take into account several different conditions and parameters were established to test the network and measure the obtained results according to a group of metrics defined for this purpose.

4.2 Smart Charging over Public Lighting Systems

In order to improve the management of the loads connected to the electric network, is better to look at them as tasks to be dispatched. This allows to have a better control of the energy required by the loads and the total amount of energy dispatched. To better understand the effects of adding new loads to the PLS electric network, a smart charging strategy is required which takes into account the limitations, constraints and characteristics of a LV network. For the particular case considered in our model, the street lighting remains the primary service proposed by the network the whole time. Therefore, the connection or disconnection of additional loads to the network hereby represented by EVs, must be only executed if it does not interrupt the street lighting services.

The first strategy considered in this thesis is based on the well known First Come First Served scheduling policy. Within this strategy, the vehicles will be charged following the order of arrival to the charging station as long as the constraints of the network are respected and there is sufficient power available to charge an EV. This charging strategy follows a similar logic to the one known as dumb charging, where the vehicles start charging immediately after they have been plugged into the charger, hereby simply referred as ChP.

4.2.1 Task Modeling of the Loads

As presented in [34], a power system could include three different types of loads: static, deferrable and distributed electricity storage. Static loads have no flexibility in their power profile, while deferrable loads present a given energy requirement to be dispatched within a specific time interval; distributed electricity storage loads could be charged or discharged in order to adjust to the offer and demand of energy of the system. For modeling purposes, only static and deferrable loads are considered.

In the model here presented, the lamps connected to the feeder of the PLS are considered as static loads; this is because the power profile of the loads is well defined through the day. The power delivered to the lamps is scheduled in advance according to the day light conditions and its operation cannot be compromised by any other service. On the other hand, the connected vehicles are considered as deferrable loads and therefore processed as tasks, as presented in [71].

For the conservative approach, known as CoTaSch, a task T_i is parameterized by (Er_i, ta_i, td_i, r_i) , where Er_i corresponds to the energy requirement of the EV i at time of departure, ta_i refers to the time of arrival and r_i to the power delivered by the charger or better known as charge rate. At this stage, the time of departure td_i is not set by the user. It corresponds instead to the time when the vehicle has been fully charged $SoC_i = SoC_{max_i}$.

The energy requirement is calculated at time of arrival ta_i based on the battery capacity C_i of the vehicle i as shown in Equation 4.1.

$$Er_i(ta_i) = [SoCmax_i - SoC_i(ta_i)] \times C_i \quad (4.1)$$

The energy shortfall Es_i refers to the amount of energy left to complete the energy requirement, it is constantly updated. Thus, at time t is given by Equation 4.2:

$$Es_i(t) = [Er_i(ta_i) - SoC_i(t)] \quad (4.2)$$

where $SoC_i(t)$ corresponds to the battery SoC at time t . We note that Es_i is updated by the system each time a new EV arrives, when a task is finished or when the conditions on the PLS change.

4.2.2 Dumb Charging

This charging strategy is considered by some authors as the most simple scenario to implement and test over an EV charging network [31, 43, 54]. It is known as dumb charging, because the vehicles connected to a charging station start charging immediately after they have been plugged into the ChP, without any control on the power delivered from the CCM. The process does not stop until the vehicle is fully charged. This particular strategy represents a high risk for the proper operation of the electric network, specially during peak periods of the day when the energy demanded could exceed the energy available on the grid.

Previous work available in the literature has already exposed the effects on the electric grid when the EVs start charging without any further control from the network [31, 53]. The main risks from this type of strategy are the shortage of available energy and the disruption of the network, specially during peak hours of the day. Due to the lack of control on the consumed power exposed by this technique, it is not particularly recommended to be implemented over an architecture such like the PLS, at least not without some modifications.

So as to prevent any negative effects on the network, some strategies have been proposed in the literature, such as shifting the charge of vehicles to non peak hours. However, it should be considered that most part of the strategies presented have been developed within private networks or at a global scale on the power grid [17, 55, 68]. The first charging strategy in this thesis, presents a modified version of the dumb charging strategy in order to guarantee the proper operation of the PLS while charging a set of EVs, but keeping the idea of an immediate charge after the EV's connection to the ChP.

4.2.3 Conservative Charging Strategy on a First Come First Served Basis

The initial approach considered for EV charging within the present work is called CFCFS. This model introduces a conservative adaptation of the well known FCFS scheduling policy and the dumb charging strategy. It adopts the dumb charging principle of triggering the charging process of an EV immediately after it has been plugged into a given electric charger. However, due to

the fact that the recharge of the EV should never put at risk the normal operation of the PLS and considering the nature of this particular electric network, some modifications have to be performed. The main scope at this first stage is focused on demonstrating by means of the PLS electric network currently available, the possibility to charge EVs within this network without causing any perturbation in the lighting services. To do so, it is necessary for the CCM to simulate the recharge of an EV before it takes place and estimate if such operation would be possible without putting at risk the normal operation of the grid before accepting another vehicle to be charged. This strategy is the main key to avoid the problems related to overcharging the network that are normally found when dumb charging is performed.

The Private Network Operator (PNO) is responsible for distributing the power requested to all the loads connected along the PLS. In order to achieve this, the total power consumption, the levels of current and voltage at all the points of the network are continuously obtained and controlled by means of sensors deployed over the network and transmitted to the CCM. When the conservative charging strategy CFCS is implemented, the CCM executes five main routines during a common day at the PLS to react to the events registered at the PLS electric network. Such routines are the following: System Start Up, Charging Point Status Update, System Update, Round Robin Charging Algorithm and EV Charging. These routines are only valid for the CoTaSch approach.

System Start Up for Conservative Dispatch

The initial conditions of the system consider a network without any EVs connected. Depending on the season of the year, the time of the day when the system starts up will define the day light conditions and consequently, the total power available for EV charging and the total power dedicated for street lighting. The CCM calculates the current, the voltage drop and the total power consumed at every point in the network. The power losses created by the loads connected are also considered.

Charging Point Status Update

An EV should be able of start charging immediately after it is plugged into a charger, therefore it is necessary to indicate to the user if this is possible before it plugs into a given ChP. So as to do this, each ChP displays its visual indicator as available only when the parking place is free and the electric status of the charger is set as available. The ChP is considered electrically available if a new connection is feasible at that charger. On the contrary, if the addition of a new load to the network could put in danger the normal operation of the grid, the ChP should be considered as not available as long as new connection cannot be supported.

Once the system has been initialized, it must perform an electrical availability test for all the ChP. Figure 4.1 displays the flow of this procedure. The objective of this test is to update the availability status of every ChP. To do so, the CCM simulates the connection and charge of a new EV at a given ChP without modifying the actual conditions of the network at the time of the test. The EV's connection is tested at a slow charge rate, which could be considered the worst case scenario in terms of power provided to the vehicle.

The test is performed for each one of the three phases one by one. At first, the ChP located at the farthest point along the feeder on the first phase is selected. This is considered as the worst

ChP where an EV can be charged on that phase. This is due to the increment of power losses and the voltage sensitivity at this point of the feeder, which depends on the distance between the transformer and the charger.

The test computes the total power consumed, the voltage drop and the current values on the network if the new vehicle was added to the grid and compares these values with the thresholds imposed by the network. If the constraints of the grid are respected, we conclude that the connection can be supported without any disruption on the service at this ChP and any other charger placed on the same phase, as long as the remaining chargers are located closer to the transformer. This means that, if an EV can be charged at the worst ChP available, then the connection could take place at any of the remaining chargers on the same phase without any problem, as the voltage drop and power losses will be less considerable on the ChP located closer to the transformer. The ChP connected on the same phase are set as available if no EVs are connected.

If the test proves that the new connection at the selected ChP would not respect the constraints of the system, it would be set as not available for the users and the grid. However, this does not mean that the rest of the chargers connected on the same phase would present the same status. Therefore, the CCM selects the next free charger available on the same phase, which now becomes the worst possible ChP that could accept a new EV for charging and the connection is test again. This process continues until there are no more ChP left to test on the phase that is explored or until a charger that can support a new connection is found. Once that all three phases of the feeder have been explored, the CCM displays to the user the ChP as available or not available.

System Update

Every time a load is added or removed from the feeder, it causes a difference in the registered levels of voltage, current and total consumed power in the network. Such variations take place for example when an EV starts or stops charging, or when a lamp is turned on or off. When this happens, the sensors deployed over the network identify the source of the variation and send the measures back to the CCM, which decides how to react to the change in the network. If necessary, the network balances the charge rates of the connected loads to keep the system operating within the limits of the grid. Then the values of voltage, current and power consumed at every point of the topology are updated. Figure 4.2 displays the flow of this procedure.

If the variation on the network levels is a result of an EV plugging into a charger displayed as available, the vehicle starts charging immediately. If there are more vehicles charging at the same time, the charging rate of the other vehicles should remain constant as to avoid delaying the charging process if the charge rate drops. In order to achieve this, it is necessary to balance the values assigned to the resistors representing the rest of the active chargers. If the value of the resistors is not recalculated, then the power delivered at every charger will be altered by the new connection. Once all the resistors have been balanced and all the connected EVs are charging at a constant rate, the status of the free ChP is updated by the procedure previously defined.

When the difference on the network is the result of an EV completing its charging process, the charger stops feeding power to that EV and it is free to go. For the CoTaSch approach, it is assumed that as soon as an EV is fully charged, it is unplugged and then leaves the ChP. Just like in the case of a new connection, the values of the resistors which represent the occupied chargers need to be balanced in order to maintain a constant power delivered to the EVs that remain

Electric Availability Test for EV chargers

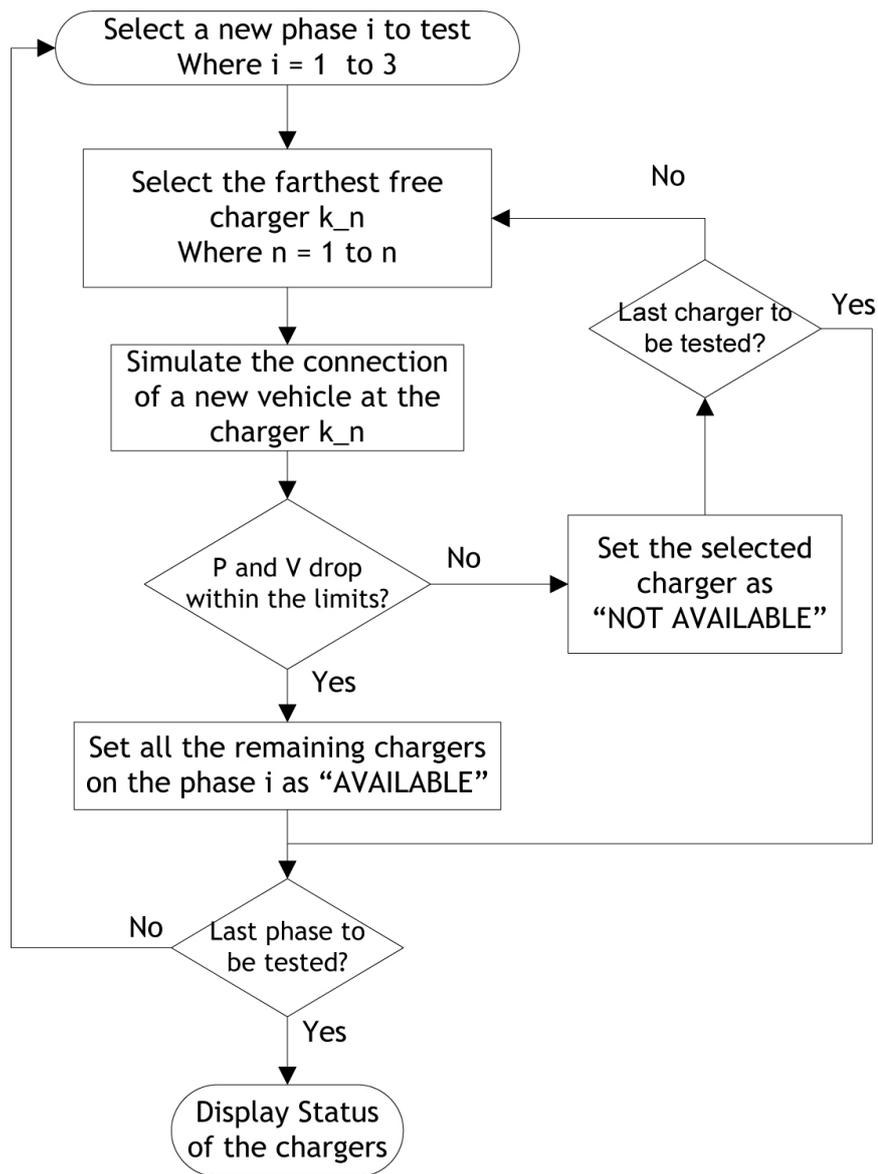


Figure 4.1 – Procedure for updating the electric availability status of a given charging point.

connected. Once the resistors have been balanced, the status of the unoccupied ChP is updated by simulating the connection of a new EV as it was formerly described.

Finally, if the variation in the consumed power is caused by some change on the lighting schedule as it occurs during the transition from the day to the night stage, all the EVs stop charging and these charging processes are put on hold. The new values of consumed power, current and drop voltage are obtained for the new conditions in the network. The availability status of the ChP with no vehicles connected is momentarily set as not available, then it is updated using the same procedure explained before. If the available power is sufficient for resuming all the charging operations at once and the constraints of the network are respected, then all EVs put on hold resume their charging procedure. On the contrary, the charging process will resume according to the policy established by the CCM for the CoTaSch approach, which corresponds to the well known Round Robin charging algorithm.

Round Robin Charging Algorithm

During the LHS, all the connected EVs stop charging and are put on hold. Once the LHS is over, the CCM updates the available power and if the conditions allow it, the charging process is resumed simultaneously for all the EVs. Nevertheless, it could happen that the available power for EV charging is not sufficient to resume all the charging process at once, but it is enough for taking at least one vehicle at a time. In such case, the CCM calculates the total available power for charging EVs and it starts charging one EV at a time at the highest possible charge rate following the well known Round Robin algorithm [7].

This strategy dispatches a task for a time slots and then switches to the next task. Time slots of 20 minutes were arbitrarily defined. During a time slot, the EV receives the highest possible charge rate. At the end of the time slot, the current EV stops charging and the following EV put on hold resumes its charging process. The duration of the slot only changes if the EV is fully charged before the end of the time slot. In such case, the EV stops charging and the next EV on hold restarts its charging process with a new 20 minutes slot. This process continues until all the EVs have been fully charged or until the power available is enough for charging all the remaining vehicles at the same time.

This strategy has been proposed to provide fairness in charging to the EVs put on hold. Therefore, the Round Robin algorithm is executed only after the end of the LHS and it should only last until all the EVs put on hold have been completely charged, or the available power is enough to resume all the charging sessions simultaneously. This normally occurs once the night stage is over and all the lamps are turned off.

EV Charging

The power delivered to the EVs depends on three factors: the available power at the network, the maximum charge rate supported by the charger and the maximum charge rate accepted according to the type of vehicle. When an EV is plugged into a ChP displayed as available, the charging process is triggered just after its connection. For this, the CCM simulates the new connection with the maximum charge rate that can be delivered to the vehicle. If the constraints of the network are respected, the EV starts charging at this rate. Otherwise, the CCM tests a lower charge rate

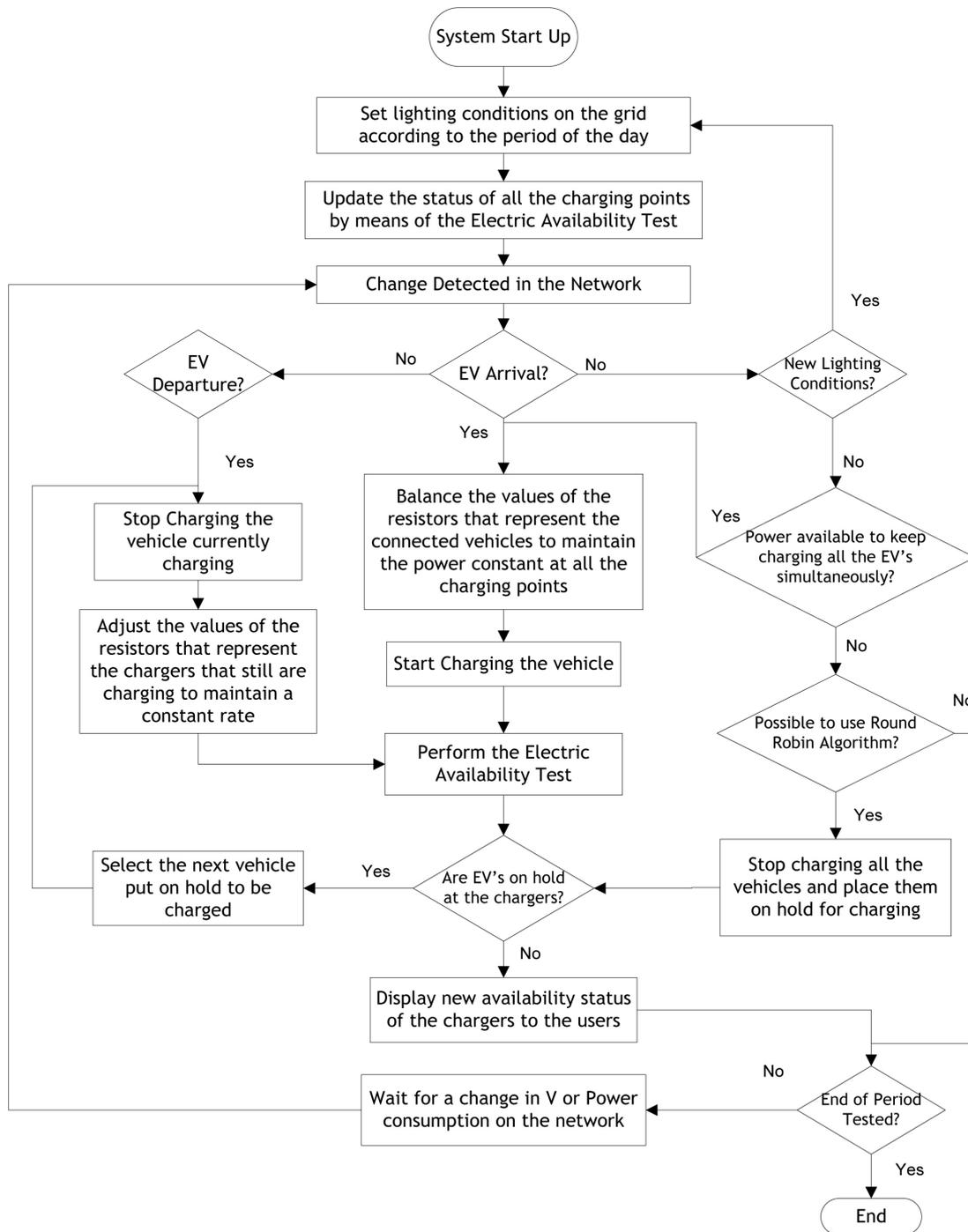


Figure 4.2 – Conservative task dispatch approach

until it is safe to start the charging process. It must be remembered that the availability test guarantees the possibility to charge the EV at least at the lowest charge rate supported at the ChP.

Once all the EVs connected are charging, the CCM updates the status of the ChP as it has been previously described. In this way, it is possible to know if the network is ready or not for the next charging request.

4.3 Experimental Setup for Conservative EV Charging

4.3.1 Electric Network Assumptions

The following section presents all the set of parameters and constraints considered for the normal operation of the electric network at the PLS. It was intended to simulate the operating constraints of the grid and the vehicles connected in the most similar real-life conditions. At the same time, it was not intended to limit the test of the model to only one type of electric network. Nevertheless, the parameters were based on available data, which corresponds to the PLS infrastructure and the EV market available in France for modeling purposes.

Electrical Network of Public Lighting Systems

The considered topology for the PLS is composed by a three phased feeder with 90 lamps connected to a 14.572 kVA transformer. Each lamp has a nominal power of 145 W and is located at 33.3 m from the previous one along the feeder. The lamps are equally distributed among the three phases and no dimming is allowed during the night stage. For the first stage of the CoTaSch approach, only 9 charging points are connected along the network. Initially the ChP can only provide the slow charge rate. In a second stage, two charge rates are considered, but exclusively for full EVs and hybrids (PHEV-2) with a considerable battery size. This means that an EV could be charged either at 1.4 kW or 3.3 kW, depending on network conditions, while PHEV-1 can only be charged at 1.4 kW.

In [54, 66, 67] authors mentioned that the location of the ChP could have an impact on the charging process of the vehicles. In order to properly analyze the impact of a certain ChP location on the voltage sensitivity, two different arrangements have been considered for the distribution of the chargers in the network.

- **Charging points distributed along the feeder** The first scenario considers 9 ChP, distributed through the feeder by groups of three. The first group is placed next to the three nearest light poles from the transformer, the second is placed at the set of lamps located in the middle of the feeder while the third one is connected to the lamps located at the end of the power line. Chargers are connected to the same phase as the lamp where they are attached.
- **Charging points placed near the transformer** The second case scenario places 9 ChP next to the first 9 lamps connected near the transformer. It is considered only one charger per lighting pole. For modeling purposes, it is assumed that the charger and the lamps are both connected to the same phase of the feeder to keep the loads balanced.

Stage	Summer	Winter	Power Consumption of the Lamps
Day light	05:00 - 21:43	08:43 - 16:43	OFF
LHS	21:43 - 22:13	16:43 - 17:13	Nominal + 15%
Early Night	22:13 - 00:00	17:13 - 00:00	Nominal
Late Night	00:00 - 04:00	00:00 - 04:00	Nominal
Early Morning	04:00 - 05:50	04:00 - 08:43	Nominal

Table 4.1 – Power consumption of the lamps on the PLS according to the daylight conditions for summer and winter scenarios

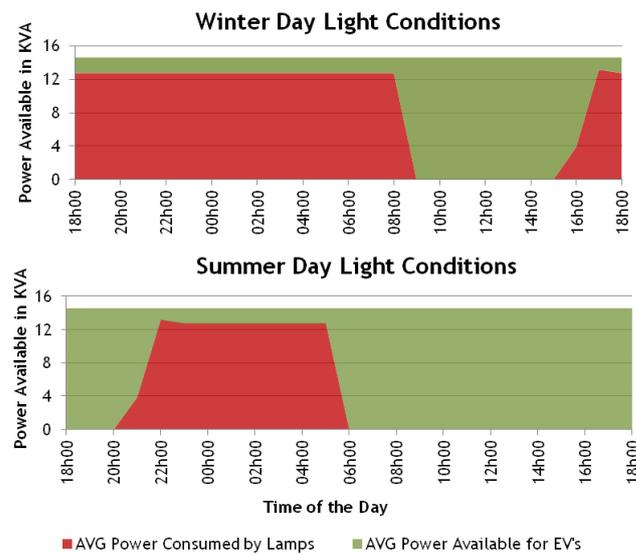


Figure 4.3 – Daily profile of power available on the network for EV charging at the PLS

Stages of the Public Lighting System

The PLS adapts the lamp’s lighting intensity according to the different day-light conditions along the year. As a result, the total power consumed by the lamps varies through the day. For this reason, the power available on the network for EV charging is not the same over a period of 24 hours. To better understand the PLS performance in different day-light conditions, we consider two scenarios for testing.

The first scenario corresponds to the network with summer day-light conditions while the second one to the day-light conditions during winter. We test the PLS network during 15 days for each scenario. The duration of each PLS lighting stage is detailed in Table 4.1. Sunset and sunrise hours are considered for the metropolitan region of Paris during the solstices of summer and winter in 2014 [12]

It must be noticed, that for the CoTaSch approach, there is no dimming of the lamps during the late night stage. Profiles of available power for EV charging depending on summer and winter day-light conditions from Table 4.1 are visually displayed in Figure 4.3.

Power Supply Control for EVs

When an EV i is connected at a ChP, the charger provides constant charge rate according to the type of vehicle. For this purpose, the CCM adjusts the charge rate of each cChP individually. The chargers are capable to provide slow, standard and high power charges. Nevertheless, for the CoTaSch approach, only the slow and standard power charges are considered at the charging points.

The SoC refers to the percentage of available energy in the battery [68]. The total time required to charge an EV will depend on: the size of the battery, its initial SoC, the charge rate provided by the ChP and the SoC requested at the time of departure which corresponds to a full charged battery for the CoTaSch approach. The battery SoC estimation at instant t during the charging process is given by

$$SoC(t) = SoC(t_0) + \frac{r_i(t) \times (t - t_0)}{C} \quad (4.3)$$

where $SoC(t)$ represents the state of charge of the battery at time t , $r_i(t)$ the charge rate at time t and C the battery capacity. It is assumed that the network can communicate with the vehicle in order to collect the initial SoC and the battery size.

For modeling purposes it is assumed that the charging process of the batteries is a linear model [62]. This allows to CCM to estimate the time required to complete the charge of a given vehicle with the present charging rate. This time, referred as Expected Time to End of Charge (ExpTiEoC) can be obtained at each time t as it is shown in Equation 4.4

$$ExpTiEoC(t) = t + \frac{SoC_{req} - SoC(t)}{r_i(t) \times (t - t_0)} \quad (4.4)$$

where SoC_{req} represents the requested state of charge for the battery at the time of departure.

When the estimated time to complete a charging process is reached, the CCM updates the SoC of the EV to verify that the tasks has been completed. However, in order to avoid any possible damages to the battery caused by an overcharge, the CCM periodically updates the SoC of the connected EVs and it adjusts the ExpTiEoC if necessary.

4.3.2 Evaluation Constraints

Type of Vehicles and Battery Size

The presence of EVs in the market has been growing during the last couple of years and it is expected to maintain this trend in the years to come. For modeling purposes, we have considered as the base of our study the distribution of EVs in France in 2013 [9]. The battery size for all three groups was taken from the models with more significative presence in the market at the time of the study [8] [35] [14]. It is assumed that all EVs have Li-ion batteries and they are modeled as constant power loads [62].

For modeling purposes, a mix of EVs and PHEVs was considered based on the sales distribution of EVs in France in [9]. Due to the current diversity of models and battery sizes available in the market, we have decided to divide the vehicles in three main groups: PHEV-1 for Plug-in Hybrids with small a battery capacity, PHEV-2 for Hybrid with medium and large battery capacity and

Arrival Group	μ	σ (in hours)	EV Arrivals
AM (μ_1, σ_1)	09h00	0.42	30%
MD (μ_2, σ_2)	14h00	3.4	30%
PM (μ_3, σ_3)	19h30	0.85	40%

Table 4.2 – Distribution of time of arrival for the vehicles during a normal day according to their group.

EVs for the set of full electric vehicles. Details of the average size of the battery and maximum supported charge rate are presented in Table 4.3.

Distribution of Vehicles

The current penetration level of EVs in the market is still low, however the potential expansion of this market should be considered for the development of the charging infrastructure. Therefore, three different penetration levels of EVs are considered for the CoTaSch approach in this thesis: low, medium and high penetration rates which are translated in sets of 10, 40 and 70 EVs arriving per day at a set of ChP connected to the same transformer. Each EV will select a given ChP and if the conditions allow it, the battery will start charging until the it is fully charged. For modeling purposes, a battery is considered fully charged when the SoC reaches 80% of its capacity.

The EVs are distributed in the following proportion: 84% of EVs, 7% of PHEV-1 and 9% of PHEV-2. This distribution is applied to the total number of vehicles that request a recharge to the network per day.

Aggregation of a Fleet of Vehicles

The EV's time of arrival to the feeder where the ChP are located is set according to the time of the day when vehicles are more suitable to request a charge of battery [68]. For modeling purposes three groups are considered. The first one considers a time of arrival around 09h00 (*Group AM*) and is conformed by 30% of the EVs. This group is based on scheduled trips during the morning, which could be considered a home-to-work trip. The second set of EVs, with 30% is referred as (*Group MD*) and has a time of arrival around 14h00 to the ChP. This group looks at lunch time scheduled trips. Finally, the third group has a time of arrival around 19h30 to the ChP, it is referred as (*Group PM*) and it refers to most of the scheduled trips referred as work-to-home transfers.

The time of arrival of all the EVs is randomly and normally distributed during the three periods previously defined as it is presented in Table 4.2. For the CoTaSch approach we contemplate that the time of departure of an EV corresponds to moment when the EV's battery has been fully charged.

4.3.3 EV Selection of a Charging Point

Voltage sensitivity of the electric network could be affected by the position of the loads over the feeder [54, 65, 66]. As part of this study, the CoTaSch considers two different placements for the

Type of Vehicle	Average Battery Size (kWh)	Allowed Charge Rate (kW)
EV	22	1.4 or 3.3
PHEV - 1	6	1.4
PHEV - 2	16	1.4 or 3.3

Table 4.3 – Battery capacity considered for each type of vehicle and the charge rates allowed by the network within the CoTaSch approach.

ChP along the feeder. For the first topology, all the ChP are connected in the proximity of the transformer, while in the second topology, ChPs are distributed in three different groups along the feeder. At the same time, the space between ChPs could be another factor to increase the network's voltage sensitivity. For this reason, we have considered three different scenarios in which the EVs select the ChP at their arrival to the feeder.

- **Closest Charger First (CCF)** When an EV arrives at the set of charging points, it is assumed that it will be directed by the CCM towards the closest available charger from the transformer.
- **Farthest Charger First (FCF)** At the time of arrival to the set of charging points, EVs are always connected at the farthest available ChP on the feeder, which could be considered as the worst possible position to connect a vehicle.
- **Random Charger Selection (RCS)** The last scenario considers the most realistic case, where users randomly choose the ChP on the feeder without any influence from the CCM.

State of Charge and Charging Rates

In CoTaSch, the initial SoC is set at 20% for all EVs at time of arrival to the ChP. The requested SoC at time of departure is set at 80% by default for all EVs, which is considered a full charge. Charging at 80% is not considered in order to avoid any damages on the batteries. For modeling purposes, the charger delivers a constant power to the vehicle. A summary of battery sizes and charge rates available for each type of vehicle [8, 14, 35] in the CoTaSch approach are displayed in Table 4.3.

4.4 Performance Metrics

We introduced in the previous section a series of constraints imposed by the PLS to assure the availability of EV charging services in the network. A set of different scenarios was established for testing this particular network in different conditions. The whole charging system performance should be measured by a group of metrics which should be valid for all the test scenarios. In this section we introduce five metrics for the analysis of the information obtained in our simulations.

4.4.1 Acceptance Rate of Vehicles

When an **EV** arrives at a set of charging points, it is accepted for charging only under two conditions. The first condition is that a **ChP** should be free of vehicles, as only one **EV** is allowed to charge per **ChP** at a time. The second condition is that the selected **ChP** should be electrically available. Both conditions must be fulfilled, otherwise the **EV** should be rejected by the **CSO**.

The goal of this metric is to obtain the percentage of rejected **EVs** for charging from the total amount of **EVs** that arrived to the set of **ChP** during the simulations. This metric is important to understand if there is a particular factor that could limit the number of **EVs** accepted for charging. The value of this metric is expressed in percentage.

4.4.2 Average Transmission and Distribution Power Losses

Power losses are estimated from the difference between the power produced and the power delivered to the lamps and customers through the charging points. These losses constitute at the same time the transmission and distribution losses, hereby simply referred as distribution losses. In the context of dedicated charging infrastructures, the power losses caused by the topology of the network can be put aside in some study cases and they are often ignored in the literature [53]. This is due to the short distances that separate the power source from the charging points which does not represent a big limitation of the system in terms of losses.

However, in the context of a shared **EV** charging infrastructure, the distance between the transformer and the **ChPs** as well as the number of loads connected to the feeder could increase considerably. When this happens, the total amount of power losses caused by the cables is accumulated and the amount of losses become more significant for the whole network. It is of our particular interest to explore the impact of the distribution losses on the **PLS** not only when the vehicles are charged at different distances from the transformer, but when they follow a different order in their connection. If it proves to have a considerable impact in the amount of remaining power for **EV** charging, it could lead to a better design and planning of the placement of **ChPs**.

It is possible to calculate the current, voltage and power values at each point in the network at any moment thanks to the sensors connected. As it has been previously presented, every transmission line is represented as a branch in our test bed. Consequently, it is possible for us to calculate the values of voltage, current and power at any branch. This allows us to periodically calculate the transmission power losses. When the instantaneous power obtained is integrated over the tested period of time, it is possible to calculate the total amount of energy that has been lost in the transmission lines. Consequently, it is possible to obtain the average amount of energy lost in the transmission lines per hour.

4.4.3 Dispatched Vs. Demanded Energy Ratio

The energy demanded corresponds to the total requested energy by each accepted **EV** at its arrival to the **ChP**, while the energy dispatched denotes the total amount of energy delivered to the **EV**, whether it is fully charged or not at the time of departure. This metric is obtained by comparing the difference between the required **SoC** at time of departure and the actual **SoC** of each **EV** leaving the **ChP**. The amount of energy will differ for each **EV** according to its battery capacity.

This metric will only help for validation of the results obtained, as the amount of dispatched and required energy should match if all the vehicles leave their **ChP** only once they have been fully charged, as it is intended by the **CoTaSch** approach.

4.4.4 Average Unserved Energy

For modeling purposes we consider that the **DSO** buys to the Electricity Supply Retailer (**ESR**) sufficient energy to operate the **PLS** electric network and provide **EV** charging services at its full capacity. Therefore, it is of the interest of the **DSO** to make the most of the deployed infrastructure and the available energy to distribute it in the most efficient way. The Average Unserved Energy refers to the energy that could be potentially used for **EV** charging but it is neither used for **EV** charging nor for lighting the lamps due to different factors. This could happen for example, when all the charging points of the network are electrically available but there are no **EVs** connected.

At the end of the day, if all the unserved energy is added, the total amount of energy that could have served for charging additional **EVs** could become quite considerable. Such unserved energy could be potentially stocked in storage systems, like super capacitors or batteries for further use. The value of this metric is expressed in kWh/h.

4.4.5 Quality of Service and **SoC** at Time of Departure

As it has been previously stated, the first stage of this thesis was primarily focused on the feasibility of proposing **EV** charging services over the **PLS**. Therefore, the possibility of offering a minimum level of **QoS** to the customers was not originally considered. The **QoS** is proposed following a best effort perspective. It is considered as best effort due to the fact that for the policy adopted, it is preferred to limit the number of accepted **EVs** according to the available resources, but assuring a full charge for the accepted vehicles, rather than accepting more **EVs** that the network can handle putting at risk its operation. Additionally, as there are no constraints in terms of a maximum time to complete a task, the process of fully charging a battery could be really long.

When an **EV** is accepted at a **ChP**, it is accepted because it is assumed that it will be charged. At first glance, this must not present any issues to the network within the **CoTaSch** approach. This is because there are no constraints from the user in terms of time to complete the task. However, for a future benchmark, we have measured the number of **EVs** that have been fully charged at time of departure from the total number of accepted **EVs**. This value will be referred as the percentage of fully charged vehicles.

Following the same line of thought, the **SoC** is measured at time of departure for all accepted **EVs**. Then, the percentage of energy delivered is obtained and a level of charge is assigned according to Table 4.4. This table considers seven different levels of charge. It is important to mention that the percentage is based on the total amount of energy requested, and not the **SoC** of the battery.

Charge Level	Percentage of Energy Requested Fulfilled at time of departure
No Charge	<1%
Weak Charge	1 % to 20 %
Low Charge	21 % to 40 %
Moderate Charge	41 % to 60 %
Major Charge	61 % to 80 %
Substantial Charge	81 % to 99 %
Full Charge	100%

Table 4.4 – Percentage of served energy to the battery from the initial energy request.

4.5 Numerical Results

As previously presented, in order to demonstrate the feasibility of the network, the PLS has to be tested under different conditions. A summary of all tested scenarios for the Conservative Task Scheduling approach (CoTaSch) is presented in Table 4.5.

Day-light conditions	Summer scenario (no dimming of lamps) Winter scenario (no dimming of lamps)
Distribution of chargers	Close to the transformer Distributed along the feeder
Selection of charger	Closest Charger First (CCF) Farthest Charger First (FCF) Random Charger Selection (RCS)
EV Penetration Rates	Low - 10 EVs/Day Medium - 40 EVs/Day High - 70 EVs/Day
EV Charge Rates Available	Slow Charge only (1.4 kW) Slow & Standard Charge (1.4 & 3.3 kW)
EV Scheduling Policy	Conservative First Come First Served (CFCFS)

Table 4.5 – Summary of network conditions and scenarios considered for the Conservative Task Scheduling approach (CoTaSch).

4.5.1 Total Number of Accepted Vehicles

We observed two main factors that have an impact on the total number of EVs accepted. These factors are the daily EV penetration rate and the season of the year. Figures 4.4a, 4.4b and 4.4c show the results of our simulations.

- **Number of Vehicles:** It was observed that the number of accepted EVs for charging is related to the number of arrivals at the charging station. As expected, with a low rate of EVs arrivals the probability of finding an available ChP is higher compared to the medium and high penetration rates. Once the network has reached the maximum number of EVs

that can be charged simultaneously without putting at risk the operation of the network, the remaining chargers are blocked and the EVs are rejected. Therefore, the difference between medium and high penetration rates is less remarkable, compared to the variation between low and medium penetration rates.

- **Season of the Year:** As mentioned before, the available power for EV charging at the network is highly limited by the power consumed by the lamps. In summer, as there is less power demanded by the lamps, more power is available for EV charging. This has a huge impact on the number of vehicles accepted for charging as it can be observed for example in Figure 4.4a, specially at a low penetration rate of EV arrivals. For example, for 10EVs arriving in summer only 5% from the total is rejected. On the contrary, the percentage of rejected EVs rises up to 43% in winter.

The selection of the ChP, according to its location over the feeder has a lower impact on the number of accepted vehicles than it was expected. We observed a slightly improvement in the rejection rate when the ChP selected is placed closer to the transformer compared to the farthest ChP is selected first. Figures 4.4a, 4.4b and 4.4c present the results obtained.

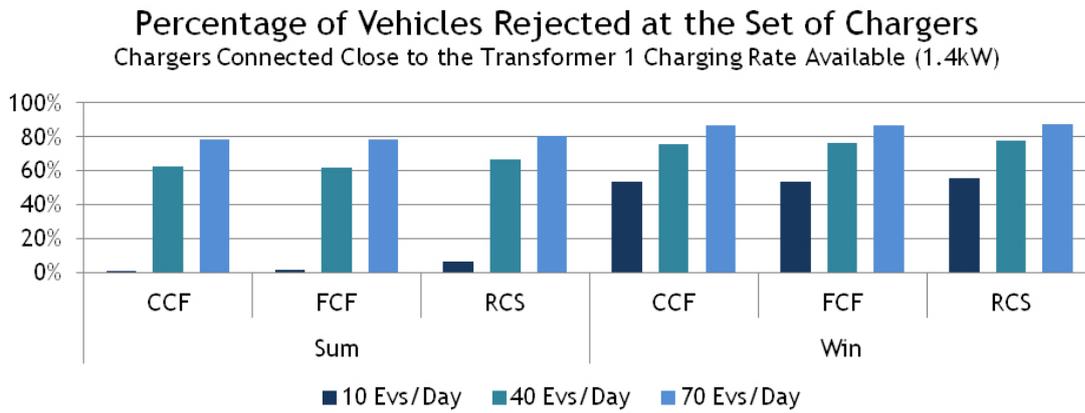
An interesting fact is that when the ChP are distributed along the feeder, instead of being placed near the transformer, the rejection rate slightly changes for medium and high levels of EV arrivals. This is partially due to the fact that during the night stage, the ChPs placed at the end of the feeder are not available, because of the potential voltage drop registered in case of a new connection, which would exceed the limits of the network, therefore the most distant ChPs are displayed as not available. In consequence, EVs are frequently directed to the chargers connected between the middle of the feeder and the proximity of the transformer. This phenomenon appears even when the first selected ChP should be the most distant one. We found as well that the voltage drops at the network gets closer to the operational threshold when an EV is connected at the most remote ChP of the feeder. This happens as well during the day stage, which could reduce the number of ChPs available and in consequence the number of accepted EVs.

4.5.2 Average Transmission and Distribution Power Losses

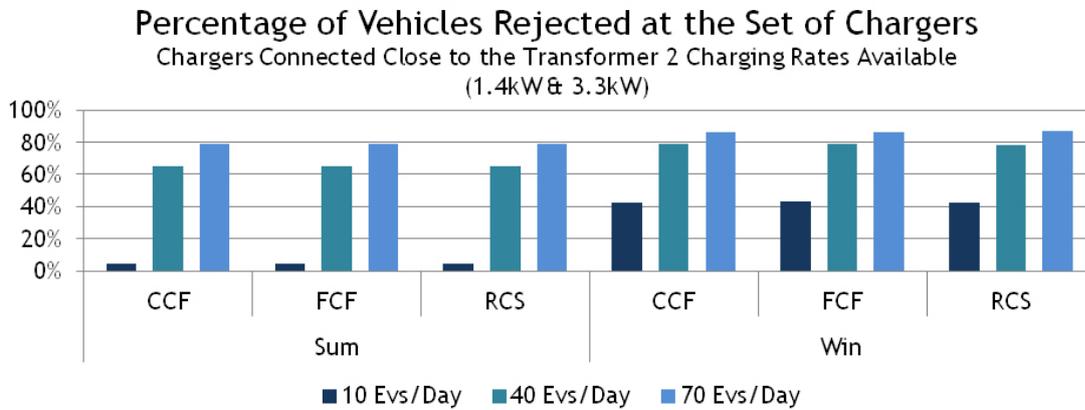
As previously mentioned, our simulation model allows us to calculate the total amount of energy that has been lost at the transmission lines during the operation of the network. With this information, it is possible to obtain the average amount of energy lost in the transmission lines per hour for all the different scenarios and compare them as shown in Figure 4.5. We observe how the performance of the network is only slightly affected by the position of the ChP or the order in which EVs are connected. On the contrary, the distribution losses at the grid increases as a consequence of two main conditions.

- **Location of the Loads**

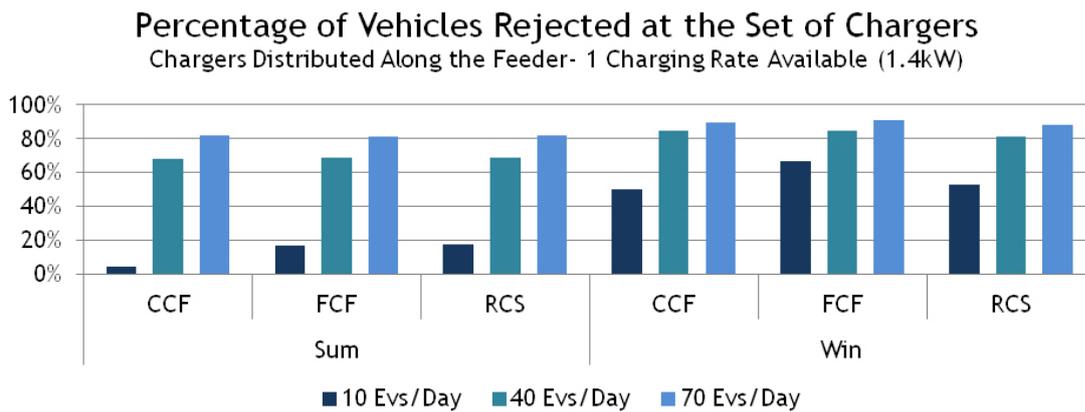
We observed that for the most part of the simulated scenarios, the losses registered at the network were always higher when EVs were directed towards the ChPs placed at the end of the line to be charged than when they were directed towards the chargers connected closer to the transformer. This result was expected, as it is highly related to the feeder effect previously mentioned, where the voltage sensitivity is higher as the distance from the power source increases.



(a) Percentage of rejected EVs when chargers are connected near to the transformer and only one charge rate is available (1.4 kW).



(b) Percentage of rejected EVs when chargers are connected near to the transformer and two charge rates are available (1.4 kW or 3.3 kW).



(c) Percentage of rejected EVs when chargers are distributed along the feeder and only one charge rate is available (1.4 kW).

Figure 4.4 – Rejection rate of vehicles within CFCFS.

- **Season of the year**

It has to be noticed that the distribution losses are not only higher in winter than in summer,

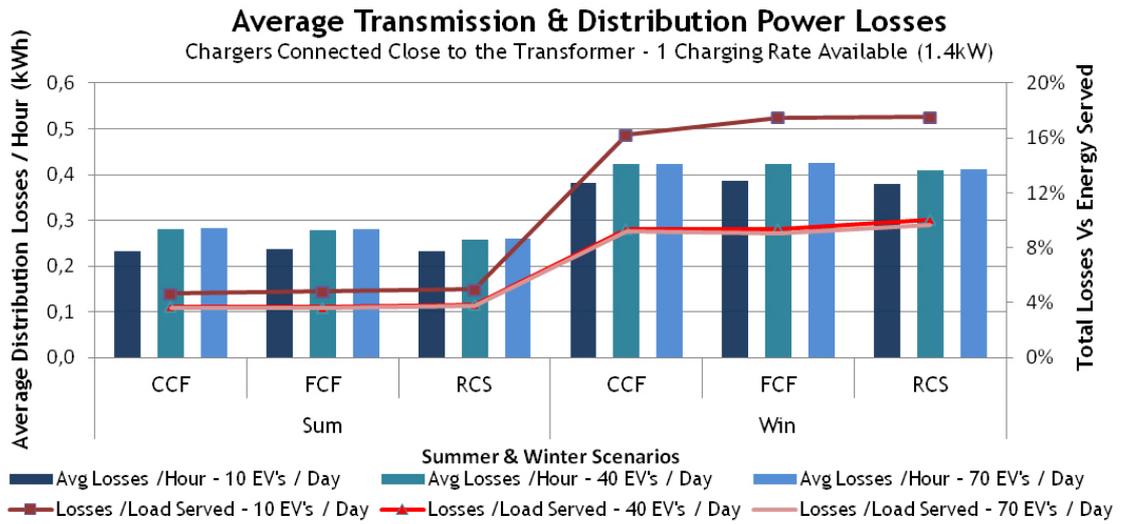


Figure 4.5 – Average transmission and distribution losses and the relation between the total energy losses Vs the total amount of served energy to the loads, considering only one charge rate available (1.4kW) and all the chargers connected close to the transformer.

but at the same time the total energy distributed to the loads is lower. We observed these results for all the tested scenarios, independently of the penetration rate taken into account, the available charge rates available, the location of the chargers or the order in which EVs were connected.

It can be observed, that the amount of registered losses increased as the penetration rate of EVs increased does. This was expected, as a higher demand of energy from the accepted EVs will result in more energy distributed and higher amounts of power losses on the transmission lines. The importance of the power losses can be presented by means of an auxiliary metric, which we call losses per energy served. This metric considers the total amount of energy lost in the transmission and distribution lines, with respect to the total amount of energy that was distributed to the connected EVs.

At the principal ordinate axis is displayed the amount of losses per hour in kWh and presented in columns, while the lines on the secondary axis shows the percentage of losses Vs. the total dispatched energy. In Figure 4.5 we can observe that the ratio of losses per served energy is considerably higher for a penetration of 10 EVs per day than for the rest. This is because the losses generated by the operation of the lamps is the same for the three penetration rates. However, as the amount of energy dispatched to the low penetration rate scenario is lower than for the other two, the proportion of losses per served loads will be higher as it is observed.

4.5.3 Dispatched Vs. Demanded Energy Ratio

This metric compares the total dispatched energy from the original amount of energy requested by the EVs. It must be noted, that it is considered as a validation metric for the CoTaSch approach, as all EVs leave the ChP only after they have been completely charged. Therefore, the amount of dispatched energy should match the amount of energy demanded by the loads. However, as it is shown in Figure 4.6 this is not the case. This is due to the EVs that have not finished their

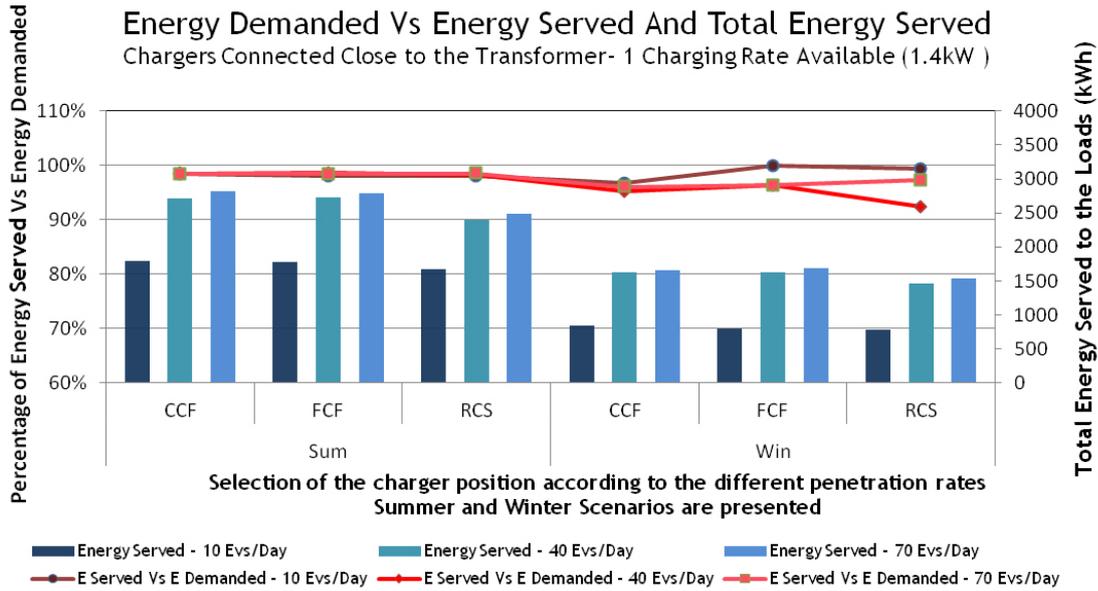


Figure 4.6 – Total served energy (in kWh) and percentage of served energy from the total demanded energy by the loads considering only one charge rate available (1.4 kW) and all chargers connected near the transformer.

charging process at the time that the simulation ended. If these EVs were not considered, the total amount of served energy would effectively match the total requested energy from the loads. As expected, the results are similar for all tested scenarios, disregarding the penetration rate of EV arrivals, the season of the year, the number of available charge rates or the distribution of chargers through the feeder.

As it was previously mentioned, the season of the year, combined with the penetration rates of EV arrivals limits the number of vehicles that can be accepted for charging. Consequently, the amount of dispatched energy during summer is considerably higher than the one dispatched during the winter, when fewer energy resources for EV charging are available and more EVs are accepted for charging. This is reflected in Figure 4.6, where the amount of energy delivered to the EVs in the summer nearly doubles the served energy during winter.

4.5.4 Average Unserved Energy

We consider that the DSO wants to make the most of the EVSE deployed over the PLS in terms of distributed energy and exploited resources. Therefore, it is important to understand if the network operates at its maximum capacity or if it could be possible to increase the number of ChP to expand the EV charging services to more users. In Figure 4.7 is possible to observe the average energy accumulated per hour that has not been consumed either by the lamps nor the EVs. The red line represents the minimum charge rate required for charging a vehicle, which means that if there is more energy available than the minimum required for a single charge, it could be possible to use the remaining energy or to stock it for future use.

We observed that in summer with a low penetration rate of vehicles, the unserved energy could

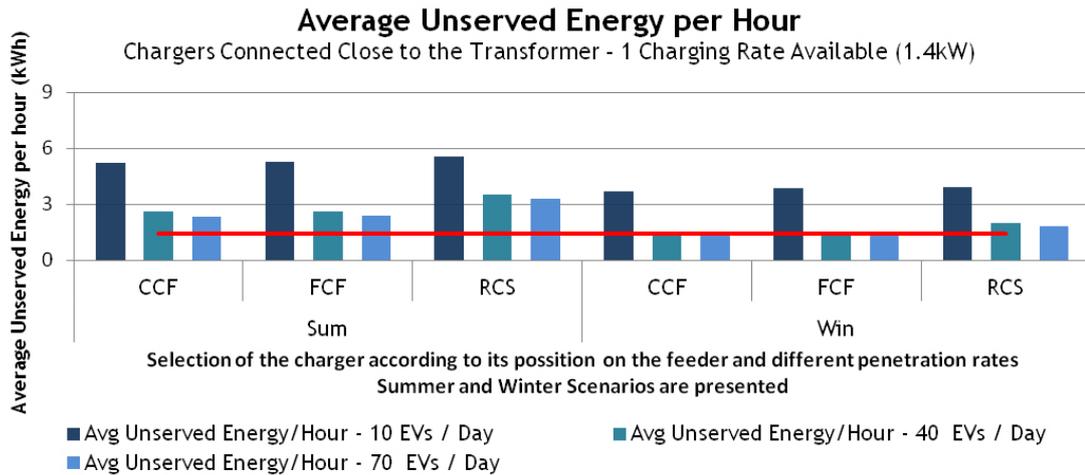


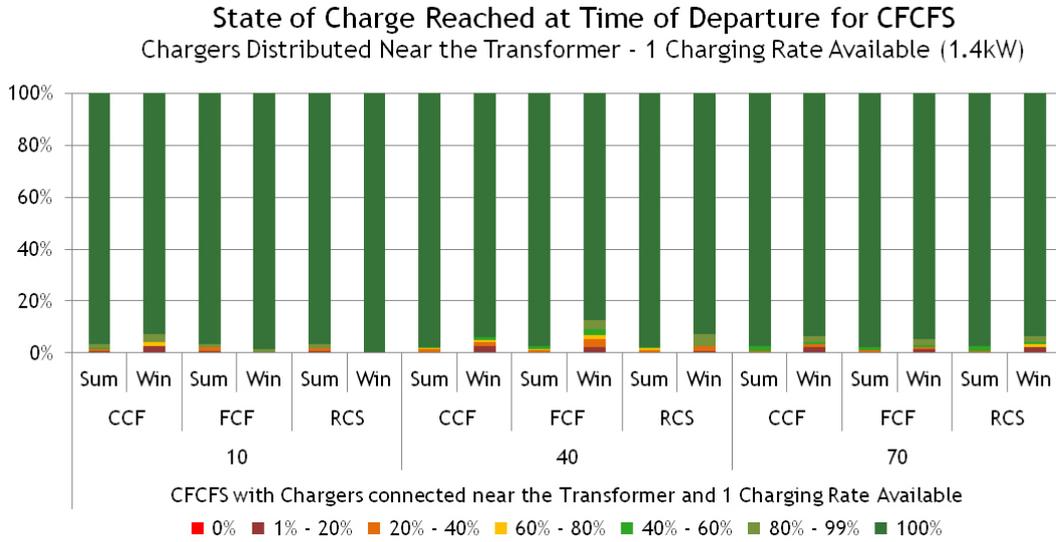
Figure 4.7 – Average energy unserved per hour at the network when chargers are connected near the transformer and only one charge rate is available (1.4 kW).

be potentially enough to charge at least three EVs at a slow charging rate (1.4 kW). Similarly, during the winter this amount of energy would be sufficient to charge at least two more EVs at the same charge rate. These results could lead us to think that the best solution to improve the performance of the network and to make the most of the available energy, would be to increase the number of ChP connected. However, if the number of ChP is only increased without a proper management of the loads, the EVSE deployed will not be fully exploited, specially during the winter at medium and high penetration rates, as the network is working near its full capacity and it will not be possible to charge at least one extra EV using the slow charge rate.

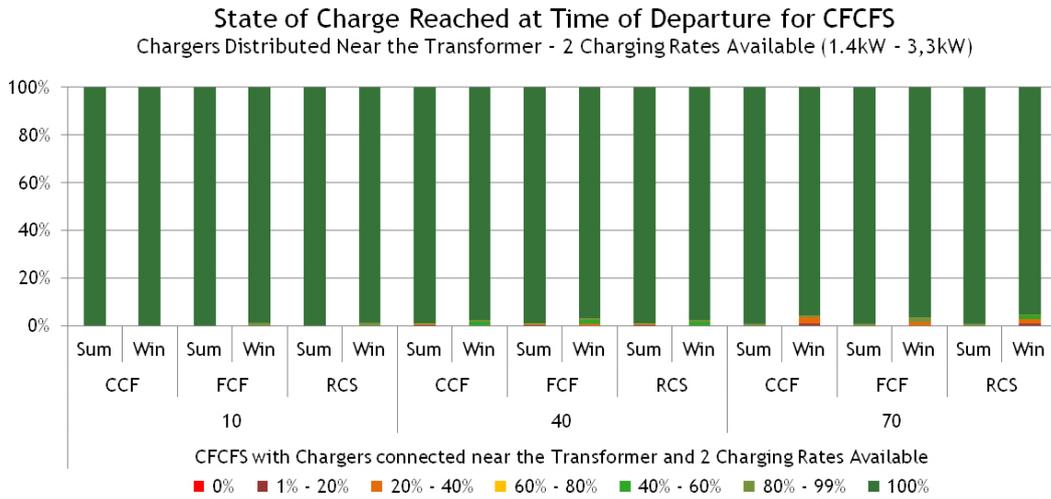
4.5.5 Quality of Service and SoC at Time of Departure

This metric is presented as a validation process for the CoTaSch approach as all accepted EVs should leave the ChP fully charged. We observe in Figures 4.8a and 4.8b the level of charge reached for the EVs at time of departure. As expected, all EVs reached the requested SoC of 80% when they left the ChP independently of the penetration rate or day-light conditions. However, we noticed during the simulations that the total time required to complete a recharge could take more time for some EVs than for others. This phenomenon is more evident when the ChP are distributed along the feeder instead of being placed at the proximity of the charger. It is due to the fact that some EVs were accepted for charging at the three farthest ChP just before the LHS, which meant that they could not be charged during the night period and they had to wait until the following day to resume their charging processes. In the end, those EVs were fully charged but the time required was too long.

Complete results obtained during the simulation are available on the annex A.2.1. In Tables A.2, A.3 and A.4 it is possible to observe that some of the EVs display a charged level slightly inferior to 100% at the time of departure. This is because those particular EVs were still charging at the time that the simulation period finished. This means that one of the principal goals of the CoTaSch approach was achieved, providing a full charge to all accepted EVs for charging.



(a) SoC reached at Time of Departure for 1 charging rate available (1.4 kW) and all the chargers connected near the transformer.



(b) SoC reached at Time of Departure for 2 charging rates available (1.4 kW or 3.3 kW) and all the chargers connected near the transformer.

Figure 4.8 – Level of fulfillment for the charge process at time of departure.

4.6 Summary

In this chapter we introduced a conservative approach to integrate EV charging services to the PLS network known as CoTaSch. We have presented the conditions under which the PLS operates and the constraints imposed to guarantee the normal operation of lighting service. For this first approach, a conservative charging strategy is presented, which is based on the well known "First Come First Served" algorithm. This strategy is referred as CFCFS, it is a conservative charging strategy because it should only accept an EV if it can start charging immediately after its connection only the constraints of the electric network are respected. These constraints are a minimum voltage drop and the available power on the network that cannot be exceeded. To achieve that, the electric network has to simulate the arrival of a new EV before it actually happens and decide if the charge could be supported. If it is not possible, the network limits the connection of new EVs until the conditions are optimal. At this stage, if an EV is accepted at a charging spot, it should start charging immediately after its arrival and it will not leave the charger until the task has been completed.

As the lighting conditions for the lighting network change along the year, the model has been simulated under two different day-light conditions for the PLS, which are the winter and summer case scenarios. At the same time, in order to test the effects of placing the chargers at different locations through the feeder, the model has been tested for different topology configurations with variable distances from the transformer and distributions through the feeder. Finally, different penetration rates of EVs arriving at have been simulated while testing the selection of the ChP in different order, from the closest charger to the transformer first, at a random order or starting by the farthest charger first.

The results of all the simulated scenarios have been compared by means of five different metrics hereby introduced: the acceptance rate of vehicles, the average transmission and distribution power losses, the average unserved energy, the QoS proposed by the network which is based on the SoC reached at time of departure and finally, the percentage of demanded energy from the total amount of energy requested by the EVs.

We can conclude that the integration of lighting and EV charging services over the PLS is feasible for all the scenarios that we have tested which were based in real life conditions. However, the performance of the network could be limited by the season of the year combined with the penetration rate of vehicles. It was possible to provide a full charge to all EVs accepted for charging as it was intended by the CoTaSch approach. Nevertheless, it should be taken into account that there were no constraints in terms of time to complete the task. As a result, we have found some process that could extend for really long periods of time before reaching a full charge, specially when the chargers were distributed along the feeder.

The continuous evolution of the EV market demands a better management of the charging processes, in order to use the resources available in a more efficient way, not only in terms of energy but in terms of infrastructure as well. This could help to extend the EV charging services to more users, which leads us to the following chapter, where we present a set of on-line scheduling strategies which will allow to respond to more charging requests.

On-Line Scheduling Strategies for Electric Vehicle Charging

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5.1 Introduction

In the previous chapter we demonstrated the feasibility of the architecture proposed for EV charging over the PLS electric network. Several parameters were considered as to create different test scenarios for the CoTaSch approach.

The charging strategy proposed, referred as CFCFS, is a conservative approach inspired by the dumb charging strategy but with several changes in order to fit the constraints of the PLS. This strategy proved to be a good starting point, as the main objective of the CoTaSch approach was accomplished and it was possible to charge several EVs without any disruption on the lighting services. However, it was observed that the network's performance could be improved with a smarter management of the connected loads. For this, in this chapter we explore some of the most well known on-line scheduling algorithms and adapt them for EV charging over the PLS.

In this chapter we present a new approach referred as FlexTaSch, which has more flexibility for treating the EV charging processes. It is focused on the proper use of the network's available power and the expansion of the EV charging service to more users. We will show how a tradeoff between the number of users that could have access to the charging network and the QoS provided by the system exists.

5.2 The Flexible Scheduling Task Model - FlexTaSch

We consider that the charging habits of EV users will evolve in the years to come. They will transform from the current habits employed to fuel an internal combustion vehicle to be more similar to the recharging habits adopted by smartphone users. Nowadays, tank fueling an Internal Combustion Vehicle (ICV) is done within a couple of minutes and it can be performed when it is actually needed. However, current limitations in terms of time of charge and disposition of charging stations for EVs have already demonstrated that most part of EV users tend to charge whenever is possible [36]. Besides, the majority of EV owners avoid to drain the battery storage under a certain limit, charging the vehicle as soon as the opportunity is presented, following the same charging pattern of smartphone users.

This change in users' habits for recharging their EV batteries will certainly be reflected on the use of the charging infrastructure. In some cases, EV users will not require a full charged battery but only a certain amount of energy to guarantee the next trip without the need of an intermediate charge. As EV users will charge whenever is possible, we can expect that the recharge of vehicles will take place during some other user's activities, such like the time spent at a shopping mall or at work. Therefore, the time available for charging could be in some cases shorter than the actual time needed to fully charge the battery of their EVs.

We assume that the time of arrival and departure of a given EV is not known by the CSO of a public charging station until the EV actually reaches the ChP. As a consequence, the recharge of an EV cannot be planned in advance, like in the case of fleet charging. Therefore, the CCM of the network has to find the best strategy to serve the connected EVs. A similarity is found between the scheduling of charging processes used for EV charging and the strategies used by some CPU processors for task scheduling when the jobs requested need to be treated in real time without any

knowledge of future requests [7,47]. In section 5.2.4 we present the adaptation of some well known on-line scheduling policies to the EV charging system and the analysis of the results obtained via simulation.

5.2.1 A Less Conservative Approach to Have More Flexible Tasks

Task scheduling was based on real-time information for CFCFS introduced in Chapter 4, where the CCM had no previous knowledge of the future EV arrivals. As a result, it was not possible to know if a new EV could start its charging process a couple of minutes later, instead of being rejected at its time of arrival if the conditions of the network were not ideal. This case scenario was constantly observed on the conservative approach CoTaSch, where the infrastructure and power resources were not fully exploited. This is due to the lack of flexibility for accepting new tasks and charging the loads previously connected, which led to a limited number of accepted EVs at the charging points, and a considerable amount of energy that was not consumed either by lamps nor by connected EVs. It should be reminded that for the CoTaSch approach, tasks are not preemptive and they should be dispatched immediately after their connection to the ChP if the new connection does not cause a disruption in the electric network.

Therefore, for improving the energy distribution through the network, it is necessary to make the tasks more flexible by considering them preemptive and deferrable based on the information collected from the user. As a result, the time of departure from the ChP and the required final SoC must be added to the task modeling. The new FlexTaSch approach does not constrain the task to start charging immediately after their connection to the ChP. It must be mentioned that lighting services remain the primary service of the network. Therefore, the operational constraints are maintained and must be verified before starting a new charging process. If a task cannot be dispatched without putting at risk the operation of the network, it will simply not be dispatched by the CSO.

Finally, the FlexTaSch approach considers that an EV does not leave the ChP once the task has been completed, but at the time of departure originally set by the user. As a consequence, it could happen that some EVs remain connected at the ChP once the task has been completed, while some other EVs leave the ChP with a lower amount of energy dispatched than their original energy request to the CCM. This last scenario could happen when the tasks are left at the bottom of the scheduler because new tasks with higher priorities are dispatched first.

5.2.2 Loads Modeled as Tasks

In Chapter 4 we explained how the EVs connected to the PLS electrical network can be considered as deferrable loads and treated as tasks. However, within the CoTaSch approach tasks were not preemptive, the energy requirement was the same for all EVs and they could only be deferrable after the LHS and during the night stage. Additionally, all EVs arrived with the same SoC (20%) and required a full charge at time of departure (SoC = 80%). Finally, EVs were not allowed to leave the ChP until the charge was completed and therefore the time of departure was not defined by the user.

Within the new FlexTaSch approach, an EV i poses a service demand S_i to the CSO, which is parameterized by $(ta_i, td_i, SoC_i(ta_i), SoC_i(td_i))$. Where ta_i is the time of arrival of the EV i , td_i

refers to its departure time, $SoC_i(ta_i)$ and $SoC_i(td_i)$ are the SoC of the battery at time of arrival and time of departure respectively. From the information provided on the service demand, the CCM estimates the energy requirement Er_i of the task T_i , which indicates the amount of energy demanded by the EV. The energy requirement is calculated at time of arrival ta_i based on the battery capacity C_i of the vehicle i as shown in Equation(5.1).

$$Er_i(ta_i) = [SoC_i(td_i) - SoC_i(ta_i)] \times C_i \quad (5.1)$$

As time passes by and the batteries are charged, the SoC of the battery evolves and the gap between the current SoC and the SoC demanded by the user to fulfill its energy requirement Er_i is reduced. The energy shortfall Es_i of the task T_i at time t indicates the amount of energy left to complete the energy requirement of the task before its time of departure td_i . It is given by Equation 5.2.

$$Es_i(t) = [SoC_i(td_i) - SoC_i(t)] \times C_i \quad (5.2)$$

where $SoC_i(t)$ corresponds to the battery SoC at time t . We note that Es_i is updated by the system each time a new EV arrives, when a task reaches its requested SoC or when the conditions on the PLS electrical network change. Thus a task T_i is characterized by (ta_i, td_i, Er_i, Es_i) .

Effective Charging Capacity

We refer as the charge rate $r_i(t)$, to the effective charging capacity that is possible to deliver by the charger at time t to the EV i . It is limited by the weakest link between the grid and the vehicle. It is within the defined in the interval:

$$\min\{P_{EVmin}, P_{bmin}\} \leq r_i(t) \leq \min\{P_{EVmax}, P_{bmax}\} \quad \text{if } P_{av}(t) \geq P_{bmin} \quad (5.3)$$

$$r_i(t) = 0 \quad \text{if } P_{av}(t) \leq P_{bmin} \quad (5.4)$$

where P_{av} is the available power in the grid for EV charging, P_{EV} is the power that can be accepted by the vehicle, and P_b is the power that can be delivered by the charger. Thus, if the available power for EV charging P_{av} at time t cannot charge the EV at least at the slowest charge rate P_{bmin} then the EV will not be charged.

Finally, the charger propose three different discrete charge rates, 1.4 kW, 3.3 kW or 7 kW.

Laxity of a Task

We refer as laxity l_i of a task T_i to the difference between the amount of time required to complete the task and the remaining time before its deadline, which for the EVs corresponds to their time of departure. Those tasks with larger laxity are more flexible for scheduling and therefore their charging process could be deferred after its arrival to the ChP, as presented by [47, 71]. When the laxity of a task T_i is negative, it means that it cannot be completed before its deadline.

More specifically, the laxity $l_i(t)$ of a task T_i at time t is defined by the following equation:

$$l_i(t) = (td_i - t) - \frac{Es_i(t)}{r_i(t)}. \quad (5.5)$$

where $(td_i - t)$ corresponds to the time remaining before the time of departure of the EV, the time needed to complete a charge request is given by the energy shortfall $Es_i(t)$ and the charge rate considered $r_i(t)$. The laxity of a given task will change and evolve through the time spent at the charging infrastructure and as a consequence, the deferrable deadline of the task.

5.2.3 On-line Scheduling and Task Dispatching

In our first conservative approach (CoTaSch), we recall, the feasibility of a given task had to be tested before it could be accepted for charging. When the CFCFS scheduling strategy is implemented with this approach, a task T_i is feasible if its connection can be supported by the grid at the slowest charge rate r_i available. As a consequence, EVs could start charging immediately after their connection to the ChP, following the same principle used in the dumb charging strategy.

In our conservative CoTaSch approach, the CCM executes five main routines to manage the loads along the day at the PLS. Such routines test the feasibility of the new tasks and follow the evolution of the charging process until it is completed. However, for the new FlexTaSch approach some changes had to be done for the management of the loads in a more flexible way. The most noticeable change are the capacity to defer the beginning of a charging process and the elimination of the Round Robin Algorithm from the routines executed by the CCM in the CoTaSch approach. For the new FlexTaSch approach, the feasibility of a task T_i no longer depends exclusively on the conditions of the network, but on the energy Er_i request demanded by the task as well.

Figure 5.1 shows how the CSO reacts to the changes on the network caused by a new request or an adjustment on the conditions of the grid. Details of the new routines added to this process for the FlexTaSch approach are described next.

A) System Start up

Like in the CoTaSch approach, initial conditions of the system are set according to the season of the year and the time of the day. These parameters will set up the day-light conditions which defines the total power consumed by the lamps and therefore the remaining available power for EV charging. The voltage drop, current and consumed power at every point of the network is calculated by the CCM.

B) Charging Point Status Availability

Within the CoTaSch approach, the ChP displayed a status indicating to the user if the position was available for an immediate charge or not. This status was set according to the availability test performed by the network for each ChP before any new connection could take place.

Based on the obtained results for the CoTaSch approach in Chapter 4, we assume that the ChPs could be displayed by default as electrically available for the new EVs arriving within the new FlexTaSch approach. We observed as well that when all ChP were located in the proximity of the charger, the voltage drop in the worst case scenario was always within the network constraints and that all chargers could be used simultaneously at least with a slow charge rate. Therefore, a ChP will be displayed as not available only when it is occupied.

C) Control and Regulation Routine

The CCM periodically collects information at all the points of the network, such as voltage drop, current and power consumption. This allows the CCM to better follow the charging progress of all connected EVs. The interval of time between every update is defined by the CSO. However, these values are specially updated each time that the CSO receives a new service request S_i , after a charge has been completed, and when a change on the network occurs. With the collected information it is possible to estimate in advance the expected time of end of charging for the connected loads, if the conditions on the grid remain unchanged and program an additional control of the network. For this process, a group of subroutines is implemented.

- **Update of the Task Scheduler by the Task Manager**

Figure 5.1 shows how the task manager reacts to the changes detected by the sensors deployed over the network. A change in the network occurs when an EV is plugged to the charger, when a task is completed, when the conditions of the lighting services change or when an update is scheduled by the CCM.

- **Feasibility Test for Accepting a New Task**

For the more flexible approach (FlexTaSch), the acceptance of a task for charging will now depend on its feasibility to be completed before its deadline. With the parameters provided by the EV i on its energy requirement Er_i , it is possible to calculate at any instant t , the laxity l_i of the task T_i at the fastest charge rate $r_{imax}(t)$ delivered by the charger and accepted by the EV. If the laxity even at the highest charge rate is negative, it means that the task cannot be completed under any circumstances before its deadline and therefore it must be rejected.

The feasibility of the tasks previously accepted is tested and updated each time that a new EV arrives, when a charge request has been completed or when the conditions on the PLS change. If a task is originally accepted at the ChP (because it proved to be feasible at its time of arrival), eventually becomes unfeasible, it would still be considered by the CCM. However, the preference for charging is given to the EVs that can be fully charged at the time of departure, therefore EVs with a positive laxity will be served first and then the EVs originally accepted but with a negative laxity when the update of the system is performed.

5.2.4 Flexible On-line Scheduling Policies

A real-time or on-line scheduling policy is an algorithm that analyzes at time t the parameters of the accepted tasks and decides the priority in which they will be processed without any knowledge of future tasks. In the model considered for this new approach, the CCM determines the priority given to the scheduled tasks according to the strategy defined by the CSO. For modeling purposes, we consider five new different on-line scheduling policies and revisited the CFCS strategy described in Chapter 4.

- **First Come First Served (FCFS)**

As presented by authors in [44], this policy sorts the accepted tasks on the task scheduler

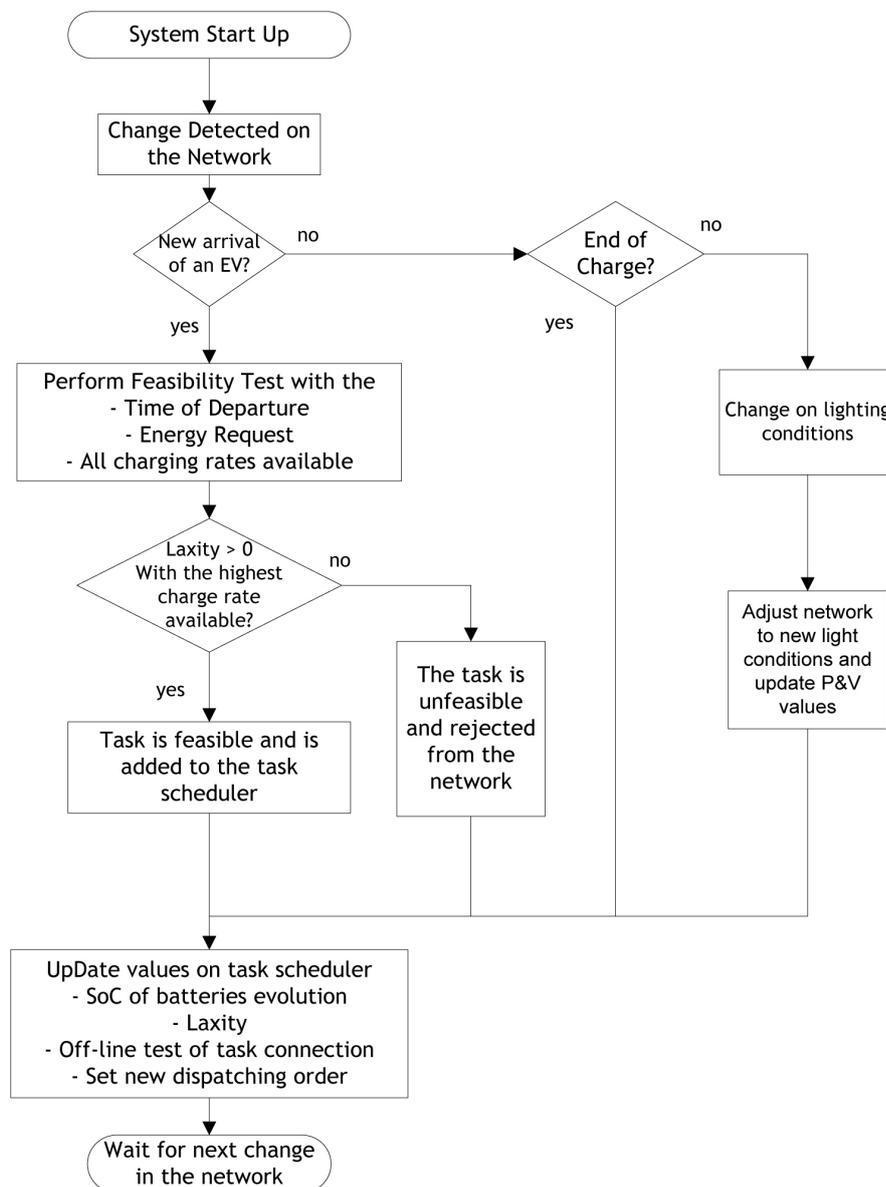


Figure 5.1 – Updating process for the task manager used for on-line scheduling strategies

list according to its time of arrival, from the earliest to the latest.

- **Earliest Deadline First (EDF)**

This strategy sorts the tasks on the scheduler according to the deadline to complete their energy requirement or also referred as the time of departure td_i defined by the user. Tasks are ordered from the closest one to time t to the latest [34, 47].

- **Lowest Energy Shortage First (LESF)**

For this strategy the energy shortage $Es_i(t)$ of each task T_i is calculated at time t . Tasks are sorted on the scheduler from the lowest energy shortage to fulfill to the highest. As the SoC of a given task can evolve through time, the energy shortage to fulfill evolves as well which could change the place of the task on the scheduler through the day.

- **Highest Energy Shortage First (HESF)**

As in the previous policy, the energy shortage $Es_i(t)$ of each task T_i is calculated at time t . However, this time tasks are sorted on the scheduler from the highest energy shortage to fulfill to the lowest.

- **Least Laxity First (LLF)**

The laxity (l_i) of a task (T_i) is obtained for each available charge rate r_i available at the ChP and supported by the EV. Tasks are sorted from the lowest to the highest positive laxity values, followed by tasks with negative laxity values. Thus, EVs with less flexibility to start charging and complete their energy requirement before the deadline are considered first [34, 47].

In order to properly compare the difference between the conservative approach CoTaSch and the new flexible one FlexTaSch. For this, we now implement the CFCFS strategy under the same scenario conditions than for the rest of the flexible on-line policies introduced in this section. But the feasibility conditions for accepting a new EV for charging, and the charging process remain the same as in Chapter 4. A brief summary of the rules considered for this strategy are presented next.

- **Conservative First Come First Served (CFCFS)**

The CCM sorts the EVs dispatches the tasks following their time of arrival to the ChP. When the round robin algorithm is used, the CCM follows the same order of arrival for the charging processes. For the new simulations we consider as for the rest of the FlexTaSch scheduling policies the following conditions:

- Round robin is still used after the LHS for resume the charging process of connected EVs.
- Tasks are not deferrable and therefore EVs should start charging immediately after their connection.
- Electric network conditions, distribution of time of arrival for EVs, time of departure and SoC follow the same rules than for the rest of the flexible policies, as presented in section 5.3.1 and 5.3.2.

The nature of on-line scheduling policies demands a certain degree of flexibility for dispatching the tasks. Some changes had to be done from the previous CoTaSch approach, such as making the tasks preemptive and defining a time of departure to complete the tasks. Further details are

presented in the following sections.

Scheduling Adjustments by the CCM's Task Manager

The flexibility given to tasks within the **FlexTaSch** approach demands a certain degree of intelligence from the **CSO** for a proper task management. Thus, we consider the addition of a task manager at the **CCM** which supervises the charging process of the connected **EVs**. The main duties of the task manager are as follows:

- To update the availability of chargers and keep a track on the charging process of the tasks.
- To test the feasibility of a task and if accepted, follow up its charging process until the task is completed or the **EV** leaves.
- To schedule the tasks to be dispatched according to the policy selected by the **CSO**.
- To regulate the charge rate of the connected **EVs** during their connection at the **ChP**.

The **CCM** task manager will handle the tasks via a group of lists referred as **task scheduler** where tasks are sorted before being dispatched as presented in Table 5.1 and Figure 5.2. As we previously mentioned, a task is considered as feasible if its laxity is positive at the maximum charge rate $rmax_i$ supported by the **ChP** and the battery charger. However, the laxity l_i of each task T_i is obtained for all the possible charge rates accepted by the battery and supported by the charger, each charge rate creates a new entry or line on the scheduler list. Thus, a different laxity is obtained for charge rate i.e. 1.4 kW, 3.3 kW and 7 kW. When the task manager is updated, the new and previous tasks are sorted into a list called *Charge Rate List*, which contains all the accepted charge rate values of a task. This list is formed by two sets as presented in Table 5.1(a). The first set contains the tasks with positive laxity, while the second one sorts tasks with negative laxity. Each set sorts the task according to its charge rate r_i from the highest or fastest $rmax_i$ to the lowest or slowest $rmin_i$. This means that a same task T_i , could be listed in both sets if a charge rate supported by the **EV** produces a negative laxity but the rest do not, for instance, task T_1 in Table 5.1(a).

Once the laxity list has been sorted, the task manager sorts the tasks on the *priority list* according to the policy selected by the **CSO**. Which as for the example shown in Figure 5.1(b), corresponds to the scheduling policy **EDF**, where task T_1 has the earliest time of departure at t_{0+4} and T_2 the latest one at t_{0+6} . Ties are broken first by the position of the **ChP** along the feeder and then by the charge rate supported, listing first the highest charge rate. Tasks with positive laxity are listed in first place. The task's position in the priority list could eventually change at a new evaluation time t , and redefine the order of in which tasks should be treated, so if a given task was previously charging it could then be paused or its charge rate could be adjusted.

It must be reminded from Chapter 4 that the voltage drop at a given charger depends on the charge rate and the distance from the transformer. This means that a given charge rate could cause a higher drop at a given **ChP** than at any other position. As the available power at the transformer is limited, it is possible that not all the tasks will be dispatched simultaneously. In order to avoid abrupt changes in the battery of the connected **EVs** and to verify that the new schedule can be implemented without any disruption in the network, the task scheduler simulates off-line the connection of the **EVs** according to the priority list before going **on-line** with the new

Charge Rate List					Priority List			Scheduler List				
Positive Laxity					Positive Laxity			Scheduler List				
T_i	Es_i	ta_i	td_i	r_i	T_i	r_i	td_i	T_i	r_i	td_i		
T_1	40%	t_0	t_{0+4}	7	T_1	7	t_{0+4}	T_1	7	t_{0+4}		
T_2	30%	t_{0+1}	t_{0+6}	7	T_1	3.3	t_{0+4}	T_1	3.3	t_{0+4}	On-line	
T_1	40%	t_0	t_{0+4}	3.3	T_3	3.3	t_{0+5}	T_3	3.3	t_{0+5}	T_i	r_i
T_3	50%	t_{0+2}	t_{0+5}	3.3	T_3	1.4	t_{0+5}	T_3	1.4	t_{0+5}	T_1	7
T_2	30%	t_{0+1}	t_{0+6}	3.3	T_2	7	t_{0+6}	T_2	7	t_{0+6}	T_3	3.3
T_3	50%	t_{0+2}	t_{0+5}	1.4	T_2	3.3	t_{0+6}	T_2	3.3	t_{0+6}	T_2	3.3
Negative Laxity					Negative Laxity			Scheduler List				
T_1	40%	t_0	t_{0+4}	1.4	T_1	1.4	t_{0+4}	T_1	1.4	t_{0+4}		
T_2	30%	t_{0+1}	t_{0+6}	1.4	T_2	1.4	t_{0+6}	T_2	1.4	t_{0+6}		
(a)					(b)			(c)			(d)	

Table 5.1 – Lists used by the task scheduler to sort and schedule the jobs according to the priority given by the CSO in the FlexTaSch. This example follows the EDF strategy.

task schedule. Figure 5.2 presents the procedure followed by the CCM to adjust the charge rate values of the connected EVs when an update of the scheduler is requested.

After all tasks have been sorted according to the policy chosen by the CSO, they are placed at the *scheduler list* (Table 5.1(c)), to test the feasibility of each one of the entries off-line before adding it to the last list, called *on-line list* (Table 5.1(d)). For that, when an entry at the scheduler list is selected, it is verified at first if the same task T_i has already been placed in the "on-line list". If that's the case, the next entry on the scheduler list is explored. Otherwise, it is verified that the available power on the grid is enough for EV charging at the requested charge rate r_i . If there is enough power, the connection is simulated off-line considering the power consumption of the network at the time of the test. If the connection can be supported, task T_i at charge rate r_i is placed at the bottom of the "on-line" list and the next task is explored, following the procedure on Figure 5.2.

When all tasks have been explored, the CCM adjusts the charge rate r_i of each connected EV according to the values of the on-line list. If a task is not listed, but the EV is still connected, then the EV charging process is paused until the conditions on the network allow to resume its charging process. All adjustments on the charge rates for the connected tasks must happen without any problem at the grid, since the connections are previously tested off-line.

5.3 Experimental Setup

5.3.1 Electrical Network Assumptions

The present section presents all the set of parameters and constraints considered for the normal operation of the electric network at the PLS. Considering the values presented for the previous

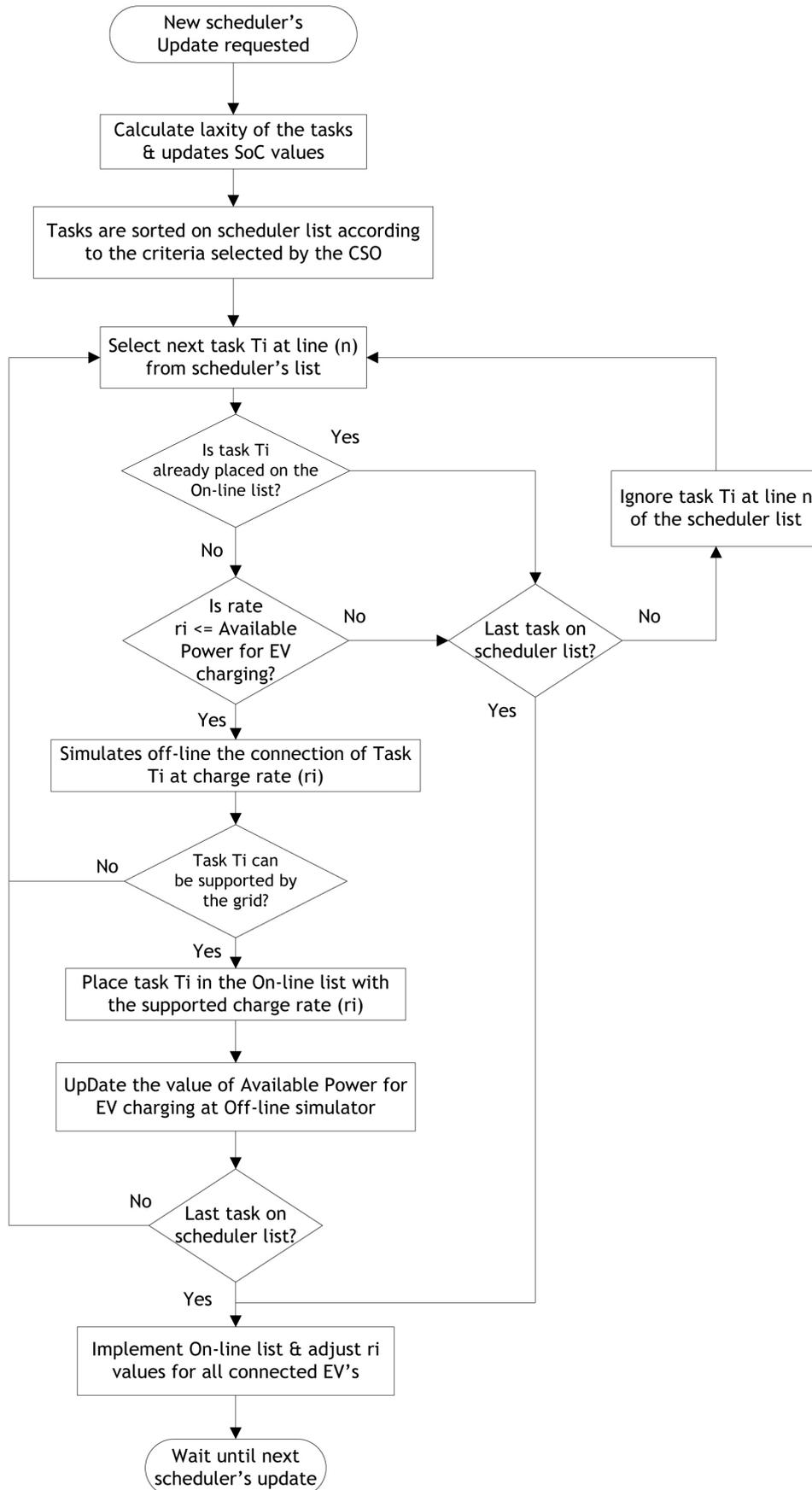


Figure 5.2 – Charge rate adjustment for all connected EVs performed by the task scheduler of the CCM.

Stage	Summer	Winter	Power Consumption of the Lamps
Day light	05:00 - 21:43	08:43 - 16:43	OFF
LHS	21:43 - 22:13	16:43 - 17:13	Nominal + 15%
Early Night	22:13 - 00:00	17:13 - 00: 00	Nominal
Late Night	00:00 - 04:00	00:00 - 04:00	Nominal -35%
Early Morning	04:00 - 05:50	04:00 - 08:43	Nominal

Table 5.2 – Power consumption of lamps on the PLS according to the daylight conditions for the summer and winter scenarios, considering the dimming of the lamps during the late night stage.

conservative charging model as point of departure, some changes were done for testing the new approach. However, following the same logic of the first model of the PLS, the objective is to simulate the electrical network close to real-life conditions.

Public Lighting System’s Electrical Network

As a previous chapter’s reminder, the topology considered for the PLS is composed of a three phased feeder with 90 lamps of 145 W equally distributed on the three phases of the 14.572 kVA transformer. For the FlexTaSch approach, lamps are dimmed during the late night stage in order to increase the available power for EV charging.

In Chapter 4, we observed how for the CoTaSch approach at medium and high penetration levels of EVs, some EVs were rejected for charging because there were no available ChP left. Therefore, we now consider two possible sets of chargers connected to the grid. The first one consists of 9 chargers and the second one of 12. Each ChP can now support slow, standard and high power charges for the PLS topology considered for the FlexTaSch approach.

Furthermore, we conclude from our results in Chapter 4 that by placing the chargers closer to the transformer and directing the EVs to the closest available ChP on the network, the power losses on the network were reduced. Taking this into account, the FlexTaSch approach for EV charging considers that all ChP are placed at the closest possible position from the transformer and that all EVs will be directed towards the closest available ChP.

Stages of the Public Lighting System

As described in Chapter 4, the available power in the network for EV charging is not the same over a period of 24 hours as it depends on the power demanded by the lamps. The profiles of power available for EV charging depending on the day-light conditions during summer and winter months are displayed in Fig. 5.3.

During winter months, sunlight is available for shorter periods of time and therefore the lamps must be operating for longer periods of time. As a result, the power consumed by the lamps per day increases when it is compared to the summer scenario. For the new flexible approach FlexTaSch, the power consumed by the lamps is defined according to the stages of the PLS for each season as presented in Table 5.2.

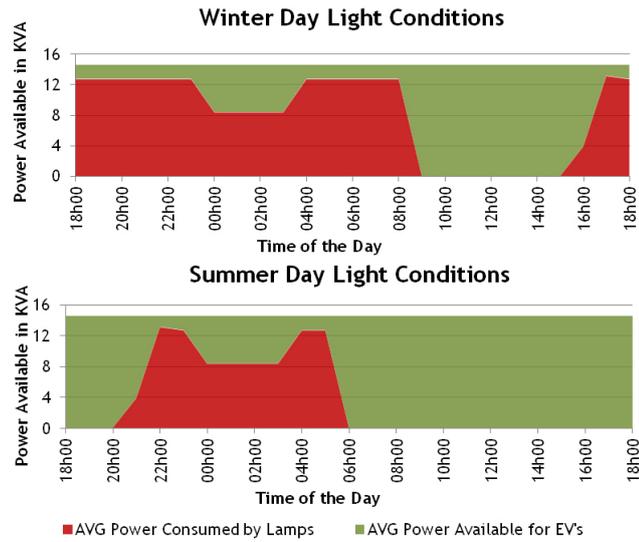


Figure 5.3 – Daily profile of available power for EV charging at the PLS within the [FlexTaSch](#) approach.

It can be noticed how by dimming the lamps during the late night stage, it is possible to dispose of more power for EV charging. For the new simulated conditions, the PLS network dims the lamps when the intensity of the lighting can be reduced without affecting the service [30].

5.3.2 Recharge Demand Parameters

Distribution of Vehicles

For modeling and benchmark purposes, the type of vehicles and the size of the battery considered are the same as in the [CoTaSch](#) approach. The distribution of the EVs per day corresponded to the French market distribution: 84% of EVs, 7% of PHEV-1 and 9% of PHEV-2. The battery capacity values considered for each type of vehicle are listed in Table 5.4.

For the [FlexTaSch](#) approach, the granularity of the penetration level of EVs is increased with respect to the [CoTaSch](#) approach. It starts at 10 EVs per day and it increases by groups of ten EVs until reaching 70 EVs per day. This helps us better understand if the performance of a given policy could change at different penetration levels.

Battery State of Charge and Charge Rates

For the [FlexTaSch](#) approach we no longer attribute the same energy requirements to all the EV. As to provide more real-life testing we obtain an individual energy requirement for each EV. The initial SoC is randomly and normally distributed with values chosen between 20% and 35% of the battery capacity at the time of arrival to the ChP while the SoC requested at time of departure is randomly distributed following a normal distribution law with values assigned between 60% and 80%.

Type of Vehicle	Average Battery Size (kWh)	Allowed Charging Rate (kW)
EV	22	1.4 or 3.3 or 7
PHEV - 1	6	1.4
PHEV - 2	16	1.4 or 3.3

Table 5.3 – Considered battery capacity according to the type of vehicle and the charge rates supported by the network chargers [8, 14, 35, 46].

Arrival Group	Proportion of EV Arrivals	Time of Arrival		Parking time	
		μ	σ (in hours)	μ	σ (in hours)
AM (μ_1, σ_1)	30 %	09h00	0.42	5	0.5
MD (μ_2, σ_2)	30 %	14h00	3.4	5	0.5
PM (μ_3, σ_3)	40 %	19h30	0.85	(7am+1day) - t	0.5

Table 5.4 – Distribution of time of arrival and parking time for EVs during a normal day according to their group of arrival.

The maximum SoC at time of departure is kept at 80% to avoid any negative effects on the battery as suggested in [38]. For modeling purposes, the charger delivers a constant power to the vehicle. The FlexTaSch proposes three possible types of charges: slow charge ($1.4 kW$), standard charge ($3.3 kW$) and high power charge ($7 kW$). A summary of battery sizes and charge rates available for each type of vehicle is presented in Table 5.3.

Aggregation of a Fleet of Vehicles

The time of arrival (ta_i) and time of departure from the charging station (td_i) are essential parameters to properly evaluate a task T_i at time t and determine its feasibility. The time of arrival and parking duration is randomly and normally distributed for three different groups of EVs arriving to the ChP during the day according to the data presented in Table 5.4.

According to [36], the average daily parking time for EV owners is approximately of five hours. Additionally, in Chapter 4 we observed that the average time needed to charge an EV is around four hours for an energy requirement of 60% of the battery capacity and a charge rate of $3.3kW$.

Taking this into account, the parking time (tp_i) for EV i is randomly and normally distributed. For groups AM and MD the mean parking time is set at five hours, or 300 minutes or 5 hours, and the variance at half an hour or 30 minutes ($\mu = 300, \sigma = 30$). For the PM group, we considered the mean for time of departure to be at 07:00 AM of the day following the arrival at the ChP. This was decided due to the fact that it is hardly probable that the EV owners would leave the ChP in the middle of the night stage. Finally, the time of departure is obtained by adding the parking time to the time of arrival to the ChP.

5.4 Performance Metrics

In previous sections we set the conditions for EV charging within the FlexTaSch approach based on on-line scheduling strategies adapted to the PLS network. As a consequence, some changes were

made for the management of the tasks as well as some adjustments in the charging infrastructure. In Chapter 4, we proposed a set of metrics to analyze the performance of a given charging strategy. For evaluation purposes, the same set of metrics is preserved to evaluate each one of the on-line scheduling policies considered in the FlexTaSch approach. In this section we present a summary of the metrics considered taking into account the changes required for the new FlexTaSch context.

5.4.1 Vehicle Acceptance Ratio

This metric measures the ratio between the number of EVs that are accepted for charging and the total number of EVs that arrive during the period of time tested. The value of this metric is expressed in percentage.

5.4.2 Average Distribution Power Losses

Power losses are estimated by the difference between the available power at the transformer and the power delivered to the customers through the ChP. In Chapter 4, we observed how the losses on the network increased not only when the loads were placed far from the power source, but also when the total consumed power increased. The scope of this metric is to understand better if the losses on the network are affected by one of the scheduling strategies more than the others. We calculate the total amount of lost energy by integrating the power losses registered during the whole simulation and then we obtain the average amount of power lost in the transmission lines per hour. This metric is presented in W/h.

5.4.3 Demanded Vs Dispatched Energy Ratio

The energy request Er_i refers to the total amount of energy demanded by an EV i . It is obtained from the difference between the SoC $_i$ requested at the time of departure td_i and the SoC $_i$ available at its time of arrival ta_i to the ChP as shown in Equation(5.1). On the other hand, the energy dispatched Ed_i refers to the total amount of energy that has been actually furnished to an EV i between its time of arrival ta_i and its time of departure td_i as shown in Equation(5.6). At the end of the simulation period, results obtained for all EVs are added up and the total amount of energy dispatched to all EVs is compared to the total amount of energy initially requested by all accepted EVs as presented in Equation(5.7).

The total energy dispatched Ed_i to task T_i at its time of departure td_i is given by:

$$Ed_i = [FSOC_i(td_i) - SOC_i(ta_i)] \times C_i \quad (5.6)$$

where $FSOC_i(td_i)$ corresponds to the battery's final SoC reached at time of departure td_i and C_i is the battery capacity of EV i in kWh.

The ratio between the total requested energy Er and the energy dispatched Ed to all EVs is given by:

$$Er_d = \frac{\sum_{i=0}^n Ed_i}{\sum_{i=0}^n Er_i} \quad (5.7)$$

Energy requirement completion level	Percentage of the energy request fulfilled at time of departure
No Charge	<1%
Weak	1 % to 20 %
Low	21 % to 40 %
Moderate	41 % to 60 %
Major	61 % to 80 %
Substantial	81 % to 99 %
Full Charge	100%

Table 5.5 – Percentage of dispatched energy from the total energy requested by the EV.

where n is the total number of EVs accepted for charging during the evaluated period. This metric is thus presented as a percentage.

5.4.4 Average Unserved Energy

This term refers to the energy that could have been potentially used for charging an EV at a certain time of the day, but was not used neither for EV charging nor for lighting the lamps, due to different factors. This could happen for example; when all ChPs are electrically available but there are no connected EVs or when the energy requirement has already been fulfilled for all EVs, leaving no more tasks to be dispatched and some ChP are blocked for new arrivals. We believe that if all the unserved energy is added up, it could be potentially stocked for further use. This metric is expressed in kWh/h.

5.4.5 Quality of Service and SoC at Time of Departure

The flexibility accorded to the tasks in the FlexTaSch approach demanded a tradeoff between the QoS proposed to the users and making the charging service reachable to more users.

For the FlexTaSch approach is not discarded the possibility to find some tasks with incomplete charges at their time of departure td_i . Therefore, the SoC_i is measured at the time of departure (td_i) for all accepted EVs and the percentage of delivered energy from the original requested energy Er_i is obtained for each EV i . Finally, the achieved percentage of the task is ranked according to the charging levels presented in Table 5.5.

5.5 Numerical Results

In addition to the CFCFS scheduling strategy previously studied in Chapter 4, five on-line scheduling policies are considered in this chapter, which are evaluated within the simulating conditions defined by the FlexTaSch approach. A summary of all scenarios and conditions taken into account in this new flexible approach is presented in Table 5.6.

Day-light conditions	Summer scenario (with dimming of lamps) Winter scenario (with dimming of lamps) 15 days tested per simulation
Distribution of chargers	Close to the transformer
Selection of charger	Closest Charger First (CCF)
EV Penetration Rates	10, 20, 30, 40, 50, 60 & 70 EVs /Day
EV Charging Rates Available	Slow & Standard Charge (1.4 & 3.3 kW) High Power Charge Added (1.4, 3.3 & 7 kW)
EV Scheduling Policy	Conservative First Come First Served (CFCFS) First Come First Served (FCFS) Earliest Deadline First (EDF) Highest Energy Shortfall First (HESF) Lowest Energy Shortfall First (LESF) Least Laxity First (LLF)

Table 5.6 – Summary of network conditions and scenarios considered for the **FlexTaSch** approach of the model, based on on-line scheduling of the tasks with more flexibility.

In this section we present the results obtained when each one of the 56 possible scenarios for each scheduling policy were tested via simulation. A total of 336 simulations were performed.

5.5.1 Vehicle Acceptance Ratio

In Figure 5.4 we show the percentage of rejected **EV** with each one of the scheduling policies tested in this thesis. In this section, the most representative scenarios are presented. As it was expected, just like we observed in Chapter 4, the number of rejected **EVs** was higher in winter than during summer for all charging strategies. We found as well that, with the exception of **CFCFS**, the rejection rate was slightly reduced when three additional chargers were added to the network, passing from 9 to 12 connected chargers. This happens as a result of **CFCFS** blocking the unoccupied **ChPs** to other **EVs** when a new connection cannot be supported.

We noticed that two factors helped to reduce the rejection rate on the network, which are the increment on the number of chargers (that enlarged the acceptance capacity of the network) and the availability of the high power charge rate (7 kW) at the chargers. However, the improvement on the number of accepted **EV** is more noticeable due to the addition of **ChP** than as a result of an additional charge rate. As it can be observed in Figure 5.4. For example, the rejection rate for **LESF** when 70 **EVs** arrive per day is higher in 5.4a than in Figure 5.4b, and it is considerably reduced in Figure 5.4c but it is in Figure 5.4d where it present the lowest rejection rate of all simulated scenarios.

We found that there is only a slightly difference on this metric among the considered scheduling policies. The only exception is **CFCFS**, which by nature presented lower levels of acceptance rate or more **EVs** rejected for charging as shown in Figure 5.4.

However, we can notice that changes made on the **FlexTaSch** approach, helped to reduce up to 12% the rejection rate for the **CFCFS** compared to the results obtained using the **CoTaSch** approach as presented in Table 5.7. This is explained by the fact that **EVs** are parked until its

	Summer			Winter		
EVs / day	10	40	70	10	40	70
FlexTaSch	11%	57%	70%	36%	67%	75%
CoTaSch	5%	65%	79%	43%	79%	86%

Table 5.7 – Comparison of rejection rates for CFCFS between the FlexTaSch and the CoTaSch approach for simulated scenarios with 9 chargers and 2 charge rates available (1.4 kW and 3.3 kW).

time of departure td_i , which liberates the chargers more frequently than when EVs remain plugged until their charge is completed. As it can be noticed, the rejection rate increased for 10 EVs/day within the FlexTaSch approach for the summer scenario. This percentage not only considers the EVs that were rejected because the grid could not support an additional task, as in CoTaSch. It considers as well all EVs rejected for demanding unfeasible service requests.

5.5.2 Average Distribution Power Losses

Results obtained via simulation showed that the season of the year is the main factor of influence on the registered power losses in the network as shown in Figure 5.5. This is due to the fact that the lamp's power consumption is more elevated in winter than in summer as a result of larger periods of time with the lamps turned on. As a consequence, power losses and the percentage of losses registered compared to the total energy served follows the same pattern.

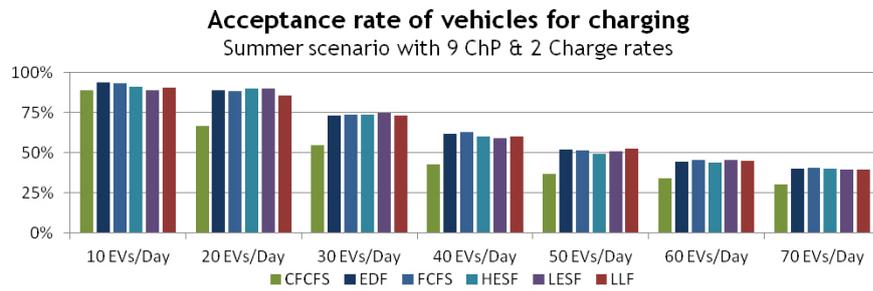
It must be remembered that during a given season of the year, power consumed by lamps remains constant, independently of the number of EVs connected to the ChPs. As a consequence, the percentage of total energy lost compared to the total amount of energy served is more affected by the number of EVs charging than by the selected scheduling policy. We observed that when more EVs are charged, the relation between distribution losses and served energy decreases. This can be observed in Figure. 5.5, where between the range of 10 EVs and 40 EVs arriving per day the percentage of losses compared to the power served reduces, while for higher penetration rates it remains rather constant.

We observed that CFCFS presents a slightly lower amount of losses compared to the other on-line scheduling policies. This is due to the fact that the number of tasks dispatched is lower and consequently, the power losses related are lower too, as shown in Fig. 5.5.

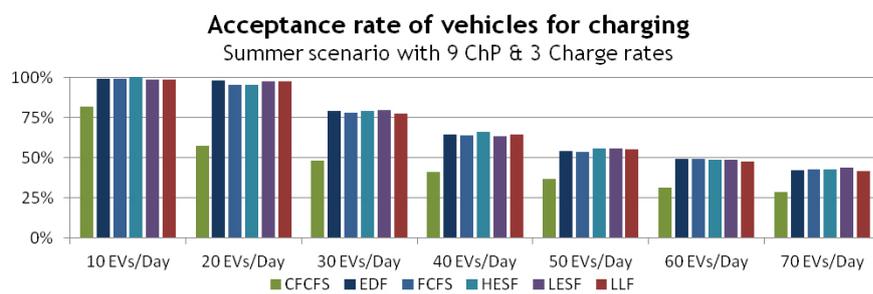
5.5.3 Ratio Between Dispatched and Requested Energy

The percentage of energy requested that was actually served to the EVs is presented in Figures 5.6 and 5.7. It is displayed as well the total amount of served energy according to the different policies. In this figure we only present four of the simulated scenarios, which correspond to the summer and winter case scenarios when 12 chargers are connected and three charge rates are available.

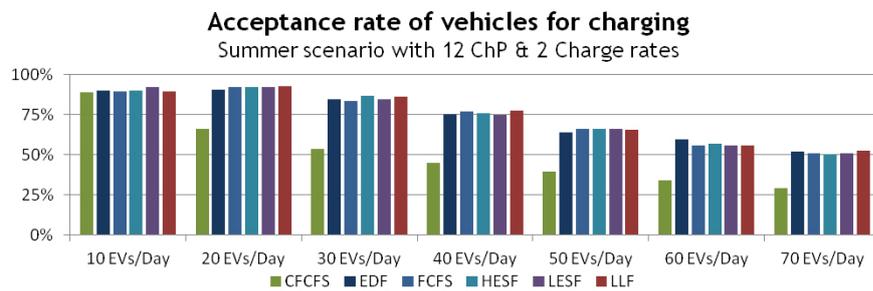
We observe that the conservative approach CFCFS is still able to fully serve the amount of energy requested by the EVs during summer independently of the penetration rate, the number of ChP or charging rates considered. However, during the winter scenario this policy struggles



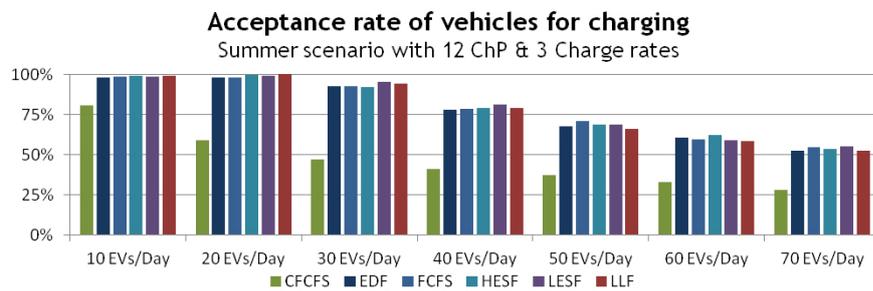
(a) Summer scenario 9 ChP and 2 charge rates available



(b) Summer scenario 9 ChP and 3 charge rates available

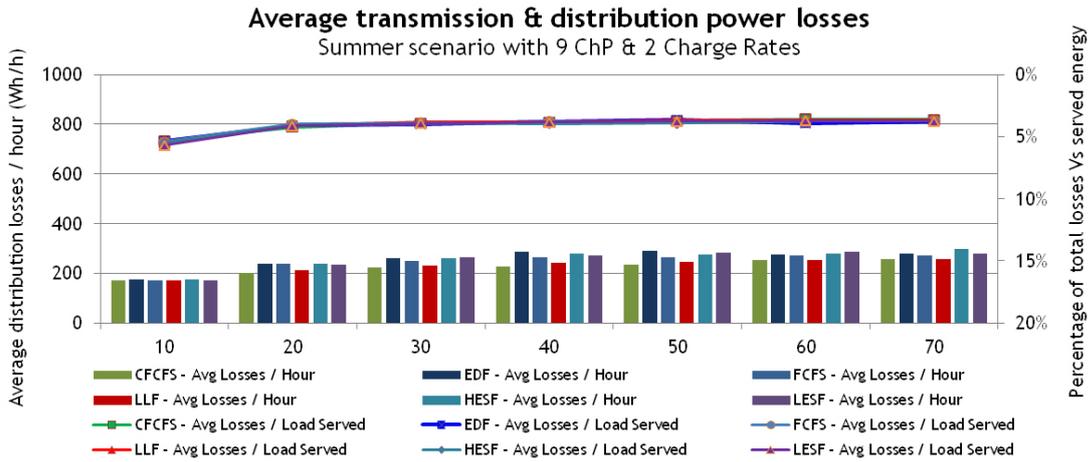


(c) Summer scenario 12 chargers and 2 charging levels

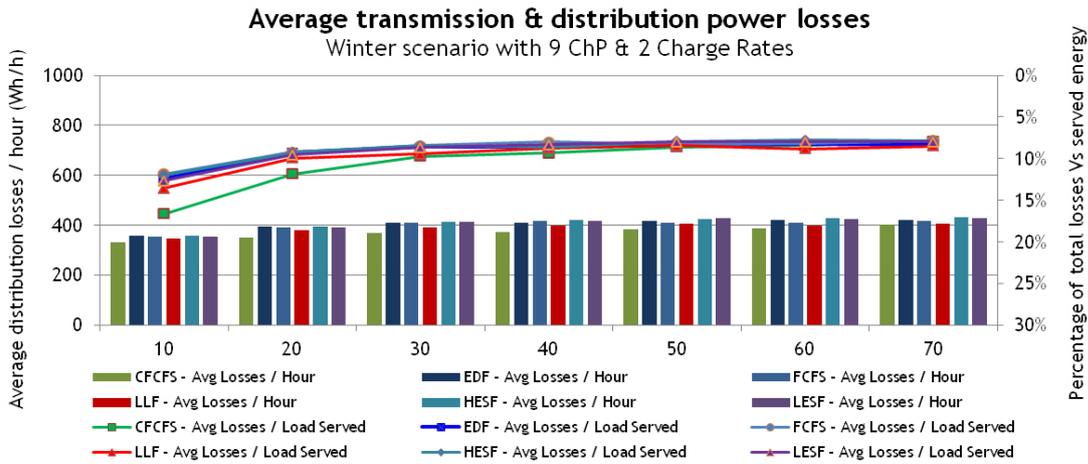


(d) Summer scenario 12 ChP and 3 charge rates available

Figure 5.4 – Percentage of accepted EVs for charging in summer and winter scenarios considering different charge rates and ChP installed.



(a) Summer scenario 9 chargers and 2 charge rates available.



(b) Winter scenario 9 chargers and 2 charge rates available.

Figure 5.5 – Average transmission and distribution losses per hour and the relation between the total energy losses Vs the total amount of energy served to the loads for winter and summer case scenarios with 9 chargers and 2 charge rate available.

like all the rest to satisfy the EVs' demanded energy due to the reduction of available power for EV charging during this season.

For the summer scenario, as more power is available for EV charging, the total amount of served energy considerably increases compared to the winter scenario. We found that the combination of 12 ChP and 3 charge rates helps to increase the amount of energy served to the EVs, which in terms of energy distribution is the best one. While it was not possible to determine a scheduling policy which clearly performs better than the rest, we noticed that CFCFS and LLF provide less energy to the EVs than the average amount of energy dispatched by the rest of the flexible policies. This is due to the fact that these two policies have higher rejection rates than the rest.

The results obtained via simulations showed that when the high power charge rate (7.7 kW) is supported by the chargers, the amount of energy served for EDF, FCFS, HESF and LESF is above the average of all flexible on-line scheduling policies (Figure 5.6 and Appendix A.3). This is valid for most of the tested scenarios either under winter or summer day-light conditions. However, EDF, FCFS and LESF have a better performance in terms of percentage of served energy from the total energy requested. As expected, CFCFS was the policy with a better relation between served and requested energy, registering for all tested scenarios values above the average obtained for all on-line scheduling policies. These results do not mean that this is the best policy, as it better distributes the available energy through the grid, but at the same time this policy rejects more EVs than the rest. On the other hand, LLF registered always values below the average obtained for flexible on-line scheduling policies.

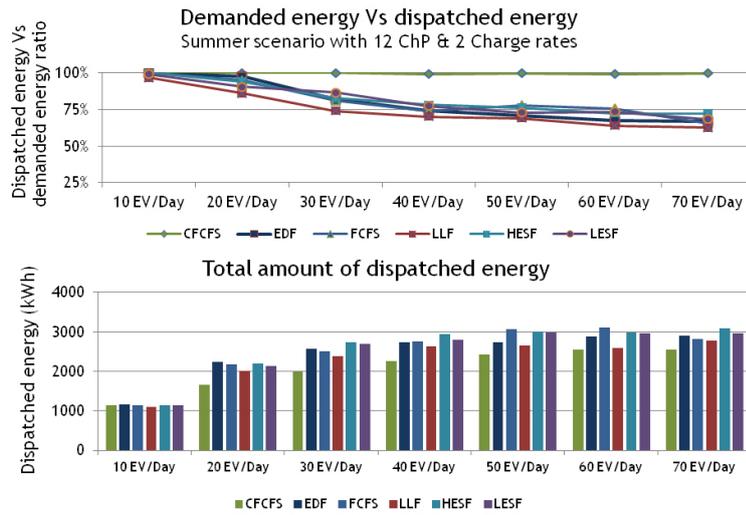
5.5.4 Average Unserved Energy

The average amount of unserved energy per hour is shown in Figure 5.8. The red line in the figures represents the minimum amount of power required to charge an EV at the slow charge rate (1.4 kW).

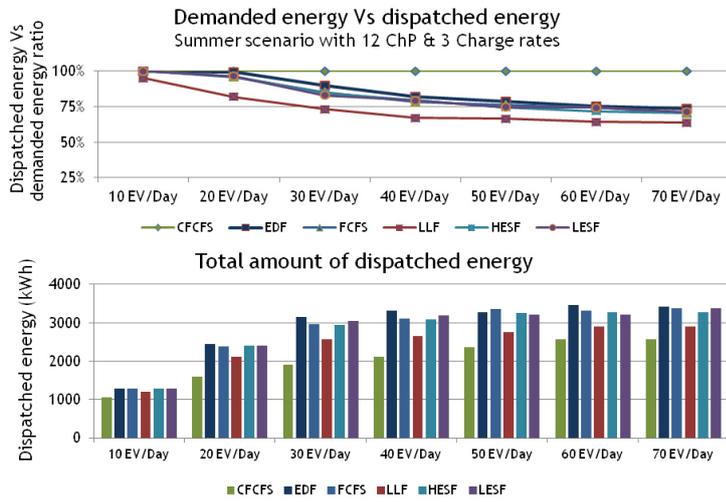
As expected, results show that the amount of unserved energy is higher at low penetration rates of EV, as less energy is demanded to the grid, and it decreases as more EV start arriving at the set of ChP. We found that the unserved energy does not only depend on the number of ChP, but also depends on the charge rates supported by the infrastructure. In fact, the amount of unserved energy was more significantly reduced when the high charge rate (7.7 kW) was added than when three additional ChP were considered (12 ChP). As it can be seen comparing Figure 5.8b and Figure 5.8c, the importance of this result relies on the fact that it reaffirms the need of aiming for a smarter infrastructure more than for only expanding the number of chargers.

As it was expected, during summer the amount of unserved energy was higher than during winter. For almost all the considered scenarios, it was found that theoretically there could be sufficient energy left on the network to charge an additional EV at the slow charge rate (1.4 kW) as shown in Figure 5.8a. On the contrary, in winter as it is presented in Figure 5.8c, the unserved energy for most of the simulated scenarios show how the network is working near its full capacity, even at low penetration rates (20 EVs per day). This is due to the limited power for EV charging at this time of the year.

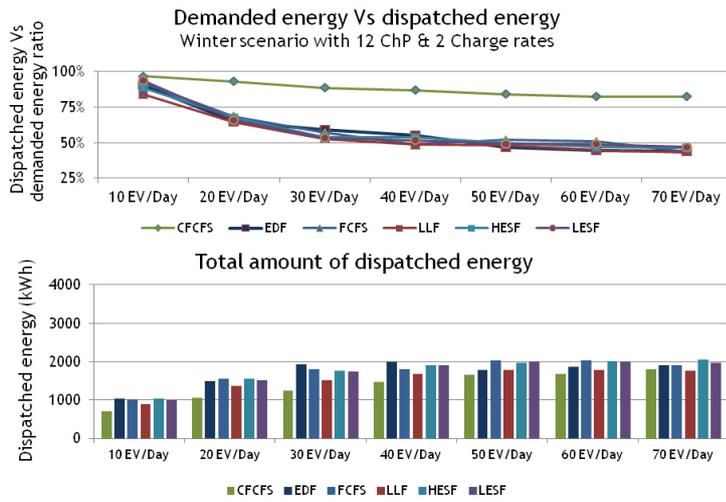
We confirmed the results presented for CFCFS in Chapter 4, where the amount of unserved energy is enough to serve at least one EV using the slow charge rate for all possible scenarios.



(a) Summer scenario 12 chargers and 2 charging levels



(b) Summer scenario 12 chargers and 3 charging levels



(c) Winter scenario 12 chargers and 2 charging levels

Figure 5.6 – Total energy served (in kWh) and the ratio between served energy and the total energy requested by the loads for summer and winter case scenarios with 12 ChP installed.

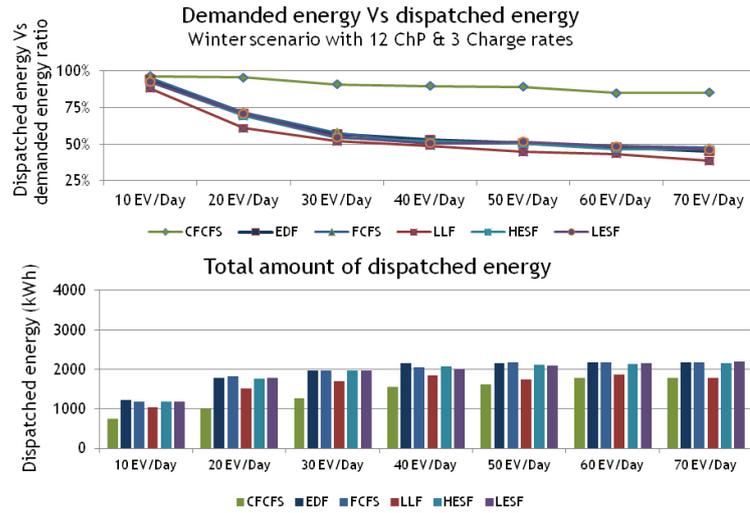


Figure 5.7 – Winter scenario 12 chargers and 3 charging levels

Similar results were observed as well for LLF. As for the rest of the scheduling policies, we did not find one particular metric that outstands its performance from the rest of the strategies in the simulated scenarios.

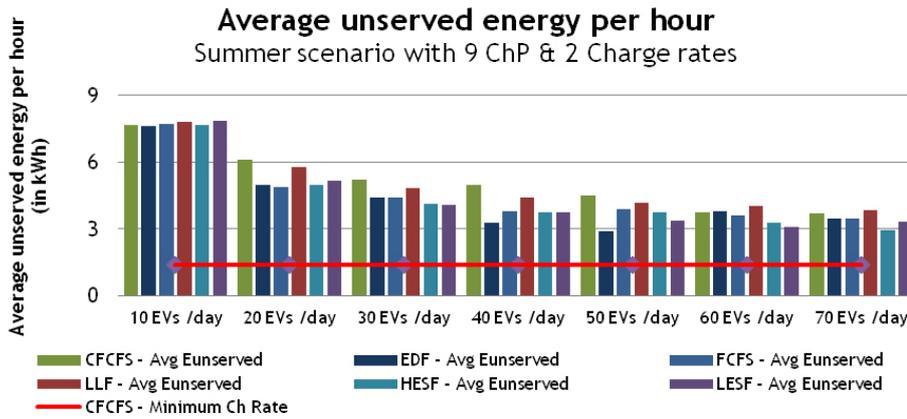
5.5.5 Quality of Service and SoC at Time of Departure

Figures 5.9 and 5.10 show the percentage of the energy requirement that has been fulfilled for each EV at its time of departure from the ChP. According to the task's energy requirement completion level, EVs are classified according to the levels presented in Table 5.5. It must be reminded that the charge level is regarding the energy request and not the battery's capacity. Therefore, the group referred as 0% or **no charge**, considers all EVs leaving the ChP without being charged after being connected a given period of time, not the EVs that left with 0% of SoC. For both figures, results for summer and winter scenarios when three charge rates and 12 ChP are considered for all scheduling policies.

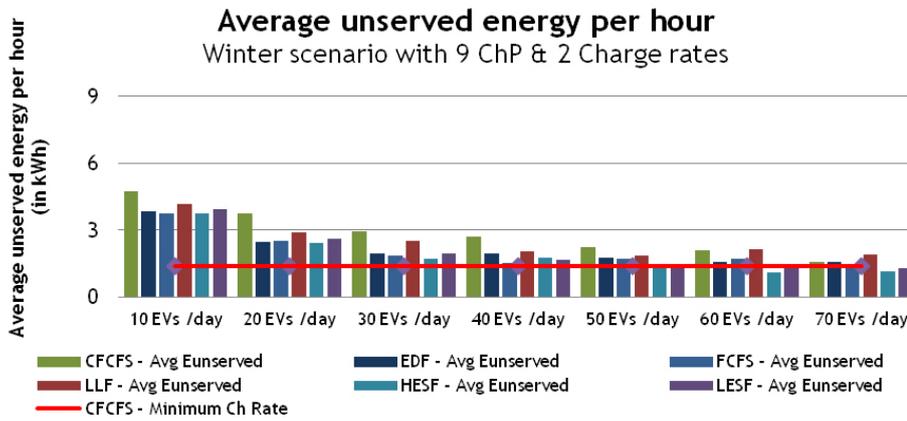
As expected, the conservative policy CFCFS used in the CoTaSch approach presented the highest levels of full charge for all tested scenarios, as shown in Figure 5.9a. However, because of the deadline introduced in this FlexTaSch approach, not all EVs are fully charged at time of departure. This is more noticeable during winter, when it is possible to observe more EVs with a weak charge level.

As we anticipated, the tradeoff between QoS and the expansion of charging services caused an increment of EVs leaving the ChP with lower levels of charge, even during the summer. It can be observed that as the number of EVs arriving to the station increases, the QoS goes down and more EVs left without being charged. This phenomenon is even visible from 20 EVs arriving per day for some winter scenarios.

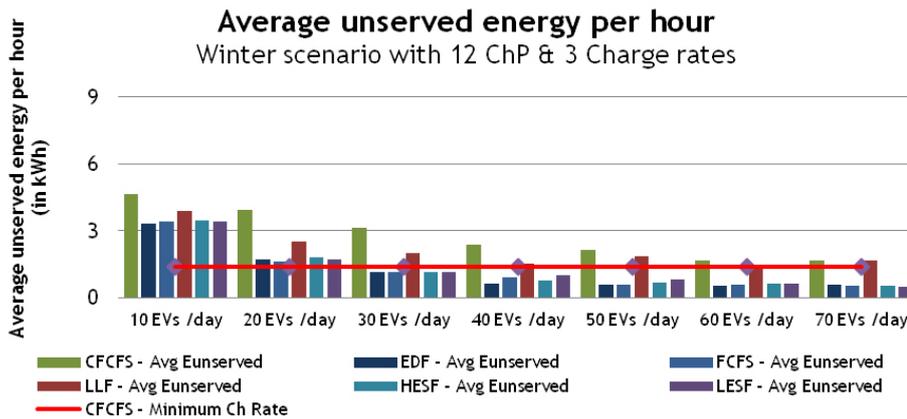
We observed that FCFS presents reasonable levels of fulfilled requirements in Figure 5.9c. For example, with 70EVs/day during summer there are more than 40% of EVs fully charged and less than 12% of EVs are leaving without charge during summer. However, for winter scenarios the



(a) Summer scenario 9 chargers and 2 charging levels



(b) Winter scenario 9 chargers and 2 charging levels



(c) Winter scenario 12 chargers and 3 charging levels

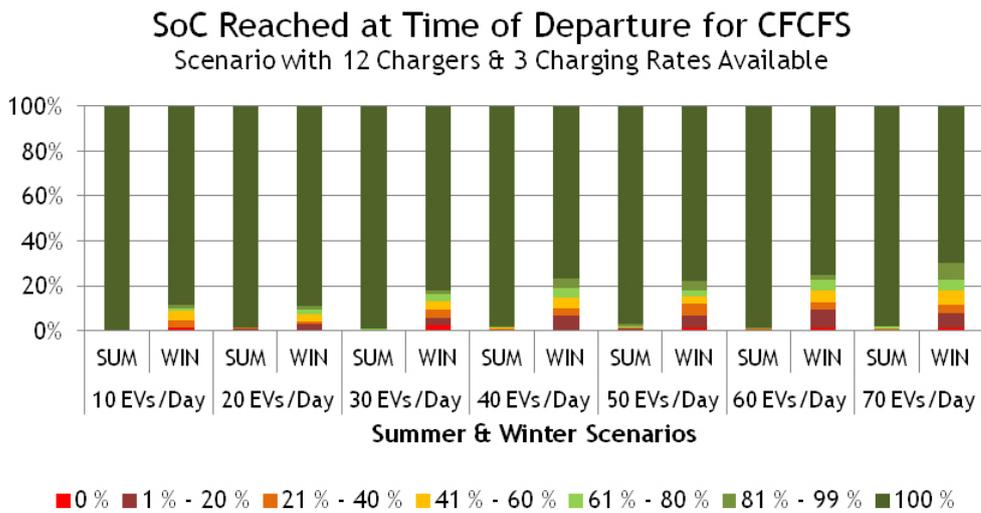
Figure 5.8 – Average unserved energy per hour at the network for different summer and winter case scenarios.

number of EVs with charge levels under 40% of the energy requirement accomplished can almost reach the same number of EVs fully charged, specially when 12 ChP are deployed. EDF and LESF presented similar performances, having the largest number of fully charged EVs than the rest of the policies and less EVs without charge than FCFS. While HESF presents fewer fully charged EVs, it also registered fewer EVs leaving the ChP with levels of charge under 20% of the energy requirement fulfilled, distributing more EVs at higher charge levels. Finally, we found that LLF has the lowest amount of EVs fully charged at time of departure and a relatively higher amount of EVs leaving the ChP with low levels of charge than the rest of the policies.

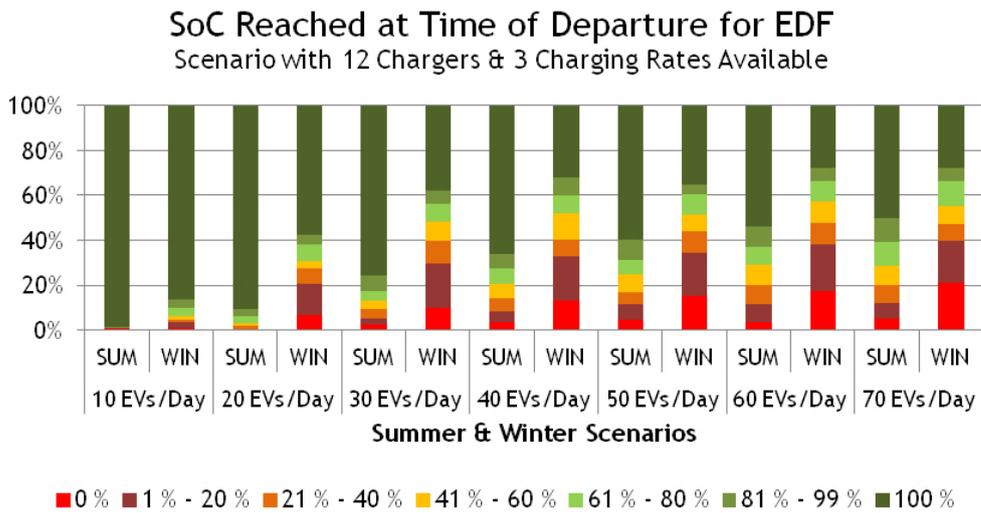
We found as well that FCFS, EDF, HESF and LESF registered more fully charged EVs at time of departure when there are 9ChP deployed and 3 charge rates available compared to the scenario when 12 chargers and 2 charge rates are available. This demonstrates that adding more chargers to the network helps to reduce the rejection rate but unfortunately reduces at the same time the amount of EVs fully charged at time of departure. This can be observed when the 3 charge rates are conserved for 9 and 12 chargers deployed.

In all the previous metrics we observed that the choice of a given scheduling policy barely had an impact on the results, with the exception of CFCFS and LLF. However, this last metric oriented towards the QoS actually exhibits larger differences in the performance according to the chosen policy.

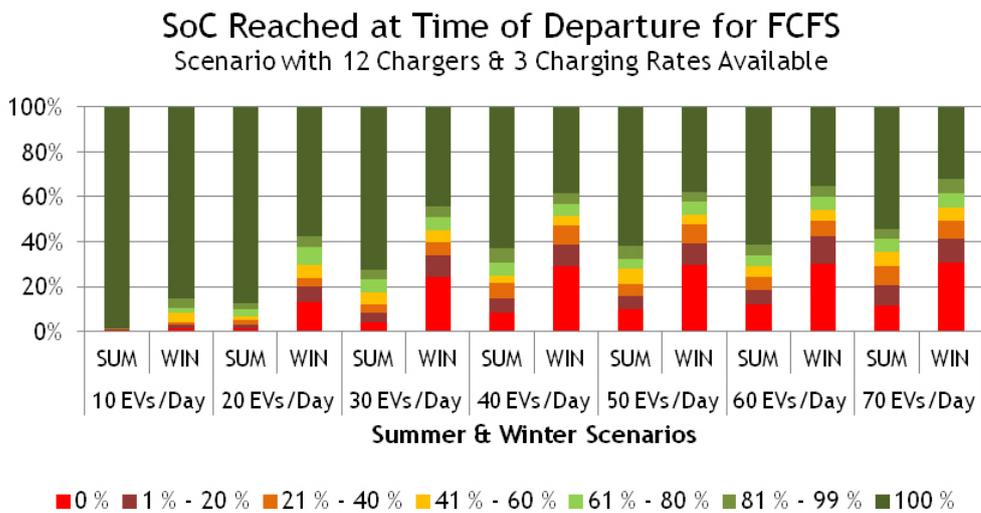
We observed that the policy can be selected according to the objectives of the CSO, either aiming at a higher number of EVs fully charged or a lower number of EVs leaving the ChP with low levels of served energy. If the first criteria is selected, LESF presented the highest record of fully charged EVs among the on-line scheduling policies followed by FCFS. On the other hand, HESF presented the lowest number of EVs that left the ChP without charging, followed by EDF.



(a) CFCFS with 2 chargers and 3 charge levels

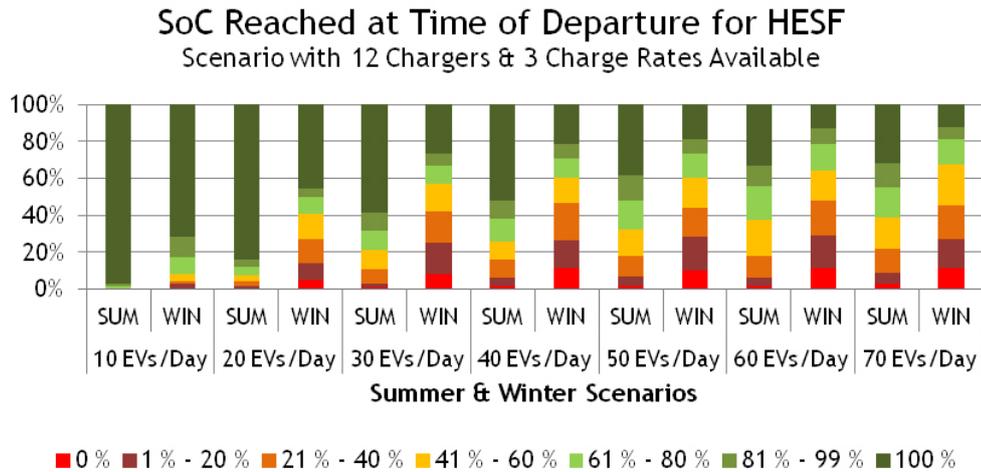


(b) EDF with 12 chargers and 3 charge levels

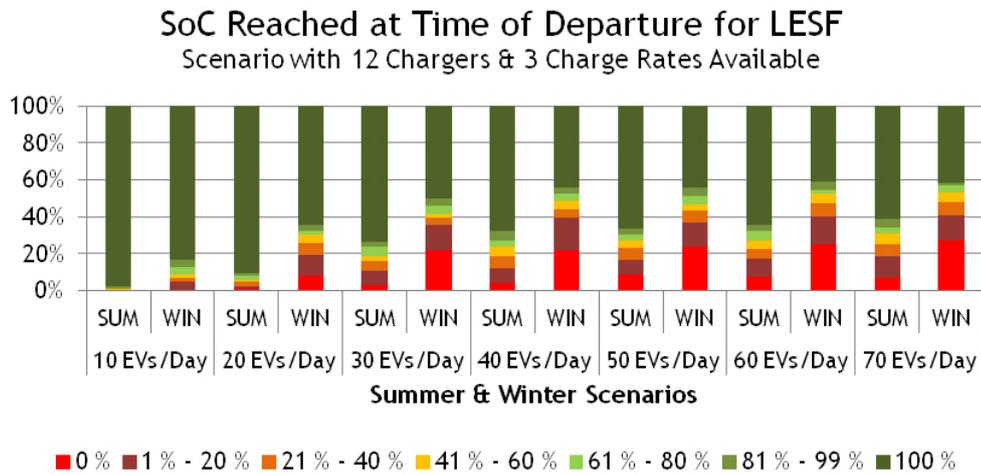


(c) FCFS with 12 chargers and 3 charge levels

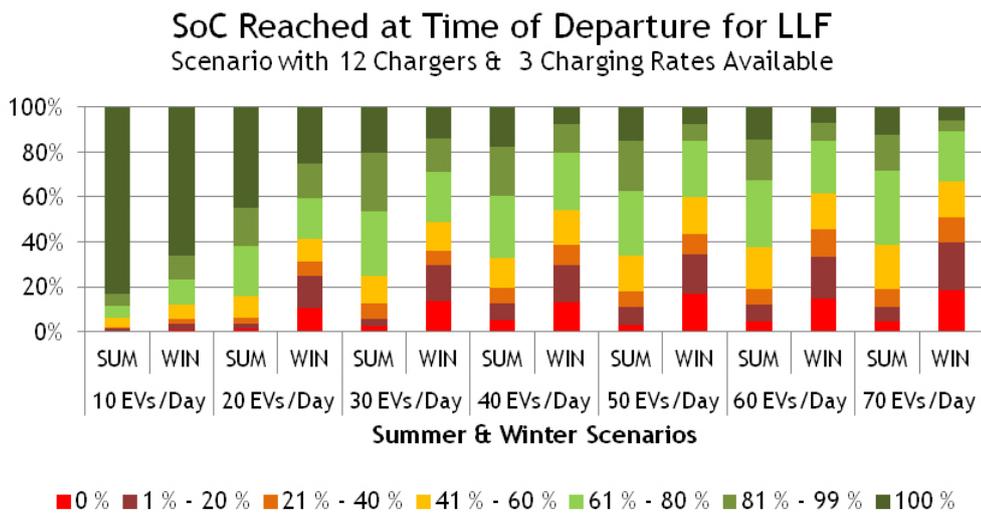
Figure 5.9 – Percentage of fulfilled energy requirement at EV's time of departure during summer and winter scenarios with 12 ChP and 3 charge rates for CFCFS, EDF and FCFS.



(a) HESF with 12 chargers and 3 charge levels



(b) LESF with 12 chargers and 3 charge levels



(c) LLF with 12 chargers and 3 charge levels

Figure 5.10 – Percentage of fulfilled energy requirement at EVs' time of departure during summer and winter scenarios with 12 ChP and 3 charge rates for HESF, LESF and LLF.

5.6 Summary

In Chapter 4, we introduced the conservative approach **CoTaSch** conceived for **EV** charging over the **PLS** which proved to be feasible. However, the performance of the network was still limited and with room for improvement. In the present chapter, we introduced a more flexible approach referred as **FlexTaSch**, which evaluates five different on-line scheduling strategies for **EV** charging, changing the way that **EVs** are managed during their charging process.

The network was tested for two different sun-light scenarios, two different number of chargers deployed over the feeder and different charge rates available. The results of all the simulated scenarios were compared by means of the metrics presented in the previous chapter which are the following: acceptance rate of vehicles, average transmission and distribution power losses, average unserved energy, **QoS** based on the **SoC** at time of departure, and finally, the ratio between dispatched and demanded energy on the grid.

We have observed that with the only exception of **CFCFS**, the rest of the policies presented similar levels of **EV** acceptance for charging. While **CFCFS** presents a lower level of acceptance of vehicles, it still maintains good levels of **QoS** proposed to the **EVs** leaving the **ChP** even when the policy was tested using the conditions of the **FlexTaSch** approach, such as the addition of a deadline for the tasks and the possibility to make tasks deferrable. The importance of reducing **EVs** rejection rate lies on the fact that as more **EVs** are accepted for charging, the dispatched energy to the users can approach more to the installed capacity of the network, which could bring more economical benefits to the **CSO**.

We have noticed that the performance of the **PLS** network slightly changed as a direct result of the selected policy for most of the metrics. Variations on the results relied more on the configuration of the network, like the number of **ChP** deployed or the charge rates supported by the **ChP**.

However, the **QoS** proposed to the user registered the most significant variations as a direct result of the policy and as a result of the configuration of the network. Depending on the priorities of the **CSO** the selection of a policy could be oriented either to reduce the number of **EVs** leaving with low charge levels or to increase the number of fully charged **EVs**. While **CFCFS** presents low levels of uncharged vehicles and high levels of fully charged **EVs**, it does not fully exploits the installed capacity of the network, leaving unused assets. We found that **LESF** and **FCFS** could be considered by the **CSO** if its priority is to increase the number of fully charged **EVs**.

Nevertheless, we consider that the **CSO** should focus more on policies like **HESF** and **EDF** which present lower amount of **EVs** leaving the **ChP** with low charge levels. As from the user's point of view, leaving the **ChP** after a period of time without increasing its driving range at all is simply not acceptable, specially when there is a low **SoC** of the battery. This issue will be considered in the following chapter, where the main objective of the **CSO** is to provide a minimum level of **QoS** to the vehicles at their time of departure.

Minimum QoS for EV Charging

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6.1 Introduction

In chapter 5 we demonstrated how more EV users can benefit from the EV charging infrastructure model proposed in this thesis, just by giving more flexibility on the way tasks are managed, as it is presented in the FlexTaSch approach. This flexibility allows the CSO to decide which tasks should receive a higher priority based on a particular criteria. By doing this, the available power at the grid is distributed more effectively through the charging infrastructure, which was not always the case when the CFCFS scheduling strategy was used within the CoTaSch approach.

However, the downside of the FlexTaSch approach is the QoS proposed to the final user, which had to be compromised. As presented in Chapter 5, the conservative approach CoTaSch guaranteed the customers that their vehicles will be fully charged when leaving the set of chargers. While the FlexTaSch approach occasionally left some EVs without being charged at all at their time of departure. From the users point of view, this is not acceptable, specially when the energy stocked in the battery would not be sufficient to cover the travel to the next destination of the driver without stopping for charging.

This chapter presents an original scheduling strategy which aims to propose a minimum QoS to drivers. Its main objective is to eliminate the EVs leaving the set of chargers without any changes in their SoC. Additionally, this strategy will try to provide a minimum amount of energy at time of departure. Such amount of energy should not be selected randomly, but based on user's needs as well as the weather conditions which could have an impact on the performance of the battery.

6.2 From Best Effort to Minimum Charge Warranty

As we previously mentioned, the final stage of this thesis is oriented towards the QoS proposed to the final user of this particular charging infrastructure. Therefore, the main objective is to eliminate the number of EVs leaving the charging station without being charged while charging as much EVs as possible. Additionally, the new strategy propose should try to guarantee a minimum amount of energy charged at the time of departure. This last condition is really important, as it could help to reduce the well known driver's anxiety by significantly increasing the driving range of an EV after a recharge.

At first glance, it could be considered as a simple solution to set a fixed minimum level of SoC by default, or a random amount of energy to deliver at the time of departure for all EVs. However, it must be reminded that the battery capacity is not the same for all EVs. Therefore, setting a minimum level of 50% of SoC, or charging 10% of the battery capacity will not correspond to the same amount of energy and driving range for all users. For this reason, choosing a minimum random amount of required energy is certainly not the best option. For providing a better QoS to the users, the DSO should have a better knowledge of their needs and the charging behavior.

6.2.1 Charging Behavior of EV Drivers

The work presented in [51] used an Activity Based Model (ABM) to generate activity travel schedules in the Flanders region of Belgium. A travel schedule consists of a trip defined by a

given time, a point of departure and its duration. This information allowed authors to predict the final destination of the vehicle and to estimate the charge requirement which is needed to cover the remaining distance. Authors in [25], considered the same ABM model to estimate the need for recharging during the day to complete the daily activity schedule of the EV drivers. The information obtained by the ABM model allowed to identify three sets of EV users. The first set consisted of EVs which cannot complete their daily schedule without modifying their path, as they require additional time for charging. This group concentrates 8% of the total. The second set considered those EVs that can finish their daily schedules without any mobility behavioral changes, such as intermediate recharging at work locations. This set was formed by 11% of the total. Finally, the third set consisted of EVs than can complete their daily activity schedule without any intermediate charging, it is represented by 81% of the EVs studied.

In a similar work, the charging patterns of EV users around Europe were studied in [36]. The study shows that the average SoC before starting a charging process is near 60% of the battery capacity, while only less than 5% of the users start a charge process or a trip with a SoC lower than 20%. This shows how the range anxiety can influence the users charging behavior, driving them to charge when the opportunity of is presented and not until it is required.

If we consider the charging patterns of the drivers from the studies previously presented, and we analyze the actual energy needed to complete a trip, it is possible to find that in some cases the connected EVs will manage to complete their next trip even without receiving a full charge. However, as part of the EV charging service, the user should receive a minimum amount of energy for increasing its driving range and reducing the range anxiety for the driver.

If the minimum amount of energy provided to the user is based only on a certain a level of SoC to be reached (i.e. 10% of the battery capacity for all the users), it will not be equal for all the users, as not all the batteries have the same capacity. However, if the energy requirement is based on an average trip schedule, it would be more fair for users, independently of the characteristics of their batteries. Therefore, our last charging strategy will consider as point of departure, the distance required to complete an average trip from home to work. This distance value will be adapted to the characteristics of each battery and converted into a service requirement S_i for each EV i .

6.2.2 Average Travel Distance

The autonomy of a typical EV is about 140 km in the real-world range [6,8] and can go up to 210 km under New European Driving Cycle (NEDC) testing. This distance range could be considered sufficient to cover the daily travel needs of an average EV driver. Looking at the values provided by different authors, the daily travel distance can be set between 50 km [62] and 70 km [36]. Moreover, it was found by [36] that 75% of the vehicles run a daily distance shorter than 47 km, which can be reduced to 35 km if only private vehicles are considered. The same study found that the average registered trip distance is about 7.4 km, which gets close to the 6.6 km of the average distance between home and work for people living in Paris and 15 km for people living in the suburbs according to [19] and [16].

In order to cover the same distance, the charge requirement of an EV should be personalized for each user. In [49], a platform is proposed to estimate the daily charge requirement of an EV charged at a household. The amount of required energy is calculated from the collected user's

data, such like driving patterns and its driving behavior. The amount of energy required should be sufficient to cover the predicted distance to complete the travel distance of the following day. However, collecting the information from the user cannot be performed directly, due to technical limitations, which forced the authors to develop a customized software.

For modeling purposes, we consider that the service requirement S_i of an EV i , corresponds to the minimum amount of energy needed to be served at the time of departure td_i , which should correspond to the equivalent distance of an average trip from home to work. Considering that most EV users will start a charge event with a SoC higher than 20% of the battery capacity. We assume that the minimum charge proposed would be sufficient to complete its following trip without an intermediate stop for a new recharge.

6.2.3 Influence of Environmental Temperature on Battery Performance

Authors in [29] estimate the EV energy requirement from the distance between charging stations of the network and propose the user a travel route with minimum energy consumption. The calculation of the battery's energy consumption considers several parameters, such as the topology of the road and traffic information among others, but not the temperature of the environment.

The work presented by [38] and [39] show the influence of the outside temperature on the attainable range of EVs. This study evaluated the relation between the energy consumption on the thermal management system and the temperature outside the EV. It was found that air conditioning loads can reduce the range by nearly 40%. Additionally, the range of the EV is reduced more considerably when the outside temperature drops. This happens because the thermal management consumption depends on thermal losses of the power train and the use of air conditioning or heating to fulfill the comfort requirements of the user.

This observation is supported by [36], where the authors identified a difference in the pattern of energy consumption according to the season of the year and the geographical location. It was found that users can double the range distance with the same storage system, simply as a result of the environmental temperature. This is translated to an energy consumption of 0.16 kWh/km in summer versus 0.32 kWh/km in winter.

6.2.4 Conversion From Minimum Range Distance Into a Charge Requirement

If the technology available at the CSO for data exchange between the EV and the EVSE allows it, the travel distance required to complete a trip from home to work can be obtained by analyzing the user's behavior. If not, the average travel distance of the users in the area could be used instead. Once this travel distance is known by the CCM, it needs to be expressed in terms of energy which will constitute the minimum charge requirement We_i of an EV i . In [78] the authors provide a model for estimating the remaining driving distance, which we have considered as a point of departure to calculate the minimum charge requirement We_i of a task T_i at its time of

arrival ta_i , which is defined by the following equation:

$$We_i(ta_i) = \frac{MTD_i \times Ec_i}{C_i}. \quad (6.1)$$

where MTD_i denotes the minimum travel distance to guarantee (km), Ec_i is the energy consumption of the battery (kWh/km) and C_i is the battery capacity of the vehicle (kWh). The values of C_i and Ec_i are obtained from the specifications provided by the manufacturer, thus We_i is expressed a percentage of the SoC of the battery.

6.2.5 Loads Modeled as Tasks

In Chapter 5, we presented how EVs arriving at the set of charging points are considered as deferrable loads and therefore they can be processed as tasks. Just like the model presented in Chapter 5, the tasks are considered as preemptive, in order to keep its flexibility. In the present chapter, we introduce an original on-line scheduling strategy referred as Minimum SoC Warranty (MSoCW). The service demand S_i of a given EV i is still characterized by $(ta_i, td_i, SoC_i(ta_i), SoC_i(td_i))$ as it was presented in Chapter 5, where ta_i corresponds to the time of arrival at the ChP, td_i is the time of departure, $SoC_i(ta_i)$ is the SoC of the EV at its time of arrival and $SoC_i(td_i)$ is the desired SoC at its time of departure. However, besides the energy requirement Er_i of the Task T_i , the CCM will now estimate the minimum energy requirement to fulfill, referred as We_i . The energy requirement Er_i of a task T_i is calculated as in Chapter 5 at its time of arrival ta_i as shown in Equation(6.2).

$$Er_i(ta_i) = [SoC_i(td_i) - SoC_i(ta_i)] \times C_i \quad (6.2)$$

Every time the CCM updates the information of the EVs connected to the grid, the CCM will update the SoC of the batteries and compare it with the SoC demanded by the user to fulfill its energy requirement. Then, the energy shortfall Es_i of the task T_i is obtained, which indicates the amount of energy left to complete the energy requirement of the task at time t before its time of departure td_i .

$$Es_i(t) = [SoC_i(td_i) - SoC_i(t)] \times C_i \quad (6.3)$$

We note that Es_i is updated by the system each time a new EV arrives, when a task reaches its requested SoC or the minimum SoC proposed by the CSO, or when the conditions on the PLS electrical network change.

As a result of adding the minimum energy requirement We_i , the minimum energy requirement shortfall WEs_i of the task T_i should be obtained as well, which indicates the amount of energy left to serve at time t to reach the minimum level of charge guaranteed by the CSO at the time of departure td_i .

$$WEs_i(t) = [WSoC_i(td_i) - SoC_i(t)] \times C_i \quad (6.4)$$

where $WSoC_i(td_i)$ denotes the SoC of the battery that must be reached in order to fulfill the minimum energy requirement proposed to the EV at its time of departure td_i .

Finally, a task T_i is characterized by $(ta_i, td_i, Er_i, Es_i, We_i, WEs_i)$.

Laxity of a Task

The laxity of the task remains an important parameter to demonstrate the feasibility of a given task. As presented in Chapter 5, a task T_i was considered as feasible if at the moment of the service request, the laxity obtained with the highest charge rate available for charging the EV was positive. However, we observed that this only guarantees a task to be only feasible if the maximum charge rate is applied during the whole process. If eventually, the priority of the task is not high enough to be charged at the maximum charge rate, it could either be charged at a lower charge rate, or in the worst case scenario the task would be relegated at the bottom of the task scheduler and it would not be charged at all. In order to avoid this possibility and to guarantee a minimum charge We_i at time of departure td_i , the EV could only be accepted if the laxity obtained for the minimum charge requirement is positive when the slowest charge rate available is applied.

Like in Chapter 5, the laxity $l_i(t)$ of a task T_i for the energy shortfall Es_i at time t is defined by the following equation:

$$l_i(t) = (td_i - t) - \frac{Es_i(t)}{r_i(t)}. \quad (6.5)$$

where $(td_i - t)$ is the time remaining before the time of departure of the EV, the time needed to complete the minimum charge is given by the energy shortfall $Es_i(t)$ and the considered charge rate $r_i(t)$ to complete the task.

Additionally, the laxity $lw_i(t)$ of a task T_i for the minimum energy requirement shortfall Wes_i at time t is defined by the following equation:

$$lw_i(t) = (td_i - t) - \frac{Wes_i(t)}{rmin_i(t)}. \quad (6.6)$$

where the time needed to complete the minimum charge is now given by the minimum energy requirement shortfall $Wes_i(t)$ and the slowest charge rate considered $rmin_i(t)$ to complete the task, which should correspond to the slow charge (1.4kW). This laxity, will be used as reference for accepting a new EV into the network.

6.2.6 On-line Scheduling and Task Dispatching

Most of the on-line scheduling strategies evaluated in Chapter 5 registered a group of tasks that are relegated at the bottom of the task scheduler by new EVs arriving to the set of chargers. In order to avoid this phenomenon, the task scheduler will implement a new on-line scheduling strategy that will not only decide the priority of a task based on a single parameter but on a combination of parameters. As in the strategies considered in Chapter 5 within the FlexTaSch approach, the feasibility of the tasks will be evaluated before being accepted for charging. If a given task is accepted, it is placed at the task scheduler where it will be sorted among the other tasks according to the priority assigned by the CCM before being dispatched.

Minimum SoC Warranty (MSoCW)

MSoCW is the new scheduling strategy proposed in this chapter. This policy sorts the tasks on the task scheduler according to their deadline and their energy shortfall Es_i . It is a combination of the charging strategies HESF and EDF previously studied in Chapter 5.

A) Feasibility Test for Accepting a New Task

Following the same logic as the rest of the on-line scheduling policies within the FlexTaSch approach, each time the CSO receives a new service request from an EV, the CCM has to test the feasibility of the task before accepting it for charging as shown in Figure 6.1. As we previously mentioned, the feasibility test evaluates if the minimum energy requirement could potentially be dispatched at the time of departure using the slowest charge rate available (1.4 kW).

B) Update of the Task Scheduler by the Task Manager

If the EV is accepted, the tasks scheduler updates the current SoC value for all the batteries of the EVs connected and sorts the tasks according to their charge rate in a list referred as *charge rate list*, as shown in Table 6.2.6(a).

Charge rate list

Tasks are sorted from the fastest to the slowest charge rate by means of two sub-lists. The first sub-list consists of all tasks with a positive laxity for their minimum energy requirement We_i , while the second list contains the remaining tasks with negative laxity. Ties are broken by the position of the ChP, from the closest to the farthest charger from the transformer.

Priority list

At a second step, the *priority list* is created as presented in Table 6.2.6(b). For this, tasks are sorted according to the priorities defined by the MSoCW policy. Which are on favor of tasks that have not yet fulfilled their We_i and have a closer deadline. Therefore, a set of sublists is used to form the priority list in the following order.

- **Highest minimum energy shortfall first**

In first place are chosen those EVs which have not reached at time t their minimum energy requirement We_i and have a positive laxity lw_i . Tasks are sorted from the highest to the lowest minimum energy shortfall Wes_i needed to reach their We_i . In our example, the current SoC of task T_3 is still 15% behind its minimum energy requirement $Wes_3 = 15\%$, while T_1 has already completed it, $Wes = -3\%$, thus T_3 goes first, considering all the charge rates with positive laxity.

- **We_i reached and closest deadline first**

The second sublist of the priority list is now filled with those EVs that have already fulfilled their We_i and it is still possible to complete their energy requirement Er_i at time of departure, which means that they have a positive laxity. Tasks are sorted according to their deadline, from the closest to the latest. In our example, this is the case of task T_1 , with charge rates of 7kW and 3.3kW. The charge rate of 1.4 kW has a negative laxity and therefore is not added at this step.

- **Negative laxity tasks**

Finally, in the third sub-list of the priority list all the EVs that remain from the charge rate list are sorted, even when they present negative laxity values. Tasks are sorted from

Charge rate list								Priority list					On-line list	
Positive laxity														
T_i	Er_i	We_i	ta_i	td_i	Es_i	WEs_i	ri	T_i	Es_i	WEs_i	td_i	r_i	T_i	r_i
T_1	51%	17%	t_0	t_{+4}	31%	-3%	7	T_3	39%	15%	t_{+5}	7	T_3	7
T_3	42%	18%	t_{0+2}	t_{+5}	39%	15%	7	T_3	39%	15%	t_{+5}	3.3	T_2	3.3
T_1	51%	17%	t_0	t_{+4}	31%	-3%	3.3	T_3	39%	15%	t_{+5}	1.4	T_2	3.3
T_2	46%	14%	t_{0+1}	t_{+7}	42%	10%	3.3	T_2	42%	10%	t_{+7}	3.3	T_1	3.3
T_3	42%	18%	t_{0+2}	t_{+5}	39%	15%	3.3	T_1	31%	-3%	t_{+4}	7		
T_3	42%	18%	t_{0+2}	t_{+5}	39%	15%	1.4	T_1	31%	-3%	t_{+4}	3.3		
Negative laxity														
T_1	51%	17%	t_0	t_{+4}	39%	-3%	1.4	T_2	42%	10%	t_{+7}	1.4		
T_2	46%	14%	t_{0+1}	t_{+7}	42%	10%	1.4	T_1	31%	-3%	t_{+4}	1.4		
(a)								(b)					(c)	

Table 6.1 – Lists used by the task scheduler for defining the order of connection of the tasks under MSoCW.

the largest energy shortfall to fulfill their minimum energy requirement We_i followed by the tasks with a higher shortfall to complete their energy requirement Er_i . For this reason, in our example, T_2 is sorted before T_1 .

- **Close deadline zero SoC dispatched**

The CCM periodically updates the evolution of all the charging processes. If it identifies a task that has not been charged, which means that a task still has the same SoC that it presented at its ta_i and its deadline is near. In this case, the task will overrule the other tasks on the scheduler and will be placed at the top of the priority list. This could be considered as the last resource of the CCM for not leaving any task without charging at their time of departure. The vicinity of the deadline is defined by the CSO.

On-line list

Finally, the CCM simulates off-line the connection of the tasks according to the order in which they are sorted in the priority list as presented in Figure 6.2. If the available power at the grid allows to charge the selected EV, the feasibility of the connection is tested. If the connection can be supported, the task T_i is added at the bottom of the last list of the scheduler, referred as on-line list as shown in Table 6.2.6(c). If the task cannot be supported at a given charge rate, then the next entry of the priority list is tested. If a task T_i has already been added to the on-line list, the scheduler skips the task in the priority list if it is found again, passing to the next entry. When all entries of the priority list have been explored, the CCM adjusts the charge rates of the connected vehicles according the values on the on-line list for each task.

6.3 Experimental Setup

This section presents the set of parameters and constraints considered for the electric network at the PLS and necessary to build up the different test scenarios conceived for the simulations.

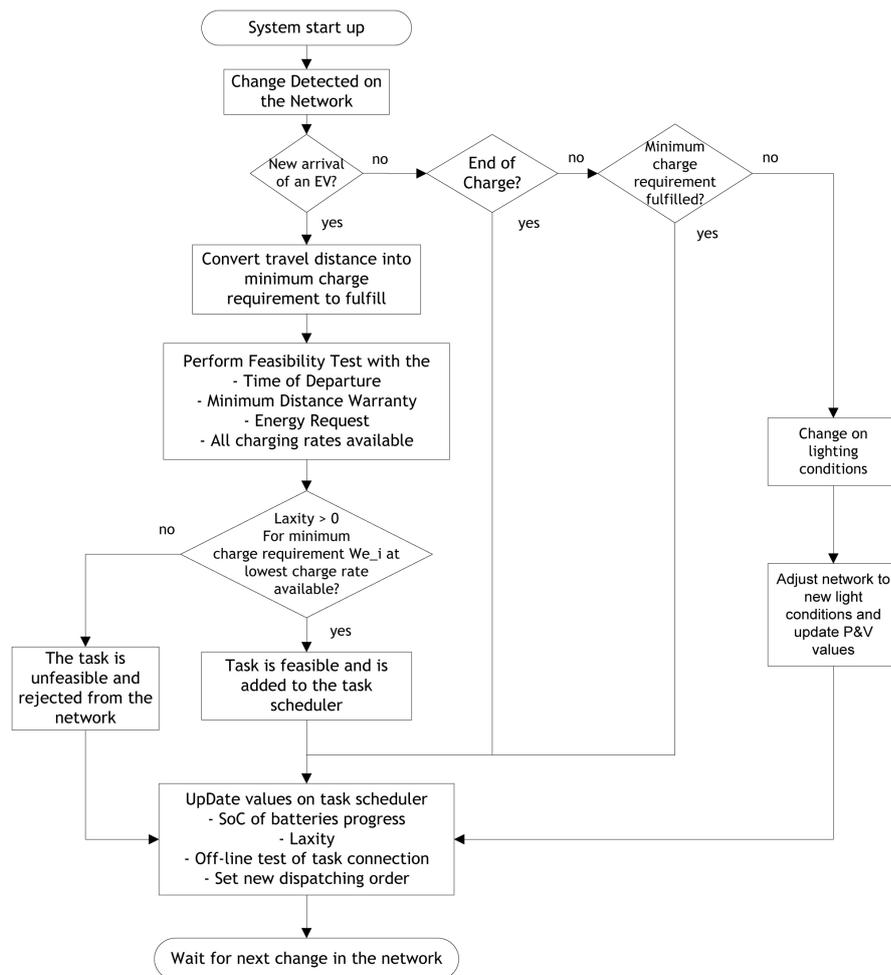


Figure 6.1 – Updating process for the task manager used for on-line scheduling strategies

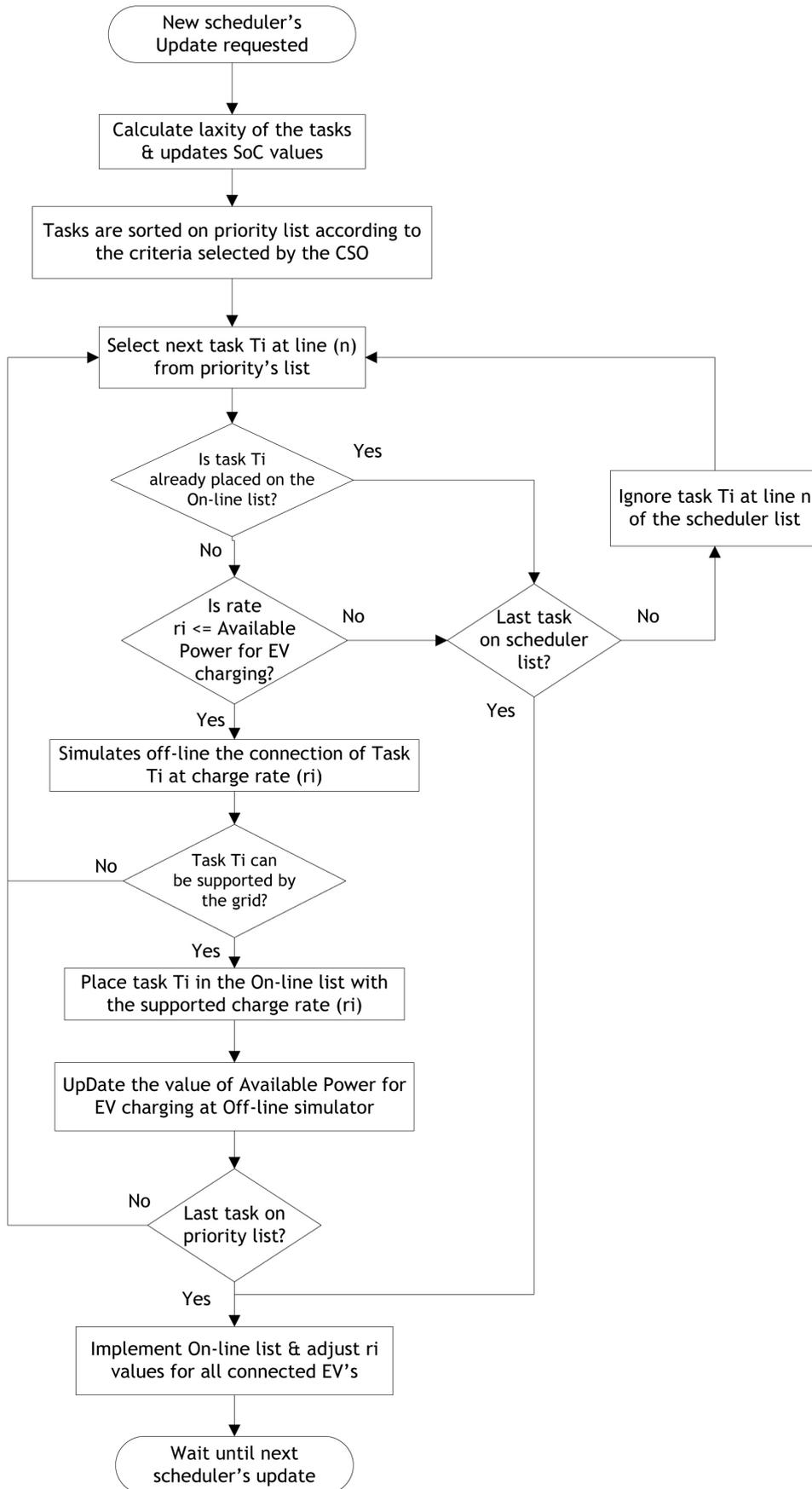


Figure 6.2 – Connection test of EVs according to the task scheduler before updating the charge rate values of the connected EVs.

Transformer	14.5 kVA of power available
Lamps	90 lamps 145 W at nominal power Dimming at night is allowed
Chargers	9 & 12 chargers Placement near the transformer Charger Selection policy : Closest Charger First (CCF) 2 supported charge rates: Slow & Standard 3 supported charge rates: Slow, Standard & High Power
Daylight Conditions	Summer & Winter scenarios 15 days of 24 hours tested
Vehicle's Distribution	84% of EVs, 7% of PHEV-1 & 9% of PHEV-2 10, 20, 30, 40, 50, 60, & 70 EV arrivals per day

Table 6.2 – Assumptions for the operational constraints of the PLS electric network.

Stage	Summer	Winter	Power Consumption of the Lamps
Day light	05:00 - 21:43	08:43 - 16:43	OFF
LHS	21:43 - 22:13	16:43 - 17:13	Nominal + 15%
Early Night	22:13 - 00:00	17:13 - 00: 00	Nominal
Late Night	00:00 - 04:00	00:00 - 04:00	Nominal –35%
Early Morning	04:00 - 05:50	04:00 - 08:43	Nominal

Table 6.3 – Power consumption of the lamps on the PLS according to the daylight conditions for the summer and winter scenarios considering the dimming of the lamps during the late night stage.

6.3.1 Electrical network assumptions

Most of the values used in Chapter 5 to simulate the conditions of the network are valid for the MSoCW charging strategy. Therefore a summary of the constraints and values considered is presented in Figure 6.2.

The day-light stages and power consumption by the lamps considered for testing FlexTaSch are the same as those presented on Table(6.3).

6.3.2 State of Charge and Charge Rates

For benchmark purposes, the SoC_i of EV i at time of arrival ta_i is randomly and uniformly distributed between 20% and 35% of the battery capacity and between 60% and 80% at time of departure td_i . However, the minimum charge requirement We_i is calculated for each EV i according to the minimum distance range guaranteed to the final user. For our test-bed, we considered this value as the average distance of a home to work trip in the parisian area [19]. A summary of battery sizes, available charge rates and minimum range distance for each type of EV is presented in Table(6.4).

The distance range for PHEVs is fixed at 7 km, while for EVs it is considered between 7 and

Type of Vehicle	Average Battery Size (kWh)	Allowed Charging Rate (kW)	Minimum Distance Range (km)
EV	22	1.4 or 3.3 or 7	7 to 15
PHEV - 1	6	1.4	7
PHEV - 2	16	1.4 or 3.3	7

Table 6.4 – Battery capacity according to the type of vehicle [8,14,35], the charge rates supported by the charger and the minimum distance range to guarantee to the driver.

Arrival Group	Proportion of EV Arrivals	Time of Arrival		Parking time	
		μ	σ (in hours)	μ	σ (in hours)
AM (μ_1, σ_1)	30 %	09h00	0.42	5	0.5
MD (μ_2, σ_2)	30 %	14h00	3.4	5	0.5
PM (μ_3, σ_3)	40 %	19h30	0.85	(7am+1day) - t	0.5

Table 6.5 – Distribution of time of arrival and time of departure for EVs during a normal day according to their group of arrival.

15 km. The time of arrival (ta_i), time of departure (td_i) and parking time (tp_i) accorded to each EV i are randomly supplied from a normal distribution which parameters are in Table 6.5.

6.4 Performance Metrics

In order to compare all the previously presented scheduling strategies, the metrics considered in Chapters 4 and 5 are maintained for the new scheduling strategy MSoCW. The performance metrics, we recall, are:

- **Acceptance rate of vehicles:** Shows the proportion of vehicles rejected from charging out of the total EVs arriving at the set of chargers.
- **Average transmission and distribution power losses:** It accumulates the total amount of power lost in the transmission lines during the simulation process and then obtains the average amount of losses per hour.
- **Dispatched Vs demanded energy ratio:** Calculates the total amount of energy dispatched to the EVs and compares it to the total amount of energy that was originally requested by the EVs accepted for charging.
- **Average unserved energy:** Measures the average amount of energy per hour that was not consumed either by the lamps nor by the vehicles. This metric is expressed in kWh/h.
- **Quality of Service and SoC at time of departure:** Evaluates the percentage of the energy requirement that was fulfilled for accepted EVs. The degree of accomplishment of the task will be graded according to the levels shown in Table 6.6. Additionally, this metric has been extended to show the achievement on the minimum charge requirement at the time of departure.

Charge Level	Percentage of the Charge Request Fulfilled at Time of Departure
No Charge	<1%
Weak	1 % to 20 %
Low	21 % to 40 %
Moderate	41 % to 60 %
Major	61 % to 80 %
Substantial	81 % to 99 %
Full Charge	100%

Table 6.6 – Percentage of energy served to the battery from the total energy requested.

Day-light conditions	Summer scenario (with dimming of lamps) Winter scenario (with dimming of lamps)
Distribution of chargers	Charger connected close to the transformer
Selection of charger	Closest Charger First (CCF)
EV penetration rates	10, 20, 30, 40, 50, 60 & 70 EVs /Day
EV charge rates available	Slow & Standard Charge (1.4 & 3.3 kW) High Power Charge Added (1.4, 3.3 & 7 kW)
EV scheduling policy	Minimum SoC Warranty (MSoCW)

Table 6.7 – Summary of network conditions and scenarios for the second approach of the model based on an on-line scheduling of the tasks with a warranty of a minimum charge requirement provided at time of departure.

6.5 Numerical Results

The parameters taken into account for the operation of the PLS electrical network slightly changed from those presented in Chapter 5, the most important change is the addition of a minimum charge requirement previously presented. This change allowed us to implement the new MSoCW charging strategy within the FlexTaSch approach. A summary of all the scenarios and conditions is presented in Table 6.7.

We have compared the results obtained for MSoCW with those obtained for the rest of the scheduling policies. Hereby, we will refer as "flexible policies" to the set of scheduling policies presented on the FlexTaSch approach, which are the following: FCFS, EDF, LESF, HESF and LLF.

6.5.1 Acceptance Rate of Vehicles for Charging

As previously mentioned, the scheduling strategies studied in Chapter 5 accepted a task for charging only when its energy requirement was feasible with the highest charge rate available at the charger and supported by the EV. However, for the new scheduling strategy MSoCW tasks are now accepted if their minimum energy requirement We_i can be fulfilled by the CSO at its time

of departure using the slowest available charge rate (1.4 kW).

This modification in the admittance conditions for charging lead to a little change in the number of accepted EVs at the set of chargers. We observed that low penetration rates (10 and 20 EVss / day) presented considerably more accepted EVs than for the rest of the strategies, specially during the summer scenario with two available charge rates. On the other hand, in winter the rejection rate presented by MSoCW is slightly lower than for LLF but higher than the rest of the flexible policies with 9 deployed chargers.

Figure 6.3a shows the values obtained via simulations for MSoCW. For medium and high penetration rates of EVs arriving at the set of chargers, the acceptance rate presented by MSoCW is between 3% and 8% lower than for all the average of the "flexible" scheduling policies considered within the FlexTaSch approach as shown in Figures 6.3band 6.3c. However, the acceptance levels are significantly higher compared to those of CFCFS. These results show that the MSoCW strategy responds in a similar way than the rest of the on-line scheduling policies, with only light variations depending more on the penetration rate of EVs and season of the year, than any other parameters. Complete simulations results are available in Appendix.

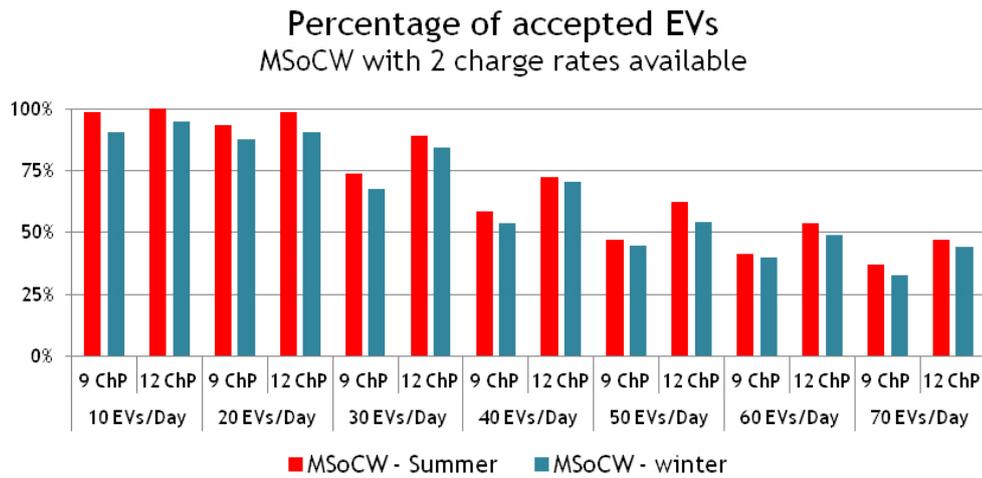
6.5.2 Average Transmission and Distribution Power Losses

MSoCW shows a similar performance in terms of energy losses than the rest of the on-line scheduling considered by the FlexTaSch approach. As presented in Chapter 5, the losses are related to the total amount of accepted EVs and by consequence the total amount of dispatched energy. For this reason, the total amount of energy losses follows the same pattern than the rejection rate. It must be remembered, that there is more power consumed by the lamps in winter than during summer, and therefore the value of losses per load served increases as well during this period. Figures 6.4a and 6.4b show the amount of losses per load, which approaches the values presented in Chapter 5 in Figure 5.5.

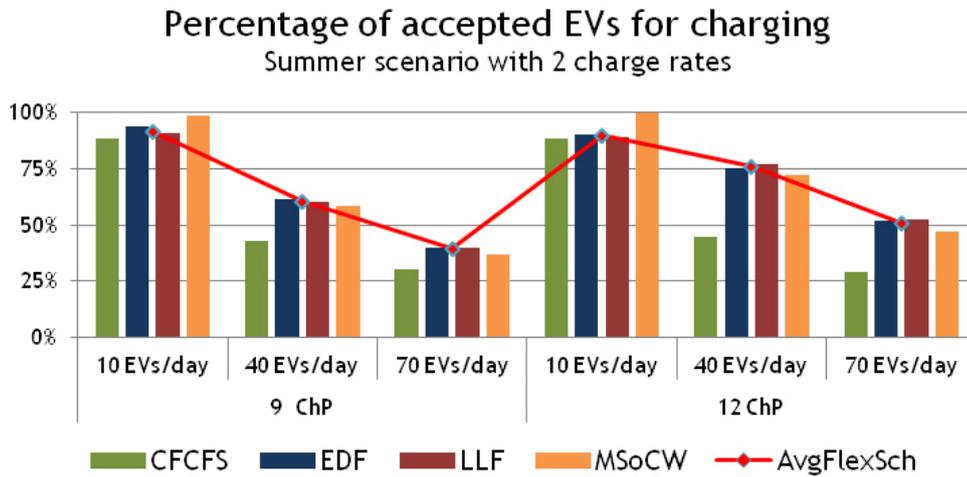
6.5.3 Ratio Between Dispatched Energy and Requested Energy

If the MSoCW scheduling strategy is analyzed separately from the FlexTaSch scheduling policies previously presented in Chapter 5, the amount of energy dispatched to the loads is considerably higher during summer than in winter, as shown in Figures 6.5a and 6.5b. This result was expected, as the power available for EV charging during summer allows to serve more EVs than in winter. This behavior is valid for all tested penetration rates. Additionally, there is more energy dispatched to the EVs when three charge rates are supported by the chargers, than the case where only two charge rates are available.

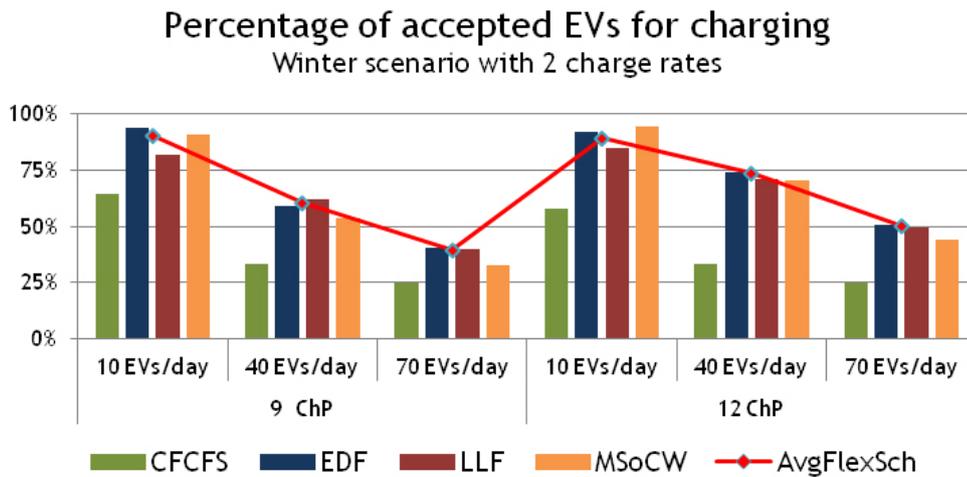
When MSoCW is compared to the rest of the scheduling policies (FCFS, EDF, LESF, HESF, LLF), the total amount of dispatched energy is within the average of the other policies at low penetration rates of EVs. While for medium and high penetration rates, the result is slightly lower, that can be related to the rejection rate and the arrival of EVs to the set of chargers. When more EVs request a charge to the CSO, the number of rejected EVs grows as well. This is because more chargers are occupied by other EVs, which means that more EVs need to be charged and therefore, more energy is dispatched to those chargers, which does not happen at low penetration rates of EVs.



(a) Percentage of accepted EVs for summer and winter scenarios with 9 and 12 ChP deployed under MSoCW with 2 charge rates available.

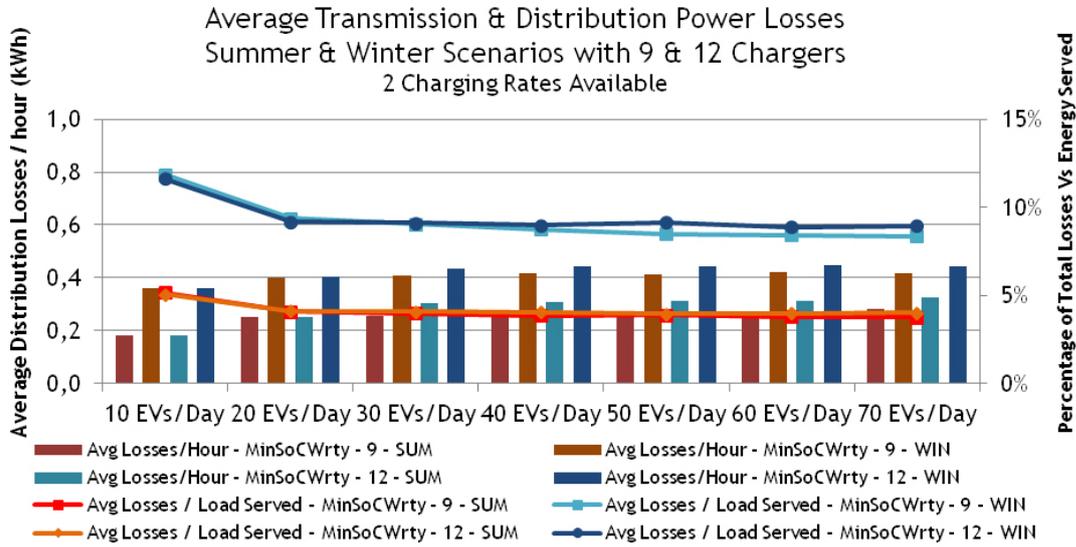


(b) Percentage of accepted EVs for summer scenarios with 9 and 12 ChP deployed with 2 charge rates available for MSoCW, CFCFS, LLF and the average rate obtained for the flexible policies.

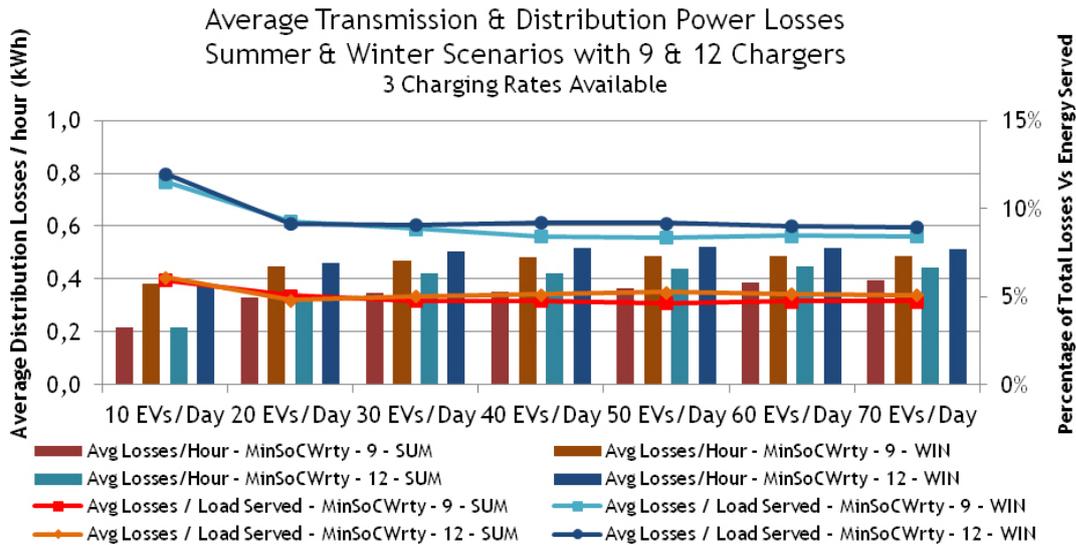


(c) Percentage of accepted EVs for winter scenarios with 9 and 12 ChP deployed with 2 charge rates available for MSoCW, CFCFS, LLF and the average rate obtained for the flexible policies.

Figure 6.3 – Average acceptance rate of EVs with MSoCW and a comparison with the rest of the flexible policies and CFCFS.



(a) Average transmission and distribution power losses and the relation between the total energy losses Vs the total amount of energy served to the loads, considering the summer and winter scenarios with two charge rates proposed by the network under *MSoCW*.



(b) Average transmission and distribution power losses and the relation between the total energy losses Vs the total amount of energy served to the loads, considering the summer and winter scenarios with three charge rates proposed by the network under *MSoCW*.

Figure 6.4 – Average transmission and distribution power losses and the relation between the total energy losses Vs the total amount of energy served to the loads, considering the summer and winter scenarios under *MSoCW*.

However, it must be mentioned that for the majority of the simulated scenarios using the **MSoCW** strategy, the amount of dispatched energy to the **EVs** in comparison to the total requested energy is above the average presented by the rest of the flexible policies. This caught our attention, as despite of the fact that **MSoCW** presents a slightly higher rejection rate, the same available energy on the grid could be distributed better and it could reach more users. A similar scenario was previously observed for **CFCFS** in Chapter 5. However, the results for **MSoCW** are better, because **MSoCW** has a lower rejection rate than **CFCFS** and more users can benefit from the service.

6.5.4 Average Unserved Energy

If only two charge rates are supported by the chargers on the grid, it can be observed in Figure 6.7a that even in winter it could potentially be possible to connect an additional charger to the grid and charge one more vehicle at least at 1.4 kW. On the contrary, when three charge rates are supported by the chargers, we observe how the grid is working at its limits, which would make it difficult to consider adding another charger as a good choice for the **CSO**.

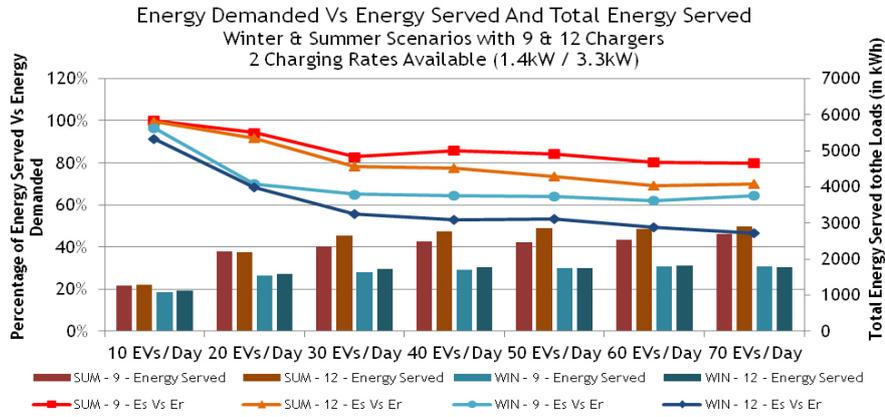
When **MSoCW** is compared to the rest of the policies, we found that at low penetration rates the values presented are within the average of the flexible policies, as shown in Figure 6.7b. However, when there are more **EVs** arriving per day, the average unserved energy values could be higher than the average. This result is once again a direct consequence of the higher rejection rates found for **MSoCW**, which could present some chargers without any connected **EVs** during longer periods of time.

In general terms, we can conclude that the amount of unserved energy may not significantly change with the addition of chargers to the infrastructure. As it can be observed in Figures 6.7a and 6.7b, for the winter scenarios the amount of average unserved energy is quite similar, whether 9 or 12 connected chargers are connected and they support the same charge rates. The real change on the network is when three different charge rates are considered (1.4 kW, 3.3 kW or 7 kW), instead of only the first two. As even with only 9 chargers and 3 available charge rates, there is less energy unserved than when 12 chargers are deployed but they only support two charge rates.

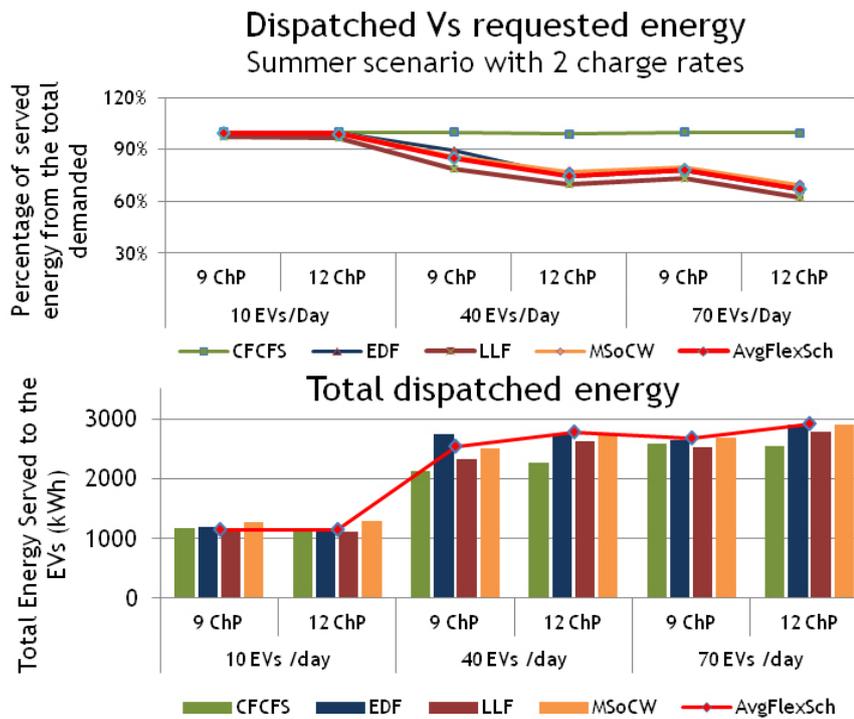
6.5.5 Quality Of Service and SoC at Time of Departure

As we presented in Chapter 5, it is the **QoS** provided to the **EVs** which shows the most significant differences in the results among the considered scheduling strategies. The most remarkable result obtained for **MSoCW** is the elimination of **EVs** leaving their **ChP** without receiving any amount of energy. As shown in Figure 6.8, the group **0%** is not visible anymore for this particular policy. Which is not the case for the rest of the policies presented in Chapter 5, where all charging strategies registered some **EVs** at this group, with the only exception of **CFCFS**.

On the other hand, the group of **EVs** that receive a full charge at time of departure (**group 100%**) registered considerable good figures overall, which is similar to the results obtained using the **HESF** policy. We observed that most of the time, the total amount of fully charged **EVs** was higher than the same values obtained using **LLF**, with the major difference that **LLF** presents a considerable larger amount of **EVs** leaving the charging station without charge, specially under winter day-light conditions.



(a) Total served energy (in kWh) and the ratio between dispatched and requested energy for summer and winter scenarios with 2 charge rates under MSoCW.



(b) Total served energy (in kWh) and the ratio between dispatched and requested energy for summer scenarios with 2 charge rates for MSoCW in comparison with the rest of the policies.

Figure 6.5 – Total dispatched energy (in kWh) and the ratio between dispatched and requested energy by the loads for MSoCW with 2 charge rates available.

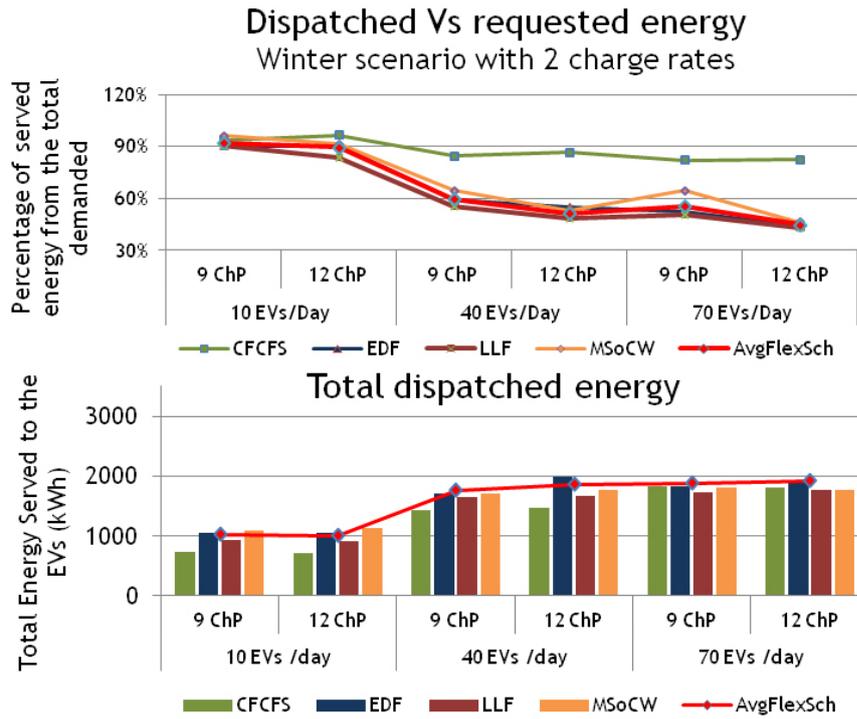
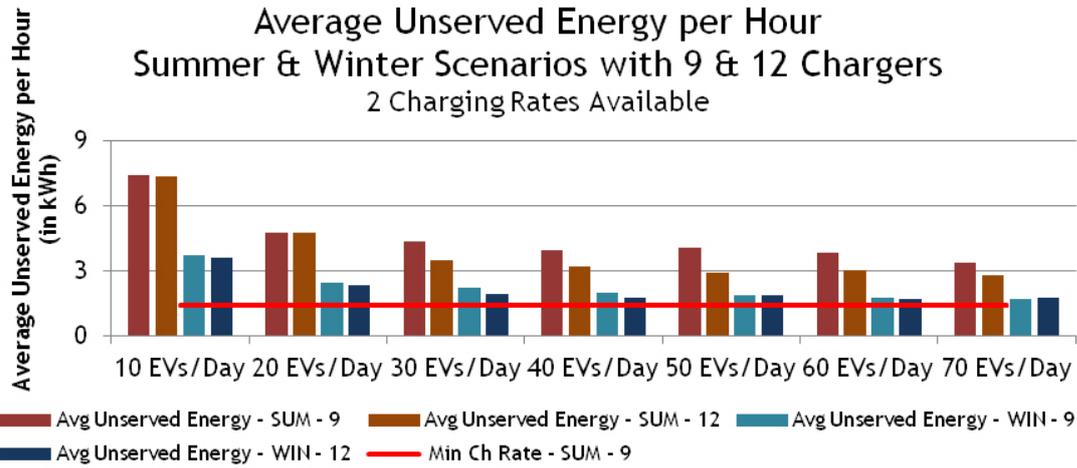


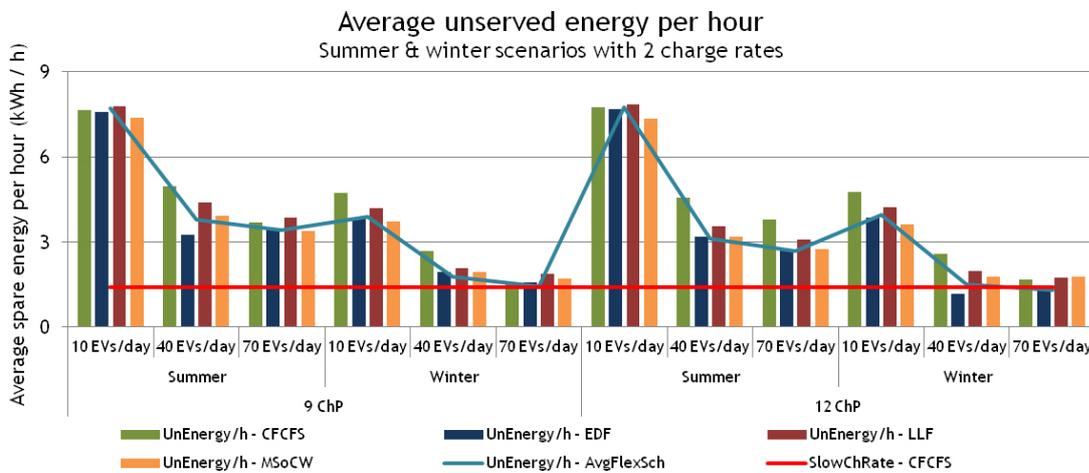
Figure 6.6 – Total served energy (in kWh) and the ratio between dispatched and requested energy for winter scenarios with 2 charge rates for MSoCW in comparison with the rest of the policies.

When MSoCW is compared to the flexible strategies that registered better QoS performance (LESF or EDF), it is certain that MSoCW has lower levels of EVs fully charged, but at the same time this policy has more EVs with **major** (61% to 80%) or **substantial** (81% to 99%) levels of charge from the demanded energy. As a result, there are fewer EVs with a **weak** charge (1% to 20%) for MSoCW. This means that even during the winter scenarios and high penetration rates, more than 35% of accepted EVs leave their ChP with more than 61% of the total requested charge. This could be considered an improvement on the service for the final user, since there are no more EVs leaving the set of chargers without being charged.

Regarding the QoS for the minimum charge requirement of the tasks, MSoCW manages to fulfill all the charging requests under summer day-light conditions. However, within the winter scenario some EVs could not complete the minimum energy requirement. In first place, this is due to the fact that the power available for EV charging is reduced in winter as it has been stated previously in this work. Additionally, the minimum charge requirement depends on the conversion from the minimum travel distance into an energy requirement. Under winter day-light conditions the same distance corresponds to the double amount of energy required by the tasks in the summer scenario. Therefore, in winter there is a higher demand of energy from the tasks in order to reach the minimum charge requirement and less power available in the electrical network.

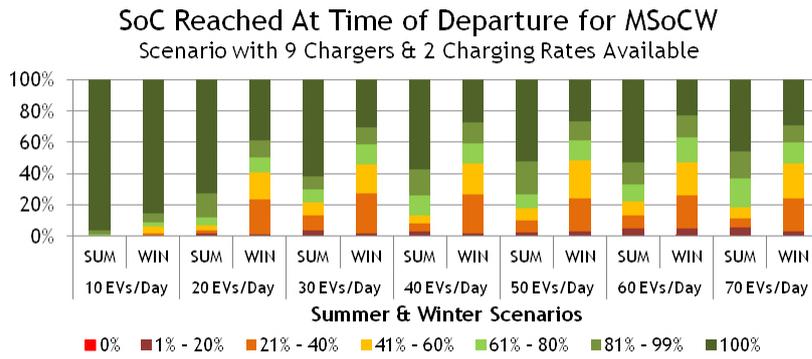


(a) Average Unserved Energy per hour at the network for all summer & winter case scenarios with 2 charging rates available and MSoCW

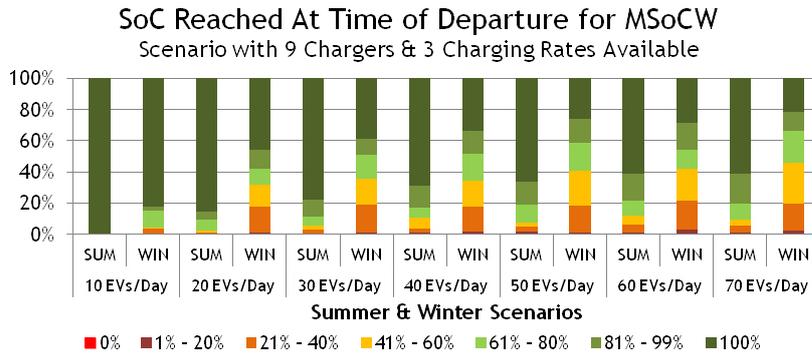


(b) Average Unserved Energy per hour at the network for all summer & winter case scenarios with 2 charging rates available and MSoCW

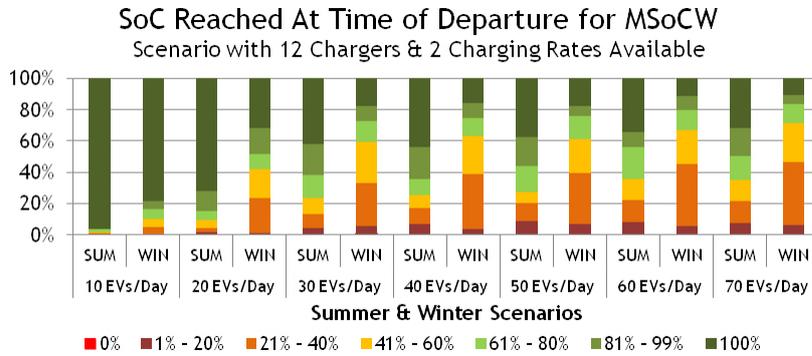
Figure 6.7 – Average Unserved Energy per hour at the network for all summer & winter case scenarios and MSoCW



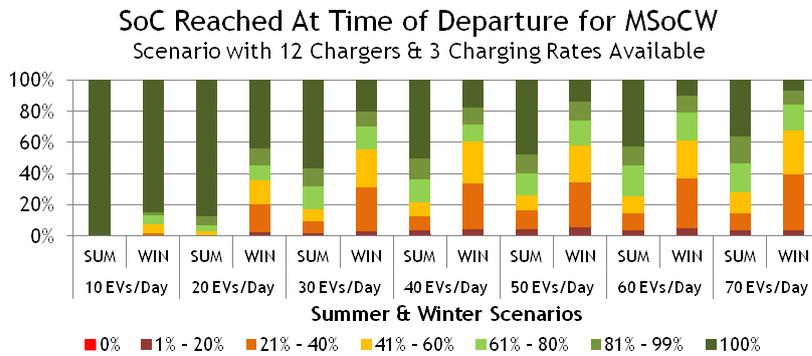
(a) MSoCW with 9 chargers and 2 charging levels



(b) MSoCW with 9 chargers and 3 charging levels

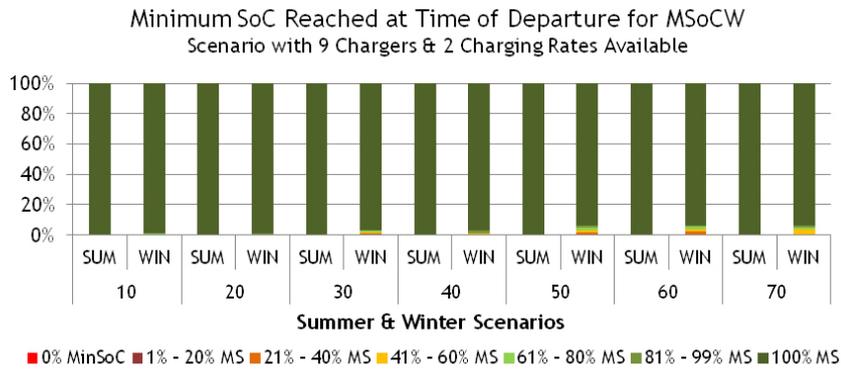


(c) MSoCW with 12 chargers and 2 charging levels

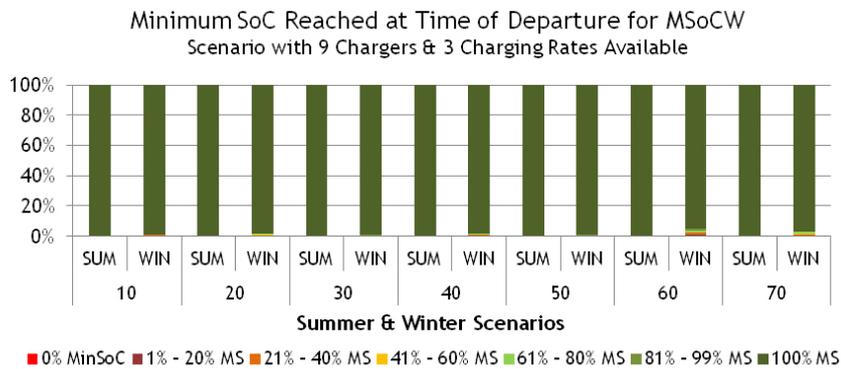


(d) MSoCW with 12 chargers and 3 charging levels

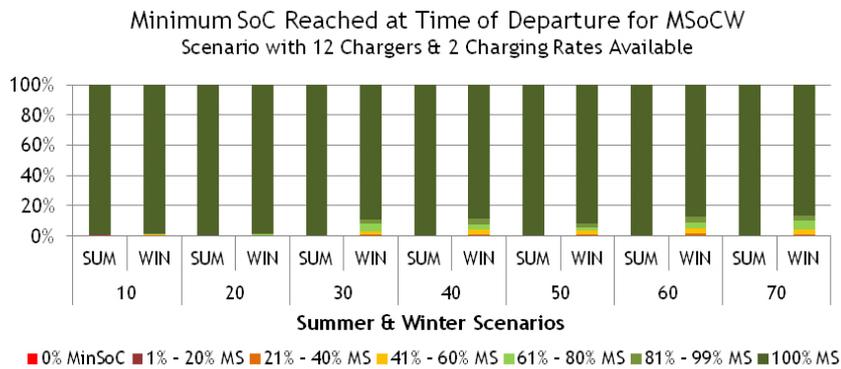
Figure 6.8 – Percentage of charge reached at the time of departure from the total energy requirement demanded at arrival time for all summer and winter scenarios under MSoCW



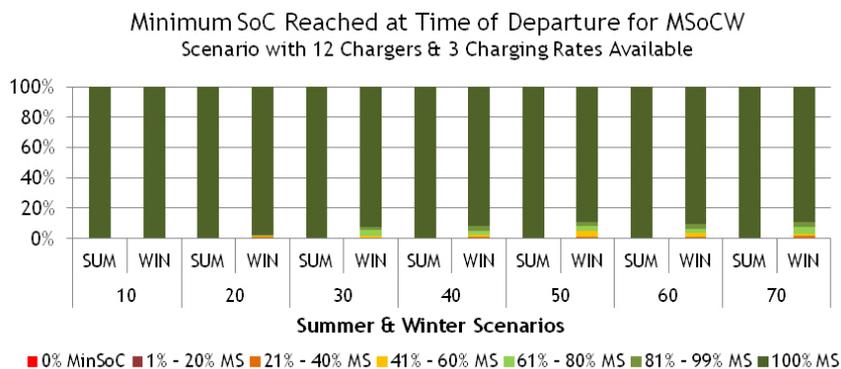
(a) MSoCW with 9 chargers and 2 charging levels



(b) MSoCW with 9 chargers and 3 charging levels



(c) MSoCW with 12 chargers and 2 charging levels



(d) MSoCW with 12 chargers and 3 charging levels

Figure 6.9 – Percentage of charge reached of the minimum energy requirement corresponding to the minimum charge requirement demanded at the time of departure for all summer and winter scenarios under MSoCW

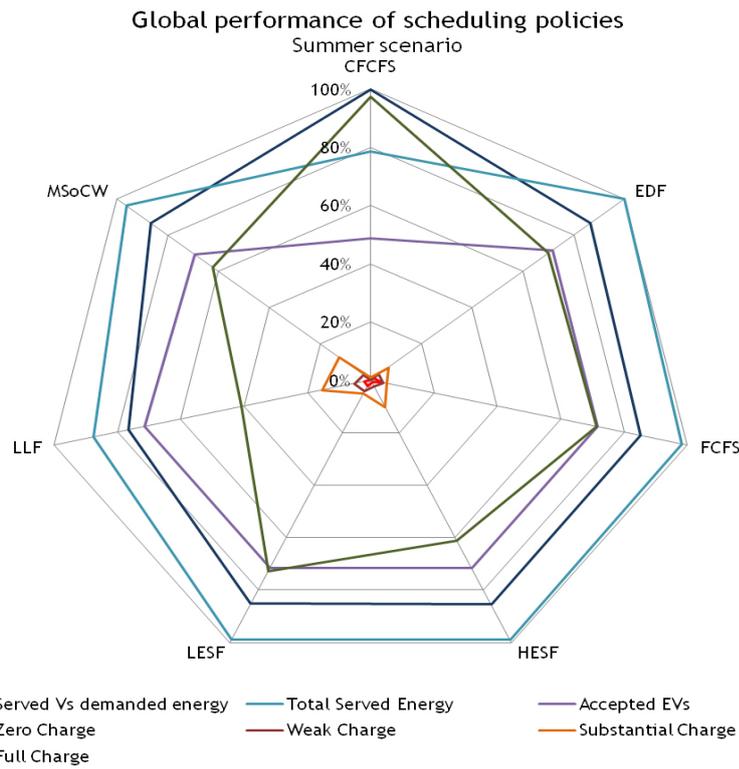
6.5.6 Global Results for Scheduling Policies

To conclude this analysis, we have considered all the results obtained for each scheduling policy studied in this thesis in order to give a global view of the results obtained. For this, we have separated the obtained results for summer and winter and then considered all the penetration rates, charge rates and number of ChP available on each simulated scenario for each policy according to each metric. Figures 6.10a and 6.10b show for each scheduling policy, the percentage of the objective achieved for a given metric or a particular parameter of the metric. Thus, we display, the ratio between the served and demanded energy, the percentage of accepted EVs and the total amount of served energy. For the former, the percentage is in comparison to the scheduling policy with the maximum value achieved, which was EDF in summer and HESF in winter.

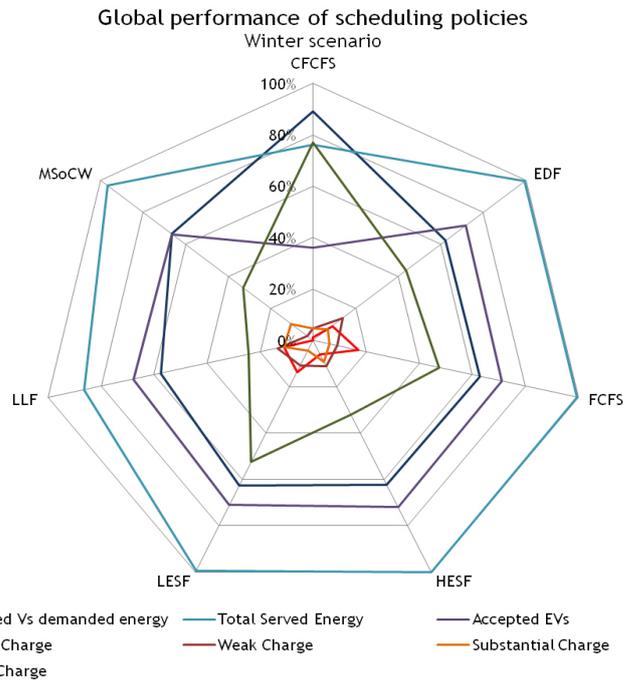
Additionally, due to the importance of the QoS, Figure 6.10a and 6.10b show as well, the percentage of EVs leaving without any charging gain or *zero* level of charge; the percentage of EVs leaving with a *weak* and a *substantial* level of charge, and a full charged energy requirement as well.

The scheduling policy selected by the CSO should be based on its business model as previously mentioned. In both figures we can observe how CFCFS offers high levels of QoS by having the highest ratio of dispatched Vs. demanded energy and the highest number of full charged EVs. Nevertheless, it is possible to notice how the acceptance rate and the total served energy in comparison with the rest of the policies is less efficient. This strategy could suit CSO aiming for high QoS at the price of limiting charging services to less users. If there could be a tradeoff on the QoS and the number of accepted EVs, EDF or LESF could be considered as options by the CSO when they aim having reasonable levels of fully charged EVs. These two policies, as we can observe, distribute the highest amount of energy among the vehicles and have reasonable rates of dispatched Vs. demanded energy. However, it should be considered by the CSO that by having some EVs leaving without a significant charge, could lead to compensation fees or complaints from the customers.

Finally, it is possible to observe how MSocW eliminates the issue of EVs leaving without charging at the same time that it presents considerable good levels of energy served, as well as the ratio between served and demanded energy.



(a) Global evaluation of the performance of all scheduling strategies with the summer scenario.



(b) Global evaluation of the performance of all scheduling strategies with the winter scenario.

Figure 6.10 – Average performance for each scheduling policy according to a given metric.

6.6 Summary

As it was presented in Chapter 5, the flexibility accorded to the tasks in the FlexTaSch approach, helped to improve the distribution of power available for EV charging in the PLS electrical network in comparison to the conservative approach CoTaSch. However, results have shown that the QoS proposed to the drivers had to be compromised in order to extend the charging services to more EVs. The main issue for all the charging strategies within the FlexTaSch approach was the presence of a group of EVs leaving the set of chargers without being charged after all the time they were connected to the ChP. This is not acceptable from the users point of view, which would only discourage the adoption of EVs by potential users.

In this chapter we proposed a solution to solve this issue on QoS, which aims to guarantee a minimum amount of energy served at the time of departure to EV drivers. The option was to provide the amount of energy required to cover a distance that corresponds to the range of an average scheduled home to work trip. However, due to the performance of the batteries, the distance range will be limited by the environmental temperature. Therefore, the charge requirement to cover the same distance will be the double for the winter scenario than for the summer. Keeping in mind these conditions, the new on-line scheduling strategy proposed takes into account two different parameters for sorting the EVs on the task scheduler for charging.

The priority in the scheduler will be defined by the most significant demand of energy to fulfill the minimum charge requirement of a task and the proximity of its deadline. This policy is inspired by the HESF and EDF strategies, which presented considerable good results in terms of fully charged vehicles and a low number of EVs leaving without being charged in comparison with the other policies. This new scheduling strategy is referred as Minimum SoC Warranty (MSoCW) and its objective is to provide a minimum QoS to users.

The performance of this new scheduling strategy was analyzed and compared to the other charging flexible policies. In this chapter we have shown how MSoCW proved to accomplish the main goal originally set by eliminating all EVs that left the set of chargers without being charged. Additionally, it managed to provide the minimum charge requirement for most part of the EVs during winter and for all EVs in the summer scenario. We found the acceptance rate of MSoCW a little bit lower than for the rest of the scheduling strategies, except for CFCFS. This is because of the changes made in the conditions needed for accepting an EV for charging under the MSoCW policy, which looked at the laxity of the minimum charge requirement at the slowest charge rate, restricting more the acceptance of EVs. However, the amount of distributed energy was closer to the demanded energy by the loads, that could be considered as an important improvement from the FlexTaSch approach previously presented. Therefore, we conclude that MSoCW could represent an appealing strategy to be implemented by the CSO, as it manages to extend the service of EV charging to more users in comparison to CFCFS and at the same time it proposes a minimum level of QoS to the final user while all the constraints for the proper operation of the PLS electrical network are respected.

Conclusion and Perspectives

7.1 Conclusion

Facing the necessity to reduce carbon emissions in the very next years, we have argued in the introduction of this thesis that building from scratch dedicated **EV** charging infrastructures would be both a costly and long procedure. Inspired by our contribution to the TELEWATT French National research project, we have shown that an alternative to this dilemma could consist in connecting **EV** charging stations to existing public lighting networks. Indeed, lighting infrastructures are already deployed at a large scale in urban areas, where the majority of the **EV**'s market will be positioned in the very next years. To do so, the unique constraint to be satisfied is the simultaneous operation of the street lamps and the chargers. The aim of this dissertation was then to evaluate the practical feasibility of such an approach.

Various studies have already been dedicated to the design of **EV** charging infrastructures. In our point of view, the infrastructure considered in this thesis can be distinguished from those considered in the previous studies on two major aspects. First, to the best of our knowledge all the charging infrastructures considered up to now are applied to dedicated networks, for which the distance between each Charging Point (ChP) and the electric control cabinet is negligible in terms of electrical power losses. This is not the case for street lighting networks. Second, existing charging strategies consider the available power as constantly available through the day. In this thesis, four different lighting stages are considered: daylight, **LHS**, night and lamp dimming, which limit the available power on the system.

Globally, our manuscript was structured in two successive parts. Part one, entitled "Electric Vehicle Charging Infrastructures". It includes two chapters. In **Chapter 1** a brief overview of how the deployment of **EVs** charging infrastructures can be considered as a key point of the strategy adopted in different countries to reduce greenhouse emissions and the dependence on fossil fuels. The massive deployment of **EV** charging infrastructures should remain very progressive. It will start by urban areas where most of the **EV** market is located. By analogy with the chicken or the egg causality dilemma, it is not yet clear if the massive deployment of charging stations is a prerequisite for the emergence of **EVs** or if, facing massive sells of **EVs** in the market, the deployment of charging infrastructures will be accelerated. In order to be economically viable,

the deployment of **EV** charging infrastructures should coincide at the best with the development of the **EV** market. The initial impulsion to activate this virtuous process relies from our point of view, on the financial credits and tax incentives that are temporarily offered by the various European authorities to **EV** charging operators.

The economical viability of **EV** public charging stations manufacturers is meaningful only if the corresponding market is sufficiently large. This is why the deployment of **EV** infrastructures is considered at the European scale rather than at the national scale. At the date of publication of this thesis, numerous specifications have already been published by the ETSI CEN-CENELEC European standardization body [22]. These standards will progressively consider the design of **EV** charging infrastructures in their globality as well. Thus, power cables and specific connectors are already standardized and adopted by European vendors for low speed charging and high speed charging. This is a result of the constant collaboration between car manufacturers, the main actors of electrical industry, and the utilities market. Upstream the commercial sector, different research fields are also concerned by the design of **EV** charging infrastructures. For instance, electro-chemistry of the batteries is subject to a particular attention in order to produce lighter, more robust, high capacity batteries with faster charging speed. Smart **EV** charging demands a constant communication between the charging stations and the electric control cabinet. Power Line Communications (**PLC**) or wireless communications suited to smart grid networks are widely investigated. However, these networking aspects were out of the scope of this thesis. The **EV** charging process and batteries technologies are in continuous evolution, following the needs of the users for charging at higher speeds and extending the driving range of their vehicles **Chapter 2**. However, new options have emerged, such as battery swapping and inductive charging (**WPT**), that still have a long road ahead before being exploitable at a large scale.

As underlined since the introduction of this thesis, one of the key challenges of the **EV** industry for gaining the confidence of more potential users is to address the so-called "drivers anxiety range". In most cases, the current usage of EVs is limited to short range urban trips. This means that **EV** charging infrastructures concern in the very short term the heart of the European cities and small size urban cars. Meanwhile, a few vendors already propose in their catalogue long range EVs that correspond in most case to class-A vehicles for a niche market. Tesla in the USA, BMW and Mercedes-Benz in Germany are some examples of actors of class-A EVs. In this matter, the Corridor European project [21] targets the deployment of fast charging stations along the major motorways linking France and Germany for this niche market. By choice, this thesis has not covered fast charging infrastructures recommended for such **EVs**.

We believe that in the next years, the driving behavior of **EV** drivers will smoothly evolve from the current behavior of **ICE** vehicle users. This concern will impact the location and the frequency at which the users charge their vehicles. **EV** users will not only charge at their households, but will start charging at public locations. With the expansion of the **EV** market, the electrical distribution network should be prepared to cover the new demand of electricity without putting at risk the operation of the power distribution grid. In order to do so, electricity distribution network will probably have to be upgraded. Since a redesign of the power distribution network would be extremely costly, the transition from **ICE** to **EVs** or **PHEVs** will be very progressive over the next years. In the short term, an interesting alternative will consist in the investigation of new and efficient energy management techniques enabling a smooth transition of the grid architecture.

In **Chapter 3**, we have described the main characteristics of **PLS** electrical networks and

their operating mode. We have depicted the principles of a modeling technique available in the literature enabling to determine the behavior of electrical circuits with complex topologies. Indeed, if all of the **PLS** electrical network configurations considered in this thesis are linear, several single phase or three phase buses may be interconnected and fed by a same electric control cabinet via more complex configurations such as tree type topologies. Thanks to a graph representation of the considered topology, it is possible to determine relatively easily the electrical behavior of such configurations. We associate to the graph representation the power delivered by the electric control cabinet and the detailed characteristics of the whole infrastructure. Thanks to this graph representation and elements of circuit theory, it is possible to determine the voltage, and the current values between any pair of points in the infrastructure. In our model, we have considered each **EV** connection request as a task to be completed by the **CCM** within a given deadline. In order to make this problem tractable, we have assimilated **EV** chargers as variable resistors with the objective to provide a constant power charging. The detailed description of this technique developed in collaboration with other members of our research team is out of the scope of this thesis since it is under a patenting procedure.

The second part of this dissertation is entitled Smart Charging Strategies and it is made of three chapters. **Chapter 4** we have introduced the concept of smart charging corresponding to the guarantee of an immediate charge after connecting the vehicle without putting at risk the operation of the network. To do so, the operational requirements and parameters of a the simulated **PLS** electrical network have been set in coherence with the characteristics of the existing grid. In a first step, we have proposed a conservative approach for handling the charging process of every **EV** connected to the network. This approach is referred as Conservative Task Scheduling (**CoTaSch**). For this approach, we have proposed an on-line scheduling policy called Conservative First Come First Served (**CFCFS**). This strategy consists in testing off-line the feasibility of a new connection before actually starting the charging operation. The **CFCFS** policy limits the number of vehicles that can be served simultaneously by a same charging infrastructure. By doing so, the **CCM** of the charging network guarantees that the charging process always satisfy the operational constraints of the grid. Additionally, the **CoTaSch** approach considers that all **EVs** should start charging immediately after their connection without any interruption until the charging load reaches its targeted value. Thus, the charging tasks at this stage are not preemptive nor deferrable. The **CFCFS** strategy has been designed in order to prove the feasibility of the model and gave us the guidelines for the next stages of this thesis. Although it enables to proceed to parallel charging operations on a same street lighting network infrastructure, the **CoTaSch** conservative approach presents a few drawbacks. Thus, our simulation results have shown that it may occur that a considerable percentage of **EVs** charging requests be rejected. **Chapter 5** has been dedicated to the reduction of such a drawback.

In order to improve the usage of the installed **EVSE** and to extend the **EV** charging services to more users, a more flexible approach for handling the charging process referred as Flexible Task Scheduling (**FlexTaSch**) has been proposed. This approach allows to give a certain priority to the tasks according to the **CSO** business policy. In this perspective, we have adapted a set of well known on-line scheduling strategies to our model according to the constraints of the **PLS** electrical network. These scheduling strategies are: First Come First Served (**FCFS**), Earliest Deadline First (**EDF**), Highest Energy Shortfall First (**HESF**), Lowest Energy Shortfall First (**LESF**) and Least Laxity First (**LLF**). Hereby we refer as "flexible policies" to the set of these scheduling policies. We have observed how these flexible policies increased the number of **EVs** accepted for charging

and as a consequence, the [CSO](#) can dispatch more energy to the vehicles and extend the charging service to more users. In exchange, the level of [QoS](#) is the result of a tradeoff. Thus, a given vehicle can be accepted but it could leave its charging point without any charging gain.

Finally, [Chapter 6](#) was dedicated to the design of a charging strategy that allows to extend charging services to more users than for [CFCFS](#) at the same time that it guarantees a better [QoS](#) than the rest of the flexible policies. Such improvement in the [QoS](#) has been achieved by eliminating the [EVs](#) leaving the charging station without being charged and by guaranteeing an amount of dispatched energy sufficient for covering an average home-to-work distance.

Table [7.2](#) summarizes the positive and negative aspects of the performance of each scheduling policy studied in this dissertation, within the [CoTaSch](#) and the [FlexTaSch](#).

7.2 Perspectives

- The algorithms presented in this thesis enable to provide a certain level of Quality of Service to the end-users. In the perspective of the future commercial usage of public charging infrastructures, it should be of particular interest to include in these policies the parking fee and to determine which are the best pricing strategies for the tuple (parking spot, charging service). The location of the parking spot equipped with a charging station has a strong impact on the pricing policy. In the most popular areas of a city like the surroundings of a railway station, the unit price per hour for a parking spot coupled to a charging service should be much higher than for the same type of service in a suburban area.
- The emergence of microgrids relies on the capacity of a set of buildings located in a same neighborhood to become transitorily independent from the public grid for its energy provisioning. A microgrid is made of one or several buildings in a same neighborhood. These buildings are characterized by their capacity to take advantage of local wind turbines and solar panels to cumulate for free energy in stationary batteries. Based on 24 hours weather predictions, it is possible to schedule the activity periods of the various electrical equipment within the buildings of a microgrid in order to erase the periods during which the price of public electricity is at its maximum. During these peak periods, it is preferable to consume the free energy that has been cumulated in the stationary batteries the day before. The [EV](#) charging infrastructures considered in this thesis can then be viewed as a new element of such microgrids. It may occur that under low activity of the various loads within a microgrid, the stationary batteries of this microgrid be fully charged. Whereas, energy is still produced by [RES](#). In that scenario the batteries of the [EVs](#) could be used as energy overflow storage devices.

Policy	Possitive performance	Negative performance
CFCFS	+ High QoS	- Low acceptance rate of EVs
	+ 100% Fully charged EVs in summer and over 90% in winter	- High number of unused ChPs
	+ High ratio of dispatched Vs requested energy	- Less energy dispatched (- 25% less compared to EDF)
	+ No EVs leaving without being charged at time of departure	- Unused energy left enough for charging in average 2 extra EVs @ 1.4kW
FCFS	+ High percentage of dispatched energy	- Highest number of EVs leaving without being charged at time of departure (up to 17% of EVs in winter)
	+ Average rate of accepted EVs than the flexible tasks	- 1 EV not charged at time of departure for each 3 EVs fully charged
	+ More accepted EVs than CFCFS and less unused ChP	
EDF	+ Highest amount of energy dispatched to the vehicles	- EVs leaving without charge at time of departure in summer & winter
	+ Less unserved energy left without dispatching	- 9% of EVs leaving the ChP without charge in winter
	+ Average rate of accepted EVs compared to "flexible policies"	- 14% of EVs leaving the ChP with a weak level of charge in winter
LESF	+ High amount of served energy	- EVs leaving without charge at time of departure in summer & winter
	+ Near 75% of fully charge EVs in summer and over 50% in winter, highest number after CFCFS	- 15% of EVs leaving without charging in winter
	+ Average rate of accepted EVs compared to "flexible policies"	- 25% of EVs leaving with zero or weak level of charge in winter
HESF	+ High ratio of dispatched Vs requested energy	
	+ High amount of dispatched energy which means better usage of installed EVSE	- EVs leaving without charge at time of departure in summer & winter
	+ Lowest number of EVs leaving without charge among all the "flexible policies"	- Low number of EVs leaving fully charged at time of departure
LLF		- Highest amount of EVs leaving with zero or weak levels of charging (35% in winter and up to 55% in summer)
	+ Average rate of accepted EVs compared to "flexible policies"	- Lowest amount of fully charged EVs (only 24% in winter and 41% in summer)
		- Lowest amount of energy dispatched for all simulations
MSoCW	+ 0% of EVs leaving without charge after time of departure	
	+ High ratio of dispatched Vs requested energy	
	+ High levels of dispatched energy	
	+ Reasonable levels of fully charged EVs at time of departure	- Acceptance rate lightly lower than the average of "flexible policies"
	+ Minimum energy requirement guaranteed for all EVs in summer and near the totality in winter	

Résumé en Français

8.1 Introduction

Les émissions de carbone générées par les activités industrielles et agricoles en masse ont atteint des niveaux alarmants pendant les dernières décennies. De sorte qu'elles représentent un vrai risque pour le future de notre planète. Dans ce contexte, l'alternative la plus important pour combattre le réchauffement climatique et ainsi éviter une augmentation irréversible des températures de la planète, s'agit de réduire les émissions de carbone. Plusieurs gouvernements ont fixé des objectifs très ambitieux pour les années à venir le but principal est de diminuer les émissions de gaz à effet de serre pour améliorer la qualité de l'air dans les zones urbaines et réduire la dépendance actuelle des carburants [18,36,58,73]. L'Union Européen (UE) a fixé comme objectif la réduction des émissions de gaz à effet de serre en 20% entre 1990 et l'année 2020. Au même temps, l'UE veut augmenter dans la même proportion la production d'énergie renouvelable [3]. Dans la même ligne de travail se place comme objectif l'intégration des véhicules électriques (VE) dans le marché automobile, ainsi que ses effets sur les réseaux de distribution d'électricité actuels. A la date de publication de ce travail, la capacité installé pour la production et distribution d'électricité est encore capable de supporter la demande d'énergie d'un nombre limité de bornes de recharge des VE, qui est directement en relation au nombre des VE sur le marché. Cependant, il est remarquable l'investissement des principaux constructeurs automobiles pour réussir dans la production des modèles des véhicules électriques pour le marché des pays développés. Dans ce contexte, il est clair qu'il sera nécessaire d'envisager une mise à jour du réseau de distribution pour pouvoir supporter cette nouvelle demande énergétique. Certainement, cet objectif sera accompagné d'une substitution des sites de production d'énergie traditionnelle pour des sites de production d'énergie avec les sources renouvelables.

L'électro mobilité (ou e-mobilité) est la technologie clé nécessaire pour fournir une alternative aux sources d'énergie non renouvelables et par conséquent, conduire à long terme vers la réduction des émissions de carbone [75]. Cette technologie se caractérise par un groupe diversifié des solutions technologiques qui permettent le déploiement de batteries plus performantes et à un coût plus faible, ainsi que des moteurs à transmission électrique pour les véhicules purement électriques ou hybrides. Cependant il est encore difficile à prévoir la vitesse à laquelle les nouveaux modèles des VE vont arriver sur le marché automobile. Notamment les grands centres de recherche et cabinets

de conseil comme Gartner, Ernst and Young ou Deloitte essayent de prédire le moment et la façon dans laquelle cette révolution aura lieu. Il existe divers challenges à surmonter, du point de vue du réseau de distribution, ainsi que du point de vue de l'utilisateur final. Nous pouvons prévoir que le déploiement en masse des infrastructures de recharge pour les VEs aura besoin d'une restructuration du réseau de distribution. Dont l'analyse de cette restructuration est hors les objectifs de cette thèse.

Plusieurs facteurs doivent être prises en compte pour évaluer la vitesse à laquelle les VEs devront remplacer les véhicules à combustion interne dans les pays développés :

1. **Le coût des VEs :** D'après les résultats d'une analyse économique du marché des VEs en France [69], depuis l'année 2013, grâce aux différents crédits d'impôts et les primes accordées par le gouvernement, le prix d'achat d'un VE s'approche chaque jour de plus en plus de celui de son équivalent à combustion interne. Par exemple, la différence entre le Smart Fortwo est de 1000 euros entre la version Drive et la version Essence.
2. **Les contraintes technologiques liés aux technologies pour la batterie :** Les batteries disponibles actuellement se caractérisent pour avoir deux points négatifs. En première instance, la capacité des batteries reste limitée, ce qui est lié directement au poids de la batterie. A la date de publication de ce manuscrit, les batteries installés dans les véhicules d'une catégorie supérieur permettent d'attendre des distances entre les 200 et les 400 kilomètres [23]. Cette distance reste toujours plus courte que celle qui est proposée par les véhicules thermiques, mais chaque année la différence entre les deux devient de plus en plus courte grâce au développement d'une nouvelle génération de batteries et des technologies pour les recharger (comme les techniques de recharge sans contact). En deuxième place, la vitesse avec laquelle une batterie peut être chargé reste un réelle contrainte pour les utilisateurs finales. Comme un repère, une recharge complète peut prendre jusqu'à 8 heures quand le véhicule se charge à 3.3 kW. Cette limitation reste comme une forte contrainte commerciale qui limiterait dans le court terme l'utilisation des VEs de basse et moyenne gamme que pour les déplacements du type urbain. Au même temps qu'une amélioration dans la capacité des batteries est prévue, il est également attendue une amélioration du temps de recharge et l'installation de plus des stations de recharge à haute vitesse, qui jusqu'au présent reste toujours limités.
3. **La couverture limité de l'infrastructure disponible pour les stations de recharge :** Le coût de déploiement d'une infrastructure de recharge reste toujours très haut comme résultat des travaux d'ingénierie qu'ils doivent être réalisés. Avant de pouvoir faire un déploiement en masse, les VEs seront utilisés par la plupart des utilisateurs principalement dans les métropoles. La plupart des constructeurs automobiles encouragent également l'installation des bornes de recharge privés pour les propriétaires. Les déplacements interurbains en VE resteront limités encore pour quelques années aux propriétaires des VEs avec une grande capacité dans ces batteries jusqu'au moment que les stations de recharge rapide soient installées dans les principaux axes de connexion entre les villes.
4. **L'anxiété des conducteurs des VEs** Aujourd'hui, le déploiement des bornes de recharge publiques est concentré dans les centres urbains, comme résultat, les conducteurs des VEs peuvent avoir peur de ne pas pouvoir avoir une capacité dans ses batteries suffisante pour arriver à leur destination. En autres termes, l'anxiété de rester sans essence est souvent mentionnée dans la littérature, pourrait jouer un rôle primordial pour ralentir le déploiement

du marché des VEs, et plus particulièrement, du marché interurbain. Les contraintes technologiques inhérentes à cette dite anxiété sont particulièrement explorées dans cette thèse. Au-delà de l'analyse fournie par ce manuscrit, le Département Fédéral du Transport des Etats Unis considère qu'un marché énorme devra apparaître dans les années à venir pour les outils cartographiques. Tels outils devront réduire l'anxiété des utilisateurs de VEs en incluant la position géographique du véhicule et la disponibilité des stations de recharge pendant le trajet effectué jusqu'à la destination inséré au moment du départ.

En France, plus de 2 millions de VEs sont attendus pour l'année 2020 [41]. Sans l'infrastructure adéquate pour fournir le service de recharge, la croissance du marché des VEs pourrait être en danger. Les infrastructures de recharge pour les VEs incluent une série d'éléments connus comme Equipement d'Approvisionnement des Véhicules Electriques (EAVE) ou EVSE en anglais, ces éléments de recharge comprennent les câbles, prises et connecteurs, ainsi que toute autre équipement associé aux stations de recharge.

Pendant les dernières années, les infrastructures installées pour la recharge des VEs ont évolué significativement, en proposant nouvelles approches et en encourageant les équipes de recherche à trouver nouvelles solutions pour réduire le temps de recharge ou à améliorer les mécanismes de recharge qui pourraient en profiter l'utilisation des énergies renouvelables. Les recharges par fil ont passé de connexions lentes et risqués faites dans les prises électriques domestiques à recharges rapides dans des stations de recharge sécurisée dans différents endroits publiques et privées pour la convenance des utilisateurs. Néanmoins, il reste encore quelques points à améliorer. Pour cette raison, la standardisation des équipements de connexion au niveau européen et à l'international sont à la clé de la viabilité du marché des VEs. En fin, les contraintes techniques et économiques posent également un autre problème assez complexe, qui est lié du placement optimal des nouvelles stations de recharge.

Le marché américain de VEs a développé différents approches basés sur le concept des stations d'échange de batteries BSS. Ce concept consiste à remplacer les batteries avec un niveau faible d'énergie par des batteries complètement chargés dans quelques minutes au sein d'une station d'échange conçue particulièrement pour cette tâche [4, 24]. Cependant, cette approche et son modèle économique associé ont besoin d'être remises en examen avant de pouvoir être exploités complètement et avec succès. L'échec de l'expérimentation pre-commercial de la plateforme Better Place a mise en garde les limitations de cette approche [15]. De l'autre côté, la recharge sans fil WPT, est un autre concept qui a attiré l'attention de plusieurs chercheurs et des constructeurs des bornes de recharge ces dernières années. Ce concept de recharge sans fil envisage la réduction des dangers liés aux recharges filaires. Il a été démontré qu'il est possible de charger des VEs en mouvement en installant des éléments inductives sous la surface de roulement au long de la route. Cette approche alternative pourrait entre autres, résoudre le problème des distances énergétiques atteignables par la prochaine génération de VEs. A la date de la publication de ce manuscrit, le déploiement à grande échelle de ce type d'éléments inductifs sur la route dépend toujours de l'efficacité de l'infrastructure de recharge à un coût raisonnable.

Le besoin plus urgent à résoudre dans le marché des VEs est le financement des infrastructures de recharge pour un déploiement à grande vitesse [20]. Les coûts d'installation des EAVE peuvent être assez élevés, spécialement quand le réseau électrique (le transformateur et/ou les câbles de distribution) doivent être remplacés ou si des travaux d'ingénierie civile doivent être réalisés. Sans la planification correcte, l'infrastructure de recharge pourrait être surestimée par rapport

aux besoins réels du marché et avoir des actifs non utilisés. Pour cette raison, dans un contexte publique, le déploiement des EAVE ne devrait pas envisager une simple installation massive de bornes de recharge, mais plutôt envisager l'optimisation des coûts d'opération qui mieux s'adapte au modèle économique mis en place.

Le déploiement à grande vitesse des stations de recharge dans les zones urbaines n'est pas seulement important pour réduire l'anxiété des conducteurs, il constitue en lui-même un grand défi. Dans cette thèse, nous présentons une approche innovante qui consiste à réutiliser le réseau électrique d'éclairage public PLS pour fournir un service de recharge des VE. Dans cette architecture, le service principal du PLS reste le service d'éclairage public. Cependant, pendant les heures du jour quand les lampes ne sont pas allumées, la puissance disponible dans le transformateur qui alimente les lampes, peut être utilisée potentiellement pour alimenter les bornes de recharge des VE. À la date d'aujourd'hui nous avons connaissance de deux implémentations de test dans les villes d'Aix en Provence en France [70], et en Munich en Allemagne [11], [1]. Les avantages qui présentent ces deux approches sont présentés à continuation :

- Les infrastructures de recharge peuvent être développées rapidement (quelques semaines au lieu de quelques mois) sans ajouter des coûts élevés pour des travaux d'ingénierie civile et sans avoir besoin de mettre à jour le réseau d'éclairage public. La contrainte principale à satisfaire est la proximité entre les endroits de parking et les lampadaires. Il est également nécessaire de garantir grâce à des calculs préliminaires si le nombre de bornes de recharge actives au même temps reste compatible avec la puissance fournie par le transformateur. Dans ce sujet il faut considérer deux régimes : les profils de consommation du jour et de nuit. Ce qui résulterait dans un nombre de bornes de recharge potentiellement inférieur pendant les heures de nuit par rapport à la période du jour.
- Pour la plupart des réseaux d'éclairage public existants, une fraction de la puissance du transformateur qui n'est pas utilisée peut être utilisée par les stations de recharge. Dans cette thèse nous supposons que la capacité du transformateur installée est suffisante pour satisfaire la demande de puissance quand tous les lampadaires sont allumés. Nous savons que cette assumption est réaliste par rapport aux caractéristiques des infrastructures déployées pour l'éclairage public. Pourtant, il faut prendre en compte les limites opérationnelles établies par les opérateurs des réseaux d'éclairage public pour garantir la stabilité et la qualité du système d'éclairage public.

À notre connaissance, la façon la plus utilisée par les opérateurs des réseaux d'éclairage public pour gérer la puissance disponible dans leurs infrastructures est, pour la plupart de cas, basée sur des calculs grossiers. Sur ce sujet, la société française Citelum qui est considérée comme un leader mondial des réseaux d'éclairage nous a partagé une partie de son savoir-faire, ce qui fait partie d'une fraction du travail présenté dans cette thèse. Le but de cette thèse est de participer dans la recherche sur les nouvelles infrastructures de recharge des VE qui pourraient être rapidement déployées à un faible coût opérationnel, grâce à l'utilisation des réseaux d'éclairage public. Plus précisément, nous avons participé au sein du département d'informatique et réseaux de Telecom ParisTech dans le développement des techniques d'analyse numérique originales qui permettent de réaliser des calculs très précises en temps réel par rapport à la puissance disponible dans un moment précis dans n'importe quel point du réseau d'éclairage public qui soit équipé avec les bornes de recharge spécialement développées. Une fraction des assumptions considérées dans cette thèse ont été inspirées du projet de recherche TELEWATT. Dans le cadre de ce projet, la

collaboration entre Citelum et Telecom ParisTech était possible grâce au financement de l'ADEME, une subsidiaire du Ministère Français de l'Industrie. Les objectifs du projet TELEWATT sont plus larges que la recherche faite pendant cette thèse. Il est assumé que l'intelligence pour gérer la puissance instantanée disponible a n'importe quel point du réseau. La description du protocole de communication qui permette le dialogue en temps réel entre les bornes de recharge ou les points lumineux avec le transformateur sont hors l'objectif de cette thèse. En résumé, cette thèse a trois objectives:

- Notre premier objectif est de construire un outil de simulation qui soit générique, de sorte qu'il peut être appliqué à plusieurs configurations (pour les infrastructures monophasées ou triphasées). Les résultats numériques fournis par notre simulateur doivent correspondre aux mesures réalisés dans un vrai réseau électrique. Pour cela, plusieurs scénarios ont été créés dans le cadre du projet TELEWATT. Un minimum de qualité d'éclairage est attendu pendant la période de nuit sans importer la configuration du réseau. Notre logiciel doit être suffisamment générique pour être déployé dans plusieurs configurations du réseau. Chacune de ces configurations peut avoir besoin d'un certain nombre de marges de sécurité dans les caractéristiques électriques du système pour pouvoir garantir une qualité constante dans le service d'éclairage. Notre outil informatique doit être également assez générique pour pouvoir considérer plusieurs conditions du réseau sous différents marges de sécurité. Ces marges de sécurité peuvent varier en fonction de l'opérateur du réseau de distribution et des constructeurs des bornes de recharge.
- Le deuxième objectif est de faire un outil exploitable dans un environnement opérationnel. Dans ce contexte, des événements aléatoires correspondent aux connexions ou déconnexions d'un VE, dont l'intelligence du système installé dans le cabinet électrique puisse répondre en temps réel aux besoins d'une nouvelle requête de connexion.
- Le troisième objectif est de démontrer la faisabilité du modèle de recharge proposé par le projet TELEWATT et de développer une stratégie de recharge innovante qui permette de garantir un niveau minimum de QoS aux conducteurs. A notre connaissance, jusqu'à la date de publication de ce manuscrit, les stratégies de recharge disponibles dans la littérature envisagent principalement les infrastructures de recharge dédiées et la recharge de flottes de VEs, dont les besoins énergétiques des VEs est connu en avance. Notre objectif est de fournir une quantité minimale d'énergie à l'utilisateur, qui soit équivalent à la distance d'un déplacement moyen entre la maison et le lieu de travail. Ainsi, l'anxiété des utilisateurs pourrait diminuer.

8.2 Les Contributions de cette Thèse

Les contributions de cette Thèse sont résumées à continuation :

- Nous avons développé un outil de simulation qui permette d'émuler la performance d'une infrastructure de recharge du système d'éclairage public. L'originalité de cet outil est sa capacité de simuler des simulations complexes avec un temps de calcul qui permette de donner une réponse en temps réel à l'utilisateur. Pour ce propos, nous avons utilisé des concepts de la théorie des graphes appliqués à la théorie de circuits pour représenter le réseau électrique comme un seul graphe et ainsi être capables de calculer la tension et

le courant dans n'importe quel dipôle du réseau en temps réel. Dans le graphe considéré, chaque borne de recharge est représentée comme une résistance variable. La valeur de cette résistance doit être recalculé dynamiquement pour maintenir constant la puissance délivrée au véhicule connecté quand un nouveau VE arrive ou part de la borne de recharge.

- Nous avons simulé plusieurs scénarios et observé les stations de recharge inspirés dans les configurations observés dans le projet de recherche français TELEWATT. Nous avons démontré la faisabilité des connexions et déconnexions aléatoires des VEs sur les bornes de recharge sans mettre en risque l'opération du réseau électrique d'éclairage public. Dans un premier approche, nous avons proposé une stratégie de recharge originale qui garantie une recharge immédiate après la connexion du véhicule en respectant l'opération du réseau électrique. Dans un deuxième approche, nous avons analysé la performance d'un groupe de stratégies de recharge qui utilisent un ordonnancement en ligne, comme il est actuellement proposé dans la littérature de base pour l'Allocation des Ressources du Processeur (ARP) [71] mais adapté à notre environnement de recherche. Ces stratégies de recharge permettent d'avoir plus de flexibilité dans la gestion des processus de recharge. Nous avons démontré comment elles permettent de mieux exploiter les ressources disponibles en permettant le service de recharge à plus d'utilisateurs, ce qui peut être évalué par rapport au nombre des véhicules connectés. Finalement, dans notre dernière approche, nous avons développé une stratégie de recharge originale qui est plus orienté vers une qualité de service minimale proposé aux utilisateurs. L'originalité des simulations utilisées dépend de sa proximité des conditions réelles d'utilisation.
- Nous avons pu évaluer la performance du réseau électrique d'éclairage public grâce à l'analyse de plusieurs stratégies de recharge et divers scénarios qui prennent en compte les conditions typiques d'opération et les contraintes du réseau. Les stratégies de recharge que nous avons étudié prennent en compte les demandes de recharge selon le moment de la requête. Nos algorithmes réagissent en temps réel à divers éléments aléatoires, comme l'arrivée ou le départ d'un EV à une borne de recharge donnée. Pouvoir s'adapter aux changements du réseau en temps réel constitué une des contraintes de basse de cette thèse, car un des objectifs est de pouvoir le mettre en place dans une plateforme de test dans le cadre du projet TELEWATT.

8.3 Contenu de cette thèse

Cette mémoire est organisée en 7 chapitres. Dans le chapitre 2 nous présentons un résumé des architectures de transmission disponibles et les éléments de recharge les plus importants installés dans les bornes de recharge. Dans le chapitre 3 nous décrivons la méthodologie utilisé pour le développement de l'outil de simulation utilisé dans ce projet de recherche. Le chapitre 4 présent une approche conservative pour la gestion des processus de recharge des VEs. Au sein de ce chapitre nous présentons une stratégie de recharge en ligne avec une approche conservative pour l'acceptation des véhicules avant d'être chargés, cette stratégie a comme seul but de démontrer la faisabilité du modèle de recharge proposé par TELEWATT. Nous présentons un groupe de métriques utilisés pour évaluer la performance des stratégies de recharge présentés dans ce travail. Dans le chapitre 5 nous présentons un groupe de stratégies de recharge en ligne adaptées à notre environnement de recherche qui considèrent une approche plus flexible pour la gestion des processus

de recharge des véhicules. Dans le chapitre suivant 6, nous présentons notre propre stratégie de recharge qui est orientée vers une qualité de service minimale proposé à l'utilisateur final. Le dernière chapitre 7 conclut ce manuscrit et donne quelques perspectives pour la continuation de cette thèse.

8.4 Publications

Les travaux publiés dans des conférences scientifiques sont les suivants :

1. Ruiz, M.A.; Abdallah, F.A.; Gagnaire, M.; Lascaux, Y. "TeleWatt: An Innovative Electric Vehicle Charging Infrastructure over Public Lighting Systems" *Connected Vehicles and Expo (ICCVE), 2013 IEEE International Conference on,*), pp. 741,746, 2-6 Dec. 2013.
2. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Improving Energy Distribution for EV Charging over Public Lighting Systems" *IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Vienna, Austria, Nov. 2014. Best Paper Award Finalist.
3. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "On-line Scheduling Policies for Electric Vehicle Charging over Public Lighting Systems". *2014 IEEE International Electric Vehicle Conference (IEVC)*, Florence, Italy, Dec. 2014.
4. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Minimum Driving Distance Warranty for EV Charging over Public Lighting Systems". *2015 IEEE International Conference on Computer as a Tool (EUROCON)*, Salamanca, Spain, Sep. 2015.

Ainsi qu'un papier journal soumis à publication dans le numéro spécial IEEE Transactions on Intelligent Transportation Systems and Intelligent Transportation Systems Magazine ICCVE.

1. Alvarado-Ruiz, M.; Abi-Abdallah, F.; Gagnaire, M. "Conservative Vs Flexible Scheduling Approaches for Charging EVs over the Public Lighting Network". *IEEE Transactions on Intelligent Transportation Systems and Intelligent Transportation Systems Magazine*. Jul. 2015. Soumis à publication.

8.5 Résumé des chapitres

Dans le premier chapitre de cette thèse nous avons présenté une brève introduction au marché des Véhicule Electrique (VE) et les différentes entités qui collaborent pour le développement des infrastructures de recharge des VE. Nous avons introduit différents types des véhicules électriques disponibles sur le marché et les composants de ses architectures de transmission. Nous avons également présenté un bref résumé des différents types des batteries utilisés dans le domaine des VEs. Pour cela nous avons révisé les principales caractéristiques des batteries plus utilisés et ses algorithmes de recharge correspondants. Les caractéristiques électriques des principaux types de chargeurs, des connecteurs et des modes de recharge qui permettent jusqu'au présent de charger des VEs. Globalement, ce chapitre a donné une brève introduction du marché électrique ainsi que du marché de l'électro mobilité couverte par cette thèse. Le modèle du marché des réseaux publics d'éclairage a été discuté, car il s'agit d'un élément clé des infrastructures de recharge considérées

dans cette thèse. Dans le prochain chapitre, nous allons aborder la méthodologie utilisée pour simuler de la façon plus réaliste possible, l'opération d'un réseau d'éclairage public.

8.5.1 Développement du simulateur du réseau électrique

Dans le chapitre **Chapter 3** nous avons présenté les caractéristiques principales du Réseau Electrique d'Eclairage Public (REEP) et son fonctionnement. Nous avons également décrit les principes de la méthodologie utilisée pour modéliser le REEP en considérant les informations fournies par le DSO. Cette méthodologie permet de modéliser le comportement des circuits électriques dans des configurations du réseau assez complexes. Si les configurations du REEP présentés dans cette thèse sont des topologies linéaires, où un ou plusieurs bus soit monophasés soit triphasés sont connectés au même armoire électrique, autre configurations bien plus complexes pourraient être simulées également.

Pour gérer correctement le réseau électrique et tous les éléments connectés, nous avons besoin de connaître les valeurs des chutes de tension et les courantes dans tous les points du réseau en temps réel. Pour cette raison, le réseau électrique doit être exprimé algébriquement avant de pouvoir implémenter la théorie des circuits.

Pour ce faire, nous avons décidé d'utiliser une approche de la littérature [60], permettant de générer la topologie de n'importe quel réseau électrique à partir des données d'entrée disponibles. La topologie créée sera une topologie fixe du réseau qui contiendra tous les charges reliées à l'armoire électrique, sans prendre en compte si elles sont allumées ou éteintes. Cet algorithme nous permet aussi de construire et d'identifier les boucles qui constituent la topologie du réseau pour ensuite pouvoir implémenter les lois de tension et de courante Kirchhoff.

L'architecture proposée pour la recharge des VEs considère qu'une borne de rechargé sera liée à un lampadaire connecté au réseau électrique. Dans le modèle électrique du réseau, le chargeur est représenté comme un résisteur variable. La valeur de ce résisteur doit être calculée pour obtenir une valeur équivalant au taux de recharge livré à un VE. Dans ce chapitre, nous avons présenté un algorithme qui permette de réguler la valeur du résisteur en fonction des changements du réseau. Pour ce faire, il est nécessaire de calculer fréquemment les valeurs de tension de courante dans tous les points du réseau. Pour cela, nous avons besoin de calculer la matrice inverse de la matrice qui nous permette d'utiliser la loi d'Ohm et ainsi obtenir les résultats souhaités.

Nous avons évalué deux méthodologies pour calculer la matrice inverse d'une autre matrice donnée. Le premier approche, connu comme la matrice des cofacteurs nous a permit de valider notre model de simulation du réseau électrique. Cependant, la performance de cette approche en termes du temps d'exécution était très éloignée des besoins du CCM. La deuxième approche était l'algorithme de Gauss-Jordan, ce qui nous a permis d'améliorer la performance du calcul significativement. Cette méthode de calcul nous a permis ainsi d'obtenir les valeurs souhaitées du réseau en temps réel et passer à l'étape suivante de cette thèse.

8.5.2 Stratégies de recharge intelligente

Dans ce chapitre nous avons introduit un approche conservative pour intégrer les services de recharge de VEs dans le REEP que nous appelons CoTaSch. Nous avons présenté les conditions

d'opération du REEP et les contraintes imposées pour garantir l'opération correcte du service d'éclairage. Pour cette première approche, nous avons présenté une stratégie de recharge conservatrice, qui est basé sur l'algorithme "premier arrivé premier servie". Cette stratégie est référée comme CFCFS, elle est considéré comme une stratégie conservatrice car un VE pourra être accepté uniquement sous condition de pouvoir commencer à se charger immédiatement après sa connexion à la borne de recharge en respectant les contraintes opérationnelles du réseau. Ces contraintes consistent dans un niveau minimal de tension qui ne doit pas être dépassé et une puissance disponible dans le réseau qui reste limité. Pour attendre cet objectif le réseau électrique doit simuler l'arrivée d'un nouveau VE en amont et décider si une nouvelle connexion peut être faite sans danger. S'il n'est pas possible, le réseau limite la connexion de nouveaux VEs jusqu'au moment que les conditions du réseau soient optimales. A cette étape, si un VE est accepté pour être chargé, il devra commencer sa recharge immédiatement après son arrivée et la tâche ne pourra pas être arrêté avant d'avoir été chargé complètement.

Comme les conditions d'éclairage changent pour le réseau au cours de l'année, le model que nous présentons a été simulé pour deux conditions d'éclairage différents pour le REEP. Au même temps, pour tester les effets de placer les bornes de recharge à différents endroits au long du feeder. Ce model a considéré également diverses configurations dans la topologie du REEP qui considèrent différentes distances depuis le transformateur et différent placement des bornes sur le réseau. Finalement, nous avons simulé différents taux d'arrivé de VEs avec une choix de la borne de recharge différente, en partant de la borne plus proche au transformateur vers la plus éloigné ou dans l'ordre inverse et dans un ordre complètement aléatoire.

Les résultats de toutes les simulations ont été comparés en utilisant cinq métriques:

1. Le taux d'acceptation de véhicules
2. La moyenne des pertes de transmission et distribution d'énergie
3. La moyenne d'énergie non livré
4. La QoS proposé par le réseau qui est basé sur le SoC atteint au temps de départ.
5. Le rapport entre l'énergie demandé et l'énergie livré aux VEs.

Nous avons démontré la faisabilité du model de recharge des VEs en utilisant le REEP pour tous les scénarios simulés, qui prennent en compte les conditions opérationnelles du réseau. Néanmoins, la performance du réseau peut être limitée par la saison de l'année et le taux d'arrivée des véhicules aux chargeurs. Il était possible de fournir une recharge complète à tous les VEs acceptés pour être chargés, comme il était le but de l'approche CoTaSch. Il doit être considéré également qu'il n'y avait pas un temps limite pour compléter la recharge d'un VE. Comme résultat, nous avons trouvé des connexions qui pouvaient durer périodes de temps très longs avant d'être complètement chargés, spécialement quand les bornes de recharge sont placés au long du feeder.

L'évolution constante du marché des VEs demande une meilleure gestion du processus de recharge, pour utiliser les ressources disponibles de la meilleure façon possible, en termes d'énergie et d'infrastructure. Une meilleure gestion des ressources pourrait permettre de proposer les services de recharge à plus d'utilisateurs. Dans le chapitre suivant, nous explorons un groupe de stratégies de recharge qui permettent d'avoir une approche plus flexible pour répondre à plus des demandes de recharge.

Dans ce chapitre nous avons simulé différents conditions du réseau. Un résumé de tous les scénarios testés pour l'approche est présenté dans le tableau 8.1.

Conditions d'éclairage	Scenario d'été (pas de dimming) Scenario d'hiver (pas de dimming)
Distribution des bornes de recharge	La borne la plus proche du transformateur Placés au long du feeder
Sélection de la borne de recharge	La borne la plus proche d'abord (CCF) La borne la plus éloigné d'abord (FCF) Ordre de sélection aléatoire (RCS)
Taux journalière d'arrivé des VEs	Bas - 10 VEs/Jour Moyen - 40 VEs/Jour Haut - 70 VEs/Jour
Taux de recharge disponibles	Recharge lente (1.4 kW) Recharges lentes et standard (1.4 & 3.3 kW)
Stratégie de Recharge des VEs	Premier Arrivé Premier Servi Conservateur (CFCFS)

Table 8.1 – Résumé des conditions et scenarios testés pour l'approche([CoTaSch](#)).

8.5.3 Stratégies de recharge en ligne pour la recharge de VEs

Dans le chapitre 4, nous avons démontré la faisabilité d'un approche de recharge conservative référé comme [CoTaSch](#) qui permette la recharge de VEs en utilisant le [REEP](#). Cependant, la performance du réseau pouvait encore améliorer. Dans ce chapitre, nous avons présenté une approche de recharge plus flexible, référé comme [FlexTaSch](#), qui évalue cinq stratégies de recharge de VEs différentes, qui utilisent une gestion des tâches différente.

Le réseau électrique a été testé pour deux conditions d'éclairage différent, deux configurations du réseau différentes et divers taux de recharge disponibles. Les résultats de toutes les simulations ont été comparés grâce aux métriques présentées dans le chapitre précédent.

Nous avons observé que à l'exception de la stratégie [CFCFS](#), le reste des stratégies présentent des taux d'acceptation de VEs pour être chargés avec des niveaux similaires. Malgré le fait que [CFCFS](#) présent un bas taux d'acceptation de véhicules, cette stratégie reste en tête en termes de QoS proposé aux EVs en partant de la borne de recharge, même quand cette stratégie était testé sur les conditions de l'approche connu comme [FlexTaSch](#), parmi ces conditions se trouve l'addition d'un temps limite ou deadline pour compléter les tâches et la possibilité d'interrompre le recharges ou de décaler le début de recharge. L'importance de la réduction dans le taux de recharge est lié au fait que plus de VEs peuvent être acceptés pour être chargés, ainsi l'énergie livré aux utilisateurs peut s'approcher plus de la capacité du réseau, ce qui pourrait avoir une meilleure marge opérationnelle pour le [CSO](#).

Nous avons remarqué que la performance du [REEP](#) change légèrement comme résultat direct de la stratégie de recharge choisi pour la plupart des métriques. Les variations dans les résultats sont liés plus à la configuration du réseau, comme par exemple, le nombre de chargeurs installés ou les taux de recharge proposés par les chargeurs.

Par contre, la QoS proposée aux utilisateurs présenté les variations plus importants comme

Conditions d'éclairage	Scénario d'été (avec dimming des lampes) Scénario d'hiver (avec dimming des lampes) 15 jours testés par simulation
Distribution des bornes de recharge	La borne la plus proche du transformateur
Selection de la borne de recharge	La borne la plus proche d'abord (CCF)
Taux journalière d'arrivé des VEs	10, 20, 30, 40, 50, 60 & 70 VEs /Jour
Taux de recharge disponibles	Recharges lente & standard (1.4 & 3.3 kW) Recharge rapide rajouté (1.4, 3.3 & 7 kW)
Stratégie de Recharge des VEs	Premier Arrivé Premier Servi Conservateur (CFCFS) Premier Arrivé Premier Servi (FCFS) Plus Proche Délai en Premier (EDF) Plus Haut Déficit Energétique en Premier (HESF) Plus Faible Déficit Energétique en Premier (LESF) Moins de Laxité en Premier (LLF)

Table 8.2 – Résumé des conditions et scenarios testés pour l'approche [FlexTaSch](#), pour les stratégies de recharge en ligne.

VEs / jour	Été			Hiver		
	10	40	70	10	40	70
FlexTaSch	11%	57%	70%	36%	67%	75%
CoTaSch	5%	65%	79%	43%	79%	86%

Table 8.3 – Comparaison du taux de rejet de VEs pour [CFCFS](#) entre les approches [FlexTaSch](#) et [CoTaSch](#) pour les scénarios de simulation avec 9 chargeurs et 2 taux de recharge disponibles (1.4 kW et 3.3 kW).

résultat direct de la stratégie de recharge choisie et la configuration du réseau. Selon les objectives du CSO, le choix d'une stratégie de recharge peut être orienté plus vers la réduction du nombre de VEs qui partent du chargeur avec un faible niveau d'énergie reçu ou envisageant l'augmentation de VEs complètement chargés. [CFCFS](#) présente un nombre bas de VEs sans charger et hauts niveaux de VEs avec une recharge complète, cependant cette stratégie n'utilise pas toute la capacité installée du réseau. De l'autre côté, les stratégies [LESF](#) et [FCFS](#) pourraient être considérés par le CSO si la priorité est d'augmenter le nombre des VEs complètement chargés.

Nous considérons que les CSO doivent envisager plus les stratégies comme [HESF](#) et [EDF](#) qui présentent un niveau plus faible de VEs qui partent du chargeur avec un faible niveau d'énergie reçue. Du point de vu de l'utilisateur, partir du chargeur sans avoir été chargé augmente l'anxiété du conducteur, ce qui n'est pas de tout acceptable, spécialement quand le VE parte avec un niveau bas de la batterie. Cette problématique sera abordée dans le chapitre suivant, dans lequel nous présentons une stratégie qui a comme objectif de proposer un minimum de recharge aux utilisateurs au moment de départ.

En plus de la stratégie [CFCFS](#) présenté dans le chapitre 4, nous avons considéré cinq stratégies de recharge additionnelles. Ces stratégies on été évaluées sous les contraintes de simulation définies par l'approche flexible ([FlexTaSch](#)). Un résumé des scénarios et les conditions des test prises en compte dans cette nouvelle approche sont présentés dans le tableau 8.2.

8.5.4 Qualité de service minimale pour la recharge des VEs

Comme nous avons présenté dans le chapitre 5, la flexibilité donnée aux tâches dans l'approche [FlexTaSch](#) nous a permis d'améliorer la distribution de la puissance disponible pour la recharge des VEs dans le [REEP](#) par rapport à l'approche conservative [CoTaSch](#). Cependant, les résultats ont démontré qu'il fallait faire un compromis par rapport à la [QoS](#) pour pouvoir étendre le service de recharge à plus de VEs. Le principal soucis de toutes les stratégies de recharge de l'approche [FlexTaSch](#) était la présence d'un groupe de VEs qui quittaient les bornes de recharge sans avoir été chargés après tout le temps passé connectés au chargeur. Ce qui n'est pas de tout acceptable du point de vue des utilisateurs, car il pourrait décourager l'adoption des VEs comme moyen de transport par autres utilisateurs potentiels.

Dans ce chapitre nous proposons une solution au problème de la [QoS](#), qui envisage de garantir un montant d'énergie minimum délivré au moment de départ de la borne de recharge aux utilisateurs des VEs. Nous avons proposé de fournir le montant d'énergie nécessaire pour couvrir une distance équivalente à un déplacement moyen maison-travail. Cependant, dû à la performance des batteries, la distance énergétique sera limitée par la température de l'environnement. Pour cette raison, l'énergie demandée pour couvrir la même distance énergétique pendant l'hiver sera le double du montant qui est demandé pendant l'été. Si on prend en compte ces conditions, la nouvelle stratégie de recharge proposée prend en compte deux paramètres différents pour trier les tâches dans le scheduler.

La priorité des VEs dans le scheduler sera définie par la demande d'énergie plus important pour compléter le montant de recharge minimum d'une tâche et la proximité de sa date limite. Cette nouvelle stratégie de recharge a été inspirée par les stratégies [HESF](#) et [EDF](#), qui ont présenté des bons résultats en termes du nombre total des véhicules complètement chargés et un nombre faible des VEs sans avoir été chargés au temps de départ de la borne, par rapport aux autres stratégies. Cette nouvelle stratégie de recharge est appelée Minimum [SoC](#) Warranty ([MSoCW](#)) et son objectif est de fournir un minimum de qualité de service aux utilisateurs.

La performance de cette nouvelle stratégie de recharge a été analysée et comparé aux autres stratégies flexibles de recharge. Dans ce chapitre nous avons démontré comment [MSoCW](#) a pu accomplir le but principal établi originalement, qui était d'éliminer tous les véhicules qui partaient des bornes de recharge sans avoir reçu une recharge. De plus, cette stratégie de recharge a pu fournir le montant d'énergie minimum demandé par la plupart des VEs pendant l'hiver et à tous les VEs pendant l'été. Nous avons constaté que le taux d'acceptation de cette stratégie était un peu inférieur que le reste des stratégies de recharge en ligne, à exception du [CFCFS](#). Ce qui est le résultat d'avoir changé les conditions pour pouvoir être acceptés pour être chargé par les bornes de recharge. Pour cette stratégie, il devrait être possible de fournir le minimum de recharge demandé en utilisant le taux de recharge plus lent, ce qui limité plus le nombre des VEs acceptés pour être chargés. Cependant, le montant d'énergie distribué était plus proche du montant d'énergie demandé par les véhicules, ce qui peut être considéré comme une amélioration importante par rapport à l'approche [FlexTaSch](#) présenté avant. Nous avons conclu que [MSoCW](#) peut être une stratégie de recharge très attirante pour les [CSO](#). La raison principale est qu'il offre la possibilité de proposer le service de recharge à plus utilisateurs par rapport à la stratégie [CFCFS](#) et au même temps cette stratégie propose un niveau minimum de [QoS](#) à l'utilisateur final au même temps que toutes les contraintes nécessaires pour la correcte opération du [REEP](#) sont respectées.

Le tableau 8.5.4 montre une synthèse des aspects positifs et négatifs sur la performance de chaque stratégie de recharge des deux approches [CoTaSch](#) et [FlexTaSch](#) étudiés dans cet manuscrit.

Policy	Performance positive	Performance négative
CFCFS	+ Bonne QoS	- Faible acceptation de VE
	+ 100% des VE chargés pendant l'été et plus de 90% pendant l'hiver	- Grand nombre des bornes de recharge sans utiliser
	+ Grand proportion entre l'énergie fournie et l'énergie demandée	- Moins d'énergie fournie aux VE (- 25% en moins par rapport à EDF)
FCFS	+ Pas de VE sans avoir été chargés au temps de départ	- Energie sans utiliser suffisante pour charger 2 VE plus en moyenne en les chargeant à 1.4kW
	+ Grand pourcentage d'énergie fournie aux VE	- Le nombre plus important de VE en partant sans avoir été chargés au temps de départ (jusqu'à 17% de VE pendant l'hiver)
	+ Taux moyen d'acceptation de VE parmi les stratégies de recharge flexibles	- 1 VE sans charger au temps de départ pour chaque 3 VE complètement chargés
EDF	+ Plus de VE acceptés que CFCFS et moins des chargeurs sans utiliser	- Présence de VE en quittant la borne de recharge sans avoir été chargés en été et en hiver
	+ Le plus grand montant d'énergie fournie aux VE	- 9% des VE partent sans recharge en hiver
	+ Moins d'énergie sans avoir été distribué parmi les VE	- 14% des VE qui partent avec un faible montant d'énergie en hiver
LESF	+ Taux moyen d'acceptation de VE parmi les stratégies de recharge flexibles	- Présence de VE en quittant la borne de recharge sans avoir été chargés en été et en hiver
	+ Grand montant d'énergie délivré	- 25% des VE partent sans recharge ou avec un niveau d'énergie faible en hiver
	+ Près de 75% des VE complètement chargés pendant l'été et plus de 50% en hiver, le pourcentage plus élevé après CFCFS	
HESF	+ Taux moyen d'acceptation de VE parmi les stratégies de recharge flexibles	
	+ Bon raport entre l'énergie demandé et l'énergie livrée	- Présence de VE en quittant la borne de recharge sans avoir été chargés en été et en hiver
	+ Pourcentage élevé d'énergie livrée, qui se traduit dans une meilleure utilisation des ressources	- Nombre faible de VE complètement chargés au temps de départ
LLF	+ Le plus bas pourcentage des VE qui partent sans recharge parmi les stratégies de recharge flexibles	
		- Plus haut pourcentage de VE partent sans recharge ou avec un faible niveau d'énergie (35% en hiver et jusqu'à 55% en été)
	+ Taux moyen d'acceptation de VE parmi les stratégies de recharge flexibles	- Pourcentage plus bas des VE complètement chargés (uniquement 24% en hiver et 41% en été)
MSoCW		- Le niveau d'énergie livré plus bas parmi toutes les stratégies
	+ 0% des VE partent sans recharge au temps de départ	
	+ Le meilleur rapport entre énergie demandé et énergie livrée	
	+ Haut niveau d'énergie livré	- Taux d'acceptation pour être chargé légèrement plus bas que la moyen des stratégies flexibles de recharge
	+ Nombre de VE en partent avec une demande d'énergie complètement réussi au temps de départ	
	+ Demande minimale de recharge garantie pour tous les VE en été et presque la totalité des VE en hiver	

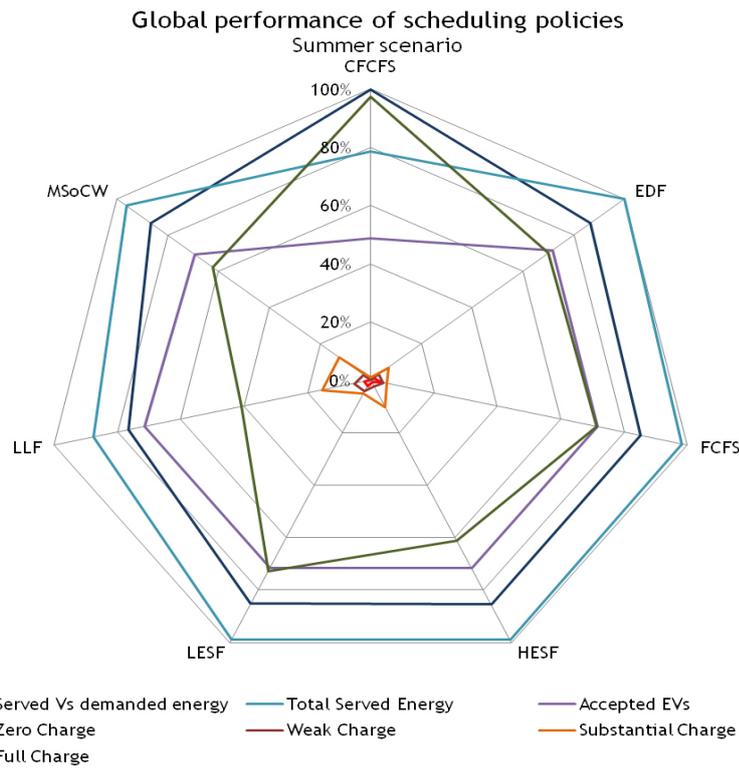
8.5.5 Résultats globales des stratégies de recharge

Nous avons considéré les résultats obtenus pour chacune des stratégies de recharge évaluées dans cette thèse pour fournir une vue globale des résultats obtenus. Pour ce faire, nous avons obtenu des résultats différents pour l'été et l'hiver en considérant toutes les taux d'arrivés, les taux de recharges et les nombres des bornes de recharge disponibles pour chaque scénario de simulation et pour chacune des stratégies de recharge disponibles. Les figures 8.1a et 8.1b montrent pour chaque stratégie de recharge, le pourcentage de la métrique qui accomplit ou un paramètre en particulier d'une métrique donnée. Pour cela, nous affichons le rapport entre l'énergie demandé et l'énergie livré, le taux d'acceptation de VEs et le totale d'énergie livré. Pour ce dernier paramètre, le pourcentage est comparé avec celui de la stratégie de recharge avec la valeur maximale obtenue, qui correspond à EDF en été et HESF en hiver.

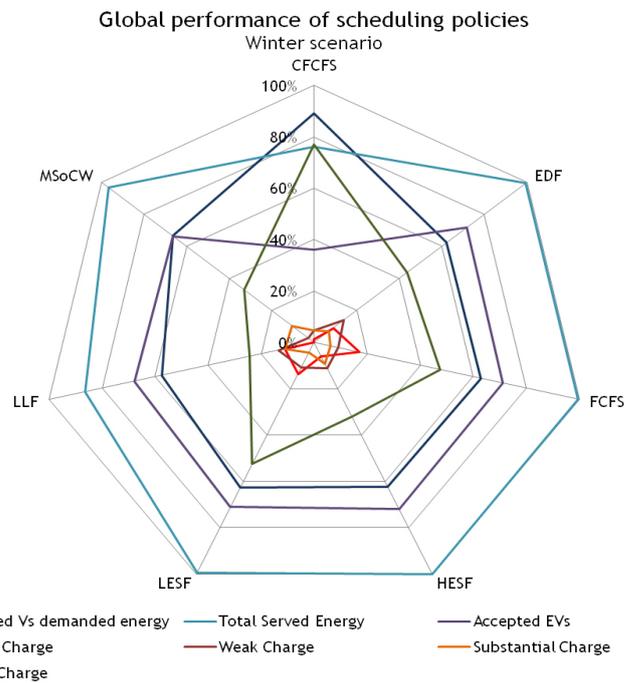
En plus, dû à l'importance de la QoS, les figures 8.1a and 8.1b montrent également, le pourcentage des VEs qui partent sans avoir été chargés au temps de départ et le pourcentage des VEs qui partent avec un niveau de recharge faible ou considérable, ainsi que les VEs avec une demande d'énergie complètement satisfaite.

La stratégie de recharge choisie par le CSO doit prendre en compte les objectifs du model économique. Dans les deux graphes nous pouvons observer comment CFCFs propose hauts niveaux de QoS, avec le plus grand rapport entre l'énergie demandé et l'énergie livré, ainsi que le plus grand pourcentage de VEs complètement chargés. Cependant, il est possible d'observer comment le taux d'acceptation et le total d'énergie livré par rapport aux autres stratégies de recharge est moins efficace. Cette stratégie pourrait être choisie par le CSO si l'objectif est de proposer une haute QoS au coût de proposer le service de recharge à moins d'utilisateurs. Avec un compromis entre le nombre des VEs acceptés et la QoS, EDF ou LESF pourraient être considérés par le CSO quand le modèle économique propose des niveaux raisonnables des VEs complètement chargés. Ces deux stratégies balancent mieux le montant d'énergie livré parmi tous les VEs avec un taux raisonnable d'énergie livré par rapport au montant d'énergie livré. Cependant, il pourrait être considéré par le CSO s'il doit faire face à une pénalité pour une faible QoS.

Finalement, il est possible d'observer comment la stratégie MSoCW élimine le problème des VEs qui partent sans avoir été chargés au même temps qu'il présente un niveau d'énergie livré plus acceptable, ainsi qu'une bonne proportion d'énergie livré par rapport à l'énergie demandé.



(a) Evaluation globale de la performance de toutes les stratégies avec les conditions d'éclairage d'été.



(b) Evaluation globale de la performance de toutes les stratégies avec les conditions d'éclairage d'été.

Figure 8.1 – Performance moyenne de chaque stratégie de recharge par rapport à chacune des métriques disponibles.

8.6 Perspectives

- Les algorithmes présentés dans cette thèse permettent de fournir une Qualité de Service aux utilisateurs finals. Les futurs travaux sur la commercialisation d'infrastructures de recharge public devront considérer également les prix du parking, ainsi que pouvoir déterminer quelle est le meilleur rapport (place de parking, service de recharge). La localisation des bornes de recharge a un impact considérable sur les politiques de pricing. Dans les zones plus demandées, par exemple: aux alentours des gares de train, le prix de recharge pourrait être plus élevé que dans une zone de la banlieue.
- Les infrastructures de recharge considérées dans ce manuscrit peuvent être vues comme des éléments des micro-grilles. Il peut arriver que l'énergie stocké dans les batteries stationnaires des micro-grilles pourrait être utilisé par les VEs ou dans les périodes de forte demande énergétique, que les VEs collaborent à équilibrer la demande énergétique du réseau.

Performance Evaluation: details and extended results

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A.1 Public Lighting System Electrical Network

The full electric diagram of the [PLS](#) electric network considered as our reference model is shown in [Figure A.1](#). The electric network for our test-bed is conformed by 90 lamps divided in three sets of 30 lamps by phase. This test-bed only considers one [EV](#) charger connected to the network.

A.1.1 EV Market in France

The [EV](#) market in France has presented a constant evolution during the last few years. For modeling purposes, we have considered in our simulations the sales distribution during 2013. As it is mentioned in [Chapter 4](#), vehicles were divided in three different groups according to its battery capacity. [Table A.1](#) shows the number of vehicles sold in 2013, the battery capacity of each type of vehicle in kWh and the group where they were sorted for our simulations.

Model	Battery Capacity in kWh	Number of Sales	Group Considered
Renault - Zoe	22	5511	EV
Nissan - Leaf	24	1438	EV
Bolloré - BlueCar	20	658	EV
Smart - Fortwo	17.7	478	PHEV-2
Mia	8	201	PHEV-1
Peugeot - iOn	22	178	EV
Citroen - C-Zero	22	80	EV
Renault - Fluence	22	18	EV
Tesla- Roadster	53	1	EV
Mitsubishi - iMIEV	16	38	PHEV-2
Lumeneo - Neoma	NAV	3	NAV
Ford - Focus	23	4	EV
Tesla - Model S	60	17	EV
BMW - i3	22	68	EV
VW - e-UP	18.7	64	PHEV-2
AMPERA	16.5	57	PHEV-2
Chevrolet - Volt	16.5	15	PHEV-2
Toyota - Prius	4	393	PHEV-1
Volvo - V60	11.4	241	PHEV-2
Porsche - Panamera S-E	9.5	90	PHEV-1
OTHERS	22	22	EV
TOTAL		9575	

Table A.1 – Sales distribution of [EVs](#) and [PHEVs](#) in France in 2013

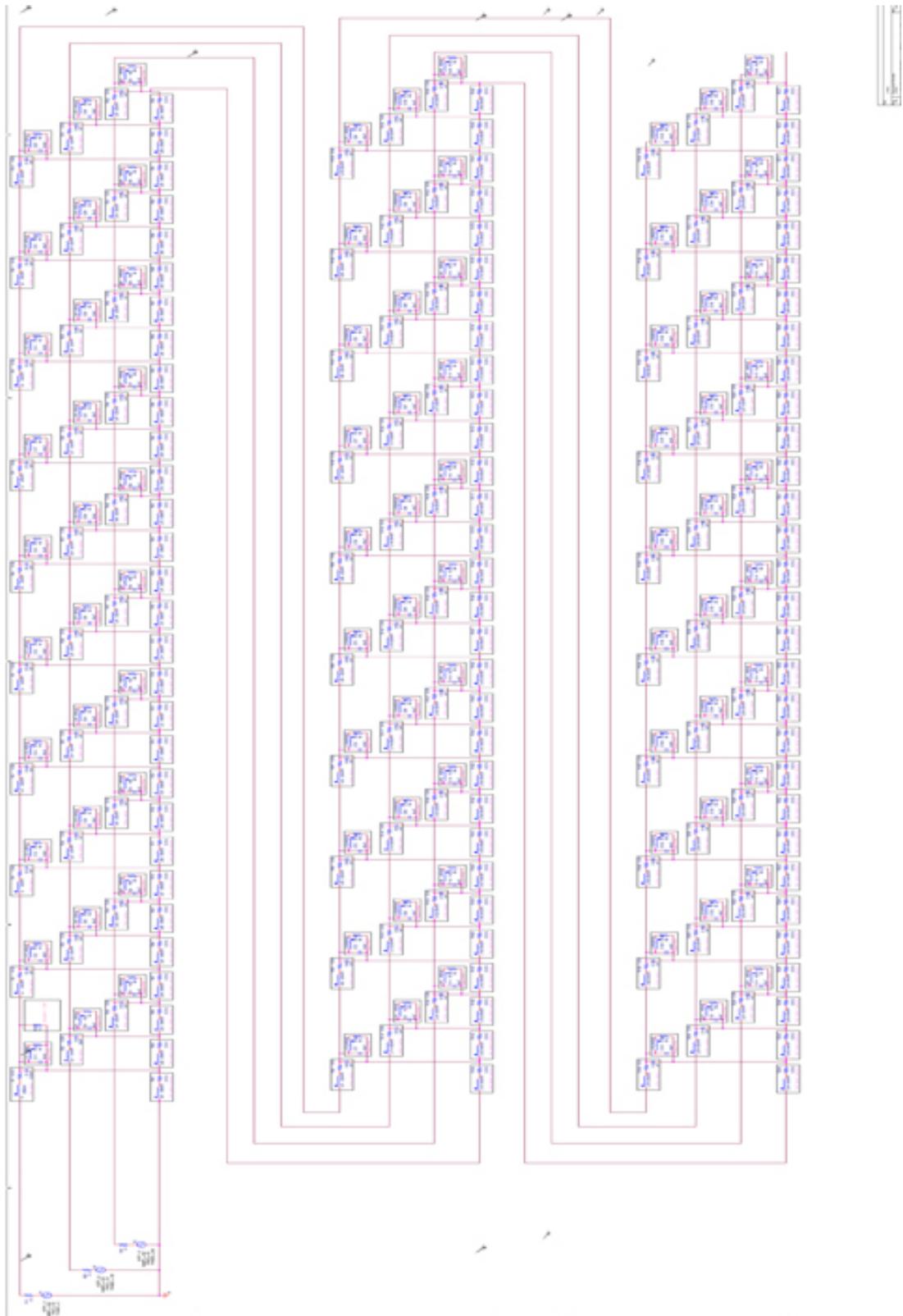


Figure A.1 – Full electric diagram of the PLS electric network with 90 lamps and 1 charger connected.

A.2 Detailed Results for CFCFS

A.2.1 Quality of Service for CoTaSch

Tables A.2, A.3, A.4 and Figures A.2, A.3, A.4 show the full details of the charging percentage of EVs at time of departure from the ChP.

It is observed that some scenarios present an amount of EVs without being fully charged. This is because at the end of the simulation period there are still EVs charging and as a consequence their charging processes are shown incomplete.

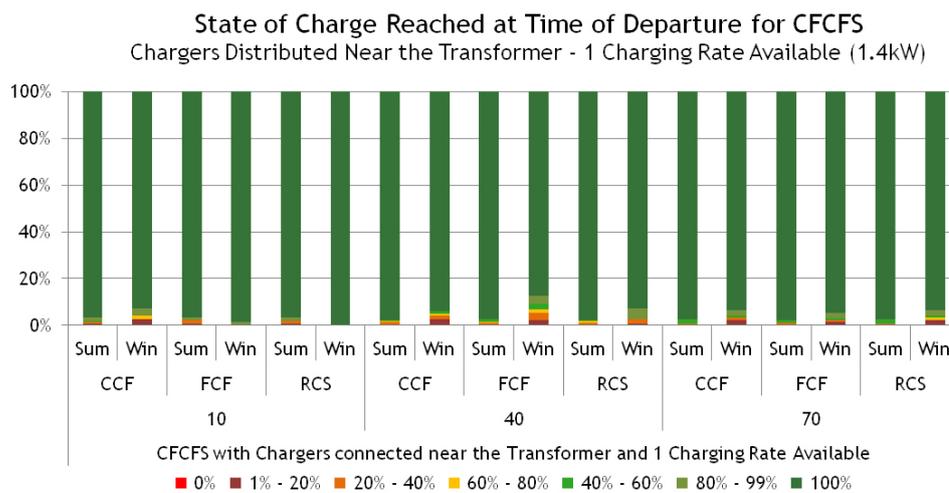


Figure A.2 – SoC reached at Time of Departure for 1 charging rate available (1.4 kW) and all the chargers connected near the transformer.

1 Charging Rate Available (1.4kW) - Chargers Placed Near the Transformer								
State of Charge Reached at Time of Departure								
Summer	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%	
EV's / Day = 10								
CCF	0.00 %	0.68 %	0.68 %	0.68 %	0.00 %	1.35 %	96.62 %	
FCF	0.00 %	0.71 %	1.43 %	0.00 %	0.00 %	1.43 %	96.43 %	
RCS	0.00 %	0.68 %	1.35 %	0.00 %	0.00 %	1.35 %	96.62 %	
EV's / Day = 40								
CCF	0.00 %	0.00 %	1.32 %	0.44 %	0.44 %	0.00 %	97.80 %	
FCF	0.00 %	0.00 %	1.01 %	1.01 %	0.50 %	0.00 %	97.49 %	
RCS	0.00 %	0.00 %	1.32 %	0.44 %	0.44 %	0.00 %	97.81 %	
EV's / Day = 70								
CCF	0.00 %	0.00 %	0.88 %	1.76 %	0.00 %	0.00 %	97.36 %	
FCF	0.00 %	0.00 %	0.98 %	1.47 %	0.00 %	0.00 %	97.55 %	
RCS	0.00 %	0.00 %	0.87 %	1.75 %	0.00 %	0.00 %	97.38 %	
Winter	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%	
EV's / Day = 10								
CCF	0.00 %	2.86 %	0.00 %	0.00 %	1.43 %	2.86 %	92.86 %	
FCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	1.61 %	98.39 %	
RCS	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %	
EV's / Day = 40								
CCF	0.00 %	2.76 %	1.38 %	1.38 %	0.69 %	0.00 %	93.79 %	
FCF	0.00 %	2.26 %	3.01 %	2.26 %	1.50 %	3.76 %	87.22 %	
RCS	0.00 %	0.71 %	2.14 %	0.00 %	0.00 %	4.29 %	92.86 %	
EV's / Day = 70								
CCF	0.00 %	2.14 %	1.43 %	0.71 %	0.00 %	2.14 %	93.57 %	
FCF	0.00 %	1.55 %	0.78 %	0.78 %	0.00 %	2.33 %	94.57 %	
RCS	0.00 %	2.11 %	0.00 %	0.70 %	1.41 %	2.11 %	93.66 %	

Table A.2 – SoC reached at Time of Departure considering only one charging rate available of 1.4 kW and all the chargers connected near the transformer.

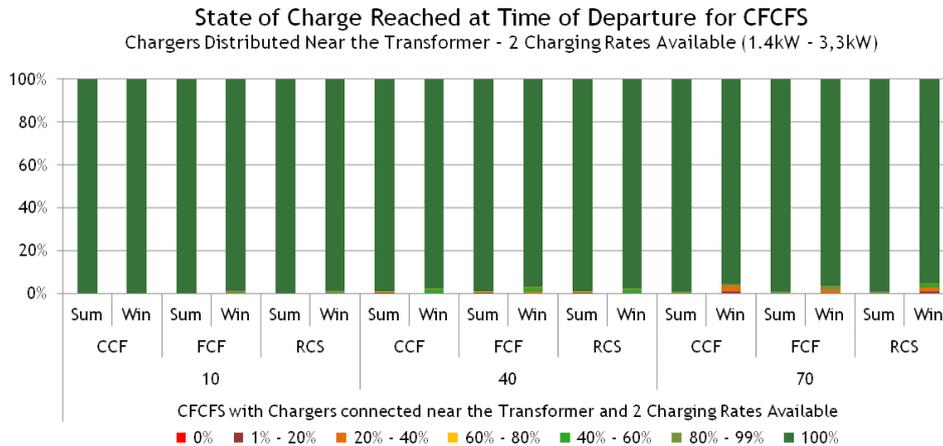


Figure A.3 – SoC reached at Time of Departure for 2 charging rates available (1.4 kW or 3.3 kW) and all the chargers connected near the transformer.

2 Charging Rates Available - 1.4 kW & 3.3 kW - Chargers Placed Near the Transformer							
State of Charge Reached at Time of Departure							
Summer	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%
EV's / Day = 10							
CCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
FCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
RCS	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
EV's / Day = 40							
CCF	0.00 %	0.48 %	0.00 %	0.00 %	0.48 %	0.00 %	99.03 %
FCF	0.00 %	0.48 %	0.00 %	0.00 %	0.48 %	0.00 %	99.03 %
RCS	0.00 %	0.48 %	0.00 %	0.00 %	0.48 %	0.00 %	99.03 %
EV's / Day = 70							
CCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.90 %	99.10 %
FCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.90 %	99.10 %
RCS	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.91 %	99.09 %
Winter	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%
EV's / Day = 10							
CCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %
FCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	1.16 %	98.84 %
RCS	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	1.18 %	98.82 %
EV's / Day = 40							
CCF	0.00 %	0.00 %	0.00 %	1.57 %	0.00 %	0.79 %	97.64 %
FCF	0.00 %	0.00 %	0.77 %	1.54 %	0.00 %	0.77 %	96.92 %
RCS	0.00 %	0.00 %	0.00 %	1.59 %	0.00 %	0.79 %	97.62 %
EV's / Day = 70							
CCF	0.00 %	0.71 %	2.84 %	0.00 %	0.00 %	0.71 %	95.74 %
FCF	0.00 %	0.00 %	1.49 %	0.00 %	0.00 %	2.24 %	96.27 %
RCS	0.00 %	0.69 %	2.08 %	1.39 %	0.00 %	0.69 %	95.14 %

Table A.3 – SoC reached at Time of Departure considering two charging rates available of 1.4 kW and 3.3 kW and all the chargers connected near the transformer.

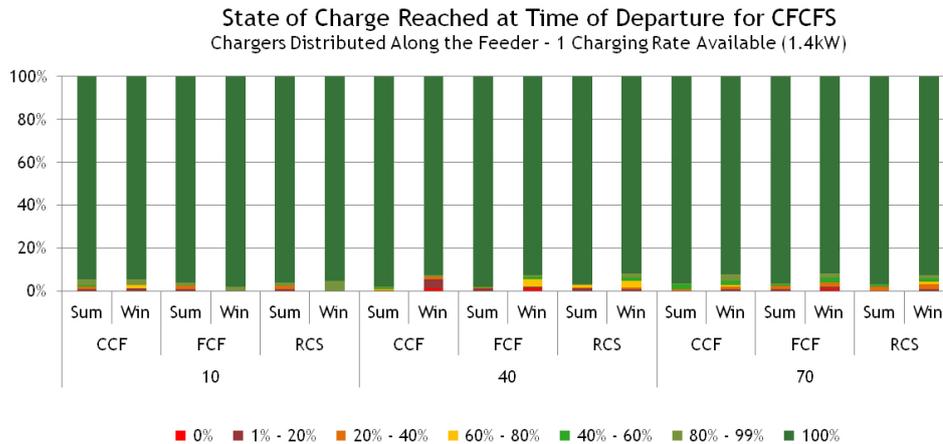


Figure A.4 – SoC reached at Time of Departure for 1 charging rate available (1.4 kW) and all the chargers connected along the feeder.

1 Charging Rate Available - 1.4kW- Distributed Chargers over the Feeder								
State of Charge Reached at Time of Departure								
Summer	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%	
EV's / Day = 10								
CCF	0.00 %	0.70 %	1.41 %	0.70 %	0.00 %	2.82 %	94.37 %	
FCF	0.00 %	0.81 %	1.61 %	0.00 %	0.00 %	1.61 %	95.97 %	
RCS	0.00 %	0.80 %	1.60 %	0.00 %	0.00 %	1.60 %	96.00 %	
EV's / Day = 40								
CCF	0.00 %	0.00 %	0.53 %	0.53 %	0.53 %	0.53 %	97.88 %	
FCF	0.00 %	1.08 %	0.54 %	0.00 %	1.08 %	0.54 %	96.77 %	
RCS	0.00 %	1.08 %	0.54 %	0.54 %	0.00 %	0.00 %	97.84 %	
EV's / Day = 70								
CCF	0.00 %	0.00 %	1.04 %	2.08 %	0.00 %	0.52 %	96.35 %	
FCF	0.00 %	0.00 %	2.17 %	0.54 %	0.00 %	0.54 %	96.74 %	
RCS	0.00 %	1.03 %	1.55 %	0.52 %	0.00 %	0.52 %	96.39 %	
Winter	0%	1% - 20%	21% - 40%	41% - 60%	61% - 80%	81% - 99%	100%	
EV's / Day = 10								
CCF	0.00 %	1.35 %	0.00 %	0.00 %	1.35 %	2.70 %	94.59 %	
FCF	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	4.55 %	95.45 %	
RCS	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	2.17 %	97.83 %	
EV's / Day = 40								
CCF	1.09 %	4.35 %	1.09 %	0.00 %	0.00 %	1.09 %	92.39 %	
FCF	0.00 %	0.91 %	0.91 %	1.82 %	2.73 %	1.82 %	91.82 %	
RCS	1.09 %	1.09 %	0.00 %	1.09 %	3.26 %	1.09 %	92.39 %	
EV's / Day = 70								
CCF	0.00 %	0.97 %	0.97 %	1.94 %	0.97 %	2.91 %	92.23 %	
FCF	0.00 %	0.84 %	2.52 %	1.68 %	0.84 %	1.68 %	92.44 %	
RCS	1.02 %	1.02 %	2.04 %	2.04 %	0.00 %	2.04 %	91.84 %	

Table A.4 – SoC reached at Time of Departure considering one charging rate available of 1.4 kW and all the chargers are distributed through the feeder.

A.3 Detailed Results for MSoCW

A.4 Total Results for all Scheduling Policies

Acceptance rate of EVs for charging									
Summer day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	88,7%	93,9%	93,3%	91,2%	89,0%	90,6%	98,6%	91,6%
	20	66,8%	89,0%	88,3%	89,7%	90,1%	85,8%	93,5%	88,6%
	30	54,7%	73,0%	73,8%	73,8%	74,6%	73,1%	73,7%	73,6%
	40	43,0%	61,7%	62,9%	60,2%	59,1%	60,1%	58,4%	60,8%
	50	36,5%	51,9%	51,4%	49,4%	50,7%	52,5%	47,3%	51,2%
	60	33,9%	44,5%	45,3%	43,5%	45,6%	44,9%	41,4%	44,8%
70	30,1%	39,7%	40,4%	40,2%	39,3%	39,7%	37,1%	39,8%	
2 charge rates & 12 chargers	10	81,9%	99,3%	99,3%	100,0%	98,7%	98,6%	99,3%	99,2%
	20	57,5%	98,0%	95,2%	95,2%	97,6%	97,6%	93,6%	96,7%
	30	48,3%	79,1%	77,8%	79,2%	79,5%	77,4%	71,4%	78,6%
	40	41,1%	64,3%	64,1%	66,2%	63,2%	64,2%	56,9%	64,4%
	50	36,9%	53,9%	53,4%	55,6%	55,9%	55,4%	48,0%	54,8%
	60	31,4%	49,1%	49,0%	48,9%	48,8%	47,5%	42,3%	48,7%
70	28,3%	42,2%	42,6%	42,5%	43,6%	41,7%	38,0%	42,5%	
3 charge rates & 9 chargers	10	88,7%	90,0%	89,3%	90,0%	92,0%	89,3%	100,0%	90,1%
	20	66,2%	90,5%	91,9%	92,0%	91,9%	92,5%	98,6%	91,8%
	30	53,7%	84,5%	83,6%	86,7%	84,2%	86,3%	89,1%	85,1%
	40	44,8%	75,3%	76,7%	75,9%	74,9%	77,3%	72,3%	76,0%
	50	39,6%	63,7%	66,0%	66,0%	66,2%	65,3%	62,2%	65,4%
	60	34,0%	59,4%	55,8%	56,8%	55,6%	55,8%	53,8%	56,7%
70	29,3%	51,7%	50,8%	50,1%	50,9%	52,3%	47,2%	51,2%	
3 charge rates & 12 chargers	10	80,7%	98,0%	98,6%	99,3%	98,6%	99,3%	99,3%	98,8%
	20	58,9%	97,9%	98,0%	99,7%	99,0%	100,0%	99,7%	98,9%
	30	46,8%	92,7%	92,4%	92,2%	95,3%	94,2%	91,6%	93,4%
	40	41,1%	78,0%	78,3%	79,1%	81,2%	78,9%	71,1%	79,1%
	50	37,0%	67,5%	70,9%	68,9%	68,8%	66,1%	60,0%	68,5%
	60	33,1%	60,7%	59,7%	62,3%	58,8%	58,3%	53,6%	60,0%
70	28,0%	52,5%	54,8%	53,6%	55,2%	52,6%	46,5%	53,7%	
Winter day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	64,2%	93,8%	94,0%	93,2%	89,3%	81,8%	90,6%	90,4%
	20	45,8%	91,8%	88,0%	89,6%	86,7%	82,3%	87,6%	87,7%
	30	42,7%	74,5%	71,7%	73,9%	73,2%	70,1%	67,5%	72,7%
	40	33,3%	59,1%	60,3%	60,8%	59,8%	61,8%	53,7%	60,3%
	50	28,2%	51,8%	52,7%	51,7%	52,3%	50,5%	44,6%	51,8%
	60	25,9%	44,8%	45,1%	46,1%	44,8%	43,7%	39,6%	44,9%
70	24,7%	40,7%	39,1%	39,7%	39,9%	39,7%	32,6%	39,8%	
2 charge rates & 12 chargers	10	56,0%	98,6%	98,0%	100,0%	98,0%	92,0%	95,3%	97,3%
	20	43,1%	96,9%	99,3%	97,0%	95,9%	89,8%	91,1%	95,8%
	30	35,3%	77,0%	77,0%	78,2%	78,9%	74,8%	71,4%	77,2%
	40	32,4%	64,0%	63,0%	65,7%	61,3%	63,3%	57,1%	63,5%
	50	27,6%	54,3%	54,1%	55,1%	54,8%	50,9%	48,8%	53,8%
	60	26,0%	48,3%	47,9%	48,2%	46,7%	47,1%	41,0%	47,6%
70	23,1%	42,9%	42,3%	42,2%	42,4%	40,6%	37,1%	42,1%	
3 charge rates & 9 chargers	10	58,0%	91,9%	89,3%	91,9%	90,3%	84,7%	94,7%	89,6%
	20	45,3%	92,8%	91,3%	91,1%	90,8%	85,8%	90,6%	90,4%
	30	37,4%	87,1%	85,8%	87,9%	88,0%	77,9%	84,5%	85,3%
	40	33,4%	74,3%	74,6%	73,6%	76,0%	71,2%	70,6%	73,9%
	50	31,6%	62,5%	64,0%	64,3%	64,9%	62,6%	54,3%	63,6%
	60	26,7%	57,3%	55,6%	57,2%	55,4%	55,8%	49,1%	56,3%
70	24,9%	50,8%	50,4%	52,2%	49,7%	49,3%	44,3%	50,5%	
3 charge rates & 12 chargers	10	59,3%	100,0%	98,6%	98,6%	98,0%	93,3%	92,7%	97,7%
	20	42,0%	98,0%	98,6%	98,3%	98,6%	95,3%	95,6%	97,8%
	30	36,0%	91,8%	92,2%	94,7%	93,7%	85,5%	90,4%	91,6%
	40	32,7%	79,9%	80,1%	81,0%	78,5%	76,4%	71,2%	79,2%
	50	28,5%	68,0%	69,4%	67,9%	66,0%	64,1%	60,5%	67,1%
	60	26,0%	60,3%	59,5%	60,4%	58,6%	57,9%	52,4%	59,3%
70	23,1%	54,2%	51,7%	53,1%	55,4%	53,6%	47,7%	53,6%	

Table A.5 – Acceptance rate of EVs for charging.

Average amount of transmission losses registered per hour									
Summer day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	62 314	63 734	62 211	63 114	62 441	61 457	65 134	62 591
	20	73 047	86 220	86 367	86 217	85 030	76 472	89 788	84 061
	30	80 155	93 375	90 317	93 976	95 762	83 864	92 736	91 459
	40	81 980	102 724	95 166	100 254	97 712	87 822	96 076	96 736
	50	84 311	103 992	94 856	99 332	101 877	88 345	95 512	97 680
	60	91 860	99 751	97 630	101 231	103 916	90 688	95 961	98 643
	70	93 167	100 561	98 529	106 777	101 132	92 500	101 124	99 900
2 charge rates & 12 chargers	10	62 633	62 160	62 363	63 285	62 465	60 885	64 532	62 232
	20	71 819	89 258	87 151	88 254	89 398	79 835	90 419	86 779
	30	78 668	103 484	98 082	111 380	105 943	93 371	108 503	102 452
	40	83 767	111 302	106 055	119 680	115 080	98 277	111 321	110 079
	50	90 654	113 530	114 107	118 365	116 480	100 914	113 042	112 679
	60	92 788	116 498	114 881	123 361	115 041	100 092	112 231	113 975
	70	92 488	119 009	111 277	123 551	122 677	106 299	116 494	116 563
3 charge rates & 9 chargers	10	69 888	76 493	76 597	77 195	77 227	64 014	78 488	74 305
	20	82 551	119 431	109 455	112 653	115 013	86 469	118 423	108 604
	30	95 890	128 327	120 492	129 891	129 026	93 728	124 354	120 293
	40	102 978	133 947	128 872	137 001	133 909	97 669	126 623	126 280
	50	110 953	138 622	129 624	137 932	145 308	101 776	131 715	130 652
	60	113 350	148 595	138 295	147 170	150 197	103 250	138 790	137 501
	70	119 589	150 055	147 639	139 996	144 617	104 299	142 703	137 321
3 charge rates & 12 chargers	10	70 163	75 700	76 473	76 531	76 933	63 229	77 175	73 773
	20	86 093	116 610	111 239	116 145	118 098	86 868	119 388	109 792
	30	94 435	157 673	133 984	150 044	149 312	105 690	151 506	139 341
	40	99 757	176 418	140 937	156 720	162 019	111 268	151 087	149 472
	50	109 186	159 090	162 042	166 609	163 008	116 762	158 499	153 502
	60	117 405	164 584	162 513	172 906	161 445	121 243	161 385	156 538
	70	116 041	169 329	162 543	169 558	174 090	118 875	159 544	158 879
Winter day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	119 830	129 033	128 024	129 089	127 706	124 983	128 904	127 767
	20	125 373	142 180	140 661	141 680	141 022	136 085	143 474	140 326
	30	132 464	147 440	147 477	148 864	148 539	140 327	147 240	146 529
	40	133 666	147 210	149 564	150 964	150 406	144 005	149 622	148 430
	50	138 208	149 608	147 829	153 172	153 651	146 254	149 128	150 103
	60	139 673	150 912	147 761	154 639	153 391	143 565	151 085	150 054
	70	144 809	151 950	149 778	155 915	153 968	146 359	150 533	151 594
2 charge rates & 12 chargers	10	119 484	128 753	127 746	128 817	127 449	125 197	130 390	127 592
	20	125 721	141 887	140 257	142 922	141 515	136 340	145 421	140 584
	30	129 913	157 635	149 057	155 003	153 661	143 001	156 648	151 671
	40	134 258	160 749	150 532	158 866	160 241	148 267	159 297	155 731
	50	139 007	159 885	157 615	163 262	160 130	151 374	159 220	158 453
	60	139 753	158 881	156 386	163 370	161 175	152 187	160 350	158 400
	70	142 989	163 807	153 735	166 565	163 233	153 117	158 689	160 091
3 charge rates & 9 chargers	10	124 760	136 693	135 360	137 029	136 701	126 324	137 608	134 422
	20	131 295	160 136	155 082	162 500	160 830	139 799	161 504	155 669
	30	138 136	168 123	163 517	166 758	170 412	147 469	168 799	163 256
	40	146 204	171 312	169 819	172 869	169 478	149 455	172 951	166 587
	50	147 526	171 219	169 279	175 172	173 599	151 599	174 751	168 173
	60	153 482	174 925	171 486	175 659	177 366	153 657	174 607	170 618
	70	155 005	174 774	173 736	182 413	175 383	153 032	175 399	171 868
3 charge rates & 12 chargers	10	125 634	137 919	136 703	136 961	136 862	127 214	136 989	135 132
	20	132 132	159 397	157 655	161 760	161 962	142 386	165 408	156 632
	30	139 460	172 223	165 993	179 701	178 352	149 573	180 872	169 168
	40	147 102	186 783	170 239	184 793	183 792	156 621	185 308	176 446
	50	150 459	190 118	178 318	185 917	188 244	156 325	187 022	179 784
	60	155 760	184 493	179 741	185 135	184 601	161 485	186 233	179 091
	70	155 214	181 354	174 767	190 466	190 273	161 361	185 026	179 644

Table A.6 – Average amount of transmission losses registered

Ratio between registered losses and the dispatched energy to the loads										
Summer day-light conditions										
Topology	EVs / day	CFEFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies	
2 charge rates & 9 chargers	10	5,3%	5,4%	5,4%	5,5%	5,7%	5,5%	5,2%	5,5%	
	20	4,2%	4,1%	4,0%	4,1%	4,1%	4,2%	4,1%	4,1%	
	30	3,9%	4,0%	3,9%	3,9%	3,9%	3,9%	4,0%	3,9%	
	40	3,9%	3,8%	3,7%	3,9%	3,8%	3,8%	3,9%	3,8%	
	50	3,7%	3,6%	3,8%	3,9%	3,8%	3,7%	3,9%	3,8%	
	60	3,6%	3,9%	3,7%	3,7%	3,7%	3,7%	3,8%	3,8%	
2 charge rates & 12 chargers	70	3,6%	3,8%	3,7%	3,8%	3,8%	3,7%	3,8%	3,7%	
	10	5,5%	5,4%	5,5%	5,5%	5,4%	5,5%	5,0%	5,5%	
	20	4,3%	4,0%	4,0%	4,0%	4,2%	4,0%	4,1%	4,0%	
	30	3,9%	4,0%	3,9%	4,1%	3,9%	3,9%	4,1%	4,0%	
	40	3,7%	4,1%	3,8%	4,1%	4,1%	3,7%	4,0%	4,0%	
	50	3,7%	4,1%	3,7%	3,9%	3,9%	3,8%	3,9%	3,9%	
3 charge rates & 9 chargers	60	3,6%	4,0%	3,7%	4,1%	3,9%	3,9%	4,0%	3,9%	
	70	3,6%	4,1%	4,0%	4,0%	4,1%	3,8%	4,0%	4,0%	
	10	6,6%	5,9%	5,9%	6,0%	5,9%	5,4%	6,0%	5,8%	
	20	5,4%	4,8%	4,7%	4,9%	4,9%	4,2%	5,1%	4,7%	
	30	4,9%	4,6%	4,5%	4,8%	4,8%	4,2%	4,7%	4,6%	
	40	4,8%	4,5%	4,4%	4,8%	4,8%	3,9%	4,8%	4,5%	
3 charge rates & 12 chargers	50	4,7%	4,6%	4,4%	4,6%	4,8%	3,9%	4,6%	4,5%	
	60	4,6%	4,6%	4,4%	4,8%	4,8%	4,0%	4,7%	4,5%	
	70	4,6%	4,7%	4,6%	4,7%	4,6%	4,0%	4,7%	4,5%	
	10	6,6%	5,9%	6,0%	6,0%	6,0%	5,2%	6,1%	5,8%	
	20	5,4%	4,8%	4,7%	4,8%	4,9%	4,1%	4,8%	4,7%	
	30	5,0%	5,0%	4,5%	5,1%	4,9%	4,1%	5,0%	4,7%	
3 charge rates & 9 chargers	40	4,7%	5,3%	4,5%	5,1%	5,1%	4,2%	5,1%	4,8%	
	50	4,6%	4,9%	4,8%	5,1%	5,1%	4,3%	5,2%	4,8%	
	60	4,6%	4,8%	4,9%	5,3%	5,0%	4,2%	5,1%	4,8%	
	70	4,5%	5,0%	4,8%	5,2%	5,2%	4,1%	5,1%	4,8%	
	Winter day-light conditions									
	Topology	EVs / day	CFEFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	16,6%	12,3%	11,8%	12,0%	12,7%	13,6%	11,9%	12,5%	
	20	11,8%	9,3%	9,2%	9,3%	9,5%	9,9%	9,4%	9,4%	
	30	9,7%	8,6%	8,4%	8,4%	8,7%	9,4%	9,0%	8,7%	
	40	9,3%	8,6%	8,0%	8,6%	8,4%	8,8%	8,7%	8,5%	
	50	8,6%	8,4%	8,3%	7,9%	8,0%	8,5%	8,5%	8,2%	
	60	8,4%	8,2%	8,2%	7,8%	8,0%	8,8%	8,4%	8,2%	
2 charge rates & 12 chargers	70	7,9%	8,3%	7,8%	7,9%	8,0%	8,5%	8,4%	8,1%	
	10	16,8%	12,3%	12,5%	12,5%	12,7%	13,9%	11,6%	12,8%	
	20	12,0%	9,5%	9,0%	9,3%	9,4%	10,0%	9,2%	9,4%	
	30	10,5%	8,2%	8,3%	8,8%	8,8%	9,4%	9,1%	8,7%	
	40	9,1%	8,1%	8,4%	8,4%	8,4%	8,9%	9,0%	8,4%	
	50	8,4%	9,0%	7,7%	8,3%	8,1%	8,5%	9,1%	8,3%	
3 charge rates & 9 chargers	60	8,3%	8,5%	7,7%	8,2%	8,1%	8,6%	8,9%	8,2%	
	70	7,9%	8,6%	8,1%	8,1%	8,3%	8,7%	8,9%	8,4%	
	10	17,2%	11,9%	11,9%	11,6%	12,0%	13,0%	11,5%	12,1%	
	20	13,0%	8,9%	8,7%	9,3%	9,0%	9,8%	9,3%	9,1%	
	30	10,9%	8,5%	8,5%	8,9%	8,6%	8,8%	8,8%	8,7%	
	40	9,6%	8,3%	8,6%	8,4%	8,6%	8,7%	8,4%	8,5%	
3 charge rates & 12 chargers	50	9,3%	8,2%	8,3%	8,4%	8,4%	8,7%	8,4%	8,4%	
	60	8,8%	8,2%	8,0%	8,3%	8,4%	8,4%	8,5%	8,3%	
	70	8,9%	8,1%	7,9%	8,5%	8,3%	8,8%	8,4%	8,3%	
	10	16,8%	11,3%	11,5%	11,6%	11,6%	12,3%	12,0%	11,7%	
	20	13,2%	9,0%	8,6%	9,2%	9,1%	9,4%	9,1%	9,1%	
	30	11,0%	8,7%	8,4%	9,1%	9,0%	8,8%	9,1%	8,8%	
3 charge rates & 9 chargers	40	9,5%	8,7%	8,3%	8,9%	9,1%	8,5%	9,2%	8,7%	
	50	9,3%	8,8%	8,2%	8,8%	9,0%	9,0%	9,2%	8,8%	
	60	8,8%	8,5%	8,3%	8,7%	8,6%	8,7%	9,0%	8,5%	
	70	8,7%	8,4%	8,1%	8,8%	8,7%	9,0%	9,0%	8,6%	

Table A.7 – Ratio between registered losses and the energy dispatched to the loads.

Total served energy for summer case scenario									
Summer day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	1 170 788	1 187 935	1 150 352	1 157 393	1 093 400	1 125 194	1 261 824	1 142 855
	20	1 723 892	2 124 115	2 159 838	2 122 786	2 056 340	1 840 877	2 201 918	2 060 791
	30	2 049 788	2 323 029	2 310 684	2 419 952	2 431 119	2 176 670	2 340 590	2 332 291
	40	2 125 657	2 733 377	2 539 676	2 543 646	2 555 645	2 318 768	2 493 812	2 538 222
	50	2 286 272	2 868 372	2 501 652	2 546 207	2 698 894	2 407 523	2 459 979	2 604 530
	60	2 563 204	2 543 296	2 603 685	2 708 892	2 797 438	2 444 738	2 526 236	2 619 610
	70	2 576 823	2 646 619	2 654 130	2 836 044	2 680 340	2 528 037	2 688 359	2 669 034
2 charge rates & 12 chargers	10	1 130 885	1 152 882	1 132 692	1 141 391	1 149 349	1 106 577	1 278 410	1 136 578
	20	1 654 433	2 228 752	2 165 934	2 185 101	2 141 604	2 006 527	2 198 104	2 145 584
	30	1 991 673	2 572 617	2 496 561	2 727 271	2 699 274	2 374 289	2 655 098	2 574 002
	40	2 254 484	2 741 991	2 758 214	2 937 944	2 788 762	2 628 171	2 754 381	2 771 016
	50	2 428 529	2 739 442	3 061 499	2 999 634	2 975 906	2 641 755	2 865 665	2 883 647
	60	2 554 223	2 877 565	3 098 921	2 991 707	2 966 858	2 588 862	2 821 691	2 904 783
	70	2 549 298	2 908 409	2 816 915	3 077 102	2 956 632	2 772 747	2 907 463	2 906 361
3 charge rates & 9 chargers	10	1 053 519	1 303 414	1 301 753	1 284 281	1 307 900	1 184 617	1 318 151	1 276 393
	20	1 540 160	2 475 067	2 319 585	2 309 465	2 347 223	2 081 622	2 340 773	2 306 592
	30	1 951 168	2 779 743	2 685 447	2 679 741	2 678 220	2 242 893	2 618 387	2 613 209
	40	2 154 526	2 972 613	2 914 577	2 852 005	2 799 849	2 483 240	2 663 606	2 804 457
	50	2 385 428	3 011 308	2 960 263	2 989 611	3 013 335	2 609 567	2 846 392	2 916 817
	60	2 465 328	3 224 805	3 113 696	3 082 465	3 116 205	2 576 074	2 929 126	3 022 649
	70	2 616 485	3 224 621	3 213 804	3 010 548	3 171 071	2 617 169	3 012 088	3 047 443
3 charge rates & 12 chargers	10	1 062 846	1 276 115	1 282 511	1 285 034	1 285 392	1 205 110	1 263 203	1 266 832
	20	1 590 332	2 439 562	2 373 453	2 402 297	2 397 100	2 109 103	2 488 667	2 344 303
	30	1 906 123	3 138 290	2 969 347	2 935 757	3 040 091	2 576 086	3 015 146	2 931 914
	40	2 106 207	3 315 980	3 106 604	3 089 546	3 198 419	2 646 022	2 955 456	3 071 314
	50	2 351 961	3 279 578	3 348 419	3 252 263	3 208 069	2 745 186	3 025 147	3 166 703
	60	2 566 796	3 456 608	3 322 336	3 275 382	3 219 834	2 902 644	3 140 906	3 235 361
	70	2 576 096	3 409 695	3 384 401	3 280 655	3 367 716	2 898 080	3 140 186	3 268 109
Winter day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	721 125	1 047 400	1 082 022	1 074 967	1 008 638	921 736	1 086 907	1 026 953
	20	1 059 475	1 534 868	1 524 516	1 527 662	1 476 998	1 371 682	1 533 398	1 487 145
	30	1 363 204	1 712 129	1 745 872	1 770 449	1 714 055	1 490 628	1 628 890	1 686 627
	40	1 434 072	1 714 709	1 870 330	1 757 014	1 800 873	1 641 042	1 713 354	1 756 794
	50	1 611 107	1 782 408	1 776 968	1 929 092	1 929 235	1 729 416	1 753 989	1 829 424
	60	1 656 543	1 837 965	1 797 800	1 989 126	1 914 275	1 625 821	1 796 257	1 832 997
	70	1 833 922	1 826 101	1 919 935	1 979 367	1 933 529	1 722 417	1 799 966	1 876 270
2 charge rates & 12 chargers	10	713 139	1 044 461	1 021 752	1 033 963	1 000 298	901 052	1 122 530	1 000 305
	20	1 051 354	1 490 714	1 559 546	1 544 036	1 504 502	1 357 534	1 587 259	1 491 266
	30	1 240 088	1 921 028	1 797 856	1 753 938	1 736 471	1 514 705	1 717 159	1 744 800
	40	1 472 326	1 993 295	1 795 027	1 900 420	1 908 820	1 674 613	1 773 454	1 854 435
	50	1 661 276	1 784 841	2 035 581	1 960 229	1 987 113	1 786 290	1 742 482	1 910 811
	60	1 678 097	1 863 988	2 029 696	1 999 308	1 995 439	1 776 409	1 808 239	1 932 968
	70	1 806 750	1 895 361	1 897 126	2 056 511	1 961 036	1 765 891	1 774 700	1 915 185
3 charge rates & 9 chargers	10	725 932	1 147 418	1 135 464	1 181 358	1 143 359	968 783	1 194 980	1 115 276
	20	1 010 005	1 797 147	1 778 004	1 743 767	1 791 380	1 431 989	1 741 665	1 708 457
	30	1 269 999	1 969 433	1 933 166	1 867 425	1 987 565	1 668 761	1 908 942	1 885 270
	40	1 520 884	2 074 055	1 981 517	2 047 942	1 981 632	1 712 736	2 049 945	1 959 576
	50	1 578 056	2 099 129	2 050 841	2 077 145	2 070 392	1 748 165	2 090 664	2 009 134
	60	1 744 508	2 139 987	2 132 365	2 109 000	2 123 548	1 839 463	2 063 154	2 068 873
	70	1 750 963	2 163 325	2 192 873	2 149 225	2 119 141	1 731 290	2 082 028	2 071 171
3 charge rates & 12 chargers	10	748 319	1 215 868	1 184 464	1 179 884	1 184 084	1 034 863	1 141 630	1 159 833
	20	1 000 682	1 774 155	1 825 048	1 753 659	1 783 505	1 509 265	1 809 057	1 729 126
	30	1 272 124	1 975 380	1 975 486	1 967 787	1 973 450	1 690 821	1 996 090	1 916 585
	40	1 549 833	2 158 510	2 045 042	2 070 018	2 010 873	1 844 909	2 011 301	2 025 870
	50	1 625 155	2 155 685	2 175 337	2 103 992	2 095 213	1 734 157	2 038 992	2 052 877
	60	1 779 754	2 164 861	2 172 960	2 134 009	2 158 707	1 862 173	2 063 847	2 098 542
	70	1 789 239	2 169 307	2 168 722	2 156 778	2 191 690	1 787 702	2 065 410	2 094 840

Table A.8 – Total served energy for the summer case scenario

Ratio between dispatched and requested energy										
Summer day-light conditions										
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average	Flex Policies
2 charge rates & 9 chargers	10	100%	100%	100%	100%	100%	98%	100%	100%	100%
	20	100%	96%	97%	95%	91%	84%	94%	93%	93%
	30	100%	85%	85%	89%	87%	81%	83%	85%	85%
	40	100%	89%	84%	86%	86%	79%	86%	85%	85%
	50	100%	89%	80%	85%	86%	76%	84%	83%	83%
	60	100%	76%	77%	85%	82%	73%	80%	79%	79%
	70	100%	78%	76%	82%	81%	73%	80%	78%	78%
2 charge rates & 12 chargers	10	100%	100%	100%	100%	99%	97%	100%	99%	99%
	20	100%	98%	95%	94%	91%	86%	92%	93%	93%
	30	100%	82%	81%	83%	87%	74%	78%	81%	81%
	40	99%	74%	74%	78%	77%	70%	77%	75%	75%
	50	100%	71%	78%	76%	73%	69%	73%	73%	73%
	60	99%	67%	76%	72%	73%	64%	69%	71%	71%
	70	100%	67%	66%	72%	68%	63%	70%	67%	67%
3 charge rates & 9 chargers	10	100%	100%	100%	100%	100%	96%	100%	99%	99%
	20	100%	99%	97%	96%	96%	83%	98%	94%	94%
	30	100%	93%	91%	88%	88%	77%	95%	87%	87%
	40	100%	92%	91%	85%	87%	77%	93%	87%	87%
	50	100%	91%	87%	87%	86%	74%	92%	85%	85%
	60	100%	86%	84%	83%	84%	71%	90%	81%	81%
	70	100%	87%	85%	80%	82%	71%	91%	81%	81%
3 charge rates & 12 chargers	10	100%	100%	100%	100%	100%	95%	100%	99%	99%
	20	100%	100%	96%	96%	96%	82%	99%	94%	94%
	30	100%	90%	85%	84%	83%	73%	86%	83%	83%
	40	100%	82%	78%	80%	79%	67%	82%	77%	77%
	50	100%	79%	76%	74%	75%	66%	79%	74%	74%
	60	100%	75%	74%	72%	74%	64%	78%	72%	72%
	70	100%	74%	70%	71%	71%	64%	77%	70%	70%
Winter day-light conditions										
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average	Flex Policies
2 charge rates & 9 chargers	10	94%	90%	95%	94%	89%	91%	96%	92%	92%
	20	93%	67%	70%	67%	68%	67%	70%	68%	68%
	30	88%	63%	65%	65%	63%	57%	65%	63%	63%
	40	85%	59%	63%	60%	62%	55%	64%	60%	60%
	50	90%	55%	54%	61%	60%	55%	64%	57%	57%
	60	84%	56%	56%	58%	59%	52%	62%	56%	56%
	70	82%	52%	58%	60%	57%	51%	65%	55%	55%
2 charge rates & 12 chargers	10	97%	90%	92%	89%	94%	84%	91%	90%	90%
	20	93%	64%	68%	68%	66%	64%	68%	66%	66%
	30	89%	59%	57%	54%	53%	53%	56%	55%	55%
	40	87%	55%	49%	54%	52%	49%	53%	51%	51%
	50	84%	46%	52%	50%	49%	48%	53%	49%	49%
	60	82%	45%	51%	47%	49%	45%	49%	47%	47%
	70	82%	44%	44%	46%	47%	43%	46%	45%	45%
3 charge rates & 9 chargers	10	97%	93%	90%	91%	92%	83%	95%	90%	90%
	20	91%	74%	71%	71%	72%	62%	76%	70%	70%
	30	92%	70%	66%	63%	68%	61%	72%	65%	65%
	40	90%	64%	62%	62%	63%	56%	72%	61%	61%
	50	90%	62%	59%	62%	60%	55%	68%	60%	60%
	60	87%	58%	59%	57%	60%	54%	68%	57%	57%
	70	84%	59%	57%	56%	58%	50%	65%	56%	56%
3 charge rates & 12 chargers	10	96%	95%	95%	92%	93%	88%	96%	92%	92%
	20	95%	71%	72%	69%	71%	61%	73%	69%	69%
	30	91%	57%	58%	55%	55%	52%	59%	55%	55%
	40	90%	53%	50%	52%	50%	49%	57%	51%	51%
	50	89%	51%	50%	50%	52%	45%	55%	50%	50%
	60	85%	48%	49%	47%	49%	43%	53%	47%	47%
	70	85%	45%	47%	46%	46%	39%	50%	45%	45%

Table A.9 – Ratio between dispatched and requested energy

Average amount of energy not used for EV charging nor street lighting									
Summer day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	7 647	7 594	7 708	7 679	7 858	7 779	7 394	7 724
	20	6 087	4 961	4 872	4 964	5 144	5 770	4 741	5 142
	30	5 182	4 384	4 400	4 132	4 089	4 827	4 349	4 366
	40	4 974	3 257	3 793	3 737	3 734	4 381	3 925	3 780
	50	4 518	2 873	3 878	3 745	3 368	4 165	4 020	3 606
	60	3 740	3 779	3 614	3 278	3 073	4 039	3 832	3 557
	70	3 695	3 463	3 473	2 919	3 340	3 840	3 374	3 407
2 charge rates & 12 chargers	10	7 754	7 695	7 748	7 732	7 704	7 837	7 344	7 743
	20	6 289	4 676	4 850	4 787	4 900	5 302	4 749	4 903
	30	5 347	3 673	3 902	3 242	3 357	4 254	3 456	3 685
	40	4 572	3 181	3 164	2 631	3 074	3 540	3 182	3 118
	50	4 089	3 185	2 326	2 462	2 517	3 498	2 867	2 798
	60	3 766	2 796	2 213	2 452	2 584	3 584	2 993	2 726
	70	3 782	2 683	2 930	2 196	2 565	3 093	2 752	2 693
3 charge rates & 9 chargers	10	7 949	7 229	7 232	7 288	7 215	7 609	7 185	7 314
	20	6 565	3 887	4 336	4 371	4 276	5 078	4 280	4 390
	30	5 403	2 999	3 302	3 256	3 323	4 597	3 485	3 496
	40	4 810	2 467	2 623	2 747	2 946	3 948	3 352	2 946
	50	4 154	2 357	2 506	2 402	2 384	3 585	2 836	2 647
	60	3 891	1 736	2 039	2 155	2 037	3 613	2 596	2 316
	70	3 474	1 669	1 763	2 282	1 916	3 543	2 371	2 235
3 charge rates & 12 chargers	10	7 913	7 289	7 274	7 291	7 282	7 557	7 338	7 338
	20	6 420	4 003	4 183	4 116	4 099	5 000	3 855	4 280
	30	5 519	2 005	2 477	2 550	2 280	3 656	2 335	2 594
	40	4 953	1 526	2 033	2 147	1 817	3 414	2 504	2 187
	50	4 257	1 526	1 367	1 575	1 767	3 137	2 296	1 874
	60	3 646	1 051	1 448	1 566	1 736	2 672	1 965	1 694
	70	3 617	1 160	1 235	1 460	1 329	2 718	1 981	1 580
Winter day-light conditions									
Topology	EVs / day	CFCFS	EDF	FCFS	HESF	LESF	LLF	MSoCW	Average Flex Policies
2 charge rates & 9 chargers	10	4 742	3 825	3 731	3 750	3 937	4 182	3 714	3 885
	20	3 744	2 448	2 493	2 430	2 608	2 897	2 448	2 575
	30	2 926	1 934	1 853	1 730	1 945	2 537	2 180	2 000
	40	2 695	1 936	1 509	1 742	1 689	2 059	1 937	1 787
	50	2 220	1 741	1 713	1 334	1 322	1 876	1 831	1 597
	60	2 069	1 576	1 698	1 111	1 344	2 146	1 719	1 575
	70	1 573	1 559	1 334	1 146	1 290	1 890	1 700	1 444
2 charge rates & 12 chargers	10	4 762	3 841	3 901	3 847	3 958	4 227	3 611	3 955
	20	3 811	2 575	2 383	2 405	2 506	2 928	2 287	2 559
	30	3 272	1 371	1 701	1 771	1 869	2 487	1 914	1 840
	40	2 589	1 170	1 688	1 354	1 359	1 991	1 760	1 512
	50	2 057	1 681	1 004	1 206	1 121	1 673	1 846	1 337
	60	2 008	1 470	1 010	1 081	1 110	1 703	1 674	1 275
	70	1 669	1 336	1 373	891	1 175	1 734	1 762	1 302
3 charge rates & 9 chargers	10	4 714	3 531	3 565	3 431	3 540	4 050	3 395	3 623
	20	3 913	1 671	1 729	1 825	1 694	2 727	1 830	1 929
	30	3 171	1 174	1 257	1 411	1 113	2 040	1 352	1 399
	40	2 444	853	1 072	899	1 143	1 900	950	1 173
	50	2 247	738	915	807	875	1 819	835	1 031
	60	1 818	627	686	720	740	1 538	888	862
	70	1 756	566	509	578	722	1 853	857	846
3 charge rates & 12 chargers	10	4 632	3 336	3 422	3 442	3 422	3 865	3 543	3 497
	20	3 938	1 728	1 598	1 796	1 721	2 519	1 638	1 873
	30	3 109	1 141	1 161	1 157	1 164	1 987	1 085	1 322
	40	2 375	617	911	792	1 009	1 546	1 040	975
	50	2 142	599	559	680	794	1 844	959	895
	60	1 685	555	601	612	624	1 437	898	766
	70	1 685	581	545	541	493	1 672	895	766

Table A.10 – Average amount of energy not used for EV charging nor street lighting

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