POLITECNICO DI TORINO

Master of Science in ICT for Smart Societies

Master Degree Thesis

Analysis and Dimensioning of Battery Switching Stations

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Abstract

The development of *Smart Cities* worldwide and the increasing issues related to sustainability and to the environment have pushed towards the electrification of transports, promoting a rapid advent of electric vehicles (EV) in the market. EVs are leading polluting emissions in the transport sector on a path towards zero, however, the charging of EVs' battery has an enormous impact on power grids. High penetration of EVs can result in extreme loads that can alter electricity prices and suddenly increase bulk generation, which in turn generate more CO2 emissions if power plants still rely on fossil fuels. Therefore, high penetration without supervision and control strategies pose a threat to the sustainability of distribution networks. At the same time, EVs are not just challenging the sustainability of the power grid, but they are also stimulating and promoting its upgrading, becoming enablers of the *Smart Grid*. It is true that EVs impose new constraints due to the extra demands they create, but they also generate opportunities thanks to their flexibility as mobile storage devices. If battery charging is properly coordinated, EVs can play a positive role in enhancing the evolution of the smart grid.

In a plausible scenario of a smart city where electric vehicles are widely used, *Battery Switching Stations (BSS)* might replace the current gas stations, as they provide services that allow to extend the traveling time of EVs. Within this context, the present thesis work studies the dimensioning of a BSS system and the possibility to exploit renewable energy sources (RES), particularly solar power, as main resource for the charging of batteries. Using battery to grid (B2G) technology to

achieve high coordination with the grid, the battery switching station could accomplish multiple benefits. In addition to providing EVs users with battery swapping services, the BSS can also serve as an energy storage station or controllable load, becoming an active contributor of the smart grid.

The complexity of this study case in terms of number of parameters is such that mathematical modelling did not represent an effective approach. Therefore, a process-based discrete-event simulator was specifically designed to study the object of this thesis. The simulator creates a digital prototype of the BSS and allows to study its performance through notions of queueing theory. Moreover, the BSS simulator can perform hourly comparisons of energy prices with RES generation profiles, with the aim of creating policies that improve the efficiency and management of the grid.

By adjusting the charging and discharging times of batteries in coordination with generation from PV panels installed on the BSS, the load fluctuation is reduced and the penetration of renewables is improved as well.

This cooperation between RES and BSS could not only benefit the power grid, but also promote the development of renewables industry and electric vehicles industry.

Contents

List of Tables

List of Figures

List of Abbreviations

B2G Battery to Grid

DA Data Analytics

DER Distributed Energy Resources

DG Distributed Generation

DoD Depth of Discharge

DR Demand Response

EVSE EV Supply Equipment

GHG Greenhouse Gas

ICE Internal Combustion Engine

ICT Information and Communication Technologies

IoT Internet of Things

LV Low Voltage

MV Medium Voltage

OLEV On-Line Electric Vehicle

PEV Plug-in Electric Vehicles

PHEV Plug-in Hybrid Electric Vehicles

PV Photovoltaic Panel

R&D Research and Development

SoC State of Charge

SoC State of Charge

SoH State of Health

UI User Interface

V2G Vehicle to Grid

Introduction

0.1 Motivations

The motives behind this work have to do with the global environmental issues of our century, which are going to affect particularly the young generations, if they are not managed properly. Sustainability is a major concern in modern cities, but the heavy reliance on fossil fuels has a tremendous impact on the environment. With more than 25% of global greenhouse gas emissions originating from electricity production and around 14% from the transport sector (Figure 1), it is clear that more could be done also from a technological perspective to help lowering these statistics.

Electrification of transports can mitigate those effects, not only because it eliminates polluting emissions from vehicles, but mostly because electric vehicles are enablers of the *Smart Grid*, a re-design of the power grid that manages electricity generation and distribution in a more efficient way. Through improved efficiency and large-scale integration of renewables, the smart grid helps to lower significantly greenhouse gas (GHG) emissions from power plants. Modelling a charging facility for EVs that fully operates with renewables is part of the global effort to promote sustainability, and this was definitely a reason that pushed me in the development of this thesis.

In addition, a persistent curiosity about technological advances has driven me to investigate more about EV, and this work represented a great chance to do so.

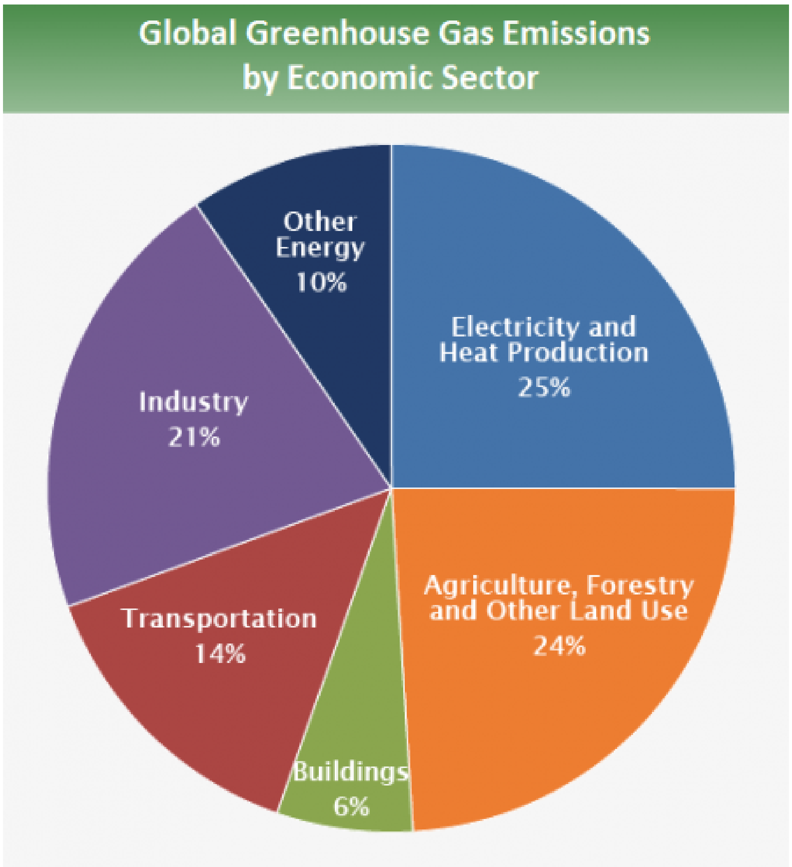

Figure 1. Global GHG emissions by economic sector, 2015

0.2 Objectives

The objective of this thesis is the performance analysis and dimensioning of a battery switching station, which means testing the correct working of the system and study its behaviour by varying the parameters.

Battery switching stations can be compared to gas stations for EVs. These stations are equipped with special docks where batteries are charged and stored. A robotic arm is used to execute the battery replacements autonomously in a fixed amount of time. The functioning of such stations can be depicted as follow: during a working day the BSS receives EVs that request a battery replacement. Serving such requests involves disassembling an empty battery from the vehicle and installing a fully charged one instead. This operation requires a fixed amount of time, that is specified later in the BSS chapter. Afterwards, the dismantled batteries are transferred to special charging docks, where they enter a charging process until they become available once again. The charging time is again specified later in chapter 3 and it depends on the state of charge (SoC) of the battery. The BSS is therefore a closed loop system, where the overall number of batteries in the system does not change.

The analysis involves performance metrics such as the availability of charged batteries at any time, that is the BSS capacity to promptly serve new costumers. The average waiting time of EVs in case they have to queue. Within this model, queues do happen in two cases: due to the fact that all batteries in the BSS are temporary under charge, or because the BSS is busy replacing the battery of a previous client. Another performance metric derived from queueing theory is the loss probability, which refers to the impatient of EVs that abandon the station due to long waiting times. The overall system operation has been verified through analytical formulas that are used in queueing systems modelling, for example the *Erlang-B* formula.

0.3 Methods

Due to the complexity of the BSS system, a process-based discrete-event simulator was specifically designed for the aim of this thesis. In fact, *mathematical modelling* didn't seem to be an effective approach because of the high number of parameters, so it was used in a complementary way to check the correct functioning of the core system. Instead, *simulation modelling* was the chosen approach to study the behaviour and the evolution of the BSS system. Simulation modelling indeed allowed to create a digital prototype of the physical model of the BSS, and to derive performance indicators from the statistical observation of the system behaviour.

The simulator was built by scratch for the purpose of this thesis, using *Python* as programming language and the library *SimPy* as framework to host the simulation. *SimPy* allows to run simulations in continuous-time but with discrete events, meaning that processes or events, like EV arrivals, occur at a particular instant in time and mark a change of state in the system [1]. Between consecutive events, no change in the system is assumed to occur.

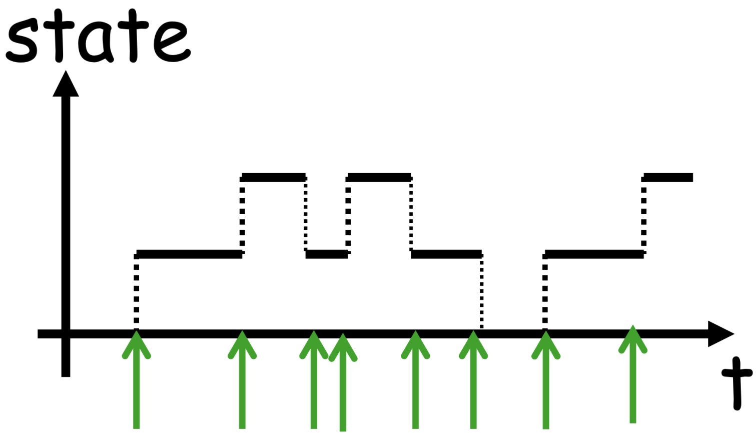

Figure 2. Discrete Model Simulation.

0.4 Structure

The thesis is divided in four chapters. The first chapter introduces the *Smart City* scenario, which represents the framework under which electric vehicles and related charging facilities have evolved during the last decades. The chapter begins with a description of the urbanisation phenomenon, which has brought several challenges in today's cities. Afterwards it gives a definition of the smart city concept, defining its features and main technologies. Finally, the sustainability aspect is investigated, as it embodies the logic behind the advent of electric vehicles and the *Smart Grid*.

The chapter carries on with the description of this concept, commenting the transition from the old centralised distribution network to a new distributed grid. The key features of smart grids are pointed out, such as flexibility, distributed generation, and integration of renewable energy sources (RES). The smart grid creates the ideal environment for EVs which are investigated in chapter two.

Chapter two begins with a discussion about the environmental challenge in the transport sector and presents the case of integration between EVs and RES, more specifically with solar energy. Afterwards, the chapter describes the existing charging facilities, including the BSS that is the one studied within this thesis. After discussing the state of the art and the operation of the BSS, it gives an overview of lithium batteries as they are key actors in the BSS system.

Chapter 3 presents the simulator, including the tools that have been used to design and build it, the main parameters and its operation mode. Furthermore, a section analyses the system performances, while another section presents the possible strategies that can be implemented by the BSS system, such as energy saving or economic strategies.

Finally, chapter 4 presents the simulation results, by showing related graphs and providing a complete description of them, and derives the final conclusions.

0.5 Results

The simulation results can be divided in two sections: one section is more trivial and it is related to the performances of the system, while the other section includes the correlation of such performances with real data regarding renewable energy production traces and purchase and sell prices of electricity.

The performance results are needed mainly to test the correct functioning of the system, and they include loss probability, batteries availability and average waiting time of EVs queueing to receive a replacement service. The second type of results are more interesting and can be used to derive strategies and algorithms that are helpful for the BSS in order to save energy and optimise its resources, while still providing EVs with battery swapping services.

Chapter 1

New Scenarios in Smart Cities

1.1 The Smart City

In order to achieve a complete understanding of this thesis work and its motives, it is fundamental to introduce the general framework within which EVs and related technologies have evolved during the last decades: the *Smart City*. The current chapter aims at introducing the *Smart City* concept from a social, technological and environmental viewpoint. At first, it provides a description of the present and future issues that cities will have to face, for example the urbanisation problem, along with the ways cities are evolving to face them. Then, it provides a description of the general characteristics of smart cities, by proposing an accurate model from the literature. Finally, it focuses on the sustainability challenge. This last passage contains the reasons and motivations that pushed the advent of electric vehicles as well as the extensive use of renewables, that are two main actors of the BSS simulation proposed in this thesis.

1.1.1 Urbanization

Before even introducing the definition of *"Smart"* in relation to cities, it is worth to explain why cities are gaining such a great importance in the present human society.

Urbanisation is actually considered one of the main issues of XXI century. According to the United Nations Population Fund, 2008 marked the year when more than 50% of world population, 3.3 billion, lived in urban areas. Globally, there are 1.3 million people moving to cities each week and by 2050, 70% of the world's population is expected to live in cities [38]. Consequently, cities are evolving into hotpoints of economy, the 600 biggest urban areas already account for 60% of global GDP, and this is expected to rise even higher as cities become larger and more prosperous. In fact, experts estimate that up to 80% of future economic growth in developing regions will occur in cities alone [44] [9].

Due to this rapid increase of the urban population worldwide, cities have to face various risks and concerns, for example physical risks such as air pollution or road congestions, and economic risks such as unemployment. The remarkable rate of urban growth is pushing the search of smarter ways to deal with these challenges [9].

On the other hand, urbanisation could potentially support a sustainable growth by increasing productivity, allowing innovation and new ideas to emerge. Despite that, there are still some improvements in energy efficiency and living quality in conventional cities in order to transform them into smart cities. It is clear that smart cities will require more intelligence in the design and planning of infrastructures and services to deal with future urbanisation problems.

What is sure so far is that cities will drive the future of human society for the 21st century. This awareness is well expressed in a quote by Wellington E. Webb, former Mayor of the City of Denver until 2003, which states that *"The 19th century was a century of empires, the 20th century was a century of nation states and the*

21st century will be a century of cities." [7]

As cities become an even more important driver of the global economy and wealth, it's becoming crucial to ensure that they are optimised in terms of efficiency and sustainability, so that they can rapidly move towards the paradigm of the *Smart City*.

1.1.2 Characteristics of Smart Cities

Smart City concept has become a new trend in global city development of the XXI century. The first academic work on *smart cities* was published in 1992, while the concept of *Smart City* was introduced by IBM's CEO in 2008. Currently disparate smart city concepts are developed worldwide by academics, governments and private industries [8].

Hence, providing an homogeneous definition of smart city is not an easy task, particularly because the description of a smart city is often context dependent. In this context, an operational definition from the literature has been selected, according to which the *Smart City* concept can be enclosed into 3 dimensions: Technology, Human and Institutional (Figure 1.1).

1. **Technology dimension** focuses on mobile and smart technologies, physical infrastructure and digital networks.

2. **Human dimension** assumes that creativity and innovation are key elements for urban development. Since all the innovative solutions are generated by creative people, the main target for cities is to attract this creative class as well as exploit human potential in the best possible way.

3. **Institutional dimension** includes smart administration and policy to build a community where each actor understands the potential of ICTs and is willing to use them to make their living environment better and more efficient.

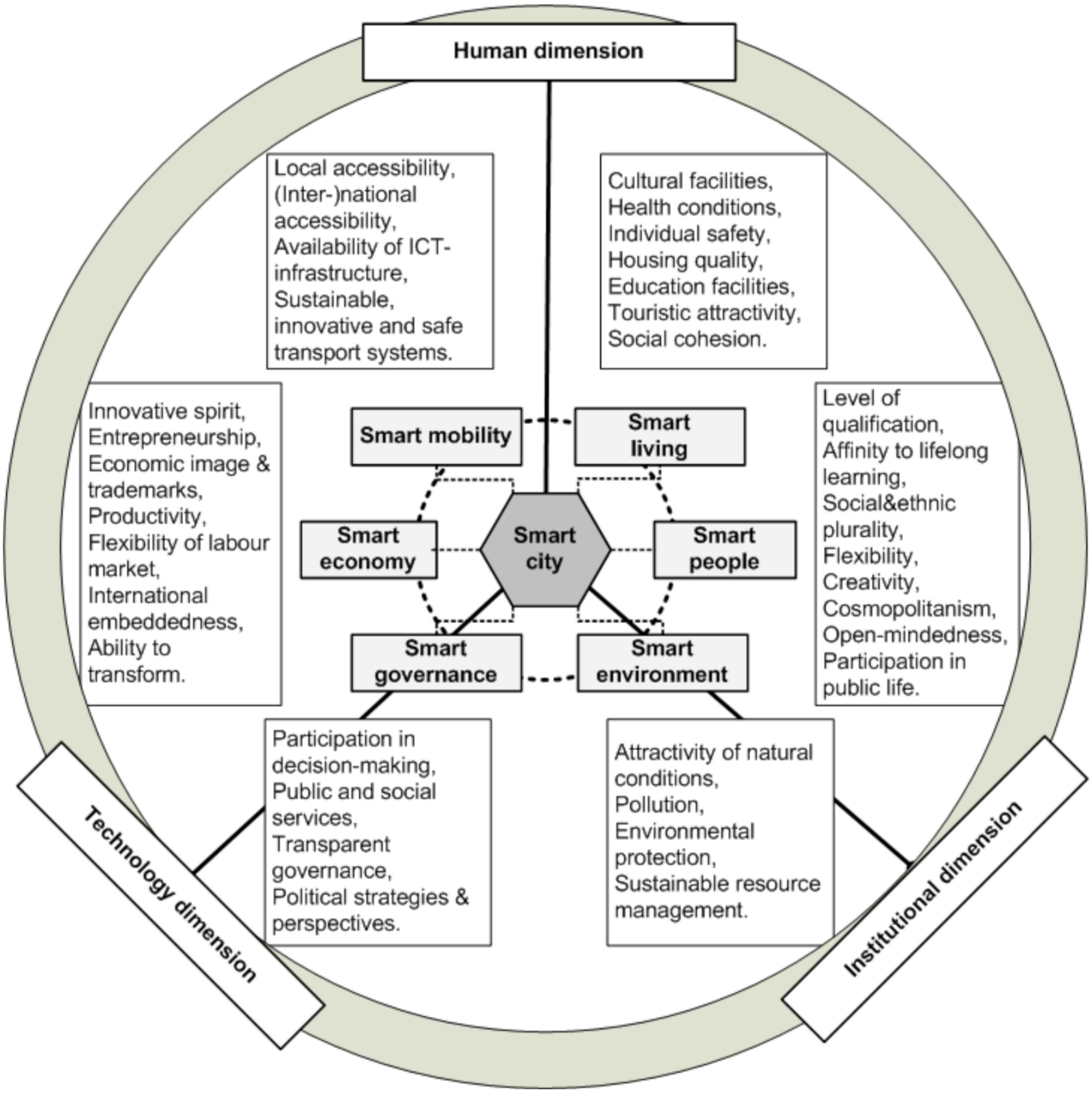

Figure 1.1. Characteristics and dimensions of Smart city.[8]

Smart cities are places that are innovative in the areas of people, living, economy, governance, environment, and mobility [10]. A city is indeed to be considered smart when there are significant investments in these fields, that can drive towards sustainability and improve wellbeing of its citizens [9].

One remarkable feature of smart cities is the intensive use of Information and

Communication Technologies (ICT) combined with other urban planning methods in order to find innovative, smarter and more efficient solutions that contribute to sustainability and liveability. However, it is important to recognise that the concept of smart cities is not just limited to technological advancements, but rather aims to promote socioeconomic development [5]. Social inclusion is actually a key element of smart cities, and this should enforce the idea that investments in human capital are needed as much as in ICT technologies [9].

Among the various definitions found in the literature, one that seems to capture the essence of the previous points is put forth by Caragliu, Del Bo, and Nijkamp: *"A city is smart "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance"*[9].

The previous definition of smart cities is actually based on the Smart City Model, developed in 2007 by Giffinger[10]. This model allows to classify smart cities through six specific attributes, as shown in figure 1.2. The Smart City Model was designed as a practical tool for the evaluation of European smart cities in diverse fields, such as economy, people, mobility, environment and living. Cities are therefore provided with a tool to evaluate their current state of development, so that they are able to detect the areas to fix in order to meet the sufficient conditions of a smart city [9] [10].

Smart Governance addresses to a governance system that is transparent and allows for citizens to take part in decision-making using e-services to connect and enhance collaboration. Platforms for information sharing, social-media networking, and crowd sourcing are useful tools to increment collaboration between the government and the city inhabitants [11]. Moreover, ICT systems allow citizens

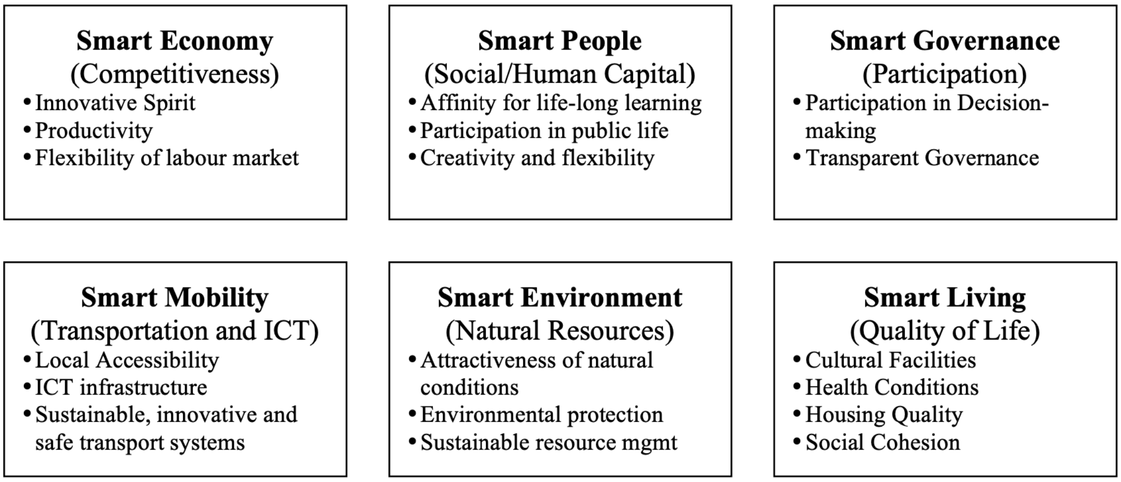

Figure 1.2. Characteristics and dimensions of Smart city.[9] [10]

to access more easily the information related to the management of the city. This open access helps eliminating the communication barrier between the government and the people.[9]

Smart Economy recalls how much the city is competitive, in terms of its approach to business, research and development (R&D), investment opportunities, productivity and flexibility of the labour markets, and the economical role of the city in the national and international market. Increased access to broadband Internet allows citizens and businesses to use electronic methods (e.g. e-banking, e-shopping) to boost business processes [12] [9].

Smart People means providing its citizens with a high level of education, keeping them open-minded, increasing their awareness on culture and participation level in the public activities. To reach this result, cities can implement actions such as computer-assisted education and other initiatives supporting distance education and online courses [12] [9].

Smart Living seeks to enhance the quality of life of citizens, by providing healthier and safer living conditions. Enhances projects in home automation (e.g. smart home, smart building) as well as an easy access to health care services, electronic health management (e-health), and to diverse social services. Also, ICT-based opportunities exist to enhance public safety, such as surveillance systems or emergency service networks, which can reduce emergency response time [11] [9].

Smart Mobility promotes more efficient transportation systems with low environmental impacts and calls for new social attitudes towards the usage of cars and vehicles, leading to a shift from individual to collective transportation methods (e.g. car-pooling). It also encourages the use of non-motorised transportation (e.g. bicycles) and the integration of electric vehicles, integrating once again ICT to increase efficiency [13] [9].

Smart Environment focuses on responsible resource management and sustainable urban planning [9]. Smart sensors are used to identify excessive levels of pollution and CO2 emissions, so that proper actions can be taken towards environmental protection. Opportunities are abundant in the infrastructure energy management. Common actions in this area involve installing innovative energy technologies (e.g. solar technologies, climate sensors) into existing buildings in order to reduce energy use and CO2 emissions. Smart cities hence promote the reduction of energy consumption, and the integration of new technological innovations that result in efficiency gains.

Considering the six characteristics of the Smart City Model in relation with the object of this thesis, it is worth to analyse more in details the last two mentioned aspects, with particular regard to ICT technology used in smart mobility, environmental impact and energy-related aspects.

1.1.3 Technology Framework

From a technological prospective, smart cities heavily relies on information and communication technologies (ICT) to increase operational efficiency, share information and improve both the quality of public services and citizens welfare [45]. The overall mission of a smart city is indeed to optimise city functions and to drive economic growth while improving quality of life for its citizens thanks to a smart use of technology and data.

ICT technologies consist on a combination of internet of things (IoT) devices, softwares, user interfaces (UI) and communication networks. Particularly, IoT is a network of connected devices, typically small, that can communicate and exchange data. Data collected by the IoT sensors and devices is stored in the cloud or on servers, and the connection of such devices combined with the use of data analytics (DA) allows an easier convergence of the digital and physical city elements [45].

ICT need solid and secure infrastructures to ensure operation and be effective. Different combinations of technological infrastructures interact to form the complexity of smart city technologies with varying levels of interaction between human and technological systems [46].

- **Digital**: A service-oriented computing infrastructure based on open standards is required to connect people and devices in a Smart city.

- **Intelligent**: Cognitive technologies, such as neural networks and machine learning, can be trained on the data generated by connected devices scattered in the city to identify patterns.

- **Ubiquitous**: A ubiquitous city provides access to public services through any connected device [27].

- **Wired**: The hardware components of IT systems are vital to early-stage smart city development. A wired infrastructure is required to support the IoT and wireless technologies that permit interconnection among city elements. [47]

- **Hybrid**: Hybrid city means the combination of physical elements and a virtual city reconstructed based on the physical space.

- **Information**: The great amount of interactive devices in a smart city generates an enormous quantity of data. All that information has to be managed and stored properly to ensure security. [48]

Due to this dependency on ICT technology, a smart city's success depends on its ability to form a strong relationship between the public and the private sectors. This relationship is necessary because most of the work that is done to create and maintain a digital, data-driven environment occurs outside of the public administration.

Thanks to a continuous negotiation between private companies and public administration, ICT technologies have already enabled endless solutions for the city management in disparate fields of application, from transports and buildings to public safety.

For example, in the transportation area IoT devices are used to monitor and analyse traffic flows in order to optimise streetlights and prevent roadways from becoming too congested based on time of day or rush-hour schedules. Smart public transit is another facet of smart cities, used to ensure that public transportation meets user demand. Smart transit companies are able to coordinate services and accomplish user's needs in real time, improving efficiency and user satisfaction.

In the energy area, the use of smart sensors and smart streetlights dim when there are no cars nor pedestrians on the roadways ensures energy conservation and efficiency, which are major focuses of smart cities.

Waste management and sanitation can also be improved with smart technology, be it using internet-connected trash cans and IoT-enabled fleet management systems for waste collection and removal, or using sensors to measure water parameters and guarantee the quality of drinking water at the front end of the system, with proper wastewater removal and drainage at the back end.

Smart city technology is increasingly being used also to improve public safety, from monitoring areas of high crime to improving emergency responses with sensors. For example, smart sensors can be critical components of an early warning system before droughts, floods, landslides or hurricanes.

As last example, smart buildings are often part of a smart city project. New buildings constructed with sensors to not only provide real time space management and ensure public safety, but also to monitor the structural health of buildings. Attaching sensors to buildings can detect damage and inform when repairs are needed. Sensors can also be used to detect leaks in water mains and other pipe systems, helping reduce costs and improve the efficiency of public workers. [45]

In conclusion, the smart city utilises ICT to meet the demands of the market (the citizens needs), and the community involvement in the process is necessary for a smart city. A smart city would thus be a city that not only exploits ICT technology in different fields, but also implements this technology in a manner that positively impacts the local community.

1.1.4 Sustainability as Key Factor

Sustainability is a major concern of smart cities. As mentioned at the beginning of this chapter, urbanisation is expected to increase even more in the years to come. The United Nations reports that nowadays, already fifty percent of the world's population resides in urban areas, and it is expected that this number will rise to 70% by 2050 [2] [9]. In Europe alone, 80% of citizens live and work within cities [3].

On one hand, cities present environmental advantages, such as smaller geographic footprints that impact fewer ecological systems. On the other hand, they also negatively impact the environment with CO2 emissions, due to their extreme use of fossil fuels. Consequently, with 80% of global greenhouse gas emissions originating from them, cities deliver a significant contribution to climate change [4]. The exceptional urban growth rate is creating an urgency to find smarter ways to manage the environmental challenges. Besides polluting emissions, other environmental problems will involve the waste management, water contamination and other technical problems related to outdated physical infrastructures. Furthermore, these problems are aggravated by the variety of stakeholders, frequent changes in political leadership, and financial resources. [49]

Smart technology and ICT could help cities support growth in a sustainable way for the coming years. However, most cities do not have strategies in place that are sufficiently progressive to adapt to the inevitable population gain occurring across the globe.

From another prospective, the peculiarities of cities make them perfect to test future sustainability initiatives. Cities have all the potentials to be fully sustainable, and through the use of smart technology and a mindful vision they can develop in ways that meet the environmental needs. [6] [9]

An example related to this thesis work is that making the switch to an electric public and private transportation system would not only decrease fuel emissions, but could also allow a closed cooperation with the city's electric power infrastructure in order to minimise the impact of charging batteries of EVs during peak hours. Furthermore, with proper coordination, electric vehicles could also be used to regulate the frequency of the city's electric grid when they're not in service.

The previous example shows how utility companies play a key role in this scenario. Electric companies, working together with city administration and technology companies, represent the major players that helped accelerate the growth of smart cities. There is still a great deal of room for improvement, but the forecasts are optimistic about energy saving in urban areas for near future. Cisco estimates that smarter cities will have impressive increases in efficiency: using many of the above concepts, cities can improve energy efficiency by 30% in 20 years, which consequently means a massive reduction in pollution from power plants, buildings and transport sector. [50]

A paper by Murray, Minevich and Abdoullaev [14] from the literature has distinguished three types of cities moving towards sustainability based on their approach:

1. **Knowledge cities**: the focus is heavily addressed on education, lifelong learning and personal growth.
2. **Digital cities**: also called cyber-cities, where large investments are put in information and communications technology companies, with the aim of enabling a massive connection between every individual and every thing.
3. **Eco-cities**: great attention is addressed to environmental sustainability and the widespread adoption of renewable resources.

The authors further state that a systemic integration of these three city types results in a new urban planning approach, namely, the smart city.

As mentioned earlier, electric power companies are game changers in the smart city scenario. The major revolution that they brought in place during the last decades is known as *Smart Grid*, basically a re-invention of the electricity services industry to face the modern challenges. The innovative concept of Smart Grid is discussed in the following section. A history of the transition from the old power generation infrastructure to the new one is presented at first, followed by an analysis of the key elements that define the smart grid itself. Finally, the relationship between the smart grid and the current work is discussed and explained.

1.2 The Smart Grid

The electricity market has recently faced a deep transformation mainly driven by an increasing energy demand. Population growth, urbanisation, and electrification of transports have in fact influenced the previous structure of the distribution network. In this macro scenario, new technological trends are playing a central role: growth of distributed power generation, increasing usage of renewables energies, demand side management and plug-in electric vehicles head the list of technologies that have had the biggest impact on the power business.

1.2.1 From Centralised to Distributed Grid

Until a few decades ago, we used to have a centralised power plant, in which a large amount of energy was generated on a large scale in facilities usually located away from the final user. The electricity generated by centralised generation was distributed through a network of high-voltage transmission lines to multiple end-users. Centralised generation facilities include fossil-fuel-fired power plants, nuclear power plants, hydroelectric dams, wind farms, and more.

Today we are migrating to distributed system, that aims to solve the issues of the centralised one. Distributed Energy is the utilisation of smaller power generation and storage systems used to power homes, businesses and communities. Most distributed energy generation systems take advantage of renewable energy sources such as solar, wind, and hydro power. In this new reality, efficiency, flexibility, reliability and cost savings become fundamental keywords and a new architecture that manages this system is necessary. The *Smart Grid* is a reinvention of how energy is transmitted, distributed, and measured. It is becoming the new standard for utilities and consumers and represents the merging of multiple technologies into a system that provides reliable and cost-effective energy (Figure 1.3).

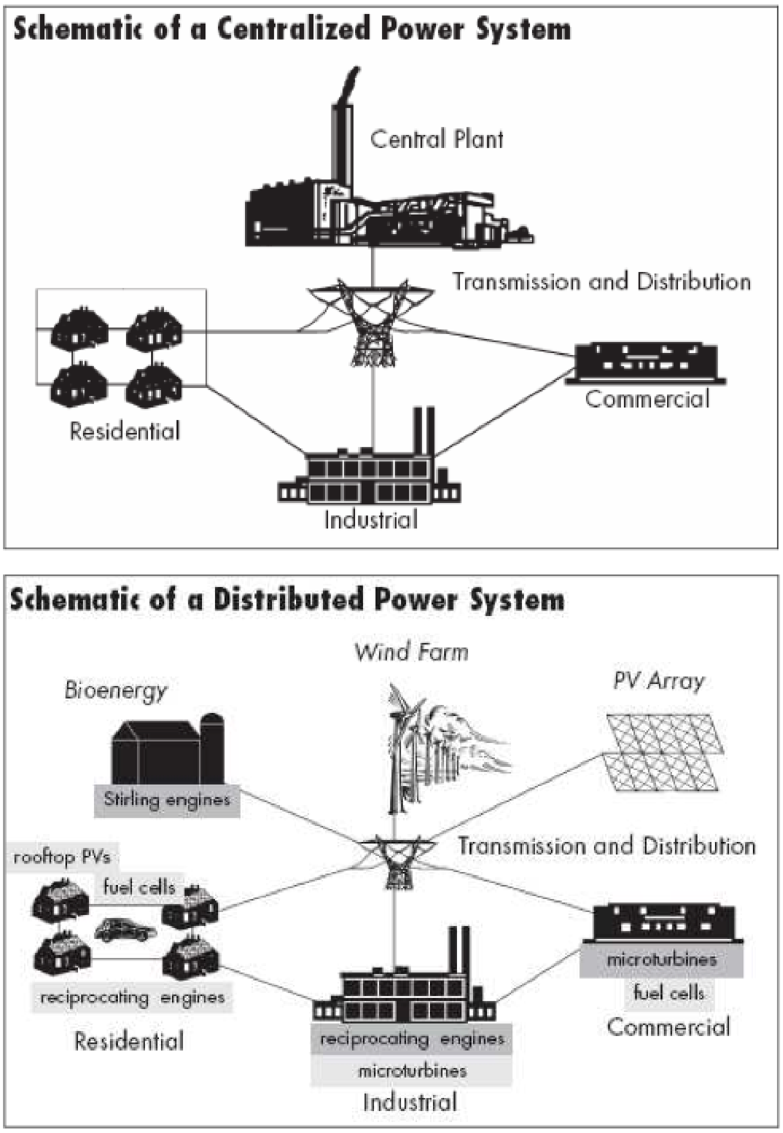

Figure 1.3. From centralised to distributed power system.

1.2.2 Key Features of Smart Grids

A definition provided by the European Union Commission Task Force for Smart Grids states that *"a smart grid is an electricity network that can efficiently integrate* *the behaviour and actions of all users connected to it (generators, consumers and those that do both) in order to ensure an economically efficient, sustainable power system with low losses and high quality and security of supply and safety".* [42]

The smart grid combines information and communication technologies (ICT) into the electric transmission and distribution networks. Two-way communication between the utility and its customers, and the sensing along the transmission lines, is indeed what makes the grid smart [41]. Also, smart grids include a set of controls, computers, automation, and new technologies which are interoperating, to respond digitally to our quickly changing electric demand.

According to the literature [15], the key features and benefits associated with the Smart Grid are:

- Optimisation of transmission and generation capacity: allows a reduction of losses in transmission system and increases the capacity of generation system
- Self-healing: refers to quick restoration of electricity after power outages. The grid itself automatically rapidly senses, detects, analyses, responds and then restores.
- Energy storage options: batteries and other energy storage devices help lower power utilisation and increase flexibility.
- Tolerance to attacks: the grid mitigates and is resilient to physical/cyber-attacks.
- Flexibility: through participation to DR programs, allows the reduction of peak demand, which also help lower electricity rates
- Distributed generation: enables individual users to become *prosumers* by producing onsite electrical power.
- Integration of renewables: integration of large-scale renewable energy generation at different levels.

Self-healing: Nowadays, an electricity breakdown such as a blackout can cause a domino effect that can hit communications, traffic, banking and security. A smarter grid will add resiliency to our electric power system and make it better prepared to address emergencies such as severe storms, earthquakes, floods and large solar flares. Because of its two-way interactive capacity, the Smart Grid will allow for automatic rerouting when equipment fails or outages occur, in order to minimise the effects when they do happen. When a power outage occurs, Smart Grid technologies will detect and isolate the outages, containing them before they become large-scale blackouts. The new technologies will also help ensure that electricity recovery resumes quickly and strategically after an emergency, for example routing electricity to emergency services first. In addition, the Smart Grid will take advantage of private power generators and storage to retrieve power when it is not available from utilities. [51]

The BSS case studied within this thesis, exploiting the two-way communication capability of the grid to achieve a proper coordination, could store energy in batteries that are not in service, for example at night time when there is low traffic of costumers. These batteries can be considered as backup power from which the smart grid could take advantage in case of an emergency or blackout. By combining this and others distributed generation resources, a neighbourhood could keep its hospital, school, police department and traffic lights operating during emergencies.

Energy storage options: Smart grid technology uses the latest energy storage devices such as compressed air energy storage, super-conducting magnetic energy storage, pumped-hydro storage, super and ultra capacitors, batteries, that not only reduces the congestion, volatility, security problems in power system but also helps in maintaining the stability of the power grid. [15]

Batteries stored in a BSS could be themselves an option for energy storage. The simulations run within this project are able to reveal the amount of batteries that are fully charged and available at any time of the day. Collecting this kind of data could be useful to establish certain policies, such as storing a certain amount of energy during night to be sold or exchanged with other participants of the grid at the right time.

Flexibility: Flexibility is a key aspect of the smart grid, required to enable Demand Side Management (DSM) programs, by managing consumption of electricity to reduce peaks, balance renewable generation and provide auxiliary services to the grid [15]. The increased production of solar and wind electricity (so called intermittent renewables) creates uncertain hourly feed of electricity into the grid and consequently it causes high volatility of the residual load, which is basically the electricity demand minus renewable energy generation. To deal with this uncertainty, power plants requires higher flexibility on the local level to balance electricity supply and demand, and prevent system overloads.

City inhabitants are soon likely to become *prosumers*, consumers and at the same time producers of renewable energy. Therefore, new strategies that helps to manage these new actors are needed. Demand response (DR) is one solution to deal with this challenge: DR gives prosumers the ability to reduce, increase or shift the electricity demand to other time periods in response to price signals or other incentives, that are monitored by smart meters and IoT devices. A potential battery switching station could cooperate with the city's electric power infrastructure in order to minimise the impact of charging EVs' battery during peak-demand hours. Additionally, extra batteries that are not in use could serve as backup energy during emergencies, or can be partially discharged to sell energy to neighbour facilities like hospitals, universities or even private buildings that requires power. Hence, a BSS is likely to become a kind of prosumer that participates in DR programs, improving energy efficiency of the whole community.

Other examples related to this work would be a utility reducing the usage of a group of electric vehicle charging stations. To motivate them to cut back use and perform what is called peak levelling, prices of electricity are increased during high demand periods, and decreased during low demand periods. It is thought that consumers and enterprises will tend to consume less during high demand periods, if it is possible for consumers to be aware of the price fluctuations. Indeed when businesses and consumers see a direct economic benefit of using energy at off-peak times, the hypothesis is that they will include energy cost of operation into their decisions and hence become more energy efficient.

Integration of Renewables: The improved flexibility of the smart grid permits greater penetration of a great variety of renewable energy sources. Renewable sources, unlike fossil fuels, are sustainable, plentiful and they are not going to expire soon. Although, also renewable sources have their own drawbacks, as they are highly dependent on weather. Any significant change in weather can reduce the production of energy from these sources, which create energy gaps.

These rapid fluctuations in distributed generation present significant challenges and to ensure stable power levels there is still the necessity to rely on more controllable generators such as gas turbines and hydroelectric generators. Smart grid technology is a necessary technology for improving the overall capacity of the grid to mitigate this effect.

There has been rapid diffusion of renewables, and increased interest in other distributed energy resources. As shown in fig. 1.4 the growth of renewable generation gets doubled in every three years for wind and solar power.

The wide spread of renewable made possible by the smart grid has shown to improve environmental goals, by substituting carbon-based power utilities hence lowering carbon impact.

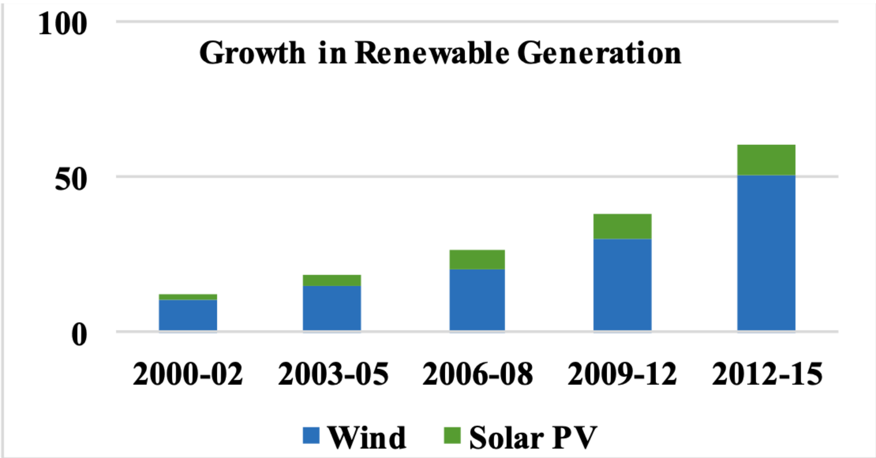

Figure 1.4. Global Wind and Solar PV Annual Installations.[15]

1.2.3 Electric Vehicles: Enablers of the Smart Grid

The core of this work itself is strongly interconnected with the key elements that define the *Smart Grid* concept, since plug-in EVs are considered enablers of the evolution of the power grid in that sense. At the same time, the establishment of battery switching stations (BSS) for electric vehicles needs a secure and flexible power infrastructure, that only the smart grid technology can offer. The smart grid would avoid sudden alterations in electricity demand and prices caused by EVs load, prevent power disruption and restore the service quickly in case outages occur. Reducing peak demands, it also contributes to lower CO2 emissions and support sustainability, that is another major goal in the smart city scenario. Two-way communication capability of the smart grid, together with internet of things (IoT) technologies, would help enormously in the management of the BSS. For example, vehicles approaching a swapping station could receive status information of the BSS in real-time, such as the waiting time before being served, batteries availability and state of charge, low busy hours suggestions and have scheduling services consequently. All this information exchange would contribute to a better management of city traffic by lowering congestions, as well as increase the quality of service of the BSS and promote the spreading of EVs, that in turn is a motor of sustainability. Finally, the simulator built within this project involves the use of renewables (RE) as main energy source for recharging batteries. The BSS was designed to use exclusively solar energy from photovoltaic panels (PV) for recharging EV batteries. To make that possible it has to deal with intermittent generation due to cloudy weather and night hours, and it could achieve that by participating to DR programs. The addition of renewables is made possible again by the smart grid, showing the inextricable relationship between the object of this thesis and the Smart City framework.

Chapter 2

The advent of Electric Vehicles

Environmental issues and decreasing fossil fuels stimulate intense research efforts toward the electrification of transportation, and technological advances have favoured a quick arrival of Electric Vehicles (EVs) in the market [17].

This chapter initially investigates the motives that have pushed the advent of EVs. Afterwards, a description of the main technologies related to EVs is introduced, mostly focused on the different charging facilities that include the case of BSS studied within this thesis. Finally, an analysis of electric vehicle integration with renewable energy sources is carried out, specifically with solar energy generated by PV panels. The last topic is particularly interesting due to its direct connection with the Smart Grid concept introduced in the previous chapter. The flexibility of EVs allows them to both participate in DR programs and serve as energy storage facilities. They can also act as distributed energy sources (DER), for example injecting electricity back to the grid.

2.1 The Environmental Challenge in Transports

The transport sector has great responsibility in the matter of air pollution, especially in European cities where it produces almost a quarter of all the greenhouse gas (GHG) emissions. Transport is the main sector in the EU where GHG emissions are still increasing; there has been a decrease since 2007, but emissions remain higher than in 1990. Among all the categories, *road transport* is considered responsible for more than 70% of GHG emissions from the transport sector, producing about one-fifth of the EU's overall emissions of CO2, the principal greenhouse gas. These statistics from year 2014 are shown in Figure 2.1. [18]

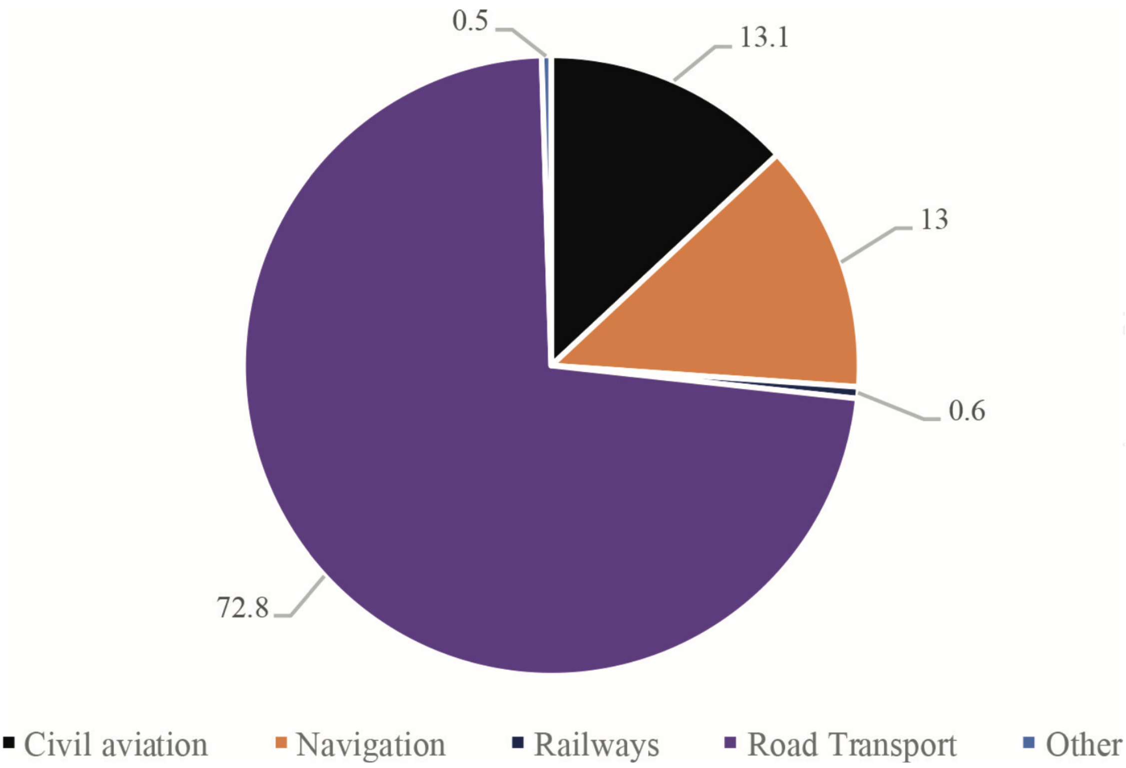

Figure 2.1. GHG emissions from transport by mode in 2014. [19]

Since 2016 the European Commission has embraced a low-emission mobility strategy, that is a global attempt to move towards a circular and low-carbon economy. The European plan for the transport sector consists in an irreversible shift to a near zero-emission mobility, mainly due to the fact that air pollutants are a serious threat for our health. According to the plans, GHG from transport will have to be at least 60% lower than in 1990 and be on a solid path towards zero

[18].

In addition to causing harms to human health, GHG are considered responsible for climate change and the rise of the planet's temperature. The consequences can be hazardous for humans' communities, for example the rising of sea level is already threatening several cities and settlements along the coasts.

The previous points are pushing the EU and other institutions to promote green technologies in the transport sector, encouraging the diffusion of EVs mostly because of their negligible flue gas emissions and less reliance on oil. Predictions tell that by 2022, EVs will be over 35 million in the World.

Using electricity for vehicle propulsion instead of fossil fuels will contribute to achieve the EU targets on lowering CO2 emissions. EVs have in fact zero emission of tailpipe CO2 and other pollutants like nitrogen oxides (NOx), non-methane hydrocarbons (NMHC) and particulate matter (PM). [18] So increasing the number of EVs can actually minimise the direct emissions of CO2 and air pollutants from road transport.

However, the increased number of EVs will cause the need for an additional generation of electricity. This results in additional emissions under the hypothesis of a continued use of fossil fuel in the power industry. Lower emissions of CO2 and air pollutants determined by an actual increase of EVs could cause higher emissions by the electricity generation when it is based on fossil fuel combustion. Overall, the avoided CO2 emissions in the road transport sector could be nullified by the higher emissions from electricity generation [18].

There is a disparity though between air pollutants resulting from road transport and from power production, if these are compared on the basis of their corresponding effects on human's health. Pollution from cars and other road vehicles happens at the ground level and usually, in such areas as residential, workplaces, stores etc.. Contamination is significant within the cities, municipalities as well as towns. A considerable portion of the population is exposed to pollution. In contrast, power plants are built outside the cities where there is scarce population.

All things considered, blindly substituting the conventional cars is not a perfect solution to the transport and environmental related issues, but more precise solutions need to be pointed out [18].

As already mentioned, the high penetration of EVs can create excessive loads on low voltage (LV) and medium voltage (MV) feeders and cause critical problems to the power grid. For example, if the charging of EVs is uncoordinated, their impact on the grid is equivalent to a large electric load which causes high power systems peak-load and congestion in the distribution grid.

A joint article from Polytechnic of Milan and CanmetENERGY Research Centre of Canada[18] suggests that a possible approach to alleviate this effect is to integrate local power generation such as RESs into the EV charging infrastructure. Doing so, the production of electricity needed to charge EVs batteries is split among different carbon-free energy sources, which avoid to overload the main power system while also reducing CO2 emissions. This is the concept of distributed generation (DG), one of the greatest change in the energy sector of the past few years. In an urban district, examples of DG are PV panels and solar collectors mounted on top of buildings, as in this thesis are imagined to be installed on the BSS roof. The BSS equipped with a local array of PV panels can therefore use solar energy as main source for the production of electricity. Following this idea, the next section studies the integration of electric vehicles with solar energy, neglecting other solutions that utilise for example wind power.

2.1.1 Electric vehicle integration with RES

Electric vehicles and photovoltaic generation are two independent technologies, but when integrated together they can bring considerable benefits like the reduction of costs and ecological footprint. Eventually, the synergy between the two could also stimulate the development of each technology.

Moreover, electricity from photovoltaic panels has the advantage to be generated at both medium and low voltage levels within the power systems, which additionally reinforce the idea of embedding the photovoltaic generation with EVs.

A smart control strategy is necessary to optimise the power flows in the system, mostly by adapting the EV charging to variations from photovoltaic generation. The main idea is exploiting daytime hours, when the solar radiation is at its peak, to store solar power in car batteries for future usage, and eventually discharge part of its battery capacity back at the right time. Therefore, a key-element in these strategies is the ability of EVs to use bidirectional flow (from and to the power system), known as vehicle-to-grid (V2G) [20].

The first step of a smart strategy consists in defining a strategy objective. An objective can be either monetary, for example decreasing electricity costs, or physical, such as reducing the ecological footprint or increasing energy efficiency. The ecological footprint can be direct or indirect emissions of CO2, while energy efficiency can be the reduction of grid power imports [20].

The literature identifies two possible control modes for the coordination of EVs and PV: centralised and decentralised.

- Centralised mode: an agent usually called *aggregator* manages the scheduling of the EV fleet charging. An aggregator could be, for example, the charging station or the BSS itself. The drawback is the necessity to have an heavy communication architecture handling large amounts of data.

- Decentralised mode: EVs set up their charging themselves by reacting to incentives of an aggregator, such as dynamic changes in the electricity prices. On one hand, this requires a less complex communication architecture, on the other hand, the system events are less predictable.

In the latter case, EVs are not directly coordinated by a central entity controlling all charging processes. EVs belong to individuals with specific preferences and constraints, who would not allow control of the charging process without being properly compensated. This happens in case of plug-in charging mechanisms, where EV owners have the right and chance to charge their vehicle at any time, therefore creating an impossibility for the central power supplier to control and coordinate the charging times directly.

The former case on the contrary includes charging solution such as the one presented within this thesis. In fact, a battery switching station (BSS) can act as aggregator, collecting discharged batteries from EVs and deciding to schedule the charging of such batteries to the best available time frame, avoiding peak-demand by proper coordination with the grid. This of course should consist in a trade-off, where the BSS tries to avoid excessive loads while keeping a certain amount of charged batteries to ensure service at any time. This aspect will be investigated further on, when simulation results are presented and discussed.

Another major aspect that influences the performance of this joint system is the spatial configuration. The EV/PV pairing could be particularly efficient in certain scales, for example in an intermediate scale like the BSS case due to the fact that this configurations cannot host a large number of EVs, and so it's easier to predict the charging demand. These predictions could be less obvious on other scales [20].

With the help of vehicle to grid (V2G) technology, EVs and PV generation could achieve multiple benefits if combined together as in the case of the BSS. The BSS can serve as an energy storage station or controllable load, in addition to providing electric vehicle users with battery switching services. Therefore, the cooperation between RE (solar energy) and BSS could not only benefit the power grid, but also promote the evolution of RE business and electric vehicle industry [28].

All the aspects investigated in the previous paragraphs, such as integration of renewables, DER and flexible energy storage options through EVs are some of the main contributors of the Smart Grid revolution, that has been already discussed in chapter 1.

Moving to the technology side, the main efforts concern the on-board batteries, their reliability, durability, affordability and safety.

The next section introduces typical battery dimensions and technicalities, and investigates the problem of battery ageing, which can be a critical aspect for the BSS system studied within this work. A brief overview of smart charging solutions is then provided. Among them, battery swap is identified as a relevant solution to serve the next generation of EVs and finally the BSS model is described in detail.

2.2 Batteries Overview and Smart Charging

2.2.1 Battery Technology

Batteries are the core of electric vehicles and require large investments by EV owners in terms of upfront cost, maintenance and disposal.

Nowadays the dominant battery technology used by EV manufacturers are lithium-ion batteries, whose strengths are high power density, high energy density and efficiency, and a long operational life [35] [36].

Lithium battery capacity is more than double of traditional lead-acid or nickel-cadmium batteries introduced in 2009-2010 [37]. Typical battery capacities today lies between three levels:

1. 16-24 kWh (low capacity)
2. 24-50 kWh (medium capacity)
3. over 50 kWh (high capacity)

Recent models of EVs like the *Audi eTron* (2018) and the *Jaguar I-PACE* (2019) have 100-120 kWh batteries, which enable these vehicles to reach the same driving range of ICE cars and beyond [37]. The new *Tesla Roadster* coming in 2021 will be equipped with a 200 kWh battery enabling a 1.000 km range [37].

Such vehicles require high DC power to be charged in a reasonable amount of time, so fast and super-fast charging will be a priority for electric mobility [37]. However, fast charging does not allow much flexibility options and create spikes in the electricity demand and other threats for the grid.

The BSS system simulated within this thesis also requires supercharges to ensure continuity of service and avoid unavailability of batteries for long time intervals. The BSS though mitigates the impact on the grid by combining superchargers with locally installed PV panels and smart charging strategies, which helps levelling the electricity loads.

Nevertheless, super fast charge or discharge cycles could negatively affect the longevity of batteries, as explain in the following paragraph.

2.2.2 Battery Ageing

Despite the many advantages, lithium-ion batteries are also prone to irreversible ageing mechanisms and degradations, which can be accelerated even more by aggressive utilisation and careless management by the operator [35]. As a matter of fact, a joint research conducted by the IMT-Atlantique in France and the American University of Science and Technology in Beirut, Lebanon, estimated that, through an ageing-aware battery management, a battery could extend its life cycle up to 50% of its initial state of health (SoH) per year [35].

As explained in the next chapter, the adoption of a BSS-based system will result in a transferring of battery ownership from the EV user to the BSS firm. The latter will take full responsibility over batteries, therefore an intelligent management policy is necessary to keep the batteries in a good state of health, which ensure a long life cycle thus cushioning the costs.

Before introducing the major mechanisms involved in battery ageing, it is useful to mention the typical metrics used to describe battery state at a given time:

- **State of Charge (SoC)** is given by the ratio of the residual charge to the total charge when the battery is full [35] [36].
- **State of Health (SoH)** describes the condition of the battery compared to its ideal conditions [35] [36]. It's given by the ratio of the current capacity to the nominal capacity given by the manufacturer: $SoH(t) = \frac{C_{ref}(t)}{C_{nom}}$
  When this value falls below 70%, the battery is typically at the end of its service life [37].
- **Depth of discharged (DoD)** expresses the percentage of battery discharge [36].

There are two major ageing processes that cause battery degradation, known as *cycle ageing* and *calendar ageing*. The former occurs during battery charging and discharging cycles, while the latter occurs when the battery is stored and at rest.

More specifically, *cycle ageing* is caused by the physical and chemical changes happening in the battery cells during operation, that continuously alter its SoC. In order to slow down this ageing mechanism, lithium-ion batteries should be operated in a range of SoC between 20% and 90%, as shown in Figure 2.2 [35] [66].

High charging (SoC>90%) and low discharging (SoC<20%) stress will reduce dramatically the battery life.

calendar ageing is the service life of the battery as indicated by the manufacturer. The battery temperature particularly affects this metric, so temperature should be controlled by avoiding to charge and discharge the battery at high currents.

Taking these considerations into account, a BSS operator should be aware of the ageing mechanisms that affect batteries, in order to optimally manage and

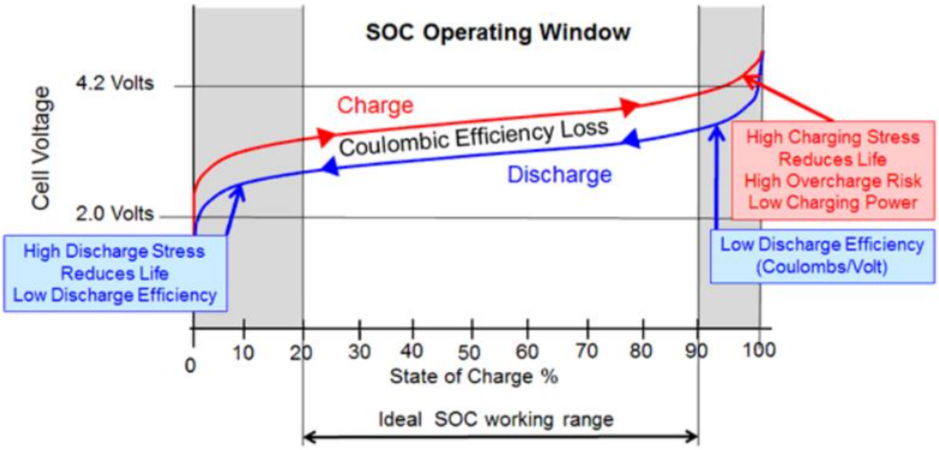

Figure 2.2. Recommended operating range of SoC for lithium-ion batteries [35][66]

operate its resources. It's been said that batteries can serve as energy storage devices, that collect electricity when the price is low and sell it back to the grid when it's profitable by discharging part of the batteries. A trade-off between high charging-discharging rates and profitability should be considered in such scenario.

2.2.3 Smart Charging

Different charging solutions for EV batteries coexists in today's market. EV charging is a delicate issue due to its impact on electricity demand, which can be threatening for the grid.

If big fleets of EVs were charged simultaneously without any control strategy, their impact in terms of peak demand could be unbearable by the current power systems. In some cases, this will create the need to upgrade or even build new power plants in order to face the extra demand.

In such scenario, smart charging is the key for distributing the additional load generated by EVs, thus reducing the overall stress on the local grid [37].

The term smart charging refers to various mechanisms that allow to strategically control the charging of EVs. These mechanisms range from simple incentives to encourage EV users to shift their charging to off-peak hours, to automatic response of EVSE to control signals and price fluctuations [37]. In the case of battery swap the BSS itself could act as a sort of aggregator that schedules the charging of batteries in economically or strategically convenient time frames.

As explained further on in the next chapter, the BSS simulator actually implements an algorithm for smart charging, which performs peak shaving to flatten the daily demand and avoid stressing the grid. Battery charging is indeed adjusted based on the local generation from PV arrays, so that less electricity from conventional power plants is needed. Moreover, the algorithm involves the use of batteries as energy storage devices, that can be discharged in response to price variations in order to make profits by selling the electricity back to the grid. Other possibilities include the use of EVs' batteries as back-up power in case of black-outs or local outages. So far, the only country that deploys this kind of service is Japan, where the Nissan Leaf 40kWh battery is able to provide approximately three days of power for an average Japanese home [37].

In summary, a BSS system that implements smart charging strategies, combines fast charging with local RE generation, and takes into the equation battery ageing, could be a relevant solution for serving the next generation of EVs. Such BSS model is finally introduced in the next section, which describes its operation and components, followed by the analysis of real cases of BSS that made their appearance on the market in recent years.

2.3 BSS

A Battery Switching Station, or BSS, is intended as a physical place, similar in size to a conventional gas station, where EVs' flat batteries can be automatically replaced with fully charged ones.

The benefits of BSS with respect to plug-in charging stations affect both single

EV users and the whole community, potentially up to country scale.

From the user's viewpoint, the key factors are the elimination of driving range limits, the transferring of battery ownership and costs to the BSS firms, and the celerity of service, since BSS eliminate the main source of delay which is the time frame needed for the battery to charge.

From the community viewpoint, the establishment of a BSS network could be beneficial in two senses. Firstly because BSS are boosters of the EV penetration in the market, which promotes the shift to an oil free economy. Secondly because the BSS is likely to become an actor of the Smart Grid, using spare batteries as energy storage devices and participating in DR programs.

2.3.1 Components and Operation of the BSS

This section presents in details the operation of a BSS system, inspired by the operating model conceived by *Better Place*, an American-Israeli startup that realised the first modern commercial network of BSS between 2009 and 2013.

The BSS includes distinct technological components, which are the corresponding of the distinct software components of the simulator developed within this thesis. All these components are listed here below:

- **Swap Platforms** can host one EV at a time, they are equipped with a robotic arm that performs the battery replacements automatically and within a short time, typically in about three minutes [29].

- **Batteries Stock**: the BSS holds a limited number of fully charged batteries, ready to be distributed to EVs that request a swapping service. Each full battery is unconditionally exchanged with a depleted one, making the BSS a closed-loop system. In the simulator the BSS is implemented as a *Container* while batteries are the *shared recource*.

- **Charging Hubs**: once a battery exchange has been carried out in the swapping platform, the depleted battery is plugged in a charging hub, where it goes through a charging process that requires some time. The actual charging time depends on two factors, the battery capacity and the hub power, according to the following relationship: *Charging Time = Battery Capacity (kWh) / Hub Power (kW)*. Once a battery has completed its charging procedure, it goes back to the stock of charged batteries again in a *FIFO* (first-in-first-out) manner.

- **Rooftop PV panels**: an array of photovoltaic panels is installed on the BSS roof and exploits solar energy to partially provide the electricity need for the charging of batteries. The electricity produced locally is useful to smooth down the power loads during daytime in sunny weather conditions. In the simulator the array size was dimensioned to fulfil the energy demand at its best.

- **EVs** are actually the clients of the BSS system. They eventually visit the switching station when they are about to exceed their driving range and request a swapping service.

For what concerns the BSS system operation, which is also the step-by-step procedure of the simulator, the complete course of actions is shown in figure 2.3.

The BSS has a finite inventory of I batteries. EVs arrives at the BSS intending to request a battery. If at least one swapping platform is available, EVs enter one at a time and begin the battery swapping procedure, which takes a fixed amount of time. Once a new battery has been correctly installed on the vehicle, the EV leaves the BSS and the depleted battery is moved to a charging process. Such process does not begin immediately in all cases, but it can be postponed to a time when

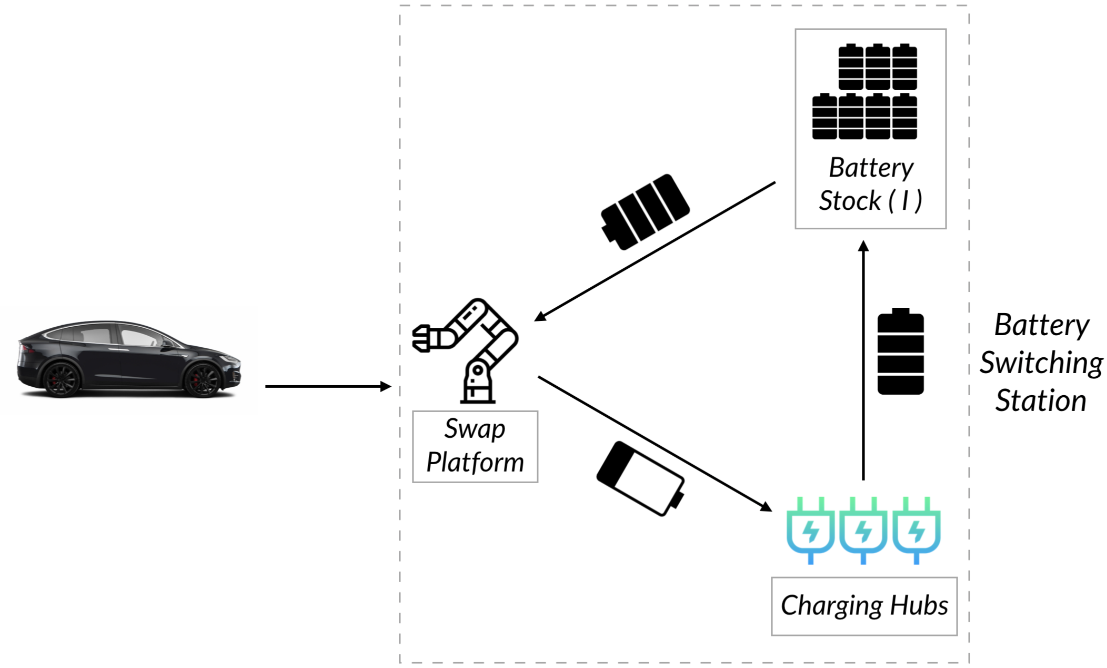

Figure 2.3. Operation of the Battery Switching Station Model.

the local PV production is at its most, avoiding to buy energy from the centralised power plan, therefore reducing peak-load in the grid.

In summary, at any given moment there are B empty batteries either in the charging process or schedule, while (I-B) others are available for arriving EVs. If an EV arrives and no battery is available (B<I), its request is postponed until a battery become fully charged and available [28].

2.3.2 Advantages and Disadvantages of BSS adoption

As mentioned at the beginning of this section, BSS could bring benefits for both single EV users and for the entire community.

From the user's perspective, there are two main reasons that typically hold back the adoption of EVs. The first is called *range anxiety* and it refers to the worry that the vehicle could run out of power before reaching its final destination. The second reason is the high cost of purchasing and maintaining the battery, which usually represents the main difference in terms of commercial price between EVs and diesel or petrol cars. For example, the battery of an mid-size electric car with a capacity that lies between 16 kWh and 24 kWh can cost up to €14.000 [28].

These two limiting factors are true in the case of conventional plug-in EVs, like PHEV or PEV. Their range is limited by the travel distance that their battery can ensure at each charge, and once they run out of power, the recharging process takes a non-negligible amount of time, depending on the battery capacity and on the charging power offered by the facility. Moreover, the battery itself is sold along with the car, so the EV owner is also in charge of the battery and its future maintenance costs.

The widespread adoption of battery switching stations could instead overcome the previous limitations. By establishing a proper network of BSS it is actually possible to extend the range of EVs, since BSS can swap a flat battery with a full one in few minutes which is a negligible delay. The second advantage is the separation of car ownership and battery ownership. Batteries are totally owned by the BSS firm, allowing users to cut down the costs of battery purchase, warranty and maintenance, which is a significant factor that drives more and more people to adopt electric mobility. While part of the risk connected to the battery maintenance is transferred by the EV users to the BSS firm, it is also admissible that the firm would charge the clients for this risk transfer [28]. The swapping service will then have a certain price which is likely to be above the mere cost of charging the battery, like it happens in a conventional plug-in facility. However, the BSS company can manage this risk at a relatively low cost due to scale economy [28]. Therefore, the extra price that costumers pay is kept quite low, so that the BSS still represents an optimal choice from the users viewpoint.

In addition to the advantages already mentioned, the BSS holds a third significant benefit, which is the possibility to plan and schedule the charging of batteries according to the grid needs, basically acting as an aggregator. The natural flexibility of BSS, owed to the fact that batteries are property of the firm, helps preventing peak-loads of electricity by shifting the charging process to less busy hours.

The participation in the smart grid is furthermore enanched if BSS make use of renewable energy sources as mentioned in the previous chapters. The easiest and natural way is the installation of PV panels on the roof of swapping stations, exploiting solar energy without transmission losses since the electricity is produced locally.

There are also some drawbacks linked to the adoption of a mobility system that relies on battery switching stations. Firstly, it is necessary to create a universal standard for batteries in order to make them swappable [28]. This means that different electric car companies should produce EV models in such way that the battery is not embedded in the vehicle and that can be dismounted easily.

Other significant drawbacks are related to environmental issues, particularly carbon emissions and oil dependence. Thanks to the cost reduction of electric cars linked to the battery ownership, BSS are actually promoting the adoption of EVs, driving more and more people to buy electric cars instead of conventional ICE cars. On one hand, this leads to an overall reduction of oil dependence. On the other hand, this shift leads to an increase in electricity consumption, which in turn rises carbon emissions if electricity is produced by fossil-based power plants, like it happens in many countries. In addition to that, a network of BSS largely eliminates the range anxiety by significantly extending the EVs travelling range, which inherently lead users to drive more, therefore consuming more electricity.

Several countries have set policies in order to achieve these dual goals of cutting down CO2 emissions and limiting oil dependence [28]. Reducing dependency on fossil fuels is critical for a country for both strategic and economic reasons. A transportation system based on oil is indeed vulnerable to geopolitical contingencies and supply disruptions, since most of the crude oil is concentrated in certain parts of the world [28]. A curtailment of the level of carbon dioxide released in the atmosphere is also crucial to mitigate the global warming phenomenon, which can spark catastrophic consequences.

In countries like China, where the electrical industry heavily depends on coal and carbon, there is a misalignment between the two environmental objectives just mentioned. On one hand, the adoption of BSS helps reducing oil dependency, on the other hand it increases polluting emissions [28].

On other countries where the electricity is produced from a mixture of diversified sources besides oil, the dual environmental objectives are more aligned and so establishing a widespread network of battery switching stations brings real benefits for these countries in economic and political terms, making them less exposed to oil price oscillations and geopolitical instabilities.

What is clear from the previous points is that switching stations highly encourage the adoption of EVs, but this increase in terms of adoption does not necessarily mean a decrease in terms of emissions [28]. The alignment of the dual objectives is a crucial aspect to take into account before the deployment of the BSS model.

2.3.3 Case Studies

This last section brings up three case studies of real existing companies that in recent years have held, or still hold, a fully operative network of battery switching stations.

Better Place

Following a chronological order, the first company that is worth to mention is *Better Place*, founded in October 2007 in Palo Alto, California, by the multimillionaire Israeli entrepreneur Shai Agassi, mostly using private investments.

The company opened its first operating switching station in December 2008 near Tel Aviv, Israel [53] [31]. Between 2008 and 2009 *Better Place* launched a campaign for the deployment of BSS networks in several countries, mostly on "Islands" such as Denmark, Australia, Hawaii and the San Francisco Bay. Israel itself can be considered a transportation island due to its rarely-crossed borders [54].

In September 2012, the company reached its peak with 21 operational BSS open in Israel [53] and 17 in Denmark [33], which were enough to cover the service for the whole country.

The first car company that signed an agreement for the use of switching stations was Renault-Nissan. According to the agreement, *Better Place* would have provided the charging infrastructure and in return Renault would have produced its prototype of EV equipped with a swappable battery, the Fluence Z.E. [53]. The battery packs mounted underneath the Fluence Z.E. were designed to be replaced automatically by a robotic claw in less than two minutes, using the same technology that F-16 jet fighter aircraft use to load their bombs [53] [54]. Such battery packs were expected to provide EV with a 160 km range, and have a life span of 2000 recharge cycles over 8 years [53].

Afterwards, *Better Place* stations evolved to accept multiple battery types of different EVs, as long as the battery pack could be extracted from under the vehicle [53] [32].

Better Place carried out a business model based on a monthly subscription that would have covered the battery pack leasing, the swapping and charging costs, the cost of either producing or purchasing electricity from renewables, and finally the profit [53] [30]. In addition, costumers would have paid for a new consumable, the electric mile. In 2010 this per-distance fee was about 8c a mile, and it was likely to decrease exponentially thanks to technological improvements that would have made batteries cheaper.

An important concept stressed by the company CEO Shai Agassi was the necessity to achieve affordability of EV, reaching a commercial price at least $5.000 below the average price of conventional vehicles. This would have made electric mobility appealing enough for most people to shift to an EV. The key element for achieving this outcome was cutting down the costs related to the maintenance of batteries, therefore, any battery issue would have been entirely handled by *Better Place*.

The company also made great efforts in pushing governments towards the adoption of international standards. However, such standards like the *SAEJ1772* did not reached global approval until few years ago [53].

Better Place was forward thinking also in the enabling of the Smart Grid. According to a simulation ran in 2009 by Israel's main utility, the nation would have spent about $1 billion on new power plants if every car was electric by 2020 [54]. The company overcame this issue by proposing a software solution for smart grid management. The switching stations were then to be managed by a dedicated software that could schedule the recharging of thousands of EV batteries away from peak demand hours, preventing overload of the grid [53] [55]. In addition to that, Shai Agassi announced that all the electricity needed to power the BSS should have come from solar arrays or wind farms. Despite this vision, countries like Israel was relying mostly on fossil fuels for bulk electricity production, making the renewable energy project really hard to achieve in the short term [53] [56].

In early 2013 *Better Place* suffered of significant financial problems due to the high initial investments in too many countries. The company had invested about $850 millions in private capital mainly for the establishment of the BSS infrastructures, and the original prediction about the EV penetration in the market was way too optimistic. Less than 1000 Renault Fluence Z.E. were deployed in Israel versus the expected 100.000, and around 400 vehicles were sold in Denmark [53] [56] [33]. Due to these problems, the company finally filed for bankruptcy in May 2013.

Tesla Motors

Tesla Motors is a worldwide famous electric car company, currently leading the market of fast charging technology.

In 2013, its founder and CEO Elon Musk announced a proprietary battery switching service complementary to the Superchargers, in order to widen the charging options for owners of *Tesla* vehicles [59], who could then chose either fast or free.

Tesla then adapted its Model S to enable fast swapping of the battery pack and showed at a demonstration event how it was possible to replace a Model S battery within 90 seconds, half the time required to refill a gas tank [59] [60].

Tesla then announced a plan to deploy the first BSS between L.A. and San Francisco, since a large number of Model S were used to make this round trip regularly. However, the project of a widespread BSS network was abandoned two years later due to a lack of demand in the only existing pilot facility at Harris Ranch CA, with only five people that tried out the service [59]. The price for battery swap was probably a decisive factor, costing around $80 against the free fast charging option offered by Superchargers.

Nio

The most recent company and actually the only one that still deploys operative switching stations is *Nio*, a Chinese EV startup founded in 2014. The company, headquartered in Shanghai, is specialised in the development of electric autonomous vehicles and since May 2018 offers battery swapping services for its costumers [61].

The first BSS called "Power Swap Station" was opened in Shenzhen, in the Guangdong province, and allowed a 3 minutes swap service for the ES8 model only. The stations have a compact modular design, with a volume of approximately three parking spaces, which enables scalability of the service [65]. Moreover, the battery swap facilities are supported by NIO Cloud, an IoT based technology that allows to plan and schedule appointments for battery swapping from costumers' mobile phones [65].

Initially the company charged 180 yuan (approximately €20) for each battery swap, but since August 2018 the company leader Lihong Qin announced that ES8 owners will be given 12 free battery swaps every year at any BSS across China [62] [64].

So far *Nio* has installed 80 BSS spread around the major Chinese cities and along the G4 Expressway connecting these cities [62] [64]. The company goal is building over 1.000 BSS all over China within the next two years.

Considering these three real cases, it's clear that battery swap is still a developing technology that has great potentialities but it's not fully mature yet at least at market level. *Better Place* was probably too precocious for its time and *Tesla* has found little demand and has favored the Superchargers instead. Now *Nio* is taking advantage of different market conditions and is pushing hard to make BSS a reality. Under these premises, the present work of thesis wants to be a contribute to the BSS model which is believed to hold lots of potential as active participant of the smart grid and of the sustainability challenge in transports.

Chapter 3

The BSS Simulator

The present chapter unfolds the main contribution of this thesis to the complex scenario reviewed in chapter 2. The core of this work was the development of a virtual model of a *Battery Switching Station*, using computer simulation to reproduce the behaviour of the physical system with a computational approach.

The custom-built simulator allowed to research and analyse the response of the BSS to different input parameters and stimuli. By varying such parameters like the total number of batteries kept in the inventory, the batteries' speed of charging and capacity, it was possible to gather statistics and performance metrics such as the availability of charged batteries in the system, the average waiting time of costumers (the EVs) in case they queue for a service, and the loss probability, which is linked to the intolerance of EVs' users that abandon the station due to long waiting times.

The collection of these responses enabled a correct dimensioning of the BSS given a certain traffic matrix. The main objective being the continuity of service, which means that the station should be able to promptly serve EVs at any time with the lowest possible waiting times.

Besides QoS, other objectives were taken into account in the design phase of the simulator, in order to exploits the advantages of the BSS model discussed in chapter 2. A smart charging algorithm was developed to optimally manage the recharge of batteries within the BSS. The algorithm avoids to create peaks in the electricity demand, thus preventing overloads of the power grid. Such result is achieved by scheduling the recharging of some batteries later in the day if it is found that at a given time there are many others already under charge, so the overall current absorption is homogeneously distributed during the day. Moreover, the algorithm considers the electricity prices hour by hour to find out the most convenient times to schedule the recharge, or eventually to sell the extra energy produced by a local solar array. The smart charging algorithm is actually the main contribution of this thesis in the context of electric mobility, as it helps enabling a smart and controlled penetration of EVs in combination with the Smart Grid.

The present chapter is divided in three parts. The first part describes the tools used to set up the different components of the simulation. The second part introduces the BSS model parameters and carries out a deep description of its operation and functioning. Finally, the third section shows and discusses the simulation results. These are further divided in performance results, which enable a correct analysis of the BSS model by comparing diverse parameters, and the results obtained after the smart charging algorithm has been applied. The latter are worth to study since they allow to make policies for the scheduling of batteries recharge that take into account energy prices and electricity demand.

3.1 Simulation Tools

As previously mentioned, a discrete-event simulator was specifically designed to reproduce the behaviour of a battery switching station. Due to the high number of parameters, mathematical modelling didn't seem to be an effective approach, so it was used in a complementary way to check the correct functioning of the core system. Instead, simulation modelling was the chosen approach to study the behavioural responses of the BSS model.

The simulator was built by scratch using *Python 2.7* as programming language and the library *SimPy* as framework to host the simulation. Both *Python 2.7* and *SimPy* along with other libraries were installed on a Mac OS Catalina environment that hosted the simulation.

3.1.1 SimPy Overview

SimPy is an object-oriented, process-based discrete-event simulation library written in *Python* [67]. This library allows to run simulations in continuous-time, though stepping through discrete events, meaning that events like the arrival of EVs occur at a particular instant in time and mark a change of state in the system.

SimPy was particularly suitable for the BSS model since it includes components such as **processes**, for active units like vehicles, and **shared recources**, for passive units that form a congestion points like the swap platform or the charging hubs.

All *processes* live in an environment (*env*) and they interact with each other via *events* [67]. *Processes* are basically class methods, that create *events* and *yield* them waiting for them to be triggered. While a *process* is yielding an *event*, the *process* gets suspended and it is resumed once the *event* is finally triggered [67].

To simulate the behaviour of the BSS, the *yield* statements were used in the case of EVs queueing to access the swap platform unit, and to decide when batteries would have accessed their hubs to get recharged.

Concerning shared resources, two different types were used:

- **Resource** is an object whose units are requested by a process. The resource can be used by a limited number of processes at a time, depending on the number of its units. The resource is the battery and only one client at a time can be served.
- **Container** is an object that models the production and consumption of specific items. The container is the battery stock (or inventory) and the items

are the batteries that can be inserted or extracted.

3.1.2 Libraries and Datasets

Other libraries used to set up the simulation were: *matplotlib* to generate the plots necessary to study the system performances and visualise the results. *random* that allowed to generate processes like the arrival of EVs using a Poisson distribution. *pandas* to deal with external datasets that were used as realistic data sources for modelling traffic, generation from PV panels and hourly prices of electricity.

The first of these three datasets used to support the simulation is a traffic trace of the city of Berlin that contains the vehicles plates, origin and destination times as well as trip duration for the year 2018. This data was used to model the inter-arrival time of EVs. The second dataset contains the hourly performance (expressed in Watts) of a PV panel located in Turin, Italy, tilted of 20 degrees and with a system loss of 14%. The third dataset contains the hourly prices of electricity for the year 2018. This data along with the PV dataset was exploited by the smart charging algorithm to set up realistic policies about batteries' schedule.

3.2 Parameters and Operation of the Simulator

3.2.1 Parameters

The BSS simulator requires some fixed parameters that were dimensioned according to examples found in the literature. The main parameters are, in order:

- **Number of Batteries**: defines the total number of batteries stored in the inventory of the BSS. Its value ranges from **4** to **20** batteries and the simulation is repeated with each one of these values in order the study the system performances and to find a good trade-off.

- **Battery Capacity**: affects the EV driving range and defines the power absorption per hour of charge. In the simulator it is assumed that EVs have a battery capacity of **16 kW**, which is a typical value for small-size EVs on the market.

- **Charging Power**: is the power in kW injected by the charging hubs into the batteries during the recharging process. In the simulator, its value ranges from **16 kW**, which enables a battery to be fully charged in 60 minutes, to **4 kW** which corresponds to a slow charge of four hours for each battery.

- **Switching Time**: is the time required by the robotic arm to swap a depleted battery with a fully charged one. By default this time is fixed at **4 minutes**, meaning that each EV event that obtains the BSS resource will be hold for four minutes before releasing the resource and leaving the station.

- **Waiting Tolerance**: defines the EVs impatient to waiting in case they are put in a queue to obtain the resource. The value varies between **10 minutes** and **15 minutes**, and directly affects the loss probability of the system.

3.2.2 System Architecture

The BSS simulator was designed with a modular and service-oriented architecture. The simulator is indeed composed of different blocks, each one corresponding to a class in the object-oriented paradigm, and the interactions between each block enables the system chain of events.

The different classes of the BSS simulator are shown in the class diagram in figure 3.1.

From right to left, the first block or class is the EV Generator. This class takes as inputs the vehicles' plates from the traffic dataset and assign them to each EV in order to identify it during the course of the simulation. It generates vehicles using

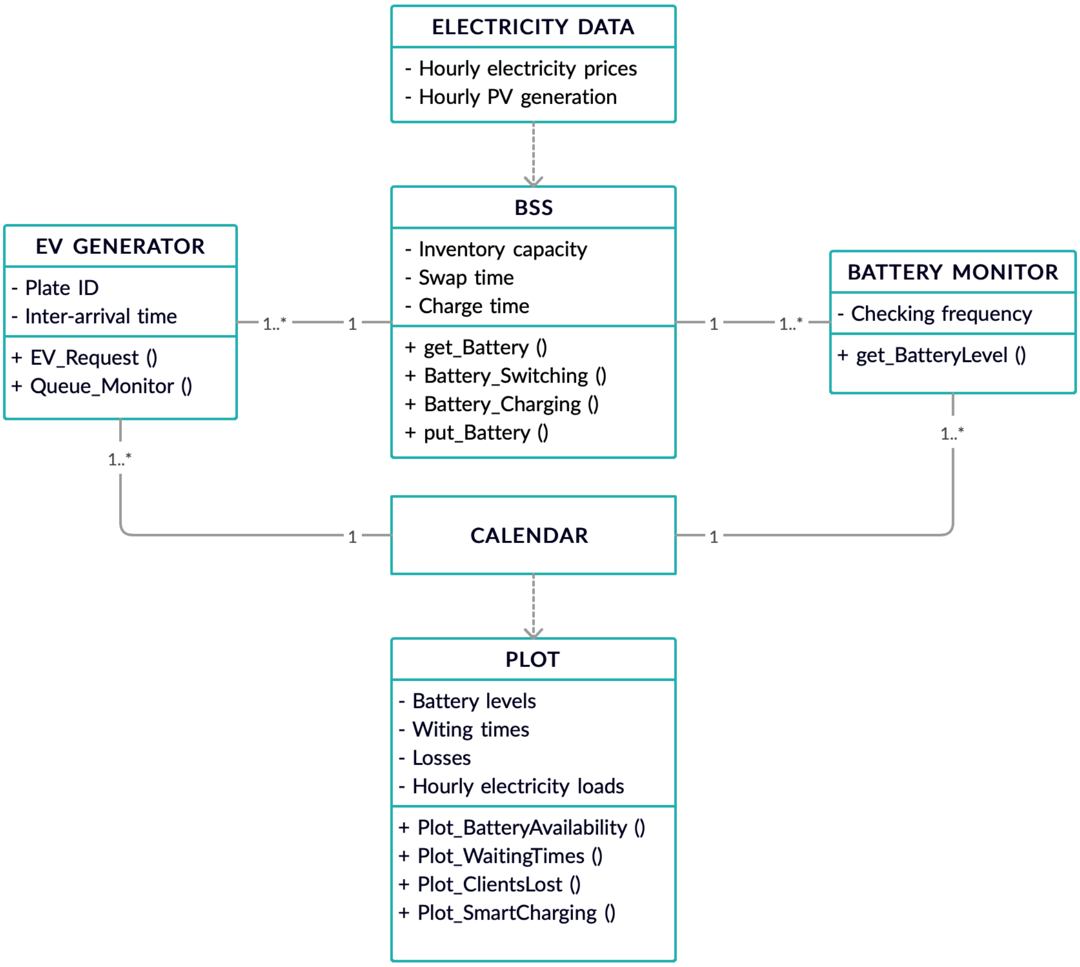

Figure 3.1. Class Diagram of the BSS Simulator Architecture.

the inter-arrival times and request a battery swap service to the BSS class, using the method *EV_Request()*. Moreover, it controls and monitor the queuing process of EVs and records statistical data in the Calendar class.

The second block is the BSS which is the core class of the simulator. This class is passed the inventory's capacity, which stands for the system container that holds a finite number of resources, namely, the batteries. The BSS class contains the *switching()* method, which gets resources from the container, and the *charging()* method, which puts back the resources after a specific time. The BSS class retrieve data about hourly prices of electricity and hourly power generation from a PV array from the Electricity Data class. These data are need to perform a smart charging algorithm within this class, which will be explain later in this chapter.

The Battery Monitor class is in charge of checking the level of the container (the inventory) with a certain frequency. The logic behind the checking frequency allows to records statistics about the battery availability for different days, weekdays and weekend days, and for different periods of the day (morning, afternoon, evening, night). These data are passed to the Calendar class and properly stored.

The Calendar class contains a dictionary where all the events of interests of the simulation are stored under the date and time at which they occurred. This allows to produce statistics useful to study the performances of the BSS system with different parameters.

Finally, data of interest are passed to the Plot class that exploits the matplotlib library to generate graphs with the simulation results.

3.2.3 Sequence of Operations

In the class *EV_generator()*, data about vehicles (plate and trip duration) are imported from the traffic dataset, and new EVs are generated based on this data using Poissonian inter arrival times. Every time an EV is generated, the method *EV()* is triggered.

EV()

EV() deals with all the actions and decisions that every EV has to face within the system. When an EV arrives at the BSS intending to request a battery, three situations are possible:

- CASE 1: if all batteries are under charge, the EV is put in a waiting queue.

- CASE 2: if at least one battery is available, but there are other EV processes queueing for the service, the EV is put in the waiting queue.

- CASE 3: if at least one battery is available and there is no EV process in the queue, send EV to the switching process.

If case 1 or 2 happen, two scenarios are then possible: if the EV stays in the queue for more than *Waiting Tolerance* time, the *queue_control()* method is triggered which remove the EV process from the system and record a loss. If instead the EV gets out of the queue within *Waiting Tolerance* time, the *switching()* method is triggered as in case 2.

Switching()

The *switching()* process is in charge of getting a resource (the battery) from the container and holding the EV process for a fixed amount of time, namely, the *Switching Time*. Afterwards, it triggers the *charging()* method.

Charging()

The *charging()* method is the core of the BSS simulator, since it encloses an algorithm that allows the simulator to take smart decisions regarding the charging of batteries.

The algorithm works in time slots of one hour each. Every time a flat battery arrives as input, the algorithm launches a forecast that includes the power absorption already in place at that very moment plus the power required by the new battery if it was plugged-in immediately.

If the sum of these values overpasses a certain threshold in terms of current absorption in kW or eventually in costs, the present battery is put in a queue so that the charge of such battery is delayed to a more convenient time. The algorithm repeats the forecast every time there is a change of state in the system until the threshold is respected.

Once the algorithm authorises the charging of a battery, the actual process lasts for *Charging Time*, then the resource which corresponds to the full battery is put back again in the inventory since it is considered available.

The whole cycle repeats for every EV at the time of its arrival and influences the decision-making path of all other EV processes.

3.3 Simulation Results

The present section shows the most significant results obtained by the BSS simulator. A simulation campaign was run with the goal of comparing two strategies that a BSS firm could potentially adopt when deploying its network of stations. The object of these strategies is the scheduling of charging times for depleted batteries dropped by EVs.

The first strategy is based on a maximum current absorption threshold and can be considered a grid-oriented strategy, since it flattens the electricity demand by avoiding peaks of current as much as possible. The second strategy is based on electricity price oscillations, which makes it a self-oriented or economic-oriented strategy that favors the income and outcome of the BSS firm.

To achieve these two approaches, a smart-charging algorithm was developed to manage the recharging of batteries. The algorithm performs a check of the thresholds every time a flat battery is dropped at the station and decides whether it is a proper time to charge such battery or not, in opposition to a *dumb* system that would charge every battery immediately, with no consideration of grid loads nor prices of electricity.

Thanks to this comparison, a company that owns a BSS network can adopt one of the strategies, or even a mix of the two, as a decision-making policy depending on the company business model.

3.3.1 Grid-oriented strategy

As previously mentioned, the grid-oriented approach relies on a smart-charging algorithm that checks the instantaneous current absorption before charging up any battery. The algorithm performs a check every time there is a change of state in the system. Figure 3.2 shows the behaviour of the system without the intervention of the smart algorithm, while figure 3.3 shows the result from the same simulation with the intervention of the smart algorithm.

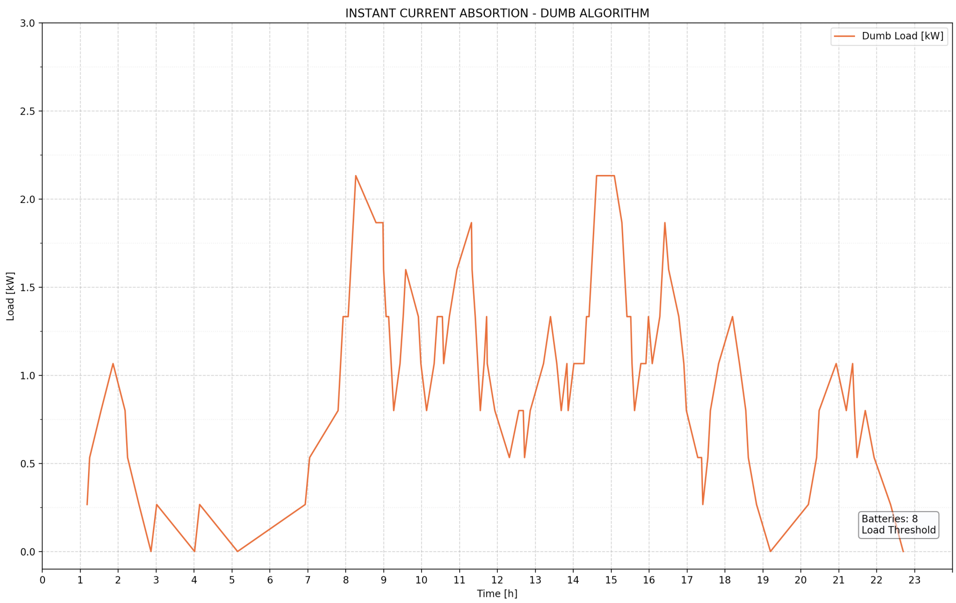

Figure 3.2. Instant Current Absorption without Smart-Charging Algorithm.

The graphs in figure 3.2 and 3.3 plot the power absorption in kW observed at every change of state in the system, cover a 24 hours scenario, and assumes the BSS holds 8 batteries in the stock. The electricity load is directly proportional to the number of batteries that are under charge at the exact moment the system is observed. In the "dumb" model (figure 3.2) the load is also proportional to the

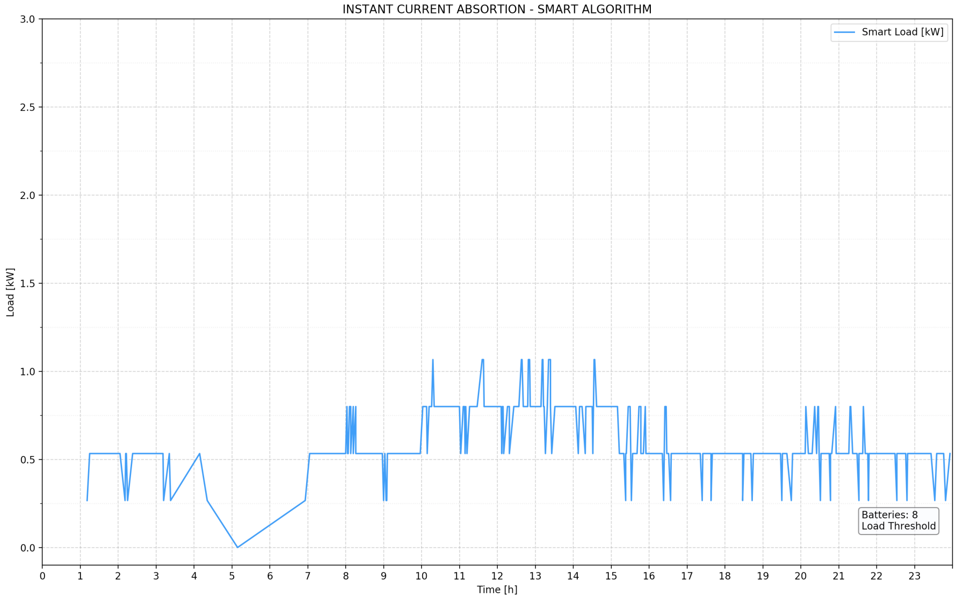

Figure 3.3. Instant Current Absorption after the application of the Smart-Charging Algorithm.

traffic pattern, therefore high peaks of current can be observed at the busiest hours of the day, for example around 08:00 am and 03:00 pm, when the BSS is visited by a considerable number of EVs.

In contrast, figure 3.3 shows how the electricity load is homogeneously distributed by the smart-charging algorithm, using a peak-levelling and valley-filling approach. The charge of part of the batteries is correctly postponed at night time and will be completed in the early morning of the day after, which helps to balance the demand for the grid.

The hourly current absorption was computed to show the effect of the smart-charge algorithm hour by hour, expressed in kWh. For each 60 minutes-long time slot, the overall consumption in that slot is given by the sum of the integrals of the power absorption at every observed moment within the present slot. Figure 3.4 shows the hourly power absorption computed on the base of the samples plotted in figure 3.3.

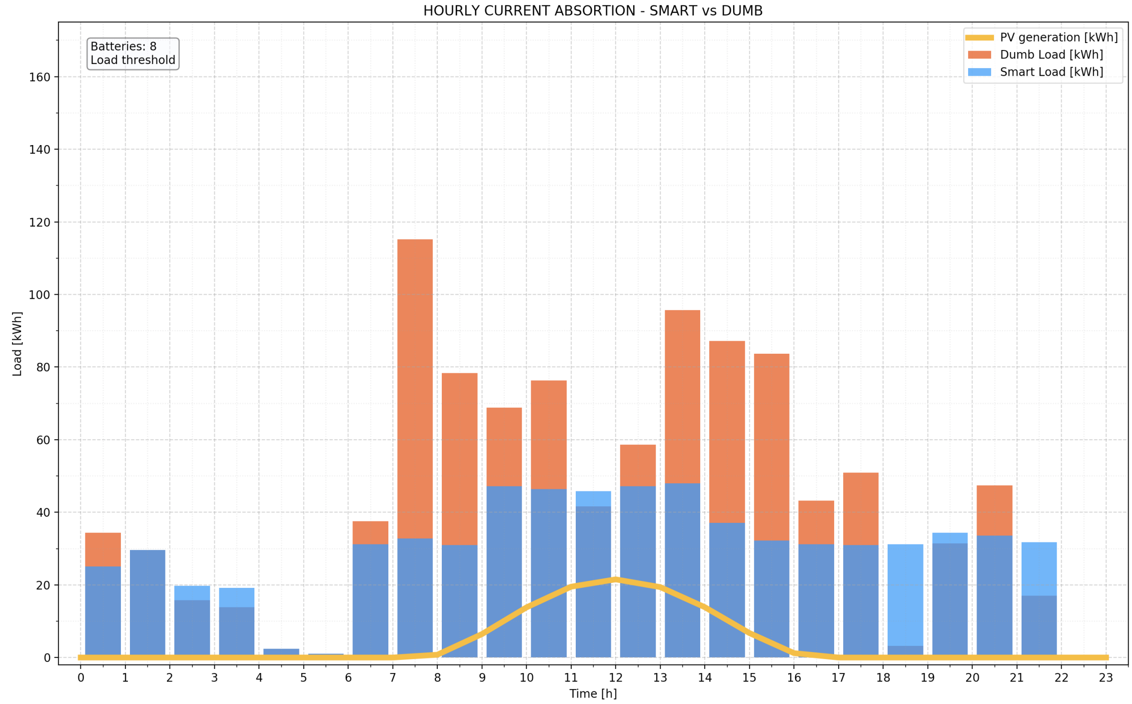

Figure 3.4. Hourly Current Absorption.

The smart algorithm visibly creates a smoother and better distributed absorption of power. The effect of the photovoltaic panels is visible in its operating hours, allowing higher current loads without overloading the grid. The PV array was dimensioned considering the physical size of a BSS, whose roof surface could cover approximately 120 mq. The array is therefore composed of 80 cells of 1.5 mq each, with a production of 2.1 kWh in favourable conditions.

Performances with Current Load Constraint

From the grid viewpoint, the result shown in figure 3.3 represents an optimal achievement, however, the comparison of performances of the two models (figure 3.5, 3.7, 3.6) reveals that when the smart algorithm is applied the BSS has a drop in terms of quality of service (QoS).

The system performances are studied comparing simulations of the BSS with

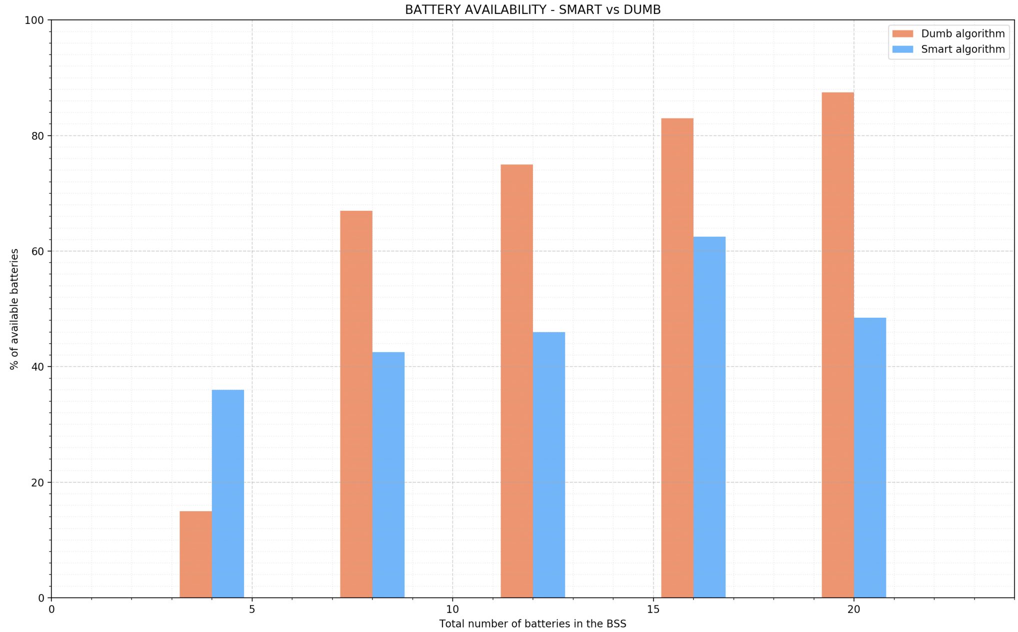

Figure 3.5. Probability of finding an available battery - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock.

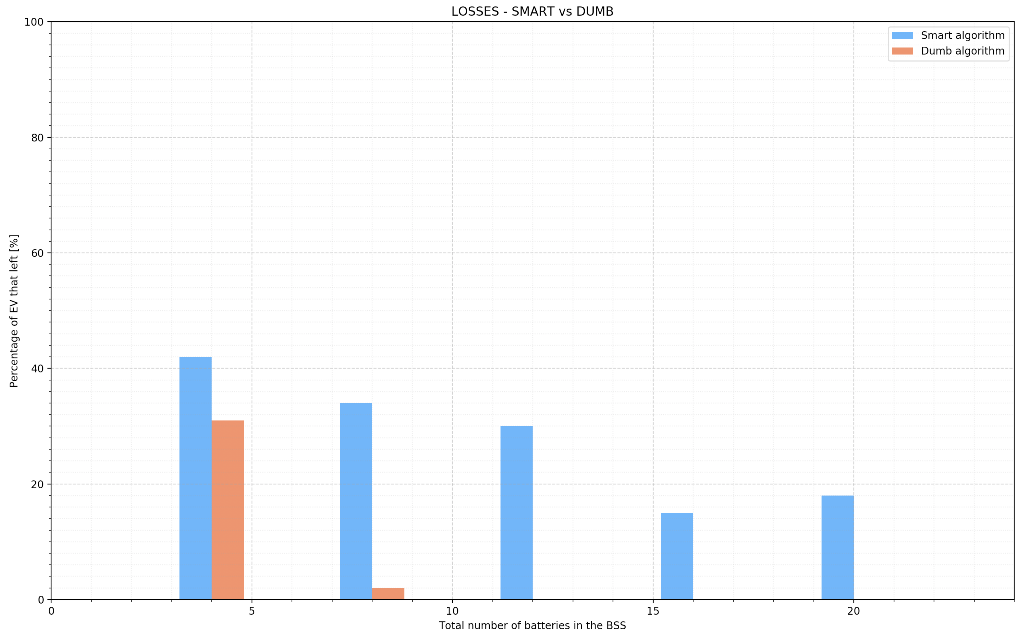

Figure 3.6. Client (EVs) losses - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock.

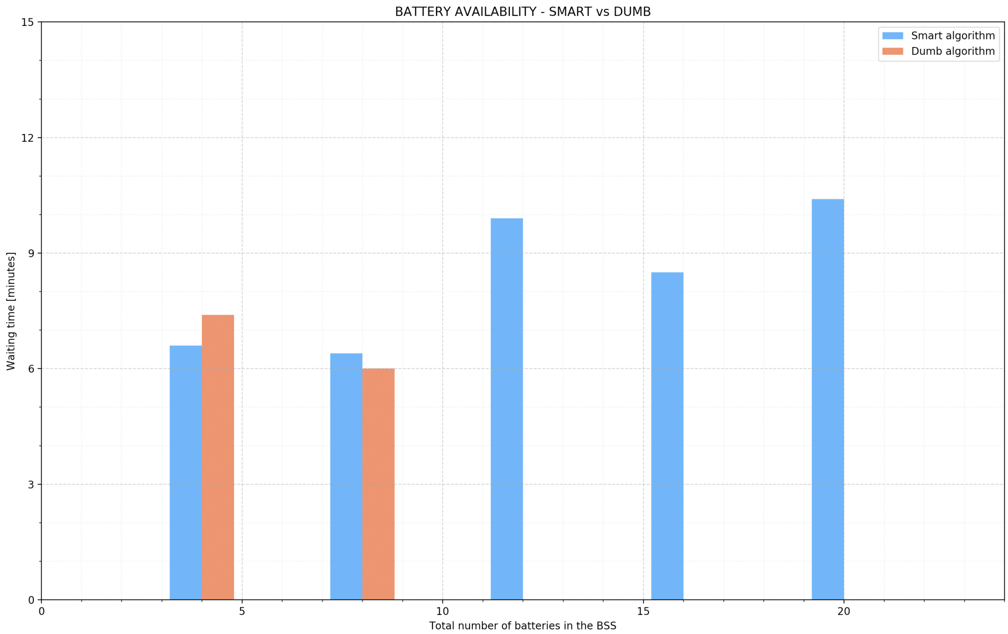

Figure 3.7. Average waiting times of EVs that wait to receive service - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock.

different amounts of batteries in stock. Particularly, BSS models with a total of 4, 8, 12, 16 and 20 batteries were simulated and compared. From figure 3.5 one can observe that, for the "dumb" case, the probability of having a fully charged and available battery every time a new client arrives increases proportionally with the number of batteries in stock, reaching 88% for a BSS with 20 batteries. In the "smart" case, this percentage is lower in most cases due to the fact that the charge of batteries is delayed to respect the load limitations imposed by the grid. Indeed the BSS does not promptly react to the clients needs, but rather favours the grid's necessities. The casuistry with 20 batteries is symptomatic, since normally a system with such resources would be able to ensure high QoS, but due to load limits it is only possible to charge simultaneously a small amount batteries over the total.

Figure 3.6 shows a similar trend, with client losses dropping to zero ("dumb" case) for a BSS with 12 or more batteries in stock. The "smart" case reveals very poor performances with percentages between 42% and 15% of vehicles that left the BSS because no battery was available at the time of their arrival.

What is clear from the analysis of these performances is that the blind application of the smart-charging algorithm without taking into account a minimum level of QoS leads to huge losses of client, which creates an economic damage to the BSS company.

Performances with QoS Constraint

Considering what just said, a trade-off solution was found using the smart algorithm with the additional constraint of charging immediately any flat battery if the BSS is running out of available batteries. The new performance results are shown in figures 3.8, 3.9, 3.7.

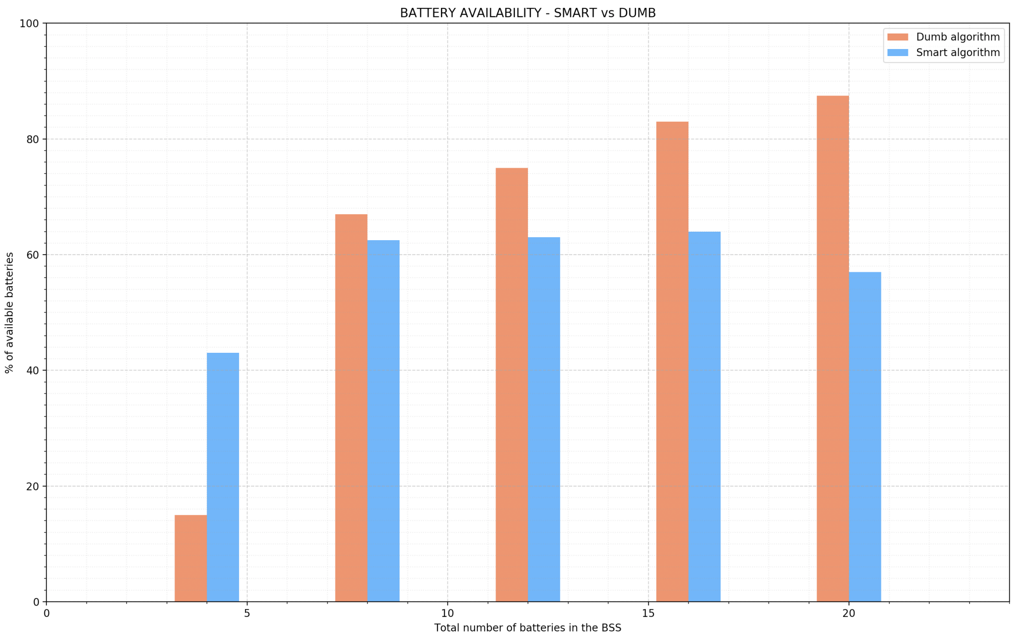

Figure 3.8. Probability of finding an available battery - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock (QoS constraint).

The system losses are drastically reduced here, reaching acceptable values under 10% for BSS with 12 or more batteries (figure 3.9). The probability of having

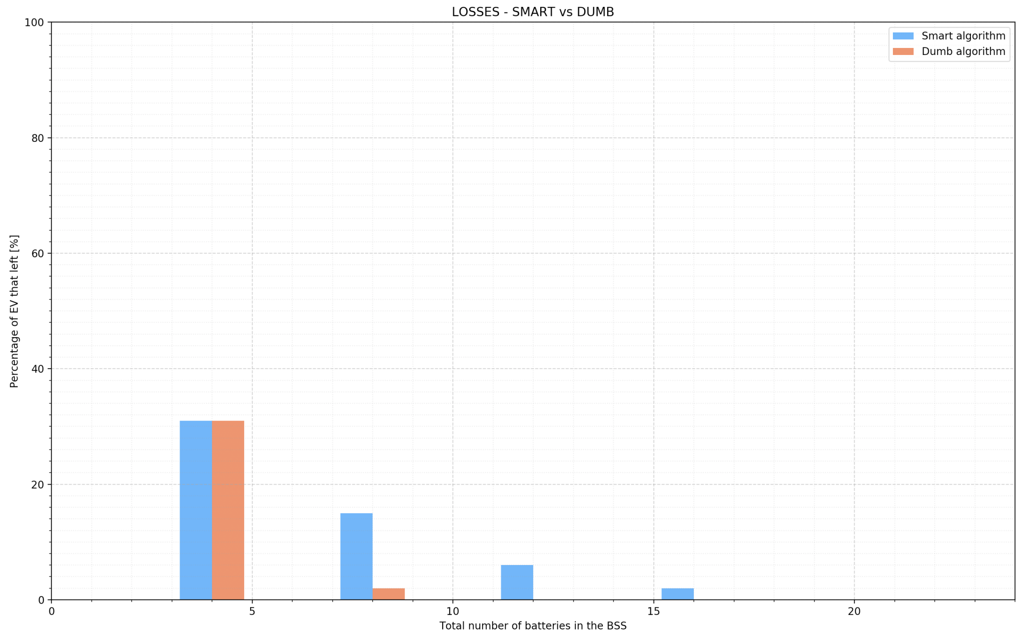

Figure 3.9. Average waiting times of EVs that wait to receive service - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock (QoS constraint).

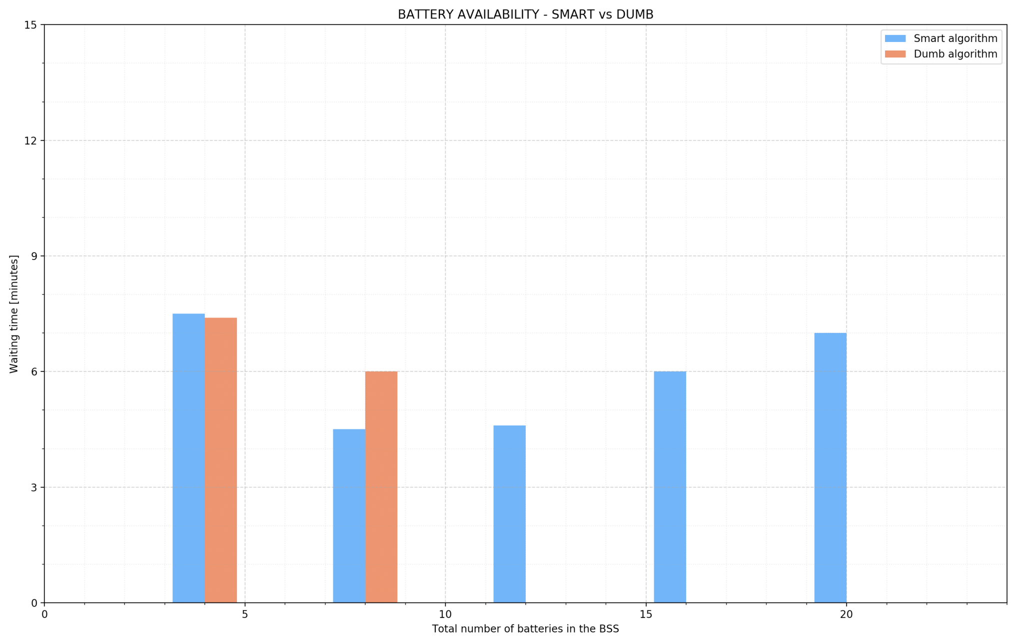

Figure 3.10. Client (EVs) losses - Comparison of BSS with 4, 8, 12, 16 and 20 batteries in stock.

available batteries at any moment is also improved and the average waiting times of EVs are lower, meaning that shorted queues are formed with respect to the previous case.

The effect of the smart-charge algorithm with a QoS constraint is visible from the comparison between figure 3.11 and figure 3.12 ,with B=16 as example.

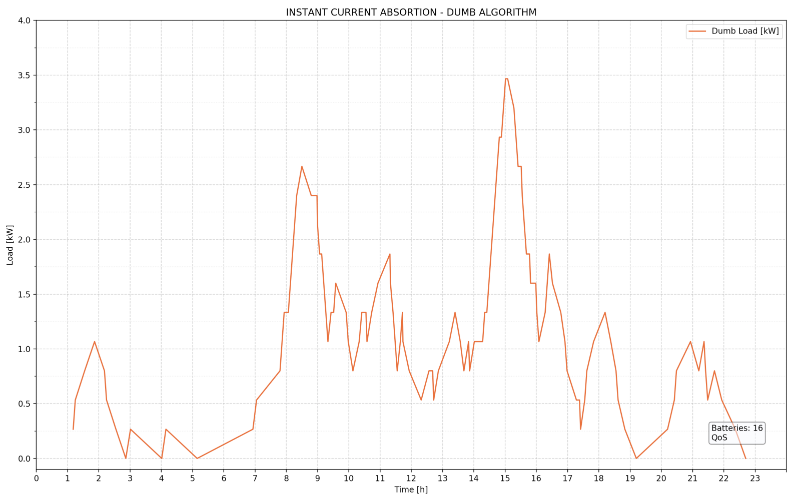

Figure 3.11. Instant Current Absorption without Smart-Charging.

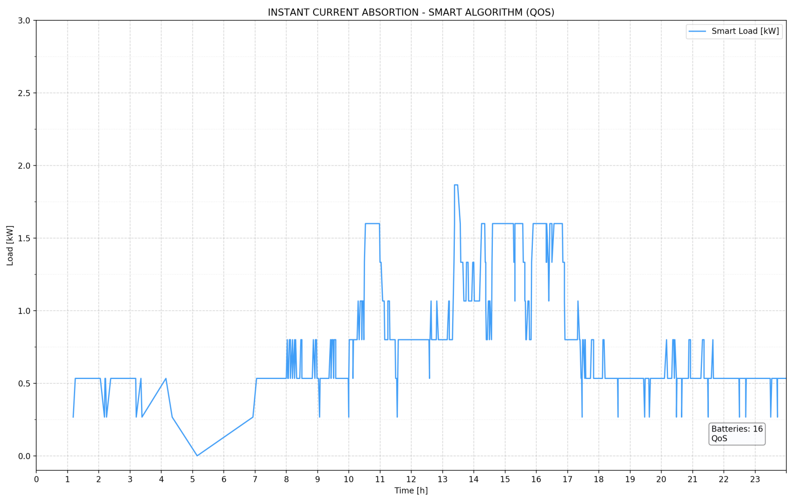

Figure 3.12. Instant Current Absorption with Smart-Charge Algorithm and QoS constraint.

Furthermore, figure 3.13 shows the same effect in the hourly absorption scope.

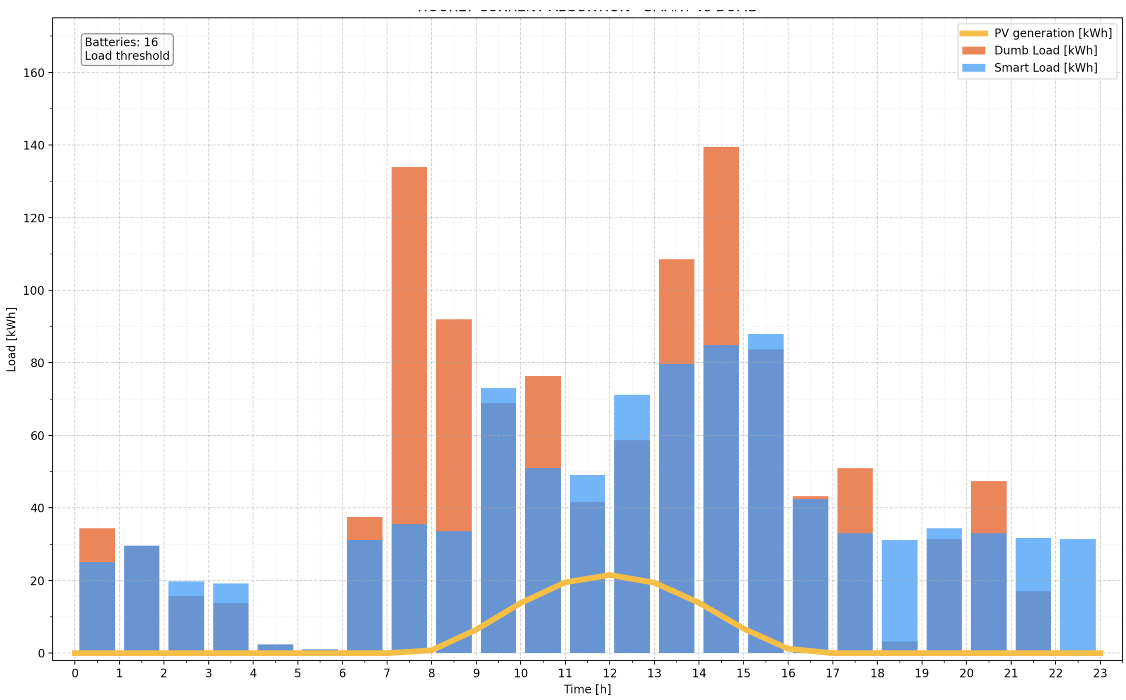

Figure 3.13. Hourly Current Absorption - Smart-Charge Algorithm with QoS constraint.

As observable in figure 3.13, the power demand generated after the smart algorithm does not always respect the load threshold as there are waves of quite high electricity consumption, for example between 02:00 pm and 04:00 pm. In these moments the BSS would suffer of a lack of charged battery due to high requests, therefore it is necessary to charge simultaneously more batteries to ensure continuity of service. Off the busy hours, the algorithm compensates peaks and valleys as visible in the time frame between 5:00 pm and 11:00 pm, and keep going covering the night hours.

Chapter 4

Conclusions

This final chapter retraces the logical line followed in this thesis work and derives conclusions, leaving an open door for future developments and ideas.

This work began in the framework of the sustainability challenge that modern cities have been facing in the last decade. Specific aspect investigated in this thesis concern GHG emissions from the transport sector and from electricity production based on fossil fuels. The global amount of Carbon Dioxide released in the atmosphere depends heavily on these two sectors, with 25% of CO2 emissions from fossil-based power plants and around 15% from road transport.

These issues have surely pushed the advent of sustainable solutions both in the energy production and transport sectors, leading in one case to the concept of *Smart Grid* and in the other case to a rapid advent of EVs in the market.

The smart grid allows a more efficient management of electricity generation and distribution, exploiting distributed renewable energy sources and demand-response programs to achieve less emissions.

EVs on their side are leading polluting emissions in the transport sector on a path towards zero, however, the charging of EVs' battery has an enormous impact on power grids. High penetration of EVs can result in extreme loads that are translated into a rise of bulk generation, which in turn generate more polluting emissions. Therefore, high penetration without supervision and control strategies pose a threat to the sustainability of distribution networks. The increased number of EVs will cause the need to build new power plants in order to face the rise of demand. This results in additional emissions under the hypothesis of a continued use of fossil fuel in the power industry. Lower emissions of CO2 and air pollutants determined by an actual increase of EVs could cause higher emissions by the electricity production. Overall, the avoided CO2 emissions in the road transport sector could be nullified by the higher emissions from the generation of electricity. Nevertheless, if battery charging is properly coordinated, EVs can actually become a relevant player in the sustainability game, acting in a complementary way with the smart grid.

Assuming a plausible scenario of a smart city where electric vehicles are widely used, this work of thesis proposed a model of charging facility for EVs that operates in high coordination with renewables and with the smart grid, referred to as *Battery Switching Station* (BSS).

Chapter 2 reviewed the design and functioning a BSS model, based on real working systems that have been deployed since early 2010s till now by EV companies such as *Better Place*, *Tesla Motors* and the Chinese *Nio*. More importantly, the chapter carried out a comprehensive analysis of the advantages and disadvantages of the adoption of a network of BSS. The most significant ones, which are linked to the results of this work, involves benefits for the community up to a city or potentially a country scale.

Such advantages includes the possibility to plan and schedule the charging of batteries according to the grid needs, which basically converts the BSS in a sort of aggregator. It has been discussed how the natural flexibility of BSS, owed to the fact that batteries are property of the firm, helps preventing peak-loads of electricity by shifting the charging process to less busy hours. A trade-off should be also found, such that the BSS would avoid excessive loads while keeping a certain amount of charged batteries to ensure service at any time. The participation in the smart grid was though to be even more enanched if BSS make would make use of renewable energy sources. The easiest and natural way adopted within this thesis was the installation of solar PV arrays on the roof of the swapping station.

In contrast, several drawbacks were discussed along the chapter, particularly once concerning the environment, like carbon emissions and oil dependence. Thanks to the cost reduction of electric cars linked to the battery ownership, BSS are found to be promoters of the adoption of EVs, driving more and more people to buy electric cars instead of conventional ICE cars. On one hand, it has been said that this leads to an overall reduction of oil dependence, which is also critical for geopolitical reasons. On the other hand, this shift was assumed to lead to an increase in electricity consumption, which in turn rises carbon emissions if electricity is produced by fossil-based power plants. In addition to that, a criticism was found to be in the elimination of range anxiety, which inherently lead users to drive more, therefore consuming more electricity.

From all those considerations the clear conclusion is that an increase in terms of adoption of EVs does not necessarily mean a decrease in terms of emissions.

The starting problem was therefore the misalignment of these dual objectives. An inspiration for providing a consistent solution to this problem was found in the review of an ex- BSS company named *Better Place*, which tried to deploy a fully operative network of swapping stations for EVs around several countries and islands between the years 2009 and 2013. The company proposed a software solution for an efficient management of the smart grid. The BSS were designed to be managed by a dedicated software that could schedule the recharging of thousands of EV batteries away from peak demand hours, preventing overload of the grid. Moreover, *Better Place* intended to retrieve the electricity needed to power the BSS from solar arrays or wind farms.

Starting from this idea, the main effort of this thesis was focused around the development of a smart-charging algorithm, able to schedule the charge of batteries to the most convenient hours, smoothing out the overall power consumption during the day.

A simulation campaign was then run with the goal of delivering two strategies that a BSS firm could potentially adopt when deploying its network of stations. The core of these strategies is indeed the smart-charge algorithm just mentioned. The first identified strategy is based on a maximum current absorption threshold and can be considered a grid-oriented strategy, since it flattens the electricity demand by avoiding peaks of current as much as possible. The second strategy is based on electricity price oscillations, which makes it a self-oriented or economic-oriented strategy that favours the income and outcome of the BSS firm.

The results were presented and discussed in chapter 3, and the two solutions compared. Thanks to this comparison, a potential company that would own a BSS network could adopt one of the strategies, or even a mix of the two, as decision-making policy depending on the company business model.

Moreover, the system performances derived from the simulator revealed that the blind application of the smart-charging algorithm without taking into account a minimum level of QoS would lead to lack of service from the BSS, which creates an economic damage to the company itself.

A trade-off solution was then found using the smart algorithm with an additional QoS constraint to reduce the risks for the BSS to run out of available batteries.

The overall work of development and simulation is meant to be a contribution from the technology area to the sustainability challenge faced by modern societies. The simulation outcomes obtained within this thesis provide some indicative results that could serve as guidance or starting point for deeper works of research in this field.

The range of such results brings up to light the potentialities of development and improvement of the BSS model presented along the course of the thesis. One future development could be the improvement of the smart-charge algorithm to enable a slow charge of batteries during night hours, when the demand of current is typically low.

To conclude, it has been proved after all these considerations regarding its flexibility that the BSS model holds a great potential as active participant of the smart grid and of the sustainability challenge in transports.

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