Faculdade de Engenharia da Universidade do Porto

Optimal Operation of a Rooftop Photovoltaic Electric Vehicle Parking Lot

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Resumo

Devida à rápida expansão a nível global dos veículos elétricos (VEs), surge a necessidade de desenvolver parques de estacionamento para VEs, de forma a dar resposta às necessidades de carregamento dos mesmos. Contudo, o aumento do número de VEs nos sistemas de distribuição requer uma atenção redobrada, caso contrário, a fiabilidade do sistema de energia poderá ser comprometida. Assim, parques de estacionamento de VEs poderão representar uma solução para evitar problemas de estabilidade. A instalação de painéis fotovoltaicos em parques de estacionamento tem vindo a ganhar interesse como uma abordagem apropriada para o seu *design* e operação, sendo uma solução conveniente para o carregamento de VEs. Dado que os VEs se encontram estacionados durante consideráveis períodos de tempo durante o dia, especialmente em grandes centros urbanos, podem ser carregados diretamente através de energia solar fotovoltaica.

Deste modo, o objetivo da presente dissertação foca-se na operação de dois parques de estacionamento de VEs com cobertura fotovoltaica através de um modelo de otimização, considerando vários parâmetros tais como as condições meteorológicas e o comportamento dos utilizadores de VEs. Esta análise resultará em maximizar não só o lucro, do parque de estacionamento do ponto de vista do proprietário/operador, resultante da sua interação em diferentes mercados mas também como os serviços fornecidos à rede. Além disso, o impacto do pagamento por capacidade será analisado.

Os resultados obtidos revelam que a presença de uma cobertura fotovoltaica conduz a casos mais lucrativos e que um dia típico de verão apresenta um lucro maior do que um dia de inverno. Adicionalmente, os resultados demonstram que a participação em serviços secundários como o mercado de reserva é sobretudo influenciado pelo preço, sendo economicamente viável apenas quando se assume um aumento do pagamento por capacidade.

Palavras Chave

Cobertura fotovoltaica, Mercado de regulação, Mercado de reserva, Operação ótima, Pagamento por capacidade, Serviços secundários, Veículos elétricos

Abstract

Due to the rapidly increasing share of electric vehicles (EVs) worldwide, there will be a need to offer many EV parking lots, to provide for their charging needs in addition to attempting to fully utilize them for the benefit of future smart grids. Uncontrolled charging of EVs can jeopardize stability and reliability of power systems. Hence, well-operated EV parking lots can be a good solution to increase system stability. Equipping the parking lots with rooftop photovoltaics (PVs) has been gaining interest as a good approach for their design and operation. On this basis, during the day, when EVs are stationed in the parking lot, particularly in the commercial and heavily populated parts of cities, they can be charged directly by the solar generation, so that minimal stress on the distribution system will occur.

This work aims to conduct a comparative study investigating the optimal strategies for the operation of two PV-equipped EV parking lots. Multiple parameters are taken into consideration, including weather conditions (a typical winter and summer days), uncertainty of EV owners' schedules such as arrival and departure times. This analysis will result in finding the optimal strategy for the operation of the parking lot from the owner/operator point of view in order to maximize both profits and services provided to the grid. The profit was calculated considering the interaction of parking lot in different power markets. Additionally, the effect of a capacity payment is discussed.

The results shows that the presence of a photovoltaic rooftop leads to higher profits and, a typical summer day is more profitable than a winter day. Moreover the results demonstrate that the participation in the ancillary services such as the reserve market was mainly influenced by the price, being only economically viable when an increase of the capacity payment occurs.

Keywords

Ancillary services, Capacity payment, Electric vehicles, Optimal operation, Rooftop PV, Regulation market, Reserve Market

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Helena Espassandim

“*Great is the art of beginning, but greater is the art of ending.*”

Henry Wadsworth Longfellow

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Abbreviations

EU	European Union
EV	Electric Vehicle
EVSPL	Electric Vehicle Solar Parking Lot
FEV	Full Electric Vehicle
G2V	Grid to Vehicle
GHG	Green House Gases
GSO	Grid System Operator
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
MPPT	Maximum Power Point Tracking
PL	Parking Lot
PV	Photovoltaic
RES	Renewable Energy Sources
RSP	Renewable Portfolio Standard
SOC	State of Charge
V2G	Vehicle to Grid
VAT	Value Added Tax

Nomenclature

ΔS	Upper limits of discretization of the apparent power
Act	Activated reserve by ISO
call	Being called by ISO in reserve market
Cap	Capacity of EV battery
Cap, Res	Capacity payment for participation in the reserve market
Cd	Cost of equipment degradation
down	SOC departure lower than arrival
En	Energy
EV	Electric Vehicle
F	Maximum number of blocks to linearize
f	Partition segment of the blocks
FF	Fill factor
FOR	Forced outage rate
G	Global solar irradiance
G2PL	Injection of the grid to the parking lot
G2V	Grid to vehicle
I	Current Flow
i,j	Buses
I2	Square of the current flow
K_i	Short-circuit current temperature coefficient
K_v	Open circuit voltage temperature coefficient
N	Number of buses

η	Charge/discharge efficiency of battery
n	Number of parked EVs
NCOT	Nominal operating cell temperature,
NOM	Nominated amount
P	Active power
PL2G	Injection of the parking lot back to the grid
PV2PL	Injection of the photovoltaic rooftop to the parking lot
R	Resistance
Res	Reserve
RN	Renewable generation
S	Sub-transmission
STC	Standard Test Conditions
t	Time
T^{amb}	Ambient temperature
T^{c}	Cell temperature
unavail	Being unavailable to inject to the grid
up	SOC departure higher than arrival
V	Voltage
V2	Square of voltage
V2G	Vehicle to grid
w	Index of scenarios
X	Reactance
Z	Impedance
B	Tilt angle
γ	Rate of charge/discharge of parking lot
η^{PV}	PV module efficiency
λ	Price of electricity
π	Scenario Probability
Γ	Penalty ratio for not delivering the offered energy

Chapter 1

Introduction

This chapter describes the framework of the global system energy sector and the new challenges related to renewable energy sources, in particular, photovoltaic energy, and electric vehicles, and their integration in the electricity framework. This chapter also includes the motivations that conduct the proposed thesis and provides an overview of the structure of the thesis and the notation used.

1.1. Framework

The global system energy is facing a period of paradigm change principally caused by concerns about energy supply, global heating and economic competitiveness. With the recognition of climate change as the most serious and threatening global environmental problem, the European Union (EU) has settled ambitious targets to cut greenhouse gases emissions (GHG), stimulating society's decarbonization. To achieve a sustainable future, it is crucial to look beyond the short term, by targets settlement as the Europe 2020 approach. A reduction of 20% in GHG emissions compared to 1990 level has been established to member states. Planning forward ahead 2020, the EU has committed to cutting its emission to 40% under1990 levels at the end of 2030. More recently, the EU has presented a long-run project by publishing a road map to build the low-carbon European economy by 2050. Therefore, EU governors have settled the reduction of Europe's GHG emissions by 80% compared to 1990 levels as the main objective [1] [2].

Figure 1.1 demonstrates the GHG emissions in the European Union divided by the principal source sectors, in 1990 and 2016. Energy sector was the most pollutant sector in EU-28 in 2016, counting with 54% of GHG emissions. In 1990 this sector was even more harmful, with a share of 63%. Energy sector is followed by the transport sector as the most relevant source of GHG emission with 24% in 2016, which has been increasing its contribution considerably since 1990. [1].

a. **b.**

Figure 1.1 - Greenhouse gas emissions by source sector in EU-28 (a) In 1990 (b) In 2016 [1]

As a result, renewable energy sources (RES), energy efficiency and new transport technologies will require widespread exploitation to reach GHG emissions targets. Thus, the acceleration of the improvement of green energy solutions is crucial.

Solar energy is the most plentiful resource on planet Earth. The large amount of solar energy that reaches the earth – in one hour is approximately equal to the amount consumed by all human activities in a year - allied to the fast evolution of photovoltaics (PV) due to supporting policies and competitive prices is increasing the role of this technology as part of that main solution. Hence, solar PV is projected to provide 5% of worldwide energy use in 2030, rising to 11% in 2050 [3].

Additionally, given the EU environmental goals, these aims to add profound alterations in the transport sector, resulting in a competitive transport sector able to reduce CO2 emissions at the end of 2050 [2]. As a result, a door has been opened for the integration of environmentally friendly electric vehicles (EVs) in the transportation system instead of fossil fuel bases conventional cars. EVs not only offer the possibility of free GHG emissions increasing air quality, but also a low noise level. Thus, it is clear that an eco-friendly and viable transport sector can be obtained by taking advantages of vast range of EVs benefits.

Besides from all advantages, in both PV and EV cases, the grid's penetration is not easy: their emerging integration can cause stabilization and flexibility problems, threatening the grid reliability. Variability and uncertainty are the main disadvantages of PV generation [4]. As for the EVs, they could degrade power quality and destabilize the electric system by causing a boost in electricity demand and overload the grid [5]. These issues can be prevented by meeting EV charging requirements directly through PV generation. Since charging an EV involves a large expenditure of time, car parking factor becomes a critical point to consider in this process.

A non-traditional vehicle, i.e., EV, can be charged via two modes: home or workplace charging. The first one occurs generally during evening and night-time, while the second one normally takes place during day-time and it is not require the installation of a charging facility [6]. However, daytime charging represents a supplementary load than can jeopardize grid's stability.

Therefore, the integration of renewable energy with the charging infrastructure allied to the fact that vehicles are parked over 90% of the usage time can be a solution to mitigate grid's problems [7] [8] .

In this context, charging EVs via green energy sources such as solar PV is a highly potential solution that provides several practical and economic opportunities and does not represents a source of concerns to the grid [9] . On the one hand, it does not involve a high incidence of environmental damages since it does not imply GHG emissions.

Additionally, it is a method to strengthen and publicize EVs and consequently accelerate their acceptance due to the charging infrastructure's presence. On the other hand, EVs charging directly from PV power facilities might be the key to grid's main concerns due not only to the fact that the grid would not have to integrate a large PV capacity but also it would not be necessary a large reinforcement to fulfill the increasing EV demand.

A possible solution consists on equipping parking lots with solar arrays to charge EVs during the day, emerging an original term, named electric vehicles solar parking lots (EVSPL). When carefully designed and managed, it is possible to couple the clean solar electricity and the expansion of electric mobility, overcoming possible ecological and technical problems.

1.2. Motivation

The need for alternatives that are greener and that simplify the integration of renewable energy sources in the electricity grid becomes clearly. On the one hand, the replacement of vehicles with an internal combustion engine by EVs can help the reduction of pollutant emissions; on the other hand, dispersed power allows greater flexibility for the electric power system.

Since EVs represent a high level of load difficult to predict, the massive penetration of EVs can be a threat to the electric power system in terms of stabilization and reliability. Thus, combining these loads with decentralized renewable energy represent a great advantage for the power grid. This can be achieved through solar parking lots. In order to understand the coupling of solar electricity with EVs, this thesis will set its scope on modelling the operation of a rooftop PV electric vehicle parking lot

1.3. Objectives

This work aims to find an optimal model for the charging of EV inside a rooftop PV parking lot. This model will be used from the parking lot operator's viewpoint, so that it can be helpful for future smart grids. The parking lot operator should consider different variables such as arriving and departing time of EVs, the state of charge of the EVs, the type of car. Moreover, in the proposed model the EV parking lot can participate in the electricity, reserve and regulation market.

On this basis, the behavior of the EV parking lot in a distribution system is modelled consisting on a 100 kW (with a PV panel area of approximately 558m^2) photovoltaic rooftop. The thesis webpage can be found in https://helenamdea.wixsite.com/feup-mieec.

1.4. Dissertation Structure

The contents of the dissertation are divided in five chapters, briefly described henceforth. Chapter 2 provides the necessary background on the positive and negative effects on the electrical systems of large-scale integration of photovoltaic and electric vehicles, independently and combined. It also includes a literature review of relevant works on the subject area of the present dissertation Chapter 3 consists on complete explanation of the methodology applied to conduct the work, more special the mathematical formulation of the photovoltaic rooftop system, the parking lot, the distribution system and the optimization model. Chapter 4 contains the results and its discussion. Finally, Chapter 5 summarizes the main conclusions and provides suggestions for future work.

1.5. Notation

The notation frequently used in the scientific literature is applied in the present dissertation. The mathematical formulation will be identified with reference to the subsection in which they appear. Whenever a new section is created, mathematical formulation is renumbered. Moreover, they are identified by parentheses. Concerning figures and tables, they will be identified with reference to the subsection in which they are include as the mathematical formulation, and restarted in each chapter. References are identified by square brackets.

Chapter 2

Background and State-of-the-Art

This chapter starts by describing the photovoltaic solar energy and the electric vehicles, including a description of both markets. It also provides an overall review of published studies related to RES (more specifically, wind and PV) and EV penetration on the electrical system (separately and combined), electric vehicles solar parking lots, and optimization models considering different objective functions.

2.1. Photovoltaic Solar Energy

With the fast demographic expansion and industrial and technologic evolution, world's energy demand has been considerably increasing in such a way that it is no longer possible to completely satisfy the entire population's requirements. Nevertheless, as population growths, the existing resources worldwide are getting exhausted. Moreover, due to several problems such as change in global climate, global warming and air pollution, fossil fuels from now on are not a viable alternative.

Therefore, there is a high urgency to massively develop friendly environmental energy sources for achieving a sustainable future. As green sources it is considered solar energy, wind energy, hydropower, etc. Although the great diversity of earth's endogenous resources, solar energy could be the best opportunity regards environmental sustainability due to numerous reasons. First of all, solar energy is the richest energy sources of eco-friendly energy.

The sun radiates it at the rate of 3.8×1023 kW, out of which nearly 1.8×1014 kW is received by the upper level of Earth's atmosphere due to absorption, scatter and reflection phenomenon's suffered by solar radiation [10], [11]. Second, it is an unlimited free energy for the planet Earth, giving it a promising feature and prospecting better efficiencies when compared with the remaining sources of energy.

However, the solar resource is fundamentally irregular as a result of the geographical position, season and diurnal variation, and weather conditions [10]. Therefore, solar radiation distribution and its intensity are two main aspects that meaningfully influences efficiency of solar photovoltaics (PV). Figure 2.1 shows that annual average intensity of solar radiation is not uniform worldwide [12], where the “black dots” are able to supply the total world’s primary energy demand[1][13].

Regardless of its intermittent nature, solar energy is still considered a high equitably dispersed energy resource. Third, the exploitation of solar energy does not negatively impact the environment, contrasting to what occurs in hydroelectric plant’s operation, which, for instance, through its construction it affects the natural watercourse. Finally, systems based on solar energy generation are accessible and applicable which makes them be actually used for industrialized and urban/commercial areas [14]. As shown in Figure 2.2, traditional fuel energy is getting develop radically [15].

Thus, it is urgently required a widescale provision of renewable energy to fulfill increasing demand’s requirements. Amongst worldwide industries, Solar PV stands out as a main growing industry [16]. A comparison of the global power capacities between different green energy sources is enumerated in Table 2.1.As it can be observed, Solar PV capacities have grown at impressive rates, from 227 GW in 2015 to 402 GW in 2017.

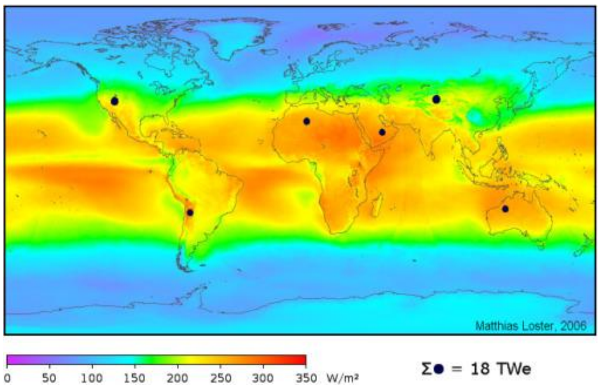

Figure 2.1 - Annual average solar irradiance distribution over the surface of the Earth [13].

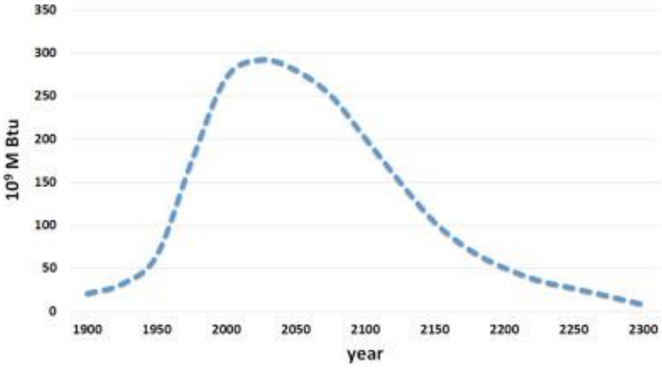

Figure 2.2 – World fossil fuel energy [15].

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[1] Assuming that a conversion efficiency as low as 8% is achieved

Table 2.1 - Comparison of the global power capacity between different renewable energy sources [16]

Power Capacity (GW)	Year		
	2015	**2016**	**2017**
Total Renewable Power	1848.0	2016.3	2204.7
Hydropower	1064.0	1096.0	1124.0
Bio-power	106.0	112.0	122.0
Geothermal	13.2	13.5	12.8
Solar PV	227.0	303.0	402.0
Concentrating solar power (CSP)	4.8	4.8	4.9
Wind Power Capacity	433.0	487.0	539.0

Photovoltaic effect is described as the generation of electricity due to solar light, have been first discovered in 1839 by Edmond Becquerel [17]. This conversion is caused in semiconductors material, which present a pair of energy bands. In one band, valence band, it is permitted the presence of electrons, while in the other, called as conduction band, electrons are not allowed, i.e., the band is fully “empty”. These energy bands are shown in Figure 2.3.

The most frequent material used as semiconductor is the silicon. Additionally, it is the second richest element on planet Earth. On the photovoltaic effect, the sunlight is in charge of delivering a certain amount of energy to the farthest electron in order for him to dislocate from the valence band to the “empty” band in the material. Through this process, electricity is produced. More specifically, regarding silicon, it is necessary 1.12 eV (electro volts) for electrons to surpass the band gap [12].

A solar cell or a photovoltaic cell is a device that incorporates a PN junction in a semiconductor material which consists in combining a p-type (high density of holes or deficiency of electron) and n-type (high content of electrons) semiconductor material. Throughout this joining, a photo voltage is created due to the movement of electrons from the n-type layer and holes to the p-type side of the junction. Figure 2.4 illustrates a representative solar cell. The cell is mainly composed by the PN junction where the N-type material receives a portion of the light, and the p-type material is located underneath it.

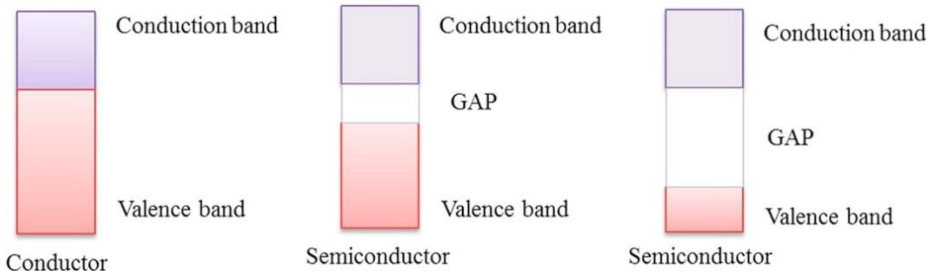

Figure 2.3 - Band of valence, band gap (GAP) and the conduction band [12].

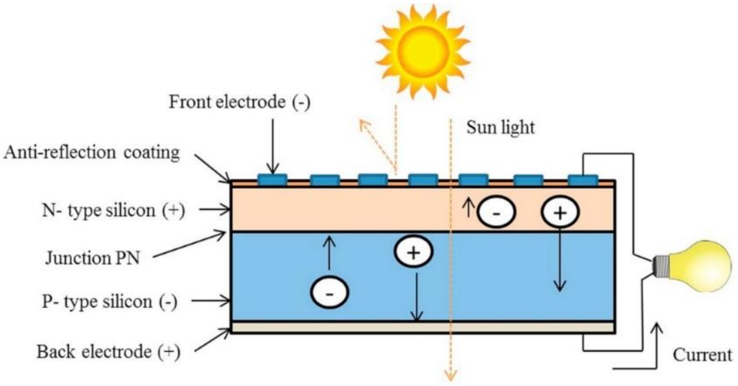

Figure 2.4 – Photovoltaic cell [12].

2.1.1. Elements of the photovoltaic solar energy system

Four simple components constitute a classic photovoltaic solar system as shown in Figure 2.5: photovoltaic module, charge controller, the inverter and battery (when necessary). The solar module is composed by photovoltaic cells, in which when exposed to sun light it occurs the electricity generation.

The second element, the charge controller, is responsible for batteries charging, i.e., it avoids that batteries are charged more than necessary and fully discharged. As for the inverter, it converts the solar power (electricity generating DC - DC) to alternating current (AC), i.e., AC voltage levels and network frequency. When necessary, batteries are used as storage devices to store the oversupply from solar modules, so that it is possible use it at night or on days where the sunlight is insufficient.

2.1.2. Photovoltaic technologies

Photovoltaic cell technologies are typed, according to two main factors: the raw material used and the maturity commercial level, being divided into three different groups:

- **First generation** (silicon wafers) use the technology of crystalline silicon (c-Si), more specifically mono crystalline (mc-Si), polycrystalline or multi-crystalline form (pc-Si), and ribbon and sheet defined film growth (ribbon/sheet c-Si). It is the most used and advanced technology representing nearly 95% of the market at the present time. Regarding efficiency, monocrystalline cells lead with rates between 16% to 22%, while for multicrystalinne cells the rates are between 14% and 18% [12], [18]-[20].
- **Second generation** use the technology of thin films and typically divides photovoltaic system into three categories: amorphous silicon (a-Si) and micro amorphous silicon (a-Si/μc-Si); cadmium telluride (CdTe); and copper indium selenide (CIS) and copper, indium gallium dieseline (CIGS). Currently thin films technology is considered as the principal candidate to replace crystalline silicon; however, it presents lower efficiency, lower stability and less durability. Amongst thin film technology, the most cheap to manufacture is currently CdTe is currently [12], [18]-[20].

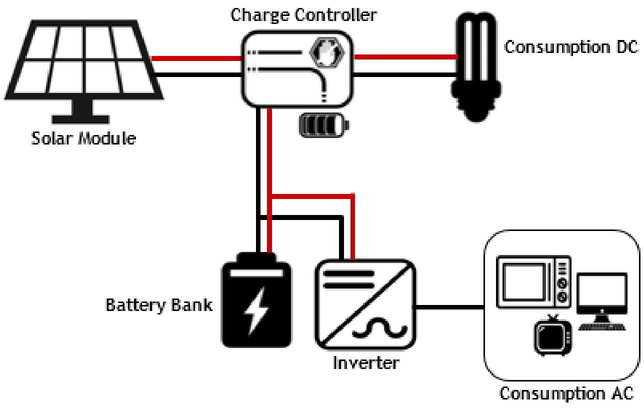

Figure 2.5- Typical System of photovoltaic solar energy [12].

- **Third generation photovoltaic** consists on novel thin-film devices, for instance organic photovoltaic technologies, that are still in a demonstration phase or are not large-scale commercialized, along with new concepts in development[12], [18]–[20].

Figure 2.6 illustrates the PV module efficiency corresponding to each generation. As can be observed, first generation technologies have a larger efficiency than second generation technologies. However, they present a considerable higher cost per m^2 which implies that they are typically more expensive than second generation per watt-peak (Wp) of module power as well [12].

2.1.3. Photovoltaic market

In the last decade, the global PV market has grown quickly. For example, as illustrated in Figure 2.7, global installed capacity PV increased from 8 GW in 2007 to approximately 402 GW in 2017 [21]. As illustrated in Figure 2.8, five countries lead the market for PV, with a market share above 10%. However, there are several countries that are experiencing a significant market growth, more specifically, India that had installed nearly 17 GW of solar PV by 2017, up from almost zero in 2007. China is also an example of how PV market is growing fast.

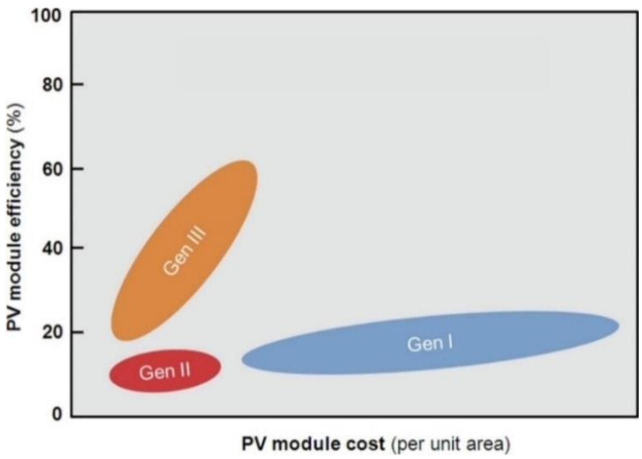

Figure 2.6 - PV technology generations [18].

By the end of 2017, China had installed a capacity of approximately 131 GW which has exceeded considerably government's minimum target for 2020 (105 GW), defined in 2016. The large market increase relative to 2016 was due mostly to China despite the decrease in new capacity in Europe [21] [16].

Additionally, the recurrent alerts to environmental problems related to CO2 emissions allied with the rising demand for electricity in developing countries were also key factors to PV market expansion. In terms of investment in renewable energy sources, it is also evident that new solar PV projects have been gaining interest.

According to [22], a larger amount of money was invested in solar power in 2017 than in coal, gas and nuclear power. Figure 2.9 illustrates how solar (and wind) stand out from the remaining type of RES in terms of investment. At 2017, investment in new solar facilities reached 160.8 billion, an increase of 18% when compared to previous year.

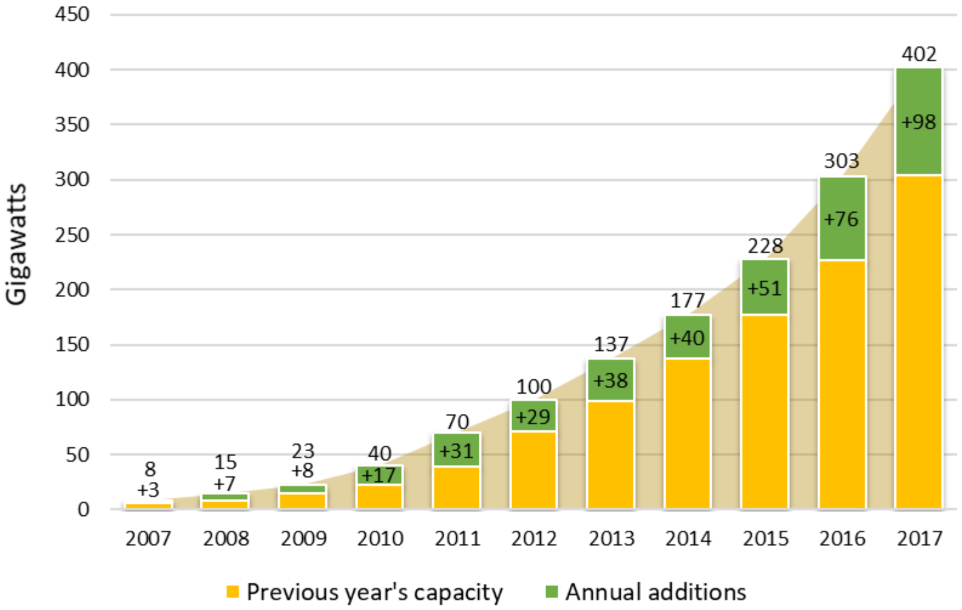

Figure 2.7 - Solar PV Global Capacity and Annual Additions from 2007 to 2017 [16].

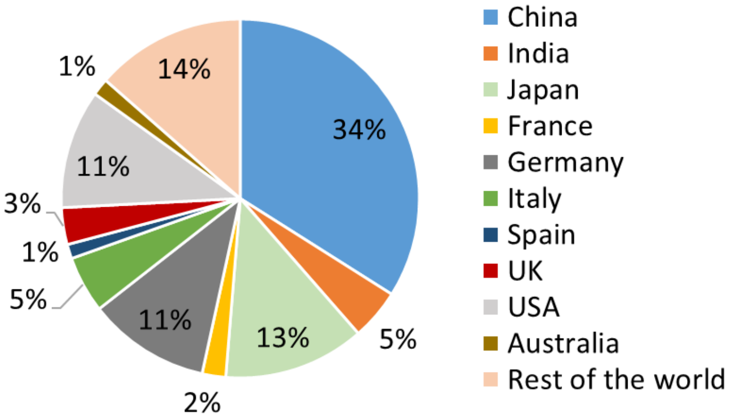

Figure 2.8 - Country share in the solar PV global capacity in 2017 [16].

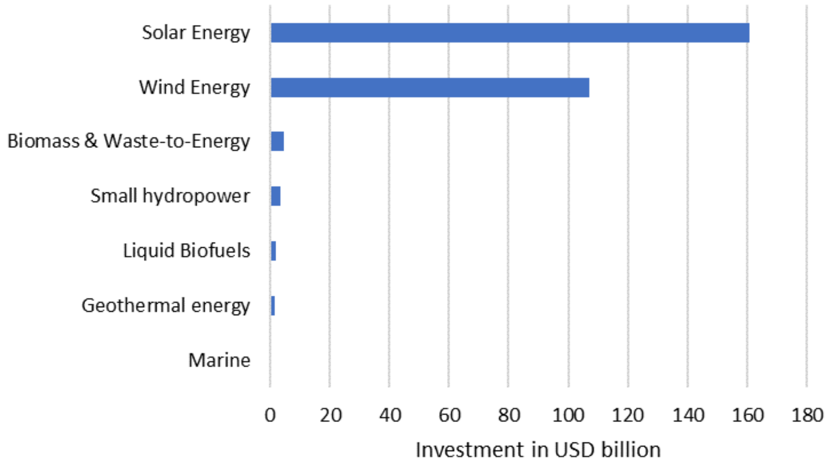

Figure 2.9 – Evolution of global investments in renewable energy by sector [23].

The PV systems market will continue to be developed in the future as strongly as far, due to the worldwide implementation of support policies as feed-in tariffs, tax incentives or tradable green certificates [24]. The purpose of these incentive strategies is the reduction of the difference between PVs cost of electricity and the conventional electricity source's price.

Figure 2.10 demonstrates that the volume of the PV market is still dependent of support strategies and Table 2.2 summarizes the application of support strategies in different countries. These support schemes can be useful in many systems according to the local requirements and it is expected that they go along with the unpredictably of PV market evolution. Five types of support mechanism are listed below:

- **Competitive Power Purchase Agreement (PPA),** a long-term contract (typically for 5 to 15 years) between two stakeholders with the objective to purchase a specific quantity of power for a certain price and a certain amount of time in order to reduce inconsistency of costs and profits. Typically, the sellers of renewable energy PPAs are project creators or autonomous power producers that own the technology. The buyers are usually utilities that have to fulfil the regulatory requirements associated to Renewable Portfolio Standard (RPS) [25]-[27]; This agreement will define the commercial terms for the sale of electricity between the two parts, including when the project will begin commercial operation;
- **Feed-in tariffs (FIT)**, a type of PPA regime to encourage and speed the interest in investing in green energy technologies. It is a policy that offers a purchase contract for an extended period for the renewable energy's sale. This is usually preferred for projects with a size under 5 MW. The renewable investor will be remunerated from the electricity's sale via the PPA, besides the income for each unit of energy that is generate, regardless of whether it is consumed locally [24];

- **Tax incentives**, associated to tax exemption, tax credits or carbon tax. Tax exemption is used as an incentive measure to enhance the deployment of RES in different countries; tax credit is used to facilitate the penetration of RES into the market and it could be functional, for example, on the purchase and installation on renewable equipment. Finally, carbon tax provides an incentive to increase investment in RES by imposing a higher cost for burning fossil fuels [24];
- **Tradable green certificates,** defined by the RSP, requires companies to intensify the amount of power generated by RES. With the implementation of this strategy, a specific share of a company's electricity must be produced by RES. By applying this policy, for each unit of power produced, they receive a tradable certificate [24];
- **Self-consumption and net-metering,** support schemes that gives the opportunity to the PV system owner to reduce his electricity bill through electricity self-production [25].

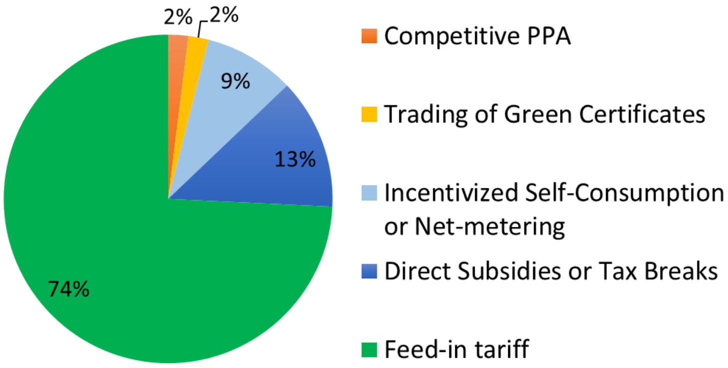

Figure 2.10 - Support strategies for PV market in 2017 [25].

Table 2.2 - Overview of support strategies in selected countries [25]

Country	Tax Incentives	Feed-in Tariff	Self-consumption	Net-metering	Green Certificates
Australia		✓	✓	✓	✓
Belgium			✓	✓	✓
China		✓	✓	✓	
Italy	✓		✓	✓	✓
Portugal		✓	✓		
France		✓	✓	✓	✓
USA	✓	✓	✓	✓	✓

Figure 2.11 shows the PV production development by technology from 1980 to 2016. Regarding PV production in 2017, multi-Si represented 60.8 GWp, mono-si contributed with 32.2 GWp, and thin film accounted with 4.5 GWp. As illustrated in the Figure 2.12 crystalline silicon technology leads the world market.

In 2017, amongst thin-film technologies, CdTe accounted with an annual output of 2.3 GWp, followed by Copper Indium (Gallium) Diselenide (CI(G)S) with 1.9 GWp and amorphous silicon (a-Si) with 0.3 GWp. In terms of the production per year, thin film technologies achieved a market portion of 5% in the year of 2017 (Figure 2.13) [28].

2.1.1. Efficiency

The solar cell efficiency is influenced by three main factors: the temperature, solar irradiance and dust as it can be observed in Figure 2.14. As for the temperature, it can affect cell's performance significantly. As the temperature increases, the efficiency of solar cells usually slightly decreases.

Regarding the problem of dust, it is recommended a frequent cleaning of the PV surface since the accumulation of dust can block the irradiance on the photovoltaic modules.In the laboratory, the cell efficiency record is of 26.7% to monocrystalline silicon and 22.3% to silicon multicrystalinne based technology. In terms of thin film technology, the highest lab efficiency is 21% for CIGS and CdTe solar cells (Figure 2.15).

The best performing laboratory modules are based on monocrystalline silicon with an efficiency of 24.4% (Figure 2.16) [28]. Figure 2.16 illustrates that the lab solar cells multi-junction high concentration reached 46% efficiency currently.

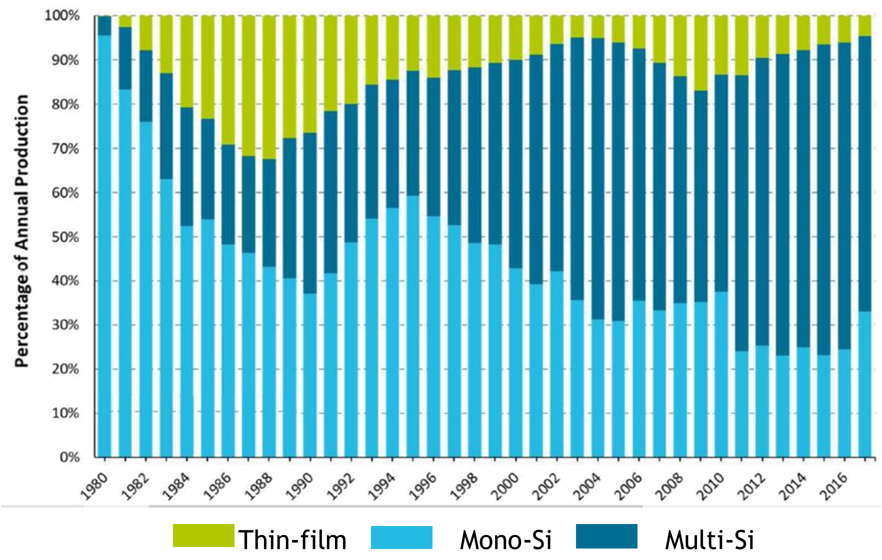

Figure 2.11 - Percentage of annual production of the main photovoltaic technologies [28].

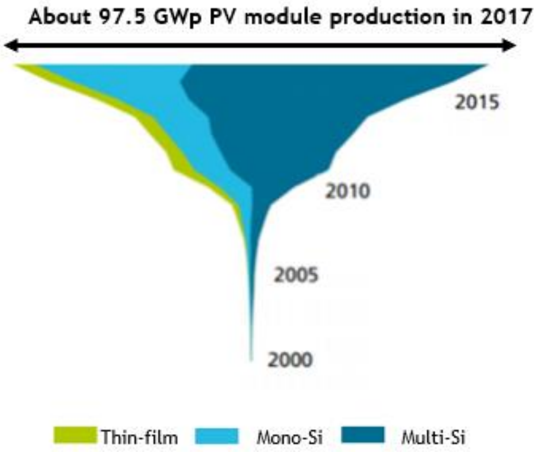

Figure 2.12 - Annual PV Production by Technology Worldwide (in GWp) [28].

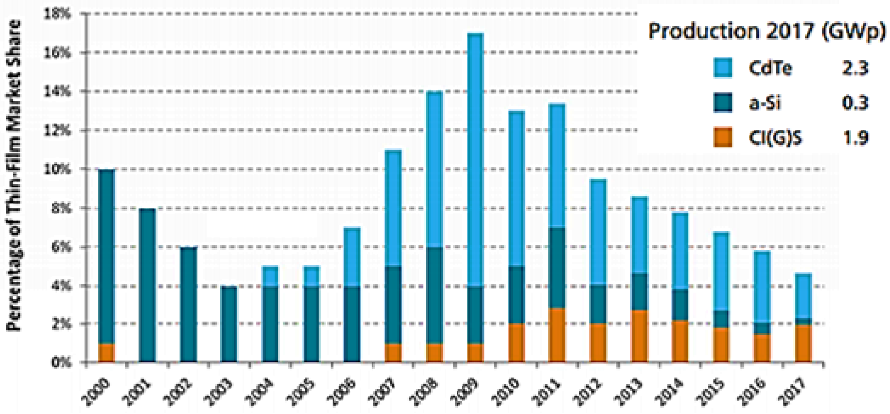

Figure 2.13 - Total annual output of the main thin film technologies [28].

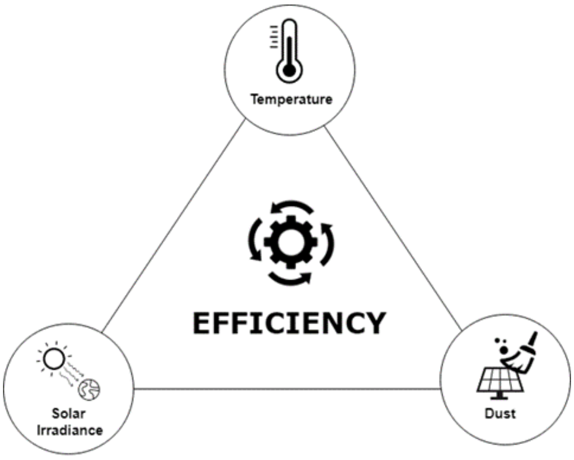

Figure 2.14 - Factors that influence efficiency of solar cells.

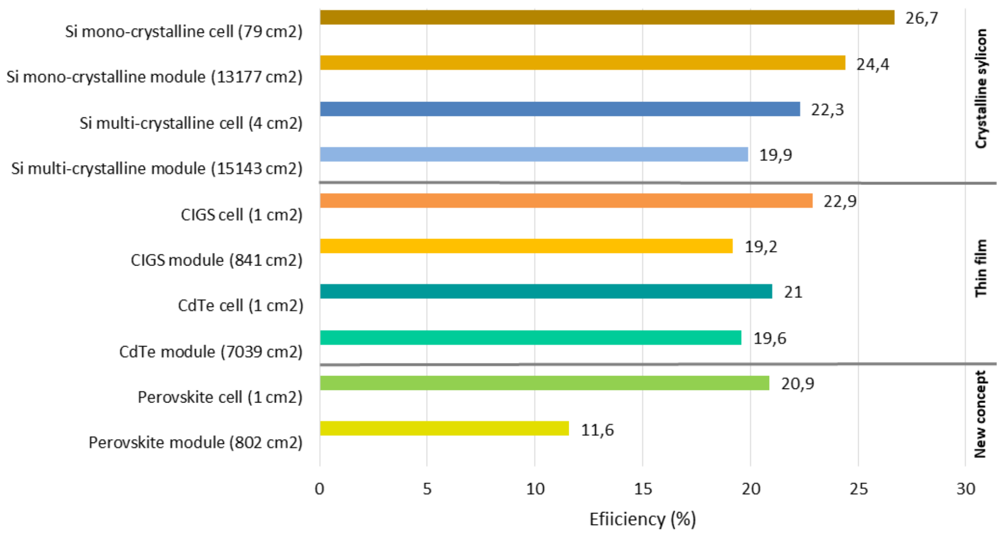

Figure 2.15 – Comparison of best laboratory cells and laboratory modules [28].

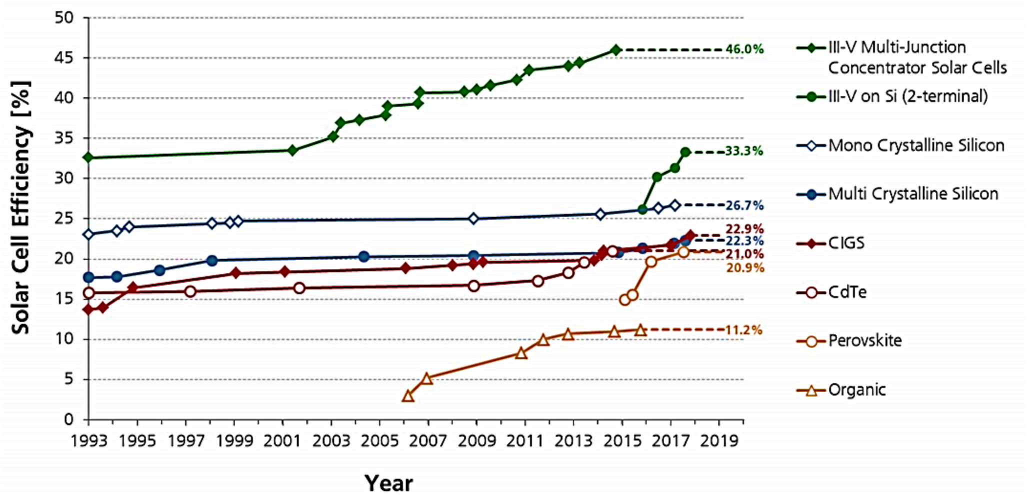

Figure 2.16 – Efficiency of solar cells [28].

2.2. Electric Vehicles

Transport sector is one of the major sources of CO_2 emissions in the EU, counting with nearly 25% of GHG emissions [1]. Therefore, its electrification is essential for accomplish the EU targets of decarbonization and energy security This process is the main strategy of national policies for a profound mobility modification, through the substitution of ICEs (internal combustion engine) with EVs. By reducing exposure to air polluting (resulting from burning fossil fuel) and limiting noise, EVs offer a cleaner alternative to vehicles with ICEs mainly in urban areas [29].

The worldwide automotive market is changing quickly and growing exponentially, contributing directly to a profound alteration of mobility culture. In 2018, the worldwide electric car fleet surpass 5.1 million, up 2 million since 2017 and practically doubling the number of new electric car registrations [30].

China remained the world's largest electric car market with nearly 1.1 million electric cars sold in 2018, with 2.3 million units, representing approximately 50% of worldwide electric car fleet. Europe assumed the second main market, with 1.2 million electric cars, followed by the United States with 1.1 million electric cars circulating by the end of 2018, representing a market growth of 385 thousands and 361 thousands electric cars from the previous year, respectively [30]. Regarding electric car market share, Norway continues the world market leader with a share of 46% of new electric car sales in 2018.

In 2018, Portugal followed along with the international path, reaching an annual record in 2018 of 8241 electric cars; approximately the same number of electric vehicles sold in the previous seven years, as it can be observed in Figure 2.18. This result represents a 95% market growth when compared with 2017. In terms of brand/model of electric cars sold in Portugal, Nissan Leaf represents the most sold car, followed by Renault Zoe. The top five electric cars are presented in Figure 2.19.

A long-term market penetration has been targeted ambitiously by national governments. For Portugal, it has been established that one-third of electric cars will be electric in 2030 [31].

However, EVs are currently non-competitive with the conventional vehicle technology, since costs are still high. As it can be observed in Figure 2.18, supportive mechanisms and policies are fundamental to foster EV penetration. Table 2.3 represents EV target penetration for other countries.

Despite some countries sales of EVS are increasing and surpassing sales of conventional vehicles, a higher penetration of electric driving it is not an easy process to achieve. A high initial investment, limited battery range, a prolonged recharging time, uncertain availability of charge stations are some of the main obstacles that EVs market have to face with, making these vehicles be seen as an expensive and risky purchase, as Figure 2.20 demonstrates.

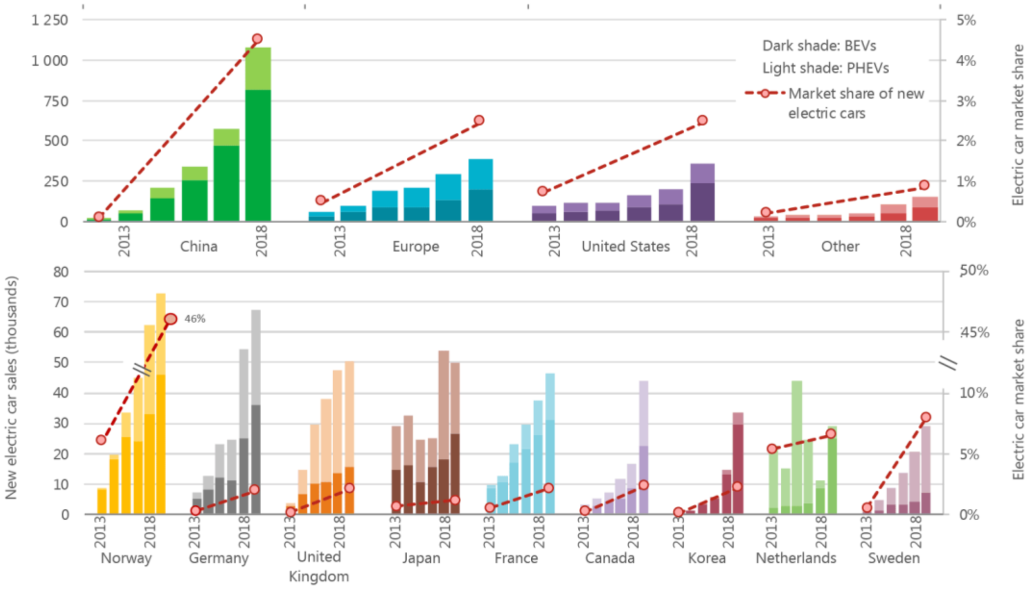

Figure 2.17 – Global electric car sales and market share from 2013 to 2018 [30].

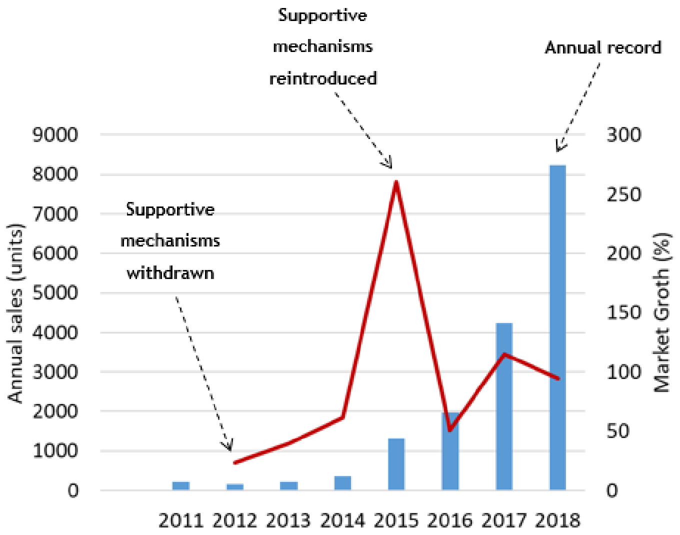

Figure 2.18 -Portuguese electric car sales (blue bar) and market share (red line) from 2011 to 2018 [32].

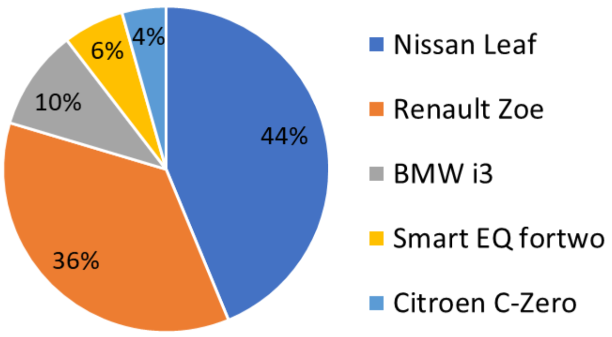

Figure 2.19 -Most sold electric car in Portugal by brand/mode in 2018l [32].

Table 2.3 - Electric vehicles penetration target according to country [33]

Country	2020-30 EV target
China	5 million EVs by 2020
Finland	250 000 EVs by 2030
India	30% electric car sales by 2030
Ireland	500 000 EVs and 100% EV sales by 2030
Japan	20-30% electric car sales by 2030
Netherlands	10% electric car market share by 2020
New Zealand	64 000 EVs by 2021
Slovenia	100% electric car sales by 2030
United Kingdom	100% electric car sales by 2030

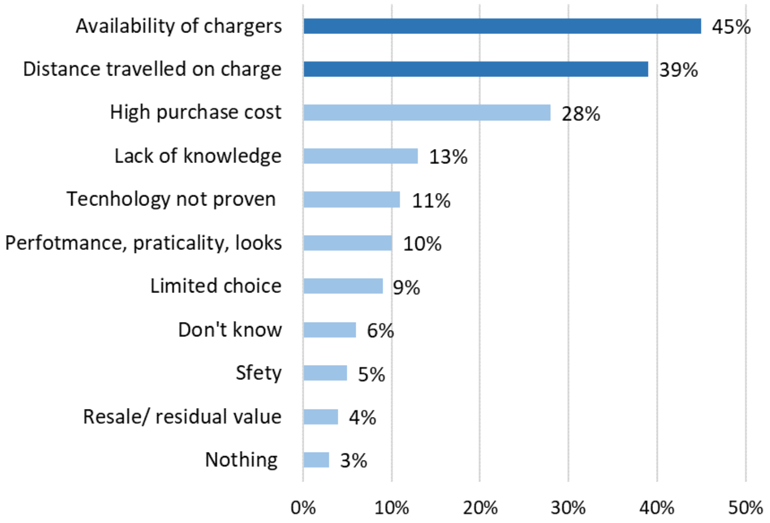

Figure 2.20 – Principal barriers for the purchase of an electric vehicle [34].

Therefore, a good solution to overcome the problems of EVs emerging market and, consequently stimulate electric mobility is the application of supportive mechanisms. Thus, several EU members have established incentive instruments to face one of the main concerns for consumers, the high purchase cost. Table 2.4 summarizes some of the policy instruments that have been implemented in European Union. There are three main policy instruments currently implemented [35] :

- **Registration or purchase tax,** it is applied to reduce the financial cost for consumers who pretend to acquire an EV. In case of applying different costs according to vehicles' CO2 emission, this type of tax is found to be as one of the most decisive factors on purchase decisions to greener vehicles. An example of this tax implementation is France that has established a bonus/malus according to CO2 emissions of the vehicles. On the one hand, vehicles above a fixed CO2 emission are obligated to pay a financial penalty. On the other hand, vehicles under a reference CO2 emissions level receive a bonus [35];
- **Circulation or motor tax**, it is paid on a monthly or annual basis which is indexed to the engine power, cylinder capacity or fuel consumption. It is consider as less effective mechanism than the previous one because consumers are more sensible to an initial purchase price than to an annual or monthly [35];
- **Fuel tax**, it makes electricity a more attractive fuel for consumers causing the limitation of energy consumption in road transport and the adjustment of driving patterns [35];

EVs are divided into two categories: hybrid (HEV) and full electric vehicles (FEV). On one hand, hybrid electric vehicles are categorized into full hybrid (FHEV) and plug-in hybrid (PHEV). On the other hand, full electric vehicles (FEV) are known as two types: battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). Figure 2.21 schematically illustrates the different classification of electric vehicles.

Table 2.4 – Policy instruments to supporting EV in EU-15 [35]

Country	Economic instruments for the support of EV
Austria	Exemption from fuel consumption tax Exemption from monthly vehicle tax Up-front purchase price bonus of 500€
Belgium	Purchasers of electric cars receive a personal income tax reduction of 30% of the purchase price (with a maximum of 9000€)
Finland	Exemption of fuel tax
Italy	A tax incentive of 800€ and a two-year exemption from annual circulation tax is granted for the purchase of an EV
Spain	Several regional governments grant tax incentives for the purchase of alternative fuel vehicles including EV, around 6000€
Portugal	Exemption from registration tax
United Kingdom	Exemption from annual road tax

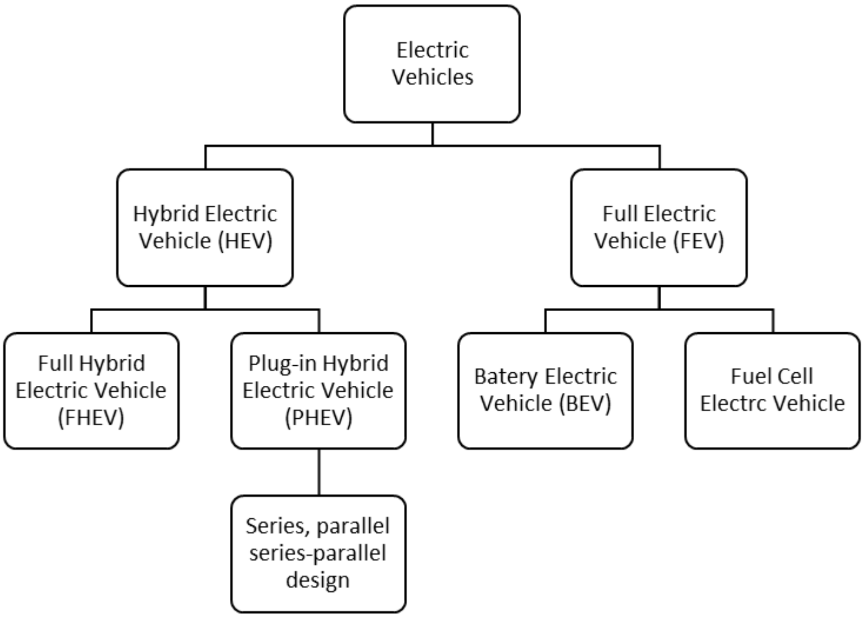

Figure 2.21 - Classification of electric vehicles.

2.2.1. Full hybrid electric-vehicles

A full hybrid electric vehicle (FHEV) is a vehicle that uses a combination of two different power sources: a conventional internal combustion engine (ICE) and a battery/electric motor. This last component is applied to either improved vehicle fuel economy or better performance than a conventional ICE vehicle [5]. The hybrid cars allow the ICE and the electric motor to cooperate in different situation to offer the possible maximum range as shown in Figure 2.23.

The connection of a standard ICE and a battery pack to an electrical motor is the classic constitution of a FHEV. In fact, a HEV has the ability to switch into two different modes due to the presence of an electric motor/generator system: generator mode that produces electrical power to charge the battery and start the vehicle's ICE when necessary and the motor mode which drives the vehicle by turning the vehicle's wheels [5].

In this type of vehicles, recharging is not a recurrent process since FHEVs maintain their batteries state of charge (SOC) practically equal while travelling. Therefore, recharging only occurs from on-board electricity generation by the ICE that is linked to the motor/generator or from the conversion of the vehicle's kinetic energy into an energy stored in the battery [5]. For these reasons, conventional FHEVs are charge-sustaining.

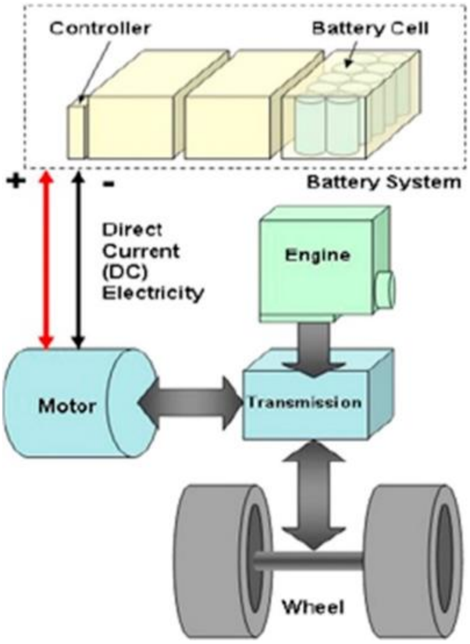

Figure 2.22 - Operational principle of a hybrid vehicle [5].

Figure 2.23 - Energy monitor of a hybrid Toyota Prius [36].

In terms of battery, FHEVs normally use a nickel cadmium (NiMH) battery, allowing not only the battery charging up to 40-60% of its maximum capacity but also to offer a backup reserve in case of charging by regenerative braking [5]. Regarding to the distance that the FHEV can travel just operating on battery, i.e., the vehicle's electric travelling range, the total hybrid traveling range per gasoline fill up is 900-1200 km [5].

As referred above, due to presence of an ICE (seen as an ancillary power source) and because of the fact that HEVs operate on charge sustaining mode, in the sizing of a HEV battery travelling range and maximum speed are not critical features to be considered contrasting to PHEVs and FEVs batteries design.

2.2.2. Plug-in hybrid electric-vehicles

Another type of EVs currently available on the automotive market is the plug-in hybrid electric vehicles (PHEV), a high potential technology. Their principle of operation is similar to FHEVs in that they have in common an ICE and a battery in their constitution [5]. In fact, they can be seen as HEVs that have the three flowing features:

- A battery storage system of 4 kW h or more;
- An external source can be used to recharge the battery;
- The facility to run on in electric mode at least a distance corresponding to 16 km.

PHEVS are considered as hybrid vehicles that can recharge their batteries via connecting a plug to an electric power source. Equally to a hybrid vehicle, it is also power-driven by an on-board engine and a battery/ electric motor. A possible alternative for an on-board battery charging is regenerative braking.

In terms of power source, this type of vehicles is able to operate with conventional fuels (fossil fuels) and on electricity. Alternatively, they can use the two power sources simultaneously. Thus, these factors provide important insights into the advantages that these type of vehicles offers: reduction of dependence on oil, improvement of fuel economy and power efficiency, decrease of GHG emissions and the emergence of a new concept, vehicle to grid technology (V2G). In Figure 2.24 is available the main operation PHEV principle.

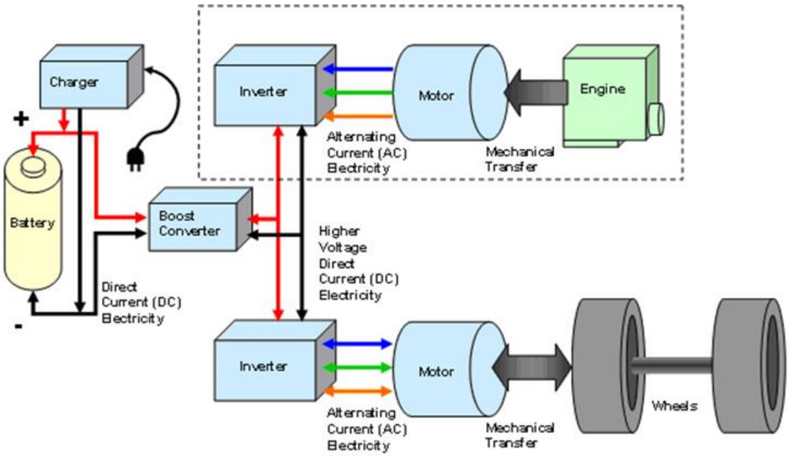

Figure 2.24 - Operational principle of a typical series plug-in hybrid vehicle [37].

PHEVs can be designed in three different ways: series, parallel and series/parallel [5]. In the series design, it is merely the electric motor and not the ICE that rotates vehicle's wheels. In parallel design, the vehicle's wheels are driven by the engine and the electric motor.

They can operate independently or even simultaneously through mechanical coupling. In the series/parallel design, the vehicle is ready for operation in either series or parallel mode. Despite of the design, PHEVs can operate in two different modes in order to manage the vehicle's battery discharge strategy:

- Charge-depleting – until the battery's state of charge is depleted to a predefined level, this mode allows a fully charged PHEV to operate only on electric power. When this predetermined level is reached, the vehicle's ICE will be turned on. It is also used in FEV;
- Charge-sustaining – it is a combination of the conventional internal combustion engine (ICE) and the battery/electric motor in order to the vehicle achieve the maximum efficiency without allowing the battery state of charge to escape of a predefined constricted range.

With regard to batteries, there are two types that adequate properly to PHEVs operation: nickel cadmium (NiMH) and the lithium-ion (Li-ion) batteries. On the one hand, NiMH batteries provides a lower energy and power densities when compared with Li-ion batteries, that leads to an inferior electric travelling range and a lower maximum vehicle speed. On the other hand, NiMH batteries can be more durable, and can also resist to a higher number of deep discharging cycles.

Despite these differences, currently PHEVs battery consists on Li-ion battery technology. The reason is not only related to the promising features of the advanced Li-ion battery technology, which is under substantial development, but also for the fact that this type of battery provides higher energy densities and life expectancy. Consequently, these factors leads to a greater electric travelling range (20-60 km) and a maximum top speeds (160 km/h) [5].

2.2.3. Full electric-vehicles

Contrasting to the last two types of EVs, fuel electric vehicles (FEV) or battery electric vehicles (BEV) principle is based only on an electric motor or traction motor rather than an ICE. Fuel cells can also be the power source of vehicles so that they can be called EVs. Electricity can be generated via two different ways: by on-board rechargeable battery packs (the most common method) or through the use of capacitors or flywheels[5], [38], [39]. Despite this main difference, the charging of the battery can be done in way analogous to PHEVs, either in conventional home electricity outlets or in external dedicated charging stations.

The ultimate FEVs batteries consist on Li-ion battery packs. As opposed to NiMH vehicles or older technology Li-ion batteries, there is an improvement of the FEV performance when using advanced Li-ion battery packs technology. A common FEV can reach an electric travelling range of 120-390 km and a top speed of 200 km/h FEV [5], [38], [39].

In general, a FEV system consists in three main components: an electric motor, a battery pack and the electric motor controller (Figure 2.25).Since there is no presence of an internal combustion engine in a FEV, it is not possible for the battery of these types of vehicles to only operate in a narrow range of vehicle speeds. Therefore, there is the need to operate through the entire speeds band. Furthermore, the battery energy potential needs to be as high as possible to assurance at least a minimum driving range that would be enough to cover a driver’s daily routine. As a consequence, battery requires a high-power and high-energy.

However, the higher the battery energy density the greater is the charging time, implying a much higher cost. Moreover, these characteristics are only available either NiMH or Li-ion batteries. The technical features of the three types of EVs are compared in Table 2.5. First, since HEVs have in their system an ICE their electric travelling range is higher in comparison with PHEVs and FEVs. Second, PHEVs can operate either on-board charging or the option of charge depleting or charge sustaining. Since they offer this possibility, their battery’s requirements are no so strict when compared to FEVs.

In addition, they can use either Li-ion or NiMH batteries. Finally, FEVs perform only through battery charge. Therefore, charge depleting mode is always active, demanding high power that can be offered by Li-ion batteries.

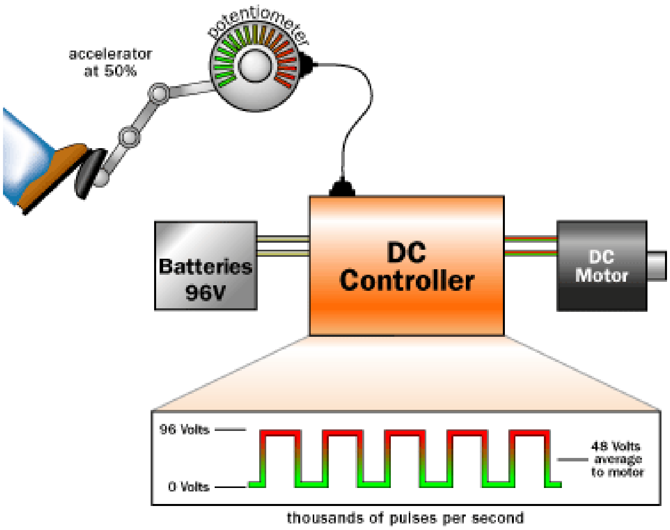

Figure 2.25 - Operational principle of a full electric vehicle [40].

Table 2.5 - Comparison of different types of electric vehicles [5]

Type of vehicle	Mode of operation	Battery Type	Maximum driving range (km)
Hybrid electric vehicle	Charge-sustaining	NiMH	900-1200 (hybrid)
Plug-in electric vehicle	Charge-sustaining	NiMH	20-60 (electric)
	Charge-depleting Mixed mode	Li-ion	900 (hybrid)
Full electric vehicle	Charge-depleting	Li-ion	120-390

2.2.4. Fuel cell electric-vehicles

Fuel cell electric vehicles (FCEV) use compressed hydrogen gas (H_2) for fuel. When hydrogen contacts with air in the vehicle's fuel cell, electricity is produced. There are two options for the generated electricity: it is either applied to drive the vehicle or it is stored in an energy storage device, such as battery pack.

In contrast with conventional ICE vehicle, they produce no tailpipe emissions of harmful air pollutants or GHGs, being considered as zero-emission vehicles. Due to hydrogen production, storage, and the technical limitations of fuel cell at the present time, FCEVs are not accessible to overall population yet [38], [39].

2.2.5. Battery

Battery represents a key role on the performance of an EV and one of the two energy sources of HEVs and PHEVs, while in FEVs is the single source of energy. Therefore, the technological promptitude of batteries is a fundamental problem in the development and market integration of EVs [41]. As the core component it is presented in this section. In order to compare battery technologies, it is convenient to understand the characteristics of an ideal battery.

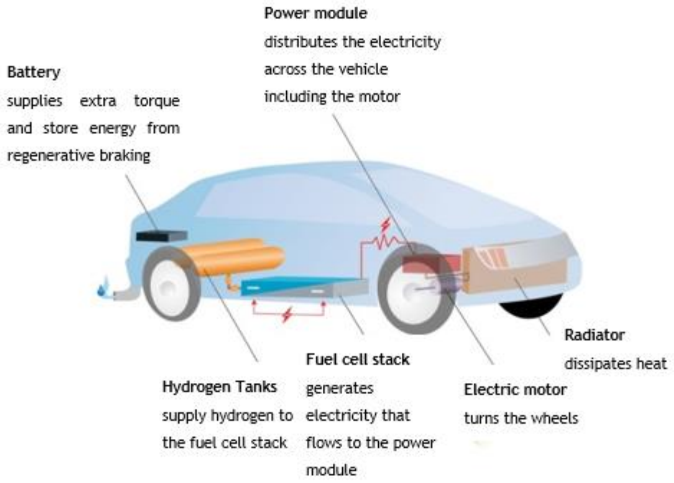

Figure 2.26 – Fuel cell electric vehicle technology [42].

There are five parameters that are considered the most important of an ideal battery:

- **Energy density** is known as the ratio of the total energy to the battery mass and is quantified in watthours per kilogram (W h/kg) or kilojoules per kilogram (kJ/kg). It is considered the most important parameter for an EV since it will directly define the maximum range of the EV [43]-[45].
- **Power density** defines the battery's efficiency and is measured in W/m. It is defined as the amount of power that the battery can deliver per mass without jeopardizing the battery [43]-[45].
- **Safety** is defined as the condition of being protected from off anomalous operating conditions such as over voltage, thermal variation and mechanical shock [43]-[45].
- **Battery lifetime** depends on both calendar life and cycle life. On the one hand, calendar life is described as the expected life duration of the battery under storage. Apart from battery's use, temperature and State of Charge (SOC)[2] during storage can strongly influence it. On the other hand, cycle life refers to both deep cycle life[3] and shallow cycle[4] [43]-[45].
- **Cost** is the most important factor that influences commercial deployment of EVs and has the major impact on EV's price. The cost to manufacture EVs is 1.5 to 2.5 times higher than for manufacturing equally sized traditional gasoline vehicles due to current batteries [46]. However, these cost disparities will decline considerably. In fact, the costs of batteries have already suffered a significant decline through the past seven years as the volume of EVs production has improved. It is estimated that battery costs suffer a reduction to a value under 200$ per kWh by 2030 as Figure 2.27 demonstrates [43]-[45].

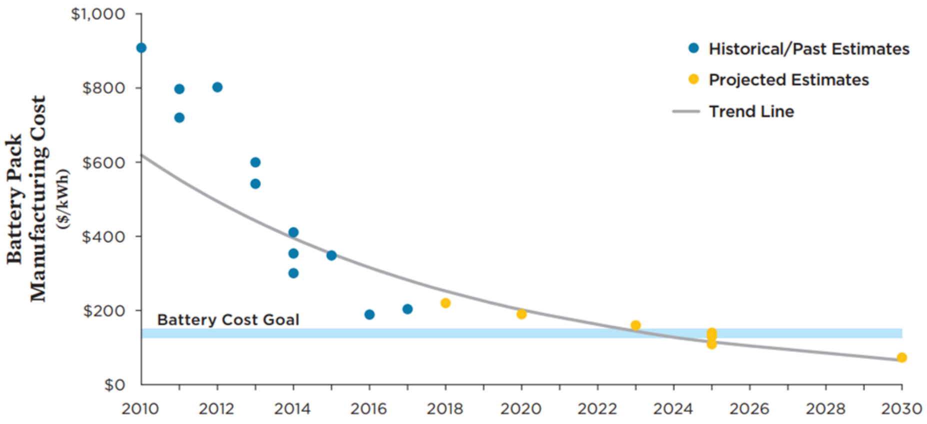

Figure 2.27 - EV Battery Pack Manufacturing Costs[46].

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[2] The remaining capacity of battery, i.e., the ratio between remaining capacity and the rated capacity.

[3] The number of full charges-discharges that a battery executes in charging mode.

[4] It is referred to variation in SOC.

2.2.6. Battery charging strategies and standards

EV charging is classified by power levels or modes. There several established international standards for EV charging, such as Society of Automotive Engineers (SAE), International Electrotechnical Commission (IEC) and CHAdeMO EV standards. These are published by regions with a larger EV stock today, which are America, European Union and Japan.

2.2.6.1. SAE EV standard

SAE charging standard uses the term "level" to categorize charging levels and divides them into three charging levels, which are level 1 ("slow charging"), level 2 and level 3("fast charging") for both AC and DC. Table 2.6 illustrates the SAE charging levels and charging rating according to SAE Electric Vehicle Conductive Charger Coupler Standard (SAE J1772).

While AC charging is performed via an on-board charger of the EV, DC charging occurs by using an off-board EV supply equipment, which is the dedicated charging station located at a permanent location, defined as Electric Vehicle Service Equipment (EVSE).

AC Level 1, known as "slow charging", is the lowest common voltage level for residential and commercial facilities in the USA. It is specifically appropriate for overnight charging. The expected charging time is up to 17 h to charge a BEV from SOC of 20% to fully charged. AC level 2 is designed for charging from a 240 VAC with charging current up to 80 A and charging power up to 19.2 kW.

To achieve a 100% charged battery fully (from a completely depleted PHEV) is required 22 min, using a 20-kW charger. On the other hand, the rating terminology of DC level 1 charging is 200-450 V_{DC} with charging current up to 80 A and charging power up to 36 kW. DC level 2 charging is designed for charging from a 200-450 V_{DC} with a charging current up to 200 A and a charging power up to 90 kW. As illustrated in Table 2.6, both AC level 3 and DC level 3 charging levels are bot finalized yet [43], [45], [47]-[51].

2.2.6.2. IEC EV standard

While SAE EV charging standards uses the terminology "level" to categorize charging rates, IEC EV standards uses "types" and "modes" for charging classification. Four charging modes are specified in the IEC 61851-1 according to four main factors: the type of power received by the EV, the voltage level, the presence or not of a control device that allows a unidirectional or bidirectional communication flow between the charging station and EV, and the integration of a protection equipment.

Modes 1 to 3 are mentioned as charging with an on-board charger in the EV, whereas mode 4 refers to the utilization of an off board charger [43], [45], [45], [48], [52]. The four modes are briefly described below and illustrated in Figure 2.28:

- **Mode 1** refers to a slow charging from a typical household socket-outlet in AC. There is no protection and communication with the vehicle. It is typically used for light vehicles such as electric motorcycles [53]-[55];

- **Mode 2** consists on a slow charging from a typical residential socket equipped with a cable protection device in AC [53]-[55];
- **Mode 3** allows both a slow or fast charging using a dedicated EV socket-outlet equipped with control and protection function installed in AC modes [53]-[55];
- **Mode 4** refers to a fast charging using an external charger in DC. The charging station integrates control, communication and protection functions [53]-[55].

2.2.6.3. CHAdeMO standard

CHAdeMO standards consists on a Japanese national standard published in October 2012. It is referred as a DC fast charging standard, projected for modern EVs in order to accelerate deployment of EVs and to solve one of the major problems related to EV driving: range anxiety. This method is able to charge an EV battery to an 80% SOC in 30 min via DC charging power of 50 kW. The charging is performed through an external dedicated EV charging equipment, which is constructed in permanent locations [45], [56]. As demonstrated above, two charging rating terminology, “level” and “mode”, exist based on different standards.

Table 2.6 - Types of charging power levels based on SAE standard [45]

Charging level	Charging rating	Charging time
AC level 1	120 V; 1.4 kW (12 A);1.9 kW (16 A)	PHEV: 7 h (SOC-0% to full) BEV: 17 h (SOC-20% to full)
AC level 2	240 V, up to 19.2 kW (80 A)	**For 3.3 kW charger:** PHEV: 3 h (SOC-0% to full) BEV: 7 h (SOC-20% to full) **For 7 kW charger:** PHEV: 1.5 h (SOC-0% to full) BEV: 3.5 h (SOC-20% to full) **For 20 kW charger:** PHEV: 22 min (SOC-0% to full) BEV: 1.2 h (SOC-20% to full)
AC level 3[5]	>20 kW, 1-phase and 3-phase	To be determined
DC level 1	200-450 V_{DC} up to 36 kW (80 A)	**For 20 kW charger:** PHEV: 22 min (SOC-0% to 80%) BEV: 1.2 h (SOC-20% to full)
DC level 2	200-450 V_{DC}, up to 90 kW (200 A)	**For 45 kW charger:** PHEV: 10 min (SOC-0 to 80%) BEV: 20 min (SOC-20 to 80%)
DC level 3[5]	200-600 V_{DC}, up to 240 kW (400 A)	**For 45 kW charger:** BEV: <10 min (only) (SOC-0 to 80%)

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[5] Not finalized

However, it is important that there is a convergence of standards and charging technology so that charging facilities are common all over the world, EV drivers are contented with the technology and manufacturing costs can be reduced. In addition to rating terms, there is also a great diversity among the plugs/connection types, due to the non-existence of standardization. Table 2.7 illustrates the different types of connectors [57]-[60] .

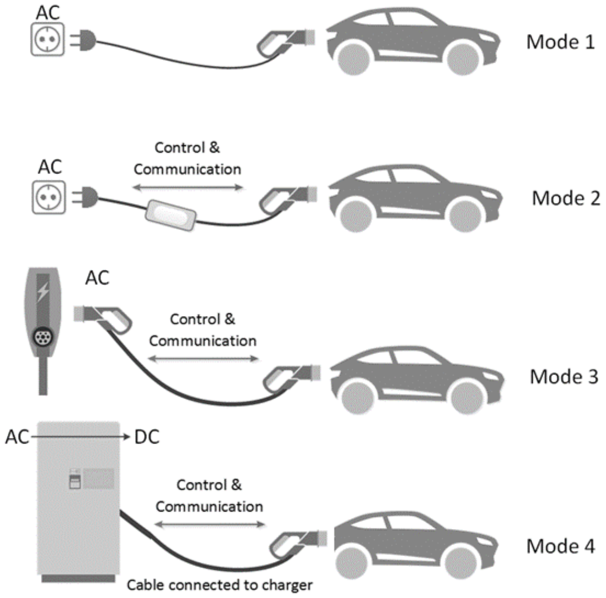
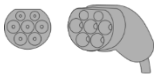
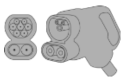
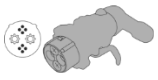
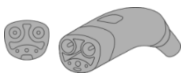


Figure 2.28 - IEC 61851-1 charging modes [53]-[55].

Table 2.7 – Different types of connectors [57]-[60]

Connector Type	Diagram	Charging level	Charging mode	Region
SAE J1772 **Type 1 AC**		Level 1 Level 2	- -	North America and Japan
IEC 62196 Type 2 **“Mennekes”**		- -	Mode 1 Mode 2	Europe
SAE J1772 DC CCS[6] **Combo 1 Connector** **Type 1**		Level 3	-	America and Japan
EU DC CCS Combo 2 **Connector Type 2**		-	Mode 2-4	European Union
Chademo Yazaki		Level 3	Mode 4	Some European countries and America
Tesla Charging		Level 1 Level 2 Level 3 -	Mode 1 Mode 2 Mode 3 Mode 4	Around the world

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[6] Combined Charging System

2.2.6.4. Principal battery technologies

At the present time, in the manufacturing industry, there are several battery's technologies that are appropriated to equip an electric vehicle:

- **Lead acid (Pb-acid) batteries** are a very mature and well-known technology used worldwide. Their most significant disadvantages are associated with managing acid substances, the existence of lead in their construction, a low stored energy/weight ratio and a low stored energy/volume ratio. On the other hand, they represent a cheap solution to equip electric vehicles due to their low-priced manufacturing technology and a high electric power/weight ratio [33], [41], [43], [44], [47], [48].
- **Nickel-Cadmium (NiCd) batteries** present the highest life duration expressed through the number of cycles of charge/discharge. However, their construction implies the use of a heavy metal (Cadmium) which represents an enormous disadvantage since this metal has a high incidence of damages on the environment and population and animal health [33], [41], [43], [44], [47], [48].
- **Nickel-Metal-Hydride (NiMH) batteries** are similar to NiCd batteries regarding technology and operation. Their most significant advantage is the deficiency of memory effect, which influences the maximum load capacity of the battery. When compared with Li-ion batteries, they have an inferior energy storage capacity. This type of batteries has been recently used in HEVs (Hybrid Electric Vehicles) such as Toyota Prius [33], [41], [43], [44], [47], [48].
- **Lithium-ion (Li-ion) batteries** are known by their large power storage capacity with a great energy density/weight ratio. At the same time, they present three main disadvantages: high cost, a high probability of overheating and a limited life cycle. They are considered as the technology with most potential in short term. Li-ion batteries technology is implemented in the most sold EV: Nissan Leaf, Mitsubishi i-MiEV, Tesla Model S and Chevrolet Volt [33], [41], [43], [44], [47], [48].
- **Lithium-ion Polymer batteries** provide a higher life cycle when compared with Li-ion batteries. However, issues associated with instability occur in case of an overload and in the case of battery discharge under a certain value [33], [41], [43], [44], [47], [48].
- **Sodium Nickel Chloride (NaNiCl)** batteries are also designated as the “Zebra battery” and have the major advantage of a high stored energy density. On the other hand, the operational safety and storage for longer periods are seen with disfavor [33], [41], [43], [44], [47], [48].

The main characteristics of today's batteries developed are presented in Figure 2.29. Additionally, charging characteristics and infrastructure parameters are detailed in Table 2.9 for a several vehicles.

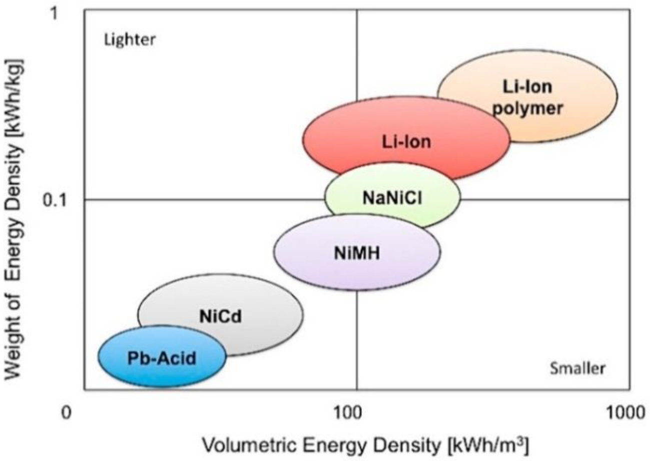

Figure 2.29 - The type of battery and energy density efficiency (weight/volume) [41].

Table 2.8 – Comparison of battery technologies [45]

Battery Type	**Energy density (Wh/kg)**	**Volumetric energy density (Wh/L)**	**Specific power (W/kg)**	**Volumetric energy density (Wh/L)**	**Memory Effect**	**Production cost ($/kWh)**
Lead acid (Pb-acid)	35	100	180	1000	No	60
Nickel-cadmium (Ni-Cd)	1.2	300	200	2000	Yes	200-300
Nickel-metal hybrid (Ni-MH)	1.2	180-220	200-300	< 3000	Rarely	200-250
Sodium Nickel Chloride (NaNiCl)	2.6	160	155	> 1200	No	230-345
Lithium-ion (Li-ion)	3.6	200-400	200-430	2000	No	150
Lithium-ion polymer (LiPo)	3.7	200-250	260-450	> 1200	No	150

Table 2.9 – Charging characteristics and infrastructures of some manufactured EVs [47]

EV Model	Battery Type Energy (kWh)	All-Electric Range (km)	Level 1		Level 2		DC Fast Charging	
			Demand (kW)	Charge Time (h)	Demand (kW)	Charge Time (h)	Demand (kW)	Charge Time (min)
Toyota Prius	Li-ion 4.4	23	1.4 (120V)	3	3.8 (240V)	2.5	N/A	N/A
Chevrolet Volt	Li-ion 16	64	0.96-1.4	5-8	3.8	2-3	N/A	N/A
Mitsubishi i-MiEV	Li-ion 16	154	1.5	7	3	14	50	30
Nissan Leaf	Li-ion 24	161	1.8	12-16	3.3	6-8	50	15-30
Tesla Roadster	Li-ion 53	394	1.8	30 +	9.6-16.8	1-12	N/A	N/A

2.3. Grid To Vehicle Charging

The process of EVs charging from the electricity grid is defined as grid to vehicle charging. As mentioned above, electric vehicles such as PHEVs and FEVs have to charge their battery through the electricity grid. Typical household outlets are the most common method to charge vehicles battery.

However, publicly charging stations are more and more recurrent due to high charging times and the need for vehicle charging in outside locations for more frequent and faster charging. These stations can be independent or be integrated in a network of stations. In this context, a new concept has emerged: the electric vehicle network: a planned infrastructure composed by publicly-accessible charging stations and battery switch stations to charge electric vehicles [5]. Figure 2.30 shows the worldwide distribution.

Considering the current travelling ranges of EVs, it is evident that until a charging infrastructure is sustainably established, EVs will not be addressed for long ranges. They will remain suitable for local driving. Thus, it is indispensable a large offer of charging points in order to facilitate the integration of EVs as a competitive alternative to conventional vehicles.

This means that each EV owner must have the possibility to recharge their electrically driven vehicle in an easy and comfort way, regardless their location. Today, there are nearly 100 000 charging points for EVs in European Union (EU), of which around 30% are locate in the Netherlands.

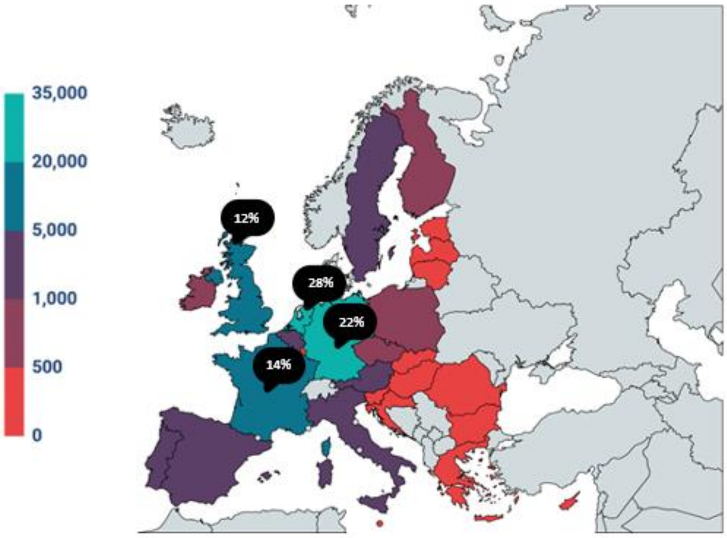

Figure 2.30 – Distribution of EV charging points across the EU [61].

Germany accounts with 22%, France with 14% and UK with 12%. These four countries represent a share of 76% of all EV charging stations in the EU. On the other hand, these same four countries correspond to around a quarter of the EU's overall superficial area. On the contrary, a bigger country like Romania, represent a share of 0.1% (11 charging points) of the EU total [61].

During off-peak hours, the existing electricity generation is practically inactive as operating reserve. Thus, in these periods, i.e., during the night, the available electric generation capacity can benefit from PHEVs and FEVs batteries charging. In this case, despite of the increase of the electrical demand during the night, utilities will be able to implement more efficient operating strategies, by improving demand and generation balance. Additionally, this concept allows to reduce the demand's disparity between off-peak and peak hours, giving the possibility to improve the use of generation units [5].

In contrast, during EVs charging, electricity grid may face several problems such as the increase of the transformer loading, unbalance of network, reduction in voltage levels, power losses and harmonic distortion [5]. If all or the majority of private vehicles charge their batteries simultaneously, for instance, during evening and night-time, this would imply a considerable energy consumption's increase and consequently of the electricity demand.

In some situations, the local transformer supply would be lower than the demand's increase causing the overload of the transformer or severe thermal loading of conductors. Furthermore, concerning the two latter problems, the situation is worse when vehicle charging is during peak periods and when the battery is fast charged with higher charging currents rather than being charged by traditional charging outlets [5].

2.4. Vehicle To Grid Electricity

Vehicle to grid (V2G) electricity is a new concept in electric vehicle design that is described as the energy and ancillary services supply from an EV to the electricity grid. The power flow in V2G can be both unidirectional and bidirectional, although in unidirectional V2G only ancillary services such as regulation, are provided to the grid [5], [39], [62]-[64].

The main concept of V2G electricity is that EVs deliver power to the grid while parked. In other words, the idea is to use EV batteries as intermediary storage facilities for providing services to the electric power system when EVs are parked, taking advantage of the long parking time (near 23 h each day in the United States) [5], [39], [62]-[64]. In general, EVs present three main advantages for the conceptualization of V2G: they can charge when it is more opportune for the system operator, which allows replacing large-scale energy storage systems, they can provide ancillary services (described below), and they can supply electricity to the grid, replacing traditional power generation.

To accomplish this idea each EV must meet 3 requirements [39]: a connection to the grid in order to provide an unidirectional or bidirectional energy flow, a control or logical device indispensable for communication with the grid operator and an on-board meter equipment.

The V2G concept was first introduced in 1997 [65] and it is illustrated in Figure 2.31. The term was conceptualized by considering the case in which EVs would have a bidirectional and computer-controlled connection to the electrical grid.

It was not only considered the interaction between EVs with electric utility system but also the interaction of EVs, especially having in account the possibility of providing opportunities for the energy producers. The study concluded that, if a small portion of the United States' vehicle fleet becomes electrified, the electrical power systems will be less concern with real time match between generation and load. Thus, the power system would be less doubtful to intermittent renewables [65].

In Figure 2.32 it is illustrated the interactions between vehicles and the electric power grid. Through the grid, electricity flows unidirectional from generators to electricity consumers. From EVs electricity flows back to the grid. In case of existing EVs batteries, the flow goes in two ways (illustrated in Figure 2.32 as bidirectional arrows).

In addition, there is a control signal from the grid operator (defined as ISO, for Independent System Operator) which can request for power to a large number of vehicles. This signal may go directly to each vehicle, schematically illustrated in the upper right of Figure 2.32, or to a fleet's operator, which alternatively controls the vehicles in a particular parking lot, schematically illustrated in the upper right of Figure 2.32 [39].

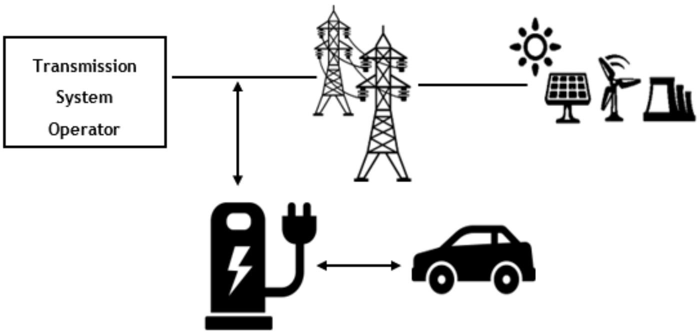

Figure 2.31 – Concept of V2G

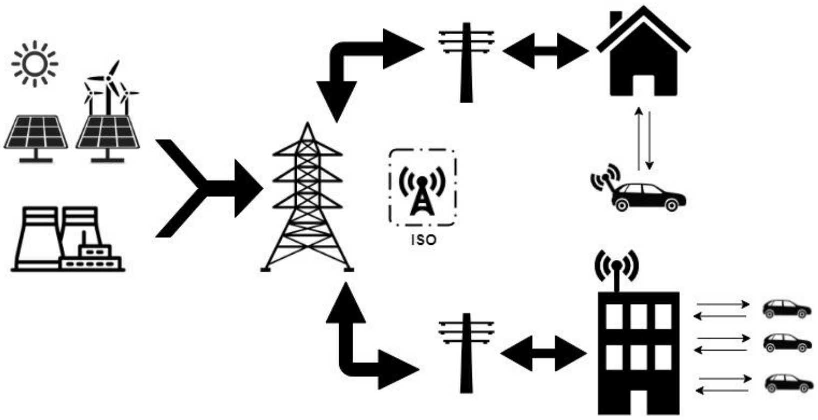

Figure 2.32 – Illustrative schematic of proposed power line and control connections between vehicles and the electric power grid [39].

Vehicle to grid electricity concept can be a valuable situation both for the grid system operator and for EV drivers, differently motivating them to operate in V2G mode. On the one hand, while EVs are stationing in a parking lot, drivers can profit. This revenue depends on different factors such as the length of time the vehicle is plugged in, the size of the vehicle's battery, the power of the chargers and the vehicle's daily drive [64].

On the other hand, GSO is mainly concern about the impacts that EVs can cause in the distribution grid since the higher the integration of EVs the greater the risk [64]. Despite the increased risk, EVs can be a good solution in terms of absorption of renewable energy sources, regulation of frequency and other ancillary services (regulation and spinning reserves). There are four power market where V2G can be included [39]:

- **Base load**, the power production that is remunerated based on an energy that is running the majority of the time at a small cost to insurance constant demand. However, due to EV restricted energy storage and battery duration, and high energy cost, V2G is not enough attractive for a participation in this market. Additionally, large generators can provide less expensively base load power;
- **Peak power,** power generated during time of expected higher demand and also paid on an energy basis. In some situations, V2G can be price competitive due to the high cost of this energy;

- **Spinning reserves,** energy provided by permanently on-service generators in case of loss of programmed generation (equipment failure or failure of a power supplier to fulfil contract requirements). Usually, this type of generation is activated for a short time a few times per year. It is paid for the time available online. These circumstances make spinning reserves market particularly attractive for V2G.
- **Frequency regulation,** generators that are used to stabilize the frequency and voltage of the grid. Usually, they are activated for up to a few minutes several times each day. This market is extremely competitive for V2G. From the electrical utilities point of view, this is a new way of a more efficient regulation of quality grid, and from the EV driver's angle, a profit source that incentives the purchase.

There has been previous research in each of these four power markets. As for using V2G as a frequency regulation provider, in [66] it is described that there is a potential economic return. Moreover, in [67],it is shown that there is a very low economic return for PHEV owners if they use V2G merely for peak load reduction. The simultaneous operation in these two V2G systems are studied in [68].

The results show that the different uses of V2G concept on the various types of energy markets are not mutually exclusive. In fact, they can occur simultaneously. The study observes that is particularly lucrative for PHEVs owners to use V2G for regulation on a daily basis and for peak reduction only on unusually high electricity demand days [68]. In [69] it is analyzed the attractiveness of EV's taking part in ancillary services.

The study demonstrates that using the V2G mode for peak load and regulation services is more profitable than when used for other ancillary services. It also demonstrates that it is not profitable to use V2G mode in the considered power market as a spinning reserve. It finishes observing that the electricity markets will always have an impact on the V2G economic value [69].

While most of the studies focus on bidirectional power flow, there are others that address unidirectional V2G. An analysis of the cost effectiveness of regulation service offered by unidirectional (power flow from the grid to the EV) and bidirectional (power flow in both directions) charging of EVs is presented in [70].

Again, the results show that EV's contribution in energy market is possible, even when working only in a unidirectional mode. Additionally, the study observes that a unidirectional power flow can achieve practically all the V2G benefits from a bidirectional power flow, even though it is necessary nearly twice EV penetration to equal the same level of regulation service. Unidirectional power flow is also study in [62], more specifically, the implementation of optimal charging strategies through the use of this concept.

The study develops an algorithm for unidirectional regulation to be used by an EV aggregator, allied to the capacity of several EVs to participate into energy markets. The study demonstrates that the optimal algorithm simultaneously maximizes the charge of batteries and minimizes the charging cost to the customers.

As for the aggregator, it maximizes the profits and for the utility it has the potential to increase power system operation and control, by providing extra flexibility with the purpose of leading with RES variability [62].

2.5. Interaction between Renewable Energy Sources and Electric Vehicles

Unpredictably and intermittency are two of the key characteristics of renewable energy sources (RES) especially wind and PV solar energies. They are strongly dependent on the existing prime energy sources, i.e., wind speed and solar irradiance, respectively. Despite the challenges that penetration of RES can introduce into to power systems such as variability along the time, the high integration of RES high is considered as a possible, promising and an enough attractive process [50] [71].

In order to accomplish this idea, it is necessary the adoption of energy storage systems or controllable dispatch loads. Through storage systems it is possible to absorb electricity (on case of excess power production) or supply electricity (in case of low power generation). However, this solution involves a higher initial investment which it is not flattering for the high penetration of the RES into the electrical power system. Accordingly, it is clear that EV batteries can play an important role in the integration of RES into the power system, acting as energy storage devices.

If RES' generation is in excess, EVs can absorb it through different charging strategies. Otherwise, EVs can apply V2G concept by delivering power to the grid. In short, EV may be an efficient answer for the problems that RES penetration may cause, since they can be used as storage devices which can help the grid to prevent irregular operating conditions [50]. However, for this to be successful, a reliable long term and steady planning is indispensable in order to assure that integration of RES and EVs into the electrical grid is not an abrupt process.

The majority of the literature about interaction between RES and electric vehicles is mainly dedicated on the study of wind and solar energy [72]. Several studies analyze the ability of EVs to support the integration of wind energy into power grids. The massive scale penetration of PHEVs on the integration of wind energy into the US electricity mix is modelled in [73]. When a 50% PHEVs integration with a smart charging strategy occurs, the installed wind capacity increases by 243GW, or 6% of total generation [72] [73].

In [74] a benefit's analysis of the interaction of large scale EVs and wind power in Inner Mongolia is presented.

It is considered an EV penetration of 100% which correspond to 2.6 million EVs. The study tests five different charging strategies: uncontrolled, night, morning, afternoon, and bidirectional smart charging (V2G).

The results demonstrate that EVs are able to balance the electricity demand and supply, promoting wind power integration by 8%. Moreover, EVs are able to reduce both the cost of the energy's system operation and the fuel cost. Regards to charging modes, EVs with afternoon charge were found to be the most favorable since they have the most excess electricity reduction potential as well as they allow a slightly higher penetration of wind power than the bidirectional smart charging.

The study finishes concluding that the EV integration with a low penetration of wind power struggles to decrease CO2 emissions. In other words, simply developing EVs in a fossil fuel dominated energy system may not be an advantage to the CO2 emissions reduction. Therefore, green energy sources, more particularly, wind power generation, is essential for transport electrification [74].

In [75] the use of excess wind power in order to charge EVs is studied considering Germany 2020 and 2030 scenarios corresponding to 1 million and 6 million EVs, respectively. The analysis assumes EV models based on real driving and car habit behaviors, considering a controlled charging strategy, i.e., shifting the charging into off-peak times. The study only models home charging and it is divided considering the grid with and without restrictions.

In 2020, the share of excess wind energy that can be used in EVs with controlled charging is limited to 7.5% by grid constrictions, compared to 8.4% with no grid restrictions. For the same conditions, in 2030 that share is 8% compared to 15% since the grid connection capacity does not follow along with the increased wind turbine capacity installed. The results show that in 2030, with grid restrictions, about 30% of EV demand can be met by excess power; without them, this value increases to 50%.

The study finishes affirming that 1 million EVs virtually have no effect on the energy balance. On the other hand, an increase of 5 million EVs might impact considerably but not dramatically the distribution system [75]. Regards to combining solar PV energy with electric vehicles, the literature can be found in section 2.8.3.

2.6. Electric Vehicles Solar Parking Lots

Electric vehicles are parked during a considerable period of time during the day being exposed to the sunlight. Additionally, as illustrated in Figure 2.33, 26% of worldwide EVs charging stations are located in parking lots [76]. If these two facts are combined to PV power production, i.e., installing a rooftop PV in the parking lot, an opportune and reasonably priced solution emerges in terms of EV charging. Thus, EVs parking lots are a good occasion regarding not only with handle the EVs energy management challenges but also it allows for an opportunity for charging while parking.

It is a possible mechanism to charge EV at places such as workplaces, shopping centers, restaurants, supermarkets, hotels, hospital, airports. An example of PV parking is shown in Figure 2.34 [77], [78].

Combining solar energy production with EV charging is not a simple problem since it is necessary to consider different parameters such as solar electric power with its innate variability and unpredictability, parking duration, state of charge of the batteries of each vehicle, and electricity prices.

Therefore, in order to achieve a successful arrangement between those two, solar energy production must synchronize as nearly as possible with the EV load profiles. There are two charging approaches that consider this fact [49]:

- **Uncontrolled charging**, a simple approach that consists in charging completely the vehicles immediately after they park. It brings technical and economic challenges to the distribution systems. From a technical point of view, it can cause several problems such as frequency and voltage oscillations, and grid overload, jeopardizing power quality and stability. From an economic perspective, it may result in a suboptimal generation dispatch and a cost efficiency [49], [79]

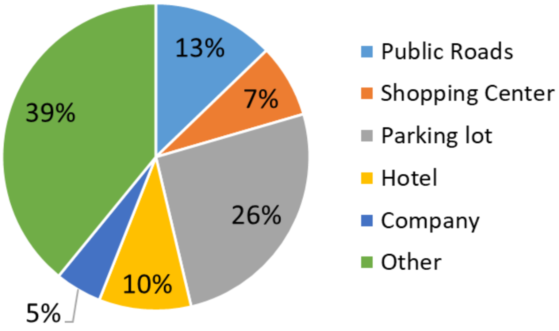

Figure 2.33 - Distribution of charge points by location type [76].

Figure 2.34 - Example of PV based parking lots for EV charging [77].

- **Controlled charging**, the basic idea of a smart parking lot (detailed in Section 2.7). It consists on an optimization problem including an objective function that is formulated in order to achieve an optimal charging schedule and charging power via an algorithm for smart power-flow and controller [49], [79].

2.6.1. Environmental and other benefits

Vehicle's ecological impact is determined by the electricity's source that is delivered the EV charging stations, i.e., emissions levels are still present if fossil fuels are used for electricity generation. However, if solar energy is used to generate electricity, EVs are considered as green vehicles, with zero emissions[7].

Furthermore, solar photovoltaics do not emit noise or pollutants during operation. Therefore, it is also an excellent path towards environmental targets. Moreover, through the existence of EVSPLs electric vehicle owners are encouraged to charge their EVs during the day causing less anxiety in terms of vehicle's daily driving range which helps increasing market acceptance by EVs.

The purchase of EVs is strongly dependent on the charging infrastructure. If there are no dedicated equipment to EV charging, citizens would not buy EVs, which implies a decrease of investment in that structures, causing a negative feedback effect. As opposed, the installation of charging stations encourages the acquisition of EV and vice-versa.

Thus, a positive feedback cycle is created. Since solar parking lots are located in the heavily populated areas, i.e., they have a great visibility, so people see them very often which makes the transition seem more close to reality [49]. This factor leads to the substitution of ICE vehicles for EVs, which in turn improves human health.

In terms of infrastructure, a solar powered charging station is typically a tall structure with solar panels installed on roofs and with an electric charging station. Thus, it becomes clears that this type of structure it is not only valuable for electricity generation but also to provide shade for the charging vehicles, which not also reduces the vehicle's internal temperature but also provides protects interiors from sun damaged [52].

At last, EVSPLs brings advantages regarding to local employment and the local economy. On the one hand, local employment is stimulated since solar electricity generation implies installation and maintenance of the charging station. On the other hand, customers by choosing a shopping center because their cars are protected from the sun as well as they are charging, local economy develops [49].

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[7] Solar panels production is associated to some carbon dioxide emissions. However, in comparison with their lifetime expectancy (20 years), panels become carbon neutral in a reduce period (2 years).

2.6.2. Configuration and operation

In an EVSPL the vehicles can be connected in two different ways: linked to a DC link after a DC/DC converter or connected to an AC link after a DC/AC converter. The management of the system is under the responsibility of control center. In the presence of additional power sources (wind power or local battery) control center is also responsible for their management.

As for the DC/DC converter, it converts the current from one voltage to another. Additionally, a MPPT (Maximum Power Point Tracking) strategy is applied with the purpose of withdrawing the highest power from the solar panels. The first priority of power produced by PV panels is charging EVs batteries. In case of existing excess of solar energy, this is injected into the grid. When PV output is insufficient to completely charge the EV demand or does not exist, the grid provides the remaining power. The architecture of an EVSPL is conceptually described in Figure 2.35.

2.7. Smart Parking Lots

As opposed to conventional parking lot, smart parking lot offers new alternatives for EV's drivers as well as utilities grid. These type of PLs have an energy management system capable to automatically receive and send data to vehicles and make smart decisions concerning the EVs charging/discharging arrangement. For this reason, it is used the term "smart" [80]. The basic idea of a smart EVSPLs is the integration of EVs as a group of energy store devices (EVs batteries) in order to maximize EVs owner's and parking lot's benefits as well as the stability of distribution power system. The smart parking lot operator is able to manage EVs charging, according to the preferences previously establish by EV owners, such as the final SOC desired.

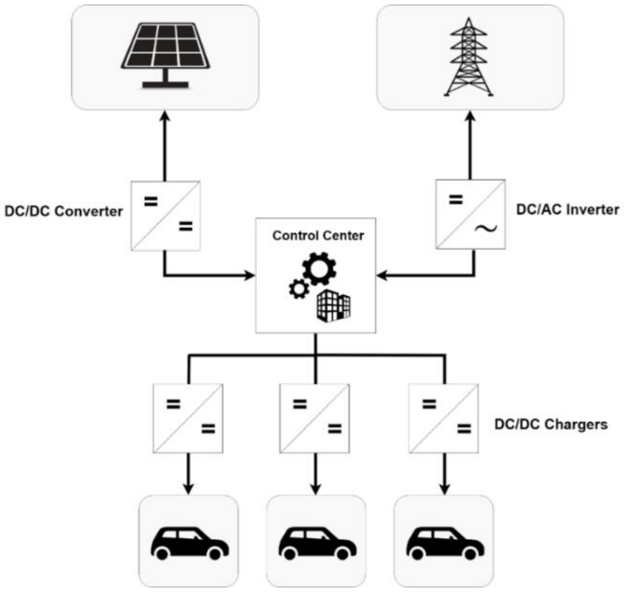

Figure 2.35 - Configuration of a PV standalone EVSPL (DC charging) [49].

In addition, EV owners can also defined the price range that are best suitable to sell their stored energy as well as to buy from the grid [80] [81] [82]. There are several types of energy flows that can occur in smart EVSPLs (Figure 2.36): the most frequent are unidirectional PV-to-vehicle (PV2V) and PV-to-grid (PV2G); bidirectional V2G and vehicle-to-vehicle (V2V) [49]. The last energy flows occur, for example, when PV energy produced is not enough.

As an alternative of purchasing energy from the grid, because the electricity price at that point is high, a good option might be the energy's injection from one vehicle that has been parked for a longer period of time to one that is leaving the parking lot sooner. In the presence of a battery that assists a local storage in the EVSPL, that may occurs additional fluxes: PV-to-battery (PV2B), battery-to-vehicle (B2V) and grid-to-battery (G2B). The first two are unidirectional while the last one is bi-directional.

Smart parking lots are is based on an energy management system that establishes communication between its different components, allowing the information flows between the EVs and the parking lot.

Using an approach of a virtual power plant[8], a smart EVSPL can group together EVs, operating as aggregator that simplifies the connection between the different elements: utility grid, electricity markets and the EV drivers. Through this strategy, it is possible to fulfil customer's needs as well as improve grid reliability and flexibility. Additionally, they can represent an integrant part of a bigger smart micro grid as it can be observed in Figure 2.37.

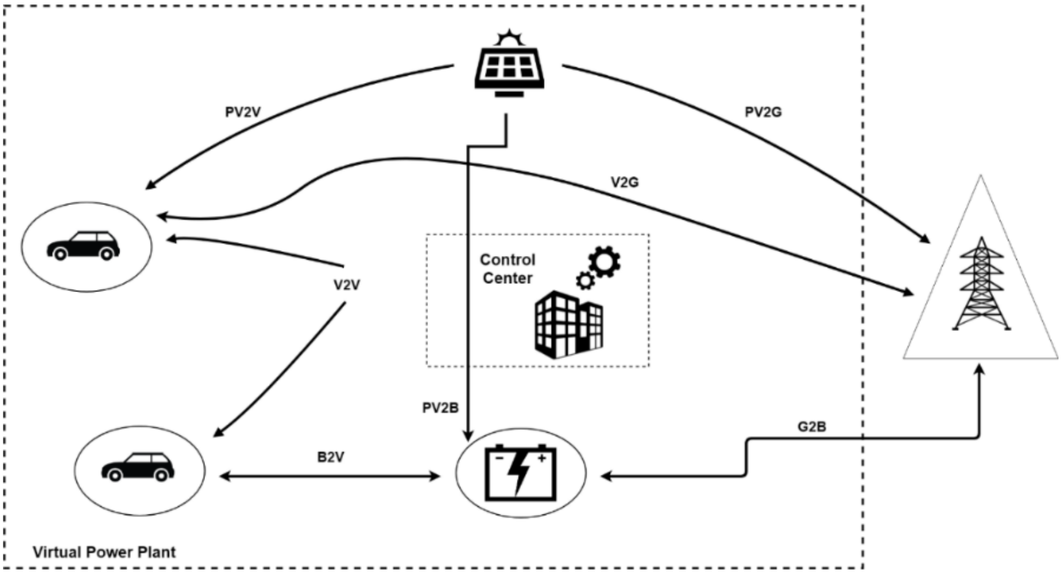

Figure 2.36 - Types of energy fluxes in a smart EVSPL with central energy storage [49].

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[8] A virtual power plant refers to a decentralized network that aggregates the capacities of distributed energy resources. It can be used to trade or sell power on the electricity market.

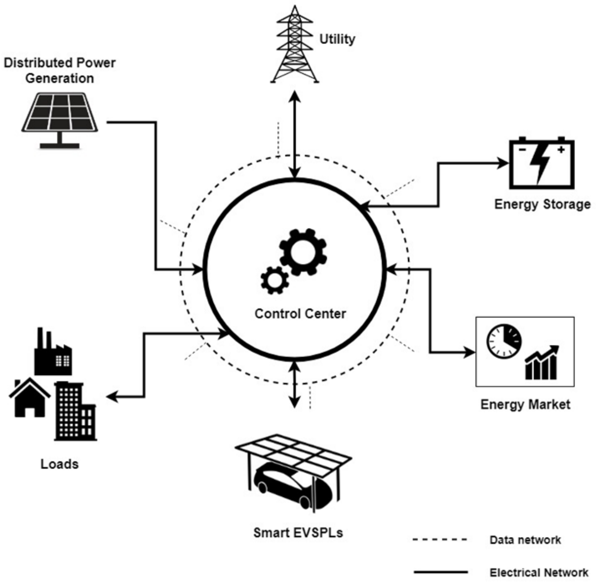
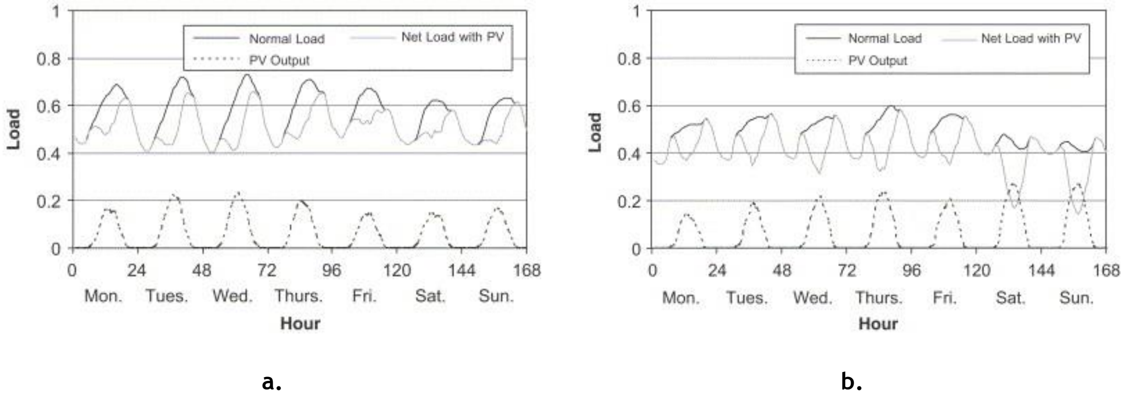


Figure 2.37 - A smart EVSPL in a micro grid context [49].

2.8. Relevant Studies

2.8.1. Solar photovoltaics' penetration on electrical system

In [83] is analyzed the large scale PV penetration effects in a conventional electric power system, more specifically, in the Electric Reliability Council of Texas (ERCOT). Figure 2.38a shows that PV generation might be the key in terms of reducing demand during peak hours, mitigating the deviation between PV generation and demand. Figure 2.38b illustrates the results for a week in March, considering equal system conditions. The results show a larger difference between demand and PV output, mostly in the weekend where the demand on the electricity system is relatively low, while PV output is reasonably high. The interaction of a low demand with a high PV output leads to an unbalance between generation and supply, jeopardizing the grid. Conventional generations (coal and nuclear plants) are obligated to reduce their output which result in considerable economic penalties.



a. b.

Figure 2.38 - Coincidence of PV generation and demand in ERCOT. (a) During a week in June 2000; (b) During a week in March 2000 [83].

In [84] it is demonstrated the impacts of solar photovoltaics system through a simulation of a low-voltage (LV) distribution network in New Zealand. In first place, it is simulated a peak load scenario without PV. Second, increasing solar PV penetration levels are modelled with reduced load. It should also be noted that results are also presented by network type, i.e., city, urban, industrial and rural.

The results Figure 2.39 illustrate that in higher levels of solar PV penetration lead to three main problems: overcurrent, reverse power flow and overvoltage. Figure 2.39a demonstrates that a relatively low solar PV output can help avoid overcurrent. Additionally, with the increase of solar PV penetration level, the percentage of overloaded conductors also suffers a significant increase. Figure 2.39b illustrates the number of transformers with reverse power flow. As long as solar PV penetration level does not reach 0.25 or higher, reverse power flow is not relevant.

Figure 2.39c demonstrates the interaction between solar PV and each type of LV network. In case of urban networks (dash-dot line), these are capable of insurance a level between 10-15% of solar PV penetration without resulting in significant problems. However, overvoltage problems become relevant above this percentage level.

On the other hand, city zones (dashed lined) are able to integrate a higher level of solar PV penetration level since they are better prepared to lead wit solar PV. In addition, rural LV networks demonstrate a good interaction between solar PV. Finally, industrial areas do not present any overvoltage issue for all penetration levels [84].

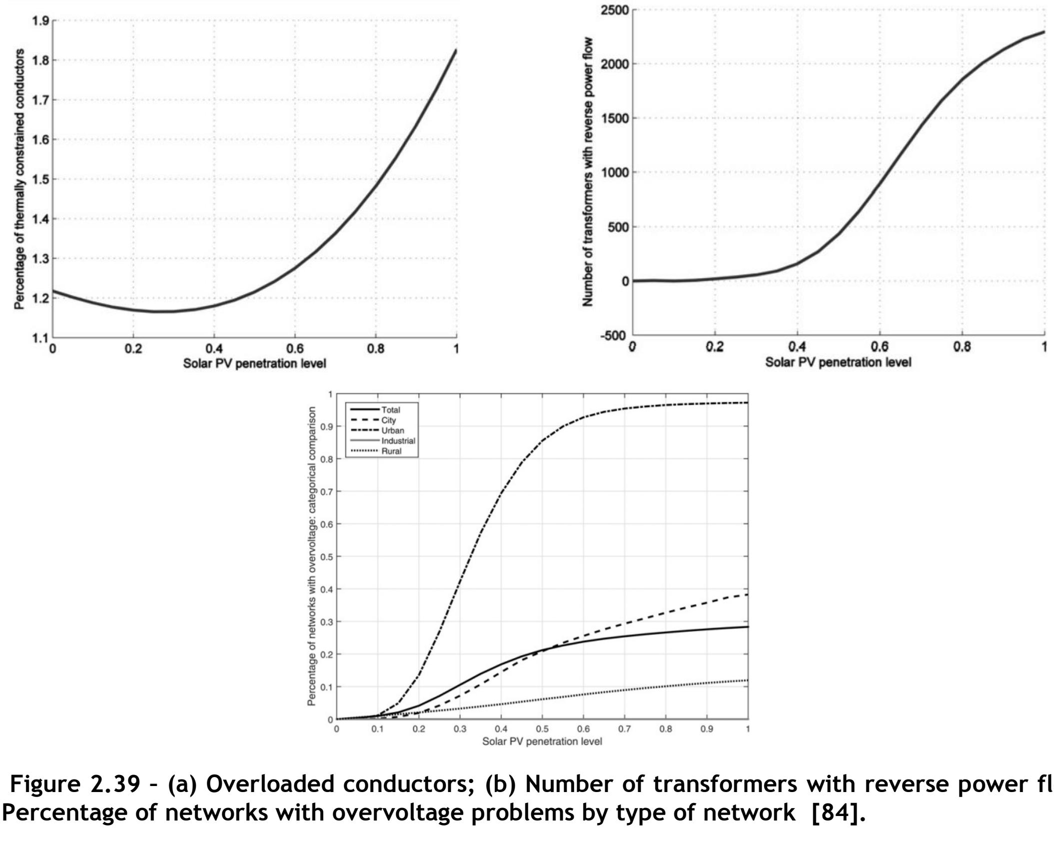


Figure 2.39 – (a) Overloaded conductors; (b) Number of transformers with reverse power flow; (c) Percentage of networks with overvoltage problems by type of network [84].

2.8.2. Electric vehicles' integration into electric grid

As mentioned in section 2.2 the mobility culture is changing, leading to considered EVs as an integrant part of the environmental solution. However, it is indispensable a conscious analysis of EV's integration into the electrical system. Therefore, several parameters such as charging strategies and levels should be taking into account with the purpose of evaluate the effects of the large-scale integration of EVs.

An analysis and quantification of the impacts of different levels of EV penetration on distribution network reinforcement and energy losses is presented in [85]. The study analyzes two distribution areas and three different EVs penetration scenarios: 35%, 51% and 62%. These scenario's results are compared with a reference case, i.e., assuming that there are no EVs penetration.

The results show that is required a 19% increase in the grid's investment at peak hours. However, it can be reduced by 60% to 70% through the implementation of smart EV charging strategies. In addition, this supplementary investment can be reduced through load shifting, by charging EVs in off-peak hours instead of peak hours. That will imply a reduction of 5% to 35% of the required investment. In terms of energy losses, the results shows that in the higher penetration scenario, they could rise up to 40% in off-peak hours [85].

In [86] it is analyzed the impact of charging PHEVs on a classic distribution feeder in Blacksburg (USA). The network includes five residences and two PHEVs. Two charging schedules are considered: at 18:00 pm and at load periods. The results show that the first scenario corresponds to the worst scenario and it represents an increase of the transformer load in 68% and 52% in winter and summer, respectively.

On the other hand, the second scenario results in a growth of the transformer load in 58% in winter and 52% in summer. Since that there is no transformer overloading in both cases, the scenarios are reconsidered using quick charging, (a smaller charging time requires a higher voltage outlet). As a result, a transformer load is verified only when charging starts at 18:00 [86].

By investigating the Belgium traffic patterns and driving routines, the impacts of PHEVs into the Belgium's distribution grid are discussed in [87]. The study considers three different scenarios of uncontrolled charging scheduling: charging begins between midnight and 2:00 am, charging starts between 6:00 am and 20:00 am, and charging occurs during the day-time.

Moreover, it considers high load scenarios (in both summer and winter), assuming four different penetration levels of PHEVs: 0%, 10%, 50%, and 100%.

The results show that the penetration of PHEVs has significant effects on the power losses and voltage fluctuations in the distribution grid. Thus, as a means to safeguard the security of the electric grid, the impacts of PHEVs on the distribution grid must be evaluated and quantified [87] .

In [88] it is analyzed the impact on the Portuguese electric transmission grid caused by three different EV charging strategies (non-smart, smart and vehicle-to-grid) considering a 100% electric vehicle penetration. In this case, the maximum increase consume will be lower than 36.5 %. For a 25% EV penetration scenario, it will be needed a supplementary energy lower than the 2009 wind production.

In Portugal, an EV that consumes 200 Wh/km produces approximately 82 grams of CO_2/km in a typical year. Being aware that the European target is to decrease the average emission of CO of traditional vehicles, to 95 g/km [89] by the year of 2020/2021, therefore 82 grams of CO_2/km is not a challenging value. However, with a high penetration of renewable energy resources, the same EV will only emit about 41 grams/km by 2020.

In this study, a one-week period is analyzed, not discussing the risk of power quality problems or the possibility of EVs participating in ancillary services. For a maximum EV penetration level (100 % EV fleet), the results show that the implementation of a non-smart charging strategy might cause a very high peak demand on the grid (around 8 GW). However, through the implementation of a smart charging strategy, this can be avoided. By performing in a smart charging mode, the maximum power that the EV fleet has to absorb is approximately 4.5 GW. The study finish observing that the V2G mode will be the majority of the time charging from the grid, and not supplying it [88].

2.8.3. Interaction between solar photovoltaic energy and electric vehicles

2.8.3.1. On the electrical grid

The EV's charging process leads to a supplementary load to the grid which according to the selected charging strategy can be reduced through the penetration of solar PV into the power electrical system. A discussion on the interaction between the PV generation and the electric vehicles is presented on [90]. The results are provided through different scenarios of EVs and photovoltaic generation penetration according to three approaches: uncontrolled charging, smart charging and vehicle-to-grid.

The analysis shows that an uncontrolled charging strategy with a high-level penetration of EVs can lead into to grid difficulties related to higher peaks. On the other hand, high level of EVs penetration does not implies any additional peak when a smart charging and a V2G strategies are performed. In fact, V2G can be a valuable help to grid since it stabilizes the grid in regards of peak-load shaving, reducing peaks in 35% (in case of high penetration of EVs and a high integration of photovoltaic generation) [90].

In [91], Electric Reliability Council of Texas (ERCOT) is used as case study location in order to analyze the positive impacts of large-scale PHEV and solar PV deployment, by simulating the Texas grid.

The study assumes a 30% penetration and 15% energy share of the system's annual electricity, for PHEVs and solar PV, respectively. The purpose of this study is to analyze the capacity of the combination of PHEVs and solar PV to mitigate global vehicle petroleum use and consumption of electricity from fossil fuels. It assumes two charging scenarios, uncontrolled and controlled after 15:00h charging.

The results demonstrate that PV's integration either reduces or eliminates the growth in peak capacity requirements due to PHEV demand. In second place, the analysis shows that energy's curtailment during PV peak generation and low demand is avoid. Another point that can be denoted from the results is that the electrical travel range is increased by allowing PHEVs to charging during mid-day. Finally, the study concludes that PHEVs can be an essential key for increasing the use of solar PV by providing a flexible source of electricity demand [91].

In [92] a study of the energy and environment impacts of PV power integration into future electricity system with EV and heat pumps under smart control strategies is presented, using a region of Japan as study location. Different scenarios are used based on the combination of different penetration levels of solar PV, EVs and heat pumps, respectively 0 to 30 GW of installed PV, 0 to 5 million EVs and 0 to 5 million houses equipped with heat pumps.

The results demonstrate that the combination of one million EVs with one million heat pumps can reduce electricity excess by 3 TWh, i.e., 2% of total electricity. Additionally, it observes that with the three technologies on the maximum level (respectively, 30 GW of solar PV, five million EVs and five million heat pumps), 11.6 Mt of CO_2 emissions are reduce, i.e., 43% of total CO2 emissions [92].

In [93] and [94] it is studied the practical feasibility of charging directly vehicles batteries through solar PV panels. By applying this technique, EVs would be able to be charged through electricity locally produced, which avoids transmissions losses from distant power plants. Moreover, this mechanism does not imply a power conversion stage, i.e., converting DC solar electricity to AC grid electricity, preventing a 10% energy lost.

A practical analysis to evaluate the capacity of vehicles to provide power without jeopardize their primary function, i.e., transportation is demonstrated in [39]. The study investigates the four electricity markets (described in Section 2.4) in which EVs are more promising. For that purpose, the model formulates equations to describe the available power and duration, the costs and market value of these forms of power.

The results show that EVs possibly will no produce bulk power due to their essential engineering features and because of the cost of energy from EVs is less cheap when compared with electricity generated via conventional generators groups. On the other hand, V2G gains interest in power market based on online and available power, with an added energy payment when power is actually dispatched, for instance spinning reserve and regulation markets. The study finishes observing that V2G can improve the reliability of the electric system, reducing its costs [39].

2.8.3.2. *In Parking Lots*

As mentioned in Section 2.4, electric vehicles are parked during a long period of time during the day, making parking lots a potential solution for EVs charging. Indeed, by analyzing the hourly parking utilization duration diagram and the forecasted PV panel's output it is clear to understand the benefits of combining these two technologies [80]. In Figure 2.40 it is possible to observe the aforementioned behavior.

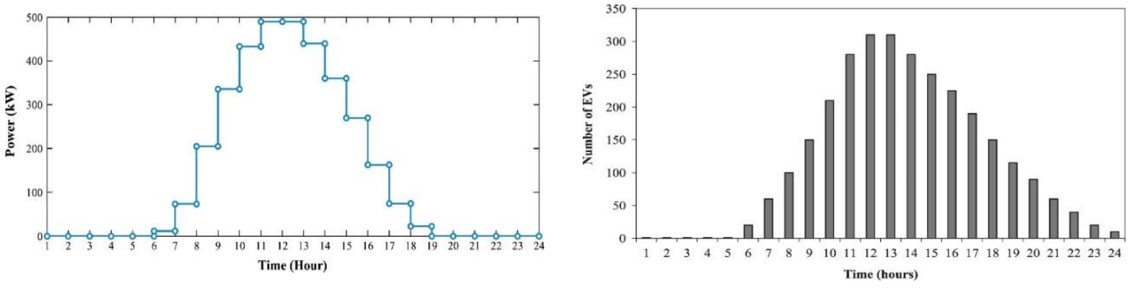
The first pilot EVSPL was created in January 1916 in Santa Monica, California, with the purpose of promoting the concept [49], [95]. It consisted on a 2.1 kWp PV array, producing power for seven parking spots. The facility generated in one year 3840 kWh, resulting in the avoidance of 150000 kg of CO_2 from penetrate the atmosphere [49], [95].

The practical feasibility and effectiveness of the integration of PV systems into parking lots is mostly influenced by two factors: the weather conditions, i.e., the regional solar energy and its seasonal variation, and the regional population density (for example, the typical customer driving routines, traffic congestion) [96]. In [96], it is simulated a parking lot in New Jersey, USA, fully covered with solar PV.

The results show that in a typical summer day, parking lot's average daily generation will be nearly 12.6 kWh while during winter average daily generation will be around 3.78 kWh. The study also concludes that the installation of solar PV panels in parking lots it is a better location comparing to home facilities since in the former it is likely that PV can be optimally positioned without any type of obstacle [96].

The solar potential of 48 parking lots in Frauenfeld, a typical Swiss medium-sized city, to meet the city's 14 thousands vehicles (assuming that they are all electric) is discussed in [97]. Every single parking lot is typed by its solar generation share, compared to the production of a non-shaded an optimally aligned equivalent parking lot. According to this percentage, parking lots are grouped into three categories: A (>95%), B (90-95%) and C (<90%).

It is considered that only the parking lots allocated to categories A or B are economic worthwhile. The study concludes that 29 of the parking lots are monetarily attractive. This study also concludes that solar parking lots can represent an annual energy production of approximately 5 GWh. It finishes comparing the use of solar and biogas to meet the driving requirements, concluding that the latter has an environmental footprint 60 times bigger [97].



(a) **(b)**

Figure 2.40 – (a) Statistical parking utilization information; (b) Forecasted PV generation [80].

In [98] a trial is conducted between 2010 and 2012 in Western Australia in which 11 electric vehicles and 23 charging stations are examined. The results prove that the majority of charging occurs at work and home locations (79%), whereas charging stations are only used for 33% of charging events.

The study shows that the daily EV charging power profile aggregated over the charging stations are similar to a solar PV curve which means that solar power is able to meet EVs charging demand. One of the conclusions is that 79% of the total energy is used during daytime, in the period between 8:00 am and 18:00 pm. Other significant conclusion is that EVs lose expressively more time at charging stations than what is really necessary for charging process.

The study also evaluates how EVs spend their time at charging station. Although EVs regularly occupy charging stations for a full work-day, only 8% of the parking time is used to actually charge the EV, while the remaining 92% is responsible for maintaining the vehicle's charge [98].

An on-grid parking lot (PL) equipped with photovoltaic panels and an energy storage unit is designed in [99]. The model proposes that the control of the charging station is based on the change of voltage level (due to the variation of sun's irradiation) in DC link, considering four operation modes. Each mode is represented by a voltage range according to a typical EV battery and a 5.5 kW PV panel. When the DC link's voltage reaches 50 V (V_{DC1}), the PV panels initiates to charge the battery until it reaches 250V (V_{DC2}). When the V_{DClink} is above 350 V (V_{DC3}) there is a PV surplus production. The four modes can be summarized as follows.

In mode 1 ($V_{DClink}<V_{DC1}$), during off-peak hours and when there is no PV production, EVs and the storage system charge from the grid, whereas in peak hours EVs charge from the storage system. In mode 2 ($V_{DC1} <V_{DClink}<V_{DC2}$), the PV production is insufficient to charge EVs, and so the grid provides the rest of the energy. If an EV peak load occurs, the PL switches to off-grid mode. In mode 3 ($V_{DC2} \leq V_{DClink}<V_{DC3}$), the EVs are exclusively charged by PV production and the PL performs at off-grid mode. Finally, in mode 4 ($V_{DClink}\geq V_{DC3}$) the excess of PV production is injected into the electric grid [99].

2.8.3.3. *Smart Parking Lots*

Smart parking lots when compared with conventional ones create new prospects for EVs drivers as well as the utility grid As mentioned in Section 2.7, these type of infrastructures can automatically receive and send data to vehicles, making wise decisions related to EVs charging/ discharging scheduling, considering simultaneously several parameters such as desired state of charge (SOC), electricity price and solar PV generation. The literature on these studies is provided below.

In [81] a model is conducted in order to maximize the profit for each EV owner by selecting a proper time for charging and discharging the EV. It also focuses in maximize the EV's state of charge.

The results demonstrate that the charging occurs with lower electricity prices, while in the hours with higher electricity prices, EVs are discharged in order to sell the stored energy to the grid, as Figure 2.41 illustrates. Through this system, EV's owners can make revenue while their vehicles are parked. Moreover, this model concludes that the use of smart parking lot has eliminated the possibility of electricity demand increase during the peak load of the network. Additionally, it finishes concluding that this concept it is a good solution in terms of providing an infrastructure for aggregate the stored energy of the EV's batteries and selling it to the grid during peak hours, when electricity prices are high [81].

The profits of a PL equipped with two gas micro-turbines and a rooftop PV are analyzed in [80], according to three different scenarios. The first considers that EVs do not participate neither in energy nor reserve scheduling, and the required spinning reserve is only provided by the micro-turbines; the second assumes that the EVs contributes in the energy scheduling by the use of V2G concept but does not participate in the reserve scheduling, and the required spinning reserve it is still supplied by micro-turbines; the third scenario takes is into account that EVs support both energy and reserve scheduling and the required spinning reserve is provided by both the EVs and micro-turbines.

Figure 2.42 demonstrates the smart parking lot's profit and EVs payment in the three case studies. As illustrated, in case 2 and 3, the total EV owner's payment is lower than case 1, due to the participation of EVs in V2G mode. Additionally, the EV owner's benefits are higher in case 3 than case 2 since EVs participate in reserve scheduling. From the PL's point of view, the parking lot benefits more in case 3 due to selling a higher amount of energy of micro-turbines during peak hours. In conclusion, the results shows that the third scenario is the most flattering case for both participants, PL's operator and EV's owners [80].

In [99] an EVSPL integrating a storage system is managed through smart charging strategies. The objective is to minimize the injection of energy from the grid, improving simultaneously the grid stability by activating the off-grid mode during the peak periods to reduce the grid's congestion. The results demonstrate that with the increase in EVs loads on the distribution system, smart charging methods can help reducing the major costs to reinforce the power system equipment, for instance the distribution transformers.

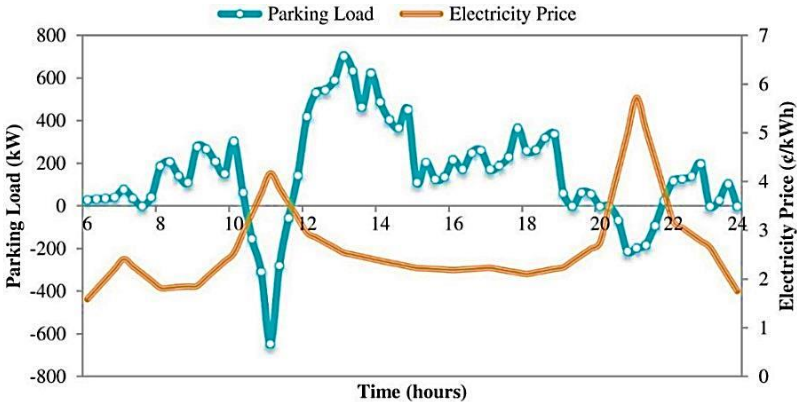


Figure 2.41 - Hourly scheduled parking electricity demand and electricity price [81].

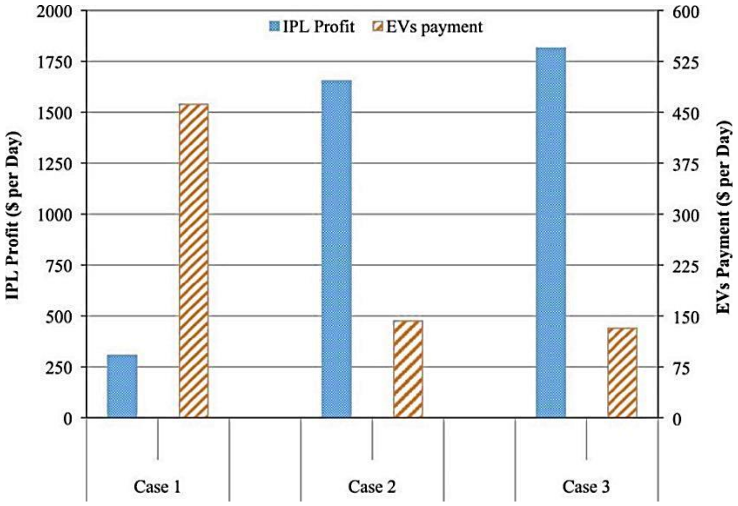


Figure 2.42 – Daily PL profit and total EVs payment [80].

2.8.4. Optimization Models

2.8.4.1. Maximization of EV's owner/PL's operator profits

Three different approaches on optimization models of an electric vehicles parking lot are presented in [80]–[82] by the same authors. These studies assume a different PL's occupation; however they are all based on those EVs owners' routines and preferences such as parking duration and charging/discharging limits prices. Furthermore, battery degradation and electricity prices in the day-ahead market are considered.

Through these parameters, the EV's charging model is formulated considering that each study has a different objective function. The three studies assume arrivals and departures times as random variables and the PL's occupation is obtained through statistical data of parking lots in Tehran. Additionally, they all consider an average electric vehicle with 16.5 kWh. Regards to input variables, they are restricted by a probability distribution function. Each of the three studies is based on this latter information.

In [80] a EVSPL equipped with distributed generators (two gas micro-turbines) and an occupation of 500 vehicles is modelled with the purpose of maximizing the PL's profit. Data from EV's owners, electricity market prices and renewable generation forecasting is the basis for the EV's charging scheduling calculated by the parking lot. Additionally, the micro-turbines operation and the provision of the spinning reserve are also formulated through these elements. Money penalties for the PL's operator are included in this model in case of the required final SOC is not fulfilled.

It is also assumed that the EVs charging price is equal to hourly electricity price of the open market, whereas discharging price is considered in such a way to be seen as enough economic encouragement for EV's owners and PL's operator for providing reserve. The objective function aims to maximize the total benefits, i.e., maximizing both PL benefits by playing the role as energy aggregator in the electricity market and EVs owner's profits by benefiting from discharging of their EVs as well as providing reserve capacity.

With the application of this objective function, the models intends to charge EVs during periods with low electricity prices so that EV owners pay a lower cost for charging their vehicles [80].

The objective of the model proposed in [81] is to maximize the profit of EV's owners, the charging/discharging rate for all EVs and the SOC level of each EV. It is assumed that each EV parked in the parking lot is situated at one of three modes: charging, discharging and inactive. Two different scenarios are proposed to evaluate the proposed model.

The first scenario does not consider the age of the EV's battery and the number of battery switches is unlimited. The second scenario considers that the number of swapping between charging and discharging mode is limited according to the battery's age. The study concludes that in the second case parking lot presents a lower demand, a decrease of fluctuations of average SOC and an increase of EV's battery lifetime.

In [82] a microgrid that integrates a smart parking lot for 200 EVs, micro-sources such as PV system, wind turbine system, micro-turbine and fuel cell is modelled. It is considered three scenarios similar to those in [80]. The objective function consists on minimizing the operation cost. The microgrid also incorporates a controller that is responsible for the management of micro sources and for receiving EV's owner's preferences.

The proposed model integrates three main constraints: renewable power forecasting errors, spinning reserve and EVs owner's requirements. As an additional constraint, EV's battery life it is also assumed. Moreover, the required final SOC is considered guaranteed. A prioritization strategy based on these elements and the remaining parameters (departure time, price limits) is applied in order to formulate the charge scheduling of each vehicle.

The proposed method incentives EV owners to contribute to spinning reserve by considering a payment. The study concludes that EV charging occurs during off-peak periods, with lower electricity prices. During peak hours, EVs tend to discharge or to participate in spinning reserve. In order to minimize operational costs, scenario 3 found to be the most favorable case despite the decrease of energy sales (due to the fact that a certain amount of energy is saved on EV's batteries in order to respond to spinning reserve requirements) [82].

In [79] a model for a smart parking lot for PHEVs with two sources of green energy, wind and PV, and a diesel generator is presented in order to optimize the charging rate of EVs. The study is conducted according to three optimizations. The first one consists on an optimal dimensioning and siting of the distributed generation resources, with the purpose of minimizing power losses and decrease voltage deviations of the distribution system.

In the second one, it is presented an optimal sizing of the parking lot with the objective of cost minimization. Finally, the third is based on PHEVs variables such as departure times aiming the optimization of EVs charging rate. Regarding renewable energy generation, the proposed model considers a critical day, i.e., when the lowest renewable energy potential is verified.

Two probability density functions are used to model arrival times: an exponential function for arrival times between 1:00 am and 8:00 am and a Weibull distribution for the period between 9:00 pm and 12:00 pm.

The objective of the charging rate's optimization is to deliver the maximum energy to EV's, considering power constraints and the PHEV's number in the parking lot. Regarding the SOC's optimization, its constraints involve the arrival time of the vehicles, the number of charging vehicles, starting and ending time of charge and the most up-to-date situation of grid and load. This model can be applied according to different objective functions such as the minimization of energy usage, peak demand, charging cost. Moreover, EV drivers options can be considered [79].

2.8.4.2. Uncertainty analysis in optimization models

The optimization models above presented consider several stochastic variables in their modulation such as: PV generation, number of arrived/departure vehicles, parking time of each vehicle, initial state of charge, and the energy demand of the vehicles. These elements are formulated according to different probability distribution functions. This section presents the variable's uncertainty related to optimization models.

The majority of the previous proposed models forecast the solar PV production to model the EV's charging schedule. Regarding the PV forecast, some authors consider probability distribution functions , more particularly Weibull distributions [80], [100]. In [79], the forecasting of solar generation is addressed according to a critical day of a certain year. In several models, with the purpose of preventing risks caused by the intermittent nature of renewable resources, reserve capacity is consider to compensate the renewable power forecasting errors [81], [82]

The elements related to parking lot's occupation and EV's charging is considered as stochastic variables in the most relevant studies. Therefore, they introduce an uncertainty level into the optimization models. Among the variables, is the parking time, the number of vehicles arriving at the PL, the desired charging/discharging limits prices, the initial state of charge (SOC). Frequently, these parameters are modelled through probability distribution functions such as exponential, Weibull, Gaussian and continuous uniform [79]-[82], [100]. In addition, some authors model the initial SOC through a probability function depending on battery capacity and daily driving range [100].

Other variable that introduces uncertainty to optimization models is the battery, more specifically its lifetime and capacity. Despite the fact that there are several types of EVs in the market with different battery capacities, the majority of the proposed models consider only one specific type of battery [80]-[82]. However, in [100] a uniform distribution is applied for three different types of vehicles with an equal market distribution. Another approach to this problem is discussed in [101], where it is used several types of vehicles with assumed market-share percentages and battery capacities.

In some models, the authors consider that vehicles are hybrid. Therefore, the final SOC it is not considered since these type of vehicles have the conventional fuel as a backup [48],[90]. The battery's degradation it is also a parameter that is take into account in several optimization models. In [81], it is assumed as constraints the switch number between charging and discharging mode along with lifetime battery.

Regarding the feasibility and viability of the evaluated models, there are some assumptions that do not demonstrate to be realist in practice. In [80]-[82], the studies consider that the PL will be allowed to access the day-ahead electricity price for following 24 scheduling, as well as it is assumed that the EV's owners send their charging requirement to the PL for placing their vehicle during the next day.

In fact, this is not close to reality since it would have to exist a quite strong communication between the parking lot and the grid. On the contrary, EVs drivers do not manage their parking schedule so tightly in advance. Moreover, in several models it is not considered the presence of incentives (for example, tax exemptions). Therefore, it is assumed that the EVs owners' preferences and behaviors do not change, i.e. the information send to PL are real [82].

2.8.5. State-of-the-art overview

The EVs integration on the electrical grid combined with high RES penetration has potentially numerous advantages, including the provision of grid support, the increase of power quality and, the reduction of the environmental footprint both in power generation and transportation sectors. Through smart charging techniques, EVs can be used as storage units for absorbing the surplus of renewable energy, which leads to extra benefits.

As shown, some studies have in account only uncontrolled or controlled charging, where others consider both types. As for uncontrolled charging, in [98] is illustrated the similarity of the daily EV charging and the solar PV curve. Among the controlled charging techniques, different approaches and objectives are considered to optimize the process.

The maximization of EVs drivers and parking lot's owner's profit is the objective in [80], [81], respectively. The maximization of all EVs charging/discharging rate is the main objective in [81] and [79]. Moreover, in [79], the optimization model's priority is not only the parking lot (by minimizing its costs) but also in the considered distribution system. The approach consists in minimizing power losses and decreasing voltage deviations on the distribution system.

Among the previous studies, different constraints are assumed. Some studies consider that the PL has different power sources, besides PV generation as in [79], [80], [82], [92], [97]. In [47], [65], [66], [72], [78], wind energy is considered. Many studies focus on a unidirectional mode as in [70], [75], [79], [87], [91] , however the use if a bidirectional V2G is also common [74], [81], [92]. In order to evidence the differences between the previous studies, Table 2.10 is presented.

Table 2.10 – Overview of the literature according to subjects

Reference	Impacts of high RES penetration on the electrical system		EV integration on the electrical system			Optimization Models				Grid Support	Other power sources
	Wind	PV	Uncontrolled charging	Smart Charging		Maximizing profits		Grid Characteristics	Minimizing costs		
				One way	Two ways	EV owner	PL operator				
[87]			X	X							
[88]	X		X	X	X						
[90]		X	X	X	X						
[91]		X	X	X							
[92]		X			X						X
[74]	X		X		X						
[75]	X		X	X							
[80]		X		X	X		X		X	X	X
[81]					X		X				
[82]	X	X		X	X				X	X	X
[79]	X	X		X					X		X
[97]		X	X								X
[98]			X								
[70]				X							X

Chapter 3

Methodology

This chapter describes in detail the method used to create the proposed optimal operation of a rooftop EVSPL. Section 3.1 provides the model architecture that has been adopted to solve the problem.

Section 3.2 is dedicated at the characterization of PV power generation according to the uncertain of solar irradiance and to the parameters of the chosen PV panels Section 3.3 focus on the mathematical model of an EV parking lot.

The distribution system model is formulated in Section 3.4. The optimization problem is described in Section 3.5, while Section 3.6 presents two case studies (a parking lot from a public middle school and a parking lot from a university) that have been analyzed.

3.1. Proposed Model Architecture

The proposed EVSPL scheme which allows bidirectional power is described in Figure 3.1. The main objective of the current thesis is to investigate the optimal operation of an EVSPL in order to gain the maximum benefit for the PL's operator. Based on this, a three-layer optimization problem is designed for this purpose. Figure 3.1 shows the model that has been adopted to solve the problem. The first layer of the problem is dedicated to the energy market.

The parking lot layer focus on the model of PL's behavior based on the input data such as PL traffic patterns and electricity market prices from the layer above. The PL operator's profit is maximized through market interactions along with the revenue from contracts with EV owners that use the PL. These results are based on the PLs participation on both energy and reserve markets. This layer also includes the distribution system.

The distribution system provides electric power to charging stations parking lots located in different areas. Electric vehicles are connected to the distribution power system in order to charge/discharge their batteries through charging stations.

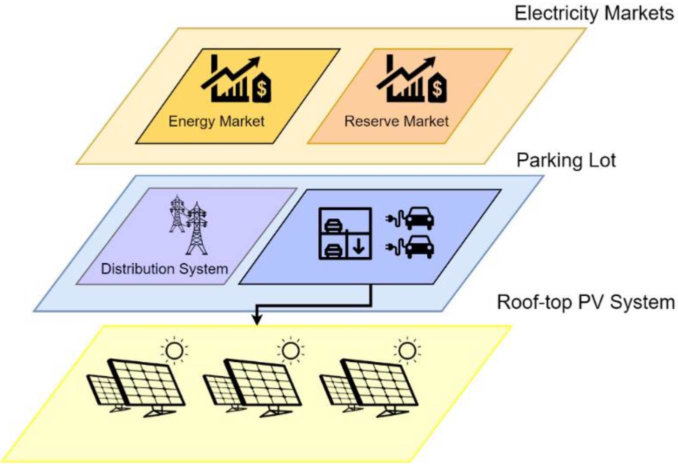


Figure 3.1 – Electric vehicle parking lot equipped with a rooftop PV.

At the distributions system, the problem is solved under network constraints considering the power generated from the rooftop PV. The last layer is dedicated to the construction of different scenarios of PV power generation according to the uncertain behavior of weather conditions. In this work, the three layers were implemented in General Algebraic Modeling System (GAMS)[102], applying the CPLEX MILP solver, and are detailly explained below.

The model is based on an hourly simulation that calculates energy output (V2G, G2V), incomes and costs of the operation the parking lot. The inputs to the model ate divided into four parts:

1. Electric vehicle – arrival time, departure time, battery capacity and state of charge;
2. PV panels – hourly solar irradiance considering seasons and location;
3. Finance – energy tariff, parking usage tariff;
4. Electricity market – energy price, reserve price and regulation up/down price.

The model and inputs considered in this analysis are shown in Figure 3.2.

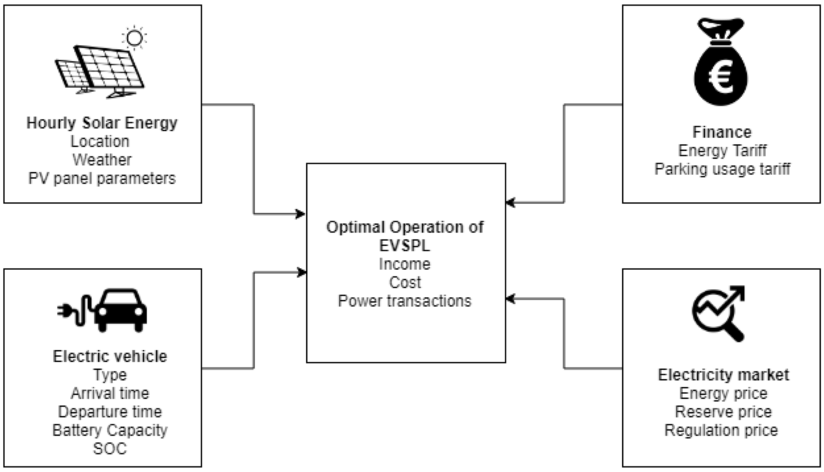


Figure 3.2 – Proposed model and its inputs.

3.2. Mathematical Model of the Rooftop PV

During daytime solar irradiance varies accordingly to sun movement, transforming PV generation extremely dependent on the local weather conditions. Based on the PV module parameters specified by the manufacturer, the maximum output at hour t can be obtained via equations (3.1)-(3.5) [99].

$$P^{PV}_{t,\beta} = N_s \times N_p \times V^{OC}_{t,\beta} \times I^{SC}_{t,\beta} \times FF \tag{3.1}$$

$$V^{OC}_{t,\beta} = V^{OC}_{STC} - K_v . T^c_t \tag{3.2}$$

$$V^{OC}_{t,\beta} = \{I^{SC}_{STC} + K_I . [T^c_t - 25°\mathrm{C}]\}\frac{G_{t,\beta}}{1000} \tag{3.3}$$

$$T^c_t = T^{amb} + (T^{NOCT} - 20°\mathrm{C}) \times \frac{G_{t,\beta}}{800} \tag{3.4}$$

$$FF = \frac{P_{MPP}}{V_{oc} \times I_{sc}} \tag{3.5}$$

where $V^{OC}_{t,\beta}$ is the PV module open circuit voltage (V) at hour t, $I^{SC}_{t,\beta}$ is the PV module short circuit current at hour t, FF_t is the fill factor of hour t, V^{OC}_{STC} is the open circuit voltage (V) under Standard Test Conditions (STC), K_v is the open circuit voltage temperature coefficient (V/°C), I^{SC}_{STC} is the short-circuit current under *STC* (A), K_I is the short-circuit current temperature coefficient (A/°C), T^c_t is the instantaneous cell temperature (°C), *NCOT* is the nominal operating cell temperature, $G_{t,\beta}$ is the global solar irradiance (W/m2) incident on the PV module at a tilt angle of β° and T^{amb} is the ambient temperature (°C).

Therefore, the total power output from the rooftop PV system is presented in (3.6) [99].

$$P^{rooftop}_{t,\beta} = \eta^{PV} \times N^S \times N^P \times P^{PV}_{t,\beta} \tag{3.6}$$

where N^S and N^P are the number of PV modules connected in parallel and in series respectively, and η^{PV} is the PV's module's efficiency.

In order to limit the injection of power from the rooftop PV to the parking lot (PV2PL), one additional constraint, presented in (3.7), has been added. According to the maximum SOC of the parking lot, the maximum power that can be injected to the parking lot depends on the SOC from the previous hour and the state of energy (SOE) from arrived/departed EVs. Furthermore, constraint (3.7) imposes that the injected energy to the parking lot must be higher than the rooftop PV power.

$$P^{rooftop}_{t,\beta} \leq P^{En,PV2PL}_{w,t} \leq SOC^{max} \times PLCapcom_t - (SOC_{w,t-1} + PLSOEnet_t) \tag{3.7}$$

where $PLCapcom_t$ represent the sum of capacity of EVs in the parking lot and $PLSOEnet_t$ consist on the net of the SOC of the EVs, i.e., $PLSOEnet_t = PLSOEin_t - PLSOEout_t$. The rooftop PV is sized according to the Hanwha QCELLS PV panel [104], which is modelled based on parameters provided by the manufacturers datasheet as presented in Table 3.1.

Table 3.1 -PV Panel Data [104]

Quantity	Value
Area of module	1.67 m^2
Nominal Power (P_{MPP})	300 W
Average panel efficiency (η)	18.0 %
Rated voltage (V_{MPP})	32.41 V
Rated current (I_{MPP})	9.26 A
Open circuit voltage (V_{OC})	39.76 V
Short-circuit current (I_{SC})	9.77 A
Nominal operating cell temperature (T^{NOCT})	(45±3)°C
Temperature Coefficient of I_{SC}	+0.04 %/K
Temperature Coefficient of V_{OC}	-0.28 %/K

3.3. Mathematical Model of an EV Parking Lot

The proposed electric vehicle PL with a rooftop photovoltaic system scheme which allows bidirectional power is illustrated in Figure 3.3. For the purpose of making accurate assumptions and investigate the impacts of EVs, due to EVs uncertainties such as the arrival and the departure times of each EV and its SOC at the arrival time, the operation of the parking lot must be limited by several constraints. These constraints are modelled in the flowing manner.

On one hand, the limit of power injection from the grid to the parking lot (G2PL) is limited by **(3.8)** according to the rate of charge of EV batteries. On the other hand, the limit of power injection from the parking lot back to the grid, i.e., PL2G, based on the discharge rate of EV batteries is presented in **(3.9)**. It has been assumed a ramp up and down of 3.3 kWh. Inequality (3.10) guarantees that the parking lot cannot exchange power can inject is back at the same time [105].

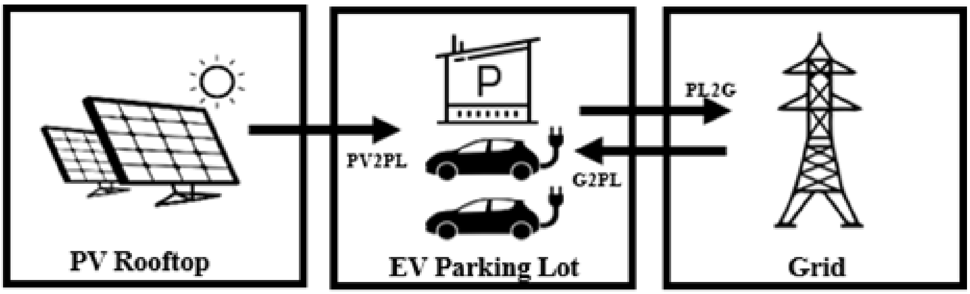


Figure 3.3 - EV parking lot equipped with rooftop PV.

$$P_{w,t}^{En,G2PL} + P_{w,t}^{En,PV2PL} + P_{w,t}^{R-down} \leq \gamma^{charge}.n_{w,t} \tag{3.8}$$

$$P_{w,t}^{En,PL2G} + P_{w,t}^{R-up} + P_{w,t}^{Res,Act} \leq \gamma^{discharge}.n_{w,t} \tag{3.9}$$

$$U_t^{G2PL} + U_t^{PL2G} \leq 1 \tag{3.10}$$

where $n_{w,t}$ represents the number of EVs in the parking lot at hour t.

The state of charge (SOC) of an electric vehicle is defined as the remaining capacity of a battery. By implementing this to an EV parking lot, the SOC of a parking lot at each hour t, presented in **(3.11)**, is dependent on the SOC from the previous hour, the power interactions with the grid in both directions (G2PL and PL2G) and the SOC from both arrived and departed vehicles [105].

$$\begin{aligned} soc_{w,t}^{PL} = {} & soc_{w,t-1}^{PL} + soc_{w,t}^{arrival} - soc_{w,t}^{departure} \\ & + \left(P_{w,t}^{En,PL2G} + P_{w,t}^{En,PV2PL} + P_{w,t}^{R-down} \right).\eta^{charge} \\ & - \frac{P_{w,t}^{En,PL2G} + P_{w,t}^{Res,Act} + P_{w,t}^{R-up}}{\eta^{discharge}} \end{aligned} \tag{3.11}$$

In turn, the SOC of the arrived and departed vehicles is presented in **(3.12)** and **(3.13)**, respectively [105].

$$soc_{w,t}^{arrival} = \begin{cases} 0, & SOC_{w,t}^{Scenario} \leq SOC_{w,t-1}^{Scenario} \\ SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & SOC_{w,t}^{Scenario} < SOC_{w,t-1}^{Scenario} \end{cases} \tag{3.12}$$

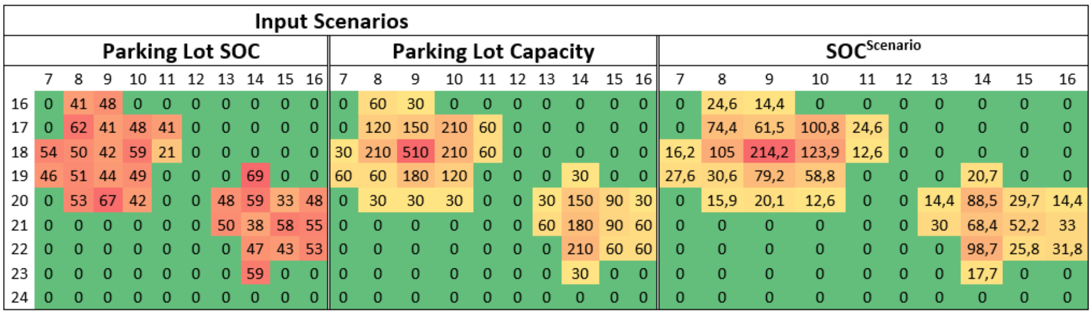
$$soc_{w,t}^{departure} = \begin{cases} 0, & SOC_{w,t-1}^{Scenario} \leq SOC_{w,t}^{Scenario} \\ \dfrac{\left(SOC_{w,t-1}^{Scenario} - SOC_{w,t}^{Scenario}\right).soc_{w,t}}{SOC_{w,t}^{Scenario}}, & SOC_{w,t}^{Scenario} < SOC_{w,t-1}^{Scenario} \end{cases} \tag{3.13}$$

where $SOC_{w,t}^{Scenario}$ represents the stored energy in the parking lot obtained from the input scenarios, and it is formulated as in **(3.14)**:

$$SOC_{w,t}^{Scenario} = \sum Cap_{w,t}^{EV}.SOC_{w,t}^{EV} \tag{3.14}$$

In above constraints (3.12) and (3.13), $soc_{w,t}^{arrival}$ and $soc_{w,t}^{departure}$refer to the aggregated amount of stored energy added to the parking lot, only because of the arrival and departure of EVs.

In order to better understand constraint (3.14), Figure 3.4 presents the parking lot's SOC and capacity between the 7:00 am and 16:00 pm, the period considered for the parking lot occupation. As it can be observed, $SOC_{w,t}^{Scenario}$ depends on the two parameters mentioned from the input scenarios. In this case, Figure 3.4 represents the input scenarios from FEUP's parking lot.



	Input Scenarios																													
	Parking Lot SOC										Parking Lot Capacity										$SOC^{Scenario}$									
	7	8	9	10	11	12	13	14	15	16	7	8	9	10	11	12	13	14	15	16	7	8	9	10	11	12	13	14	15	16
16	0	41	48	0	0	0	0	0	0	0	0	60	30	0	0	0	0	0	0	0	0	24,6	14,4	0	0	0	0	0	0	0
17	0	62	41	48	41	0	0	0	0	0	0	120	150	210	60	0	0	0	0	0	0	74,4	61,5	100,8	24,6	0	0	0	0	0
18	54	50	42	59	21	0	0	0	0	0	30	210	510	210	60	0	0	0	0	0	16,2	105	214,2	123,9	12,6	0	0	0	0	0
19	46	51	44	49	0	0	0	69	0	0	60	60	180	120	0	0	0	30	0	0	27,6	30,6	79,2	58,8	0	0	0	20,7	0	0
20	0	53	67	42	0	0	48	59	33	48	0	30	30	30	0	0	30	150	90	30	0	15,9	20,1	12,6	0	0	14,4	88,5	29,7	14,4
21	0	0	0	0	0	0	50	38	58	55	0	0	0	0	0	0	60	180	90	60	0	0	0	0	0	0	30	68,4	52,2	33
22	0	0	0	0	0	0	0	47	43	53	0	0	0	0	0	0	0	210	60	60	0	0	0	0	0	0	0	98,7	25,8	31,8
23	0	0	0	0	0	0	0	59	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	17,7	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3.4 - Input scenarios and $\boldsymbol{SOC_{w,t}^{Scenario}}$ from FEUP's parking lot.

In (3.15) is represented the SOC that is added to the EV during its stay in the parking lot, i.e., denotes the amount of energy that is injected into an EV. Contrasting, in (3.16) is represented the amount of energy that is absorbed from an EV [105].

$$soc_{w,t}^{up} = \begin{cases} 0, & soc_{w,t}^{departure} \leq SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario} \\ soc_{w,t}^{departure} - SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & Otherwise \end{cases} \tag{3.15}$$

$$soc_{w,t}^{down} = \begin{cases} 0, & SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario} \leq soc_{w,t}^{departure} \\ soc_{w,t}^{departure} - SOC_{w,t}^{Scenario} - SOC_{w,t-1}^{Scenario}, & Otherwise \end{cases} \tag{3.16}$$

where $soc_{w,t}^{up}$ and $soc_{w,t}^{down}$ are the charged and discharged SOC during the EV's parking stay.

The parking lot's SOC is limited by equation (3.17). It has been considered a minimum state of charge of 20% and a maximum of 80%, for each EV [105].

$$\sum SOC^{EV,min} \leq soc_{w,t} \leq \sum SOC^{EV,max} \tag{3.17}$$

3.4. Mathematical Model of the Distribution System

The proposed model of the EV parking lot (presented in Section 3.3) has to meet and maintain the integrity of the distribution system, which is modelled through the balance equations. Therefore, this section presents the mathematical model of the distribution system solver under networks constraints (power flow, bus voltages, reactive power) considering the power generated from the rooftop PV. The objective is the minimization of losses.

Equation (3.18) represents the power flow equation related to the active power of the system which depends on the flow of the active powers of branch ij when going upstream and downstream $\left(P_{i,j,t,w}^{+}, P_{i,j,t,w}^{-}\right)$. Similarly, equation (3.19) represents the reactive power balance, which depends on the reactive power flow of branch ij shown in the upstream $\left(Q_{i,j,t,w}^{+}\right)$ and downstream directions $\left(Q_{i,j,t,w}^{-}\right)$ [105]. These four terms represent non-negative auxiliary variables.

$$\begin{aligned} P^{S}_{i,t,w} + P^{RN}_{i,t,w} - \sum_{j}\left[\left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) + R_{i,j}.I2_{i,j,t,w}\right] + \sum_{j}\left(P^{+}_{j,i,t,w} - P^{-}_{j,i,t,w}\right) + P^{En,PL2G}_{w,t} \\ = P^{D}_{i,t} + P^{En,G2PL}_{w,t} \end{aligned} \tag{3.18}$$

$$\begin{aligned} Q^{S}_{i,t,w} + Q^{RN}_{i,t,w} - \sum_{j}\left[\left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) + X_{i,j}.I2_{i,j,t,w}\right] + \sum_{j}\left(Q^{+}_{j,i,t,w} - Q^{-}_{j,i,t,w}\right) + P^{En,PL2G}_{w,t} \\ = Q^{D}_{i,t} + P^{En,G2PL}_{w,t} \end{aligned} \tag{3.19}$$

Note that $I2$ in the equations above and thereafter, refers to an auxiliary variable representing the square root flow I2 in a given branch. In other words, the square root of I2 results in the current flow I. It is worth mentioning that, each flow is expressed as the difference of two auxiliary variables.

In the interest of completeness, the auxiliary variable of active and reactive power flows is constrained by the maximum apparent power. Inequalities (3.20) and (3.21) correspond to the constraints of the active and reactive power, respectively [105]

$$0 \leq \left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) \leq V^{NOM}.I^{MAX}_{i,j} \tag{3.20}$$

$$0 \leq \left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) \leq V^{NOM}.I^{MAX}_{i,j} \tag{3.21}$$

where t $V^{NOM}.I^{MAX}_{i,j}$ expresses the maximum transfer capacity. Note that constraints (3.20) and (3.21) may be redundant since the apparent power flow in each line should not exceed the maximum transfer capacity.

The voltage balance in the system is represented in equation (3.22). Note that $I2$ and $V2$ are auxiliary variable representing the squared current flow and the squared voltage relations, respectively [105].

$$V2_{i,t,w} - V2_{j,t,w} - Z^{2}_{i,j}.I2_{i,j,t,w} - 2R_{i,j}\left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) - 2X_{i,j}\left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) = 0 \tag{3.22}$$

The linearization constraints for the active and reactive power are presented in (3.23) [105].

$$V2^{NOM}_{i,t,w}.I2_{i,j,t,w} = \sum_{f}\left((2f-1)\Delta S_{i,j,f,t,w}.\Delta P_{i,j,f,t,w}\right) + \sum_{f}\left((2f-1)\Delta S_{i,j,f,t,w}.\Delta Q_{i,j,f,t,w}\right) \tag{3.23}$$

Equations (3.24) to (3.28) represent the piecewise linearization of the flow constraints [105].

$$\left(P^{+}_{i,j,t,w} - P^{-}_{i,j,t,w}\right) = \sum_{f} \Delta P_{i,j,f,t,w} \tag{3.24}$$

$$\left(Q^{+}_{i,j,t,w} - Q^{-}_{i,j,t,w}\right) = \sum_{f} \Delta Q_{i,j,f,t,w} \tag{3.25}$$

$$0 \leq \Delta P_{i,j,f,t,w} \leq \Delta S_{i,j,f,t,w} \tag{3.26}$$

$$0 \leq \Delta Q_{i,j,f,t,w} \leq \Delta S_{i,j,f,t,w} \tag{3.27}$$

$$\Delta S_{i,j,f,t,w} = \frac{V^{NOM} . I_{i,j}^{MAX}}{F} \tag{3.28}$$

In addition to all these constraints, the distribution system model also includes constraints related to voltage limits through $V2 \leq (V^{NOM})^2$ [105].

Inequalities (3.29) and (3.30) represent the power factor constraints, where 0.95 is taken into account [105].

$$P_{i,t,w}^{RN} \tan\big(arcos(-0.95)\big) \leq Q_{i,t,w}^{RN} \leq P_{i,t,w}^{RN} \tan\big(arcos(0.95)\big) \tag{3.29}$$

$$P_{i,t,w}^{C} \tan\big(arcos(-0.95)\big) \leq Q_{i,t,w}^{C} \leq P_{i,t,w}^{C} \tan\big(arcos(0.95)\big) \tag{3.30}$$

3.5. Optimization Model

The objective function, presented in (3.31), aims to maximize the profit from the parking lot's operator point of view. The profit results from the difference of nine income terms and nine income costs. These, in turn, are caused by the different market interactions (electricity, reserve and regulation) between the grid and EV owners that decided to perform in a V2G mode.

$$\underset{P_{w,t}^{En,PV\,2PL}, P_{w,t}^{n,PL\,2G}, P_{w,t}^{En,G\,2PL}, P_{w,t}^{Res}, P_{w,t}^{Res,Act}, soc_{w,t}^{up}, soc_{w,t}^{down}}{Maximize} \quad \{profit^{PL}\} =$$

$$\begin{aligned}
&Max \sum_{w} \pi_w \sum_{t} \{ P_{w,t}^{En,\,PL2G} . \lambda_t^{En} + P_{w,t}^{Res} . \lambda_{w,t}^{Cap,Res} + P_{w,t}^{R\text{-}up\,,\,Act} . \lambda_t^{R\text{-}up} + P_{w,t}^{R\text{-}down\,,\,Act} . \lambda_t^{R\text{-}down} \\
&+ P_{w,t}^{Res\,,\,Act} . \lambda_t^{En} + soc_{w,t}^{up} . \lambda_t^{Tariff,\,G2V} + n_t^{PL} . \lambda_t^{Tariff,stay} - P_{w,t}^{En,\,G2PL} \lambda_t^{En} \\
&-\big(P_{w,t}^{Res\,,\,Act} . \Gamma^{Res} + P_{w,t}^{R\text{-}up} . \Gamma^{R-up} + P_{w,t}^{R\text{-}down} . \Gamma^{R-down}\big) \lambda_t^{En} \pi^{unvail.} \\
&- P_{w,t}^{Res\,,\,Act} . \lambda_t^{Tariff,\,V2G} - soc_{w,t}^{down} . \lambda_t^{Tariff,\,V2G} \\
&-\big(P_{w,t}^{En,\,PL2G} + P_{w,t}^{Reg\,,\,Act}\big) Cd^{En} - P_{w,t}^{R\text{-}up} Cd^{Reg} \}
\end{aligned} \tag{3.31}$$

The first income term, presented in (3.32), results from providing energy to the electricity market, i.e., from the injection of energy from the parking to the grid (G2PL), paid at the Portuguese electricity market (λ_t^{En}) .

$$IncomePL1 = \sum_{t} P_{w,t}^{En,PL2G} \times \lambda_t^{En} \tag{3.32}$$

The second income term, illustrated in (3.33), is caused by the participation in the capacity payment of reserve. The reserve capacity payment has been extracted from [106].

$$IncomePL2 = \sum_{t} P_{w,t}^{Res,PL2G} \times \lambda_t^{Cap,Res} \tag{3.33}$$

The third income term, demonstrated in (3.34), is related to the probability of being called by the operator system generate the offered reserve. In other words, this income results from the probability of the activation of reserve by the operator system. Hourly reserve prices have been extracted from [106]

$$IncomePL3_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{call} \times \lambda_{t}^{Res} \tag{3.34}$$

The fourth income term, presented in (3.35), is caused by the process of EV charging, i.e., it represents the amount that EV owners pay to charge their EV batteries.

$$IncomePL4_{t,w} = \sum_{t} (P_{w,t}^{En,PV2PL} + P_{w,t}^{En,G2PL}) \times \lambda_{t}^{Tariff,G2V} \tag{3.35}$$

where $\lambda_{t}^{Tariff,G2V}$ represents the charging tariff from one of the Portuguese networks and it has been extracted from [107].

The fifth and sixth income terms, represented in (3.36) and (3.37), respectively, describe the profit from providing regulation up and down to the grid in regulation market. It has been considered a capacity payment for both regulation up ($\lambda_{t}^{Cap,R-up}$) and down ($\lambda_{t}^{Cap,R-down}$) markets, and have been extracted from [106].

$$IncomePL5_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \lambda_{t}^{Cap,R-up} \tag{3.36}$$

$$IncomePL6_{t,w} = \sum_{t} P_{w,t}^{Reg,G2PL} \times \lambda_{t}^{Cap,R-down} \tag{3.37}$$

The seventh term, described in (3.38), represents the parking usage tariff, i.e., the amount that EV owners pay to the parking lot for staying in the parking lot.

$$IncomePL7_{t,w} = \sum_{t} n_{t}^{PL} \times \lambda^{Tariff,stay} \tag{3.38}$$

where $\lambda^{Tariff,stay}$ corresponds to an average parking usage tariff from Porto and has been extracted from [108], and n_{t}^{PL} represents the number of EVs in the parking lot at each hour.

The eighth and ninth income terms, presented in (3.39) and (3.40), are related to the probability of being called by the operator system generate the offered regulation. In other words, these incomes result from the probability of the activation of regulation by the operator system. It have been assumed hourly regulation prices equal to regulation capacity payment, extracted from [106].

$$IncomePL8_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{call} \times \lambda_{t}^{R-up} \tag{3.39}$$

$$IncomePL9_{t,w} = \sum_{t} P_{w,t}^{Reg,G2PL} \times \pi^{call.} \times \lambda_{t}^{R-down} \tag{3.40}$$

The first cost term, presented in (3.41), results from the battery degradation due to the operation in V2G mode in reserve market.

$$CostPL1_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times Cd^{En} \tag{3.41}$$

where $Cd^{En,Res}$ represents the cost of degradation of batteries due to operate either in reserve and energy V2G mode.

The second cost term, described in (3.42), presents the cost of buying energy from grid, i.e., due to the injection of power from the grid to the parking lot (G2PL).

$$CostPL2_{t,w} = \sum_{t} P_{w,t}^{En,G2PL} \times \lambda_{t}^{En} \tag{3.42}$$

The third cost term, represented in (3.43) , describes the cost of paying to the EV owners due to discharge their EVs, in order to participate in V2G mode.

$$CostPL3_{t,w} = \sum_{t} P_{w,t}^{En,PL2G} \times \lambda_{t}^{Tariff,G2V} \tag{3.43}$$

The fourth cost term, shown in (3.44), results for the parking lot's unavailability to deliver the offered reserve. In other words, if the parking lot it is not able to provide the reserve that has been offered, it suffers a cost penalty. It has been assumed Γ^{Res} equal to the unit.

$$CostPL4_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times \lambda_{t}^{Cap,Res} \times \Gamma^{Res} \times FOR^{PL} \tag{3.44}$$

where FOR^{PL} represents the forced outage rate of the EV parking lot, considered equal to 0.02. The fifth cost term, presented in (3.45), is caused by EVs discharging due to be called by the operator system for participate in the reserve market.

$$CostPL5_{t,w} = \sum_{t} P_{w,t}^{Res,PL2G} \times \pi^{unvail.} \times \lambda_{t}^{Tariff,G2V} \tag{3.45}$$

Similar to the reserve market, the sixth and seventh terms, presented in (3.46) and (3.47), respectively, results from the battery degradation due to the operation in V2G mode in the energy and regulation market.

$$CostPL6_{t,w} = \sum_{t} P_{w,t}^{En,PL2G} \times Cd^{En} \tag{3.46}$$

$$CostPL7_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times Cd^{Reg} \tag{3.47}$$

where Cd^{En} and $\mathrm{Cd}^{\mathrm{Reg}}$ represents the cost of degradation of batteries due to operate either in energy or regulation V2G mode, respectively.

It should be noted that the operation in energy and reserve market requires deep discharging of EV's batteries, whereas shallow discharges are needed in the regulation up market.

The eighth and ninth cost term, described in (3.48) and (3.49), results for the parking lot's unavailability to deliver the offered energy in the regulation market. In other words, if the parking lot it is not able to provide the regulation that has been offered, it suffers a cost penalty. It has been assumed Γ^{R-up}, and Γ^{R-down} equal to the unit.

$$CostPL8_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-up} \times FOR^{PL} \tag{3.48}$$

$$CostPL9_{t,w} = \sum_{t} P_{w,t}^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-down} \times FOR^{PL} \tag{3.49}$$

3.6. Numerical Studies

The proposed model was implemented in General Algebraic Modeling System (GAMS) [102], applying the Mixed Integer Program (MIP) solver. The network used for the proposed model (illustrated in Figure 3.5) is composed of 15 buses and includes renewable and non-renewable production. The data of market price have been used from the Portuguese market, being extracted from [106].

In order to evaluate the proposed model, two numerical studies have been considered: the parking lot from a public middle school and the student's parking lot from the *Faculdade de Engenharia da Universidade do Porto*. These are detailed explained in Section 3.6.3, and Section 3.6.4, respectively.

Furthermore, in order to fully analyze the interaction of the EVSPL with the different electricity markets, a distinct pattern between the prices of energy, reserve, regulation and capacity payment has been considered. Thus, three different approaches have been conducted.

The first one consists of three different scenarios, for each numerical study, considering the variability of the solar irradiance during daytime and seasons and, not taking into account the capacity payment. Scenario I represent the base case that no PV generation is modelled. In Scenario II, a 100 kW rooftop PV (with a PV panel area of approximately 558 m^2) in a typical winter day has been analyzed.

Similarly, in Scenario III a 100 kW rooftop PV (with a PV panel area of approximately 558m^2) in a typical summer day has been investigated. The second approach consists on the three same scenarios for each numerical study; however, it considers the capacity payment. Finally, the third approach consists on a tenfold increase of the capacity payment

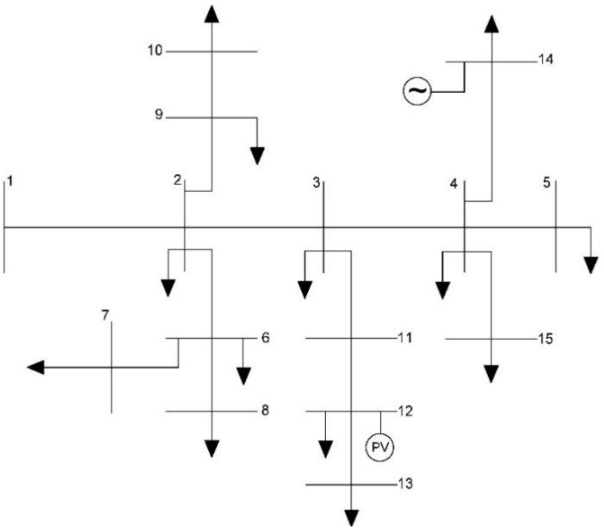


Figure 3.5 - Grid under analysis.

Figure 3.6 illustrates the load curve. It can be divided by having in account the electric demand and classifying three different time periods:

- The valley period from 2:00 am to 8:00 am;
- The off-peak period from 16:00 pm to 18:00 pm and from 23:00 pm to 1:00 am and,
- The peak period from 9:00 am to 15:00 pm and from 19:00 pm to 22:00 pm.

3.6.1. General assumptions

To test the proposed model, several assumptions had to be made. This section describes those that are common to all the scenarios.

The climate data was obtained from the Satellite Application Facility on Climate Monitoring (CM SAF) is used, which has a resolution of one hour [109]. Global in-plane irradiance $\left(G_{t,\beta}\right)$ and ambient temperature T^{amb} are obtained from [109] for the year of 2016, more specifically for January 2016 and July 2016.

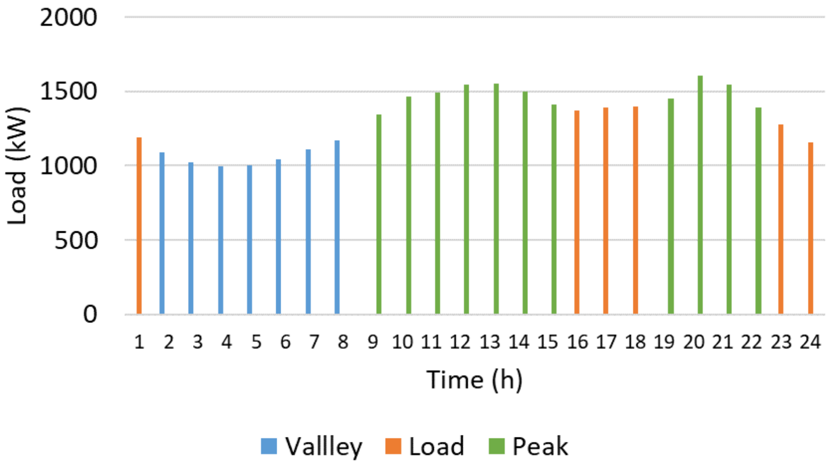


Figure 3.6 - Hourly load curve considered.

As for the energy prices, an individual pattern between the prices of energy and reserve has been taken into account in order to analyze in detail the market contribution of the parking lot. For this purpose, the data obtained from July 2016 and January 2016 of the Portuguese market have been used [106].The considered prices for energy market, reserve market and capacity payment for both months are presented in Figure 3.7 and Figure 3.8.

All EVs supposed to be Nissan Leaf [110],the third best-selling electric vehicle globally in 2018 [111] . The Nissan Leaf's features are presented in Table 3.2. Therefore, the batteries were assumed to be identical for all EVs with the capacity of 30 kWh. With regards to EV charging the following assumptions were made:

- Charging rate is 90% for all EVs;
- Discharging rate is 81% for all EVs;
- Minimum and maximum SOC is 20% and 80%, respectively.

It is also assumed that the EV owners pay 0.246 €/kWh to charge their cars, which is the current rate from one of the Portuguese operators [107]. Even though, home charging could be more economical (around 0.17 €/kWh, according to [112]), charging at the parking lot is still an attractive opportunity due to the avoidance of the need to have access to a charging station at home. It is also assumed that the EV owners pay 0.60€ for the parking usage, which is the current rate in Porto [108].

Table 3.2 – Nissan Leaf specifications [110], [113]

EV Model	**Battery Capacity**	**Real Electric Driving Range**	**Efficiency**	**Charge Power**	**Charging Costs**
Nissan Leaf	30 kWh	170 km	16.5 kWh/100km	3.3 kW	6.00 €[9] (fully charged)

Table 3.3 – Breakdown of charging tariff parameters [107], [114][10]

	Reference Price	**Excise duty**	**VAT**	**OPC[11]**	**Total**
Galp Electric	0.1989 €/kWh	0.001 €/kWh	23 %	0 €/kWh	0.24587 €/kWh

---

[9] This price is based on the average European prince of 0.20 €/kWh for charging at home

[10] A charging station in Porto was considered.

[11] As for *"Operadores de Postos de Carregamento (OPC)"*, i.e., a tax that charging stations operators can charge for EVs charging.

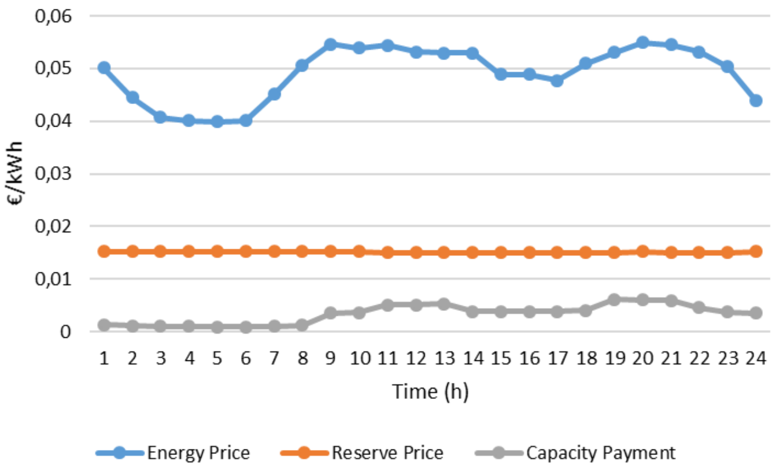


Figure 3.7 - Considered Prices (January 2016).

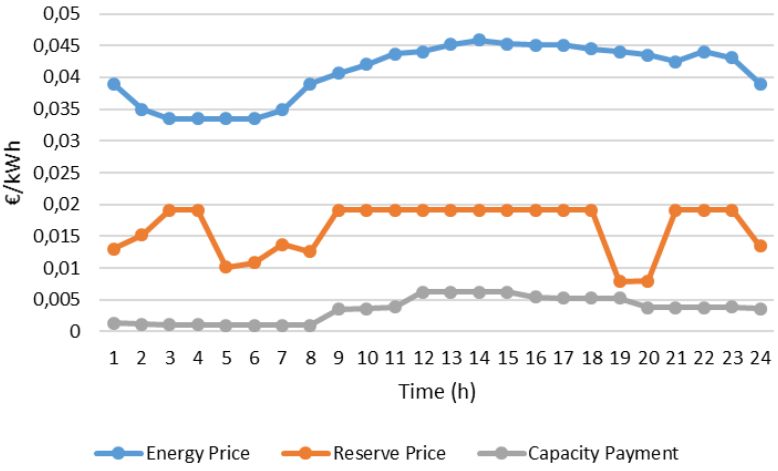


Figure 3.8 - Considered Prices (July 2016).

3.6.2. Description of ancillary services in Portugal

According to EURELECTRIC, "*Ancillary services are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality*" [115]. In Portugal, in order to guarantee the balance between production and demand, system operator has at his disposal two types of ancillary services[116]:

- **Mandatory services**, which are not remunerated and include voltage regulation, frequency regulation and maintenance of stability.
- **Additional services**, such as synchronous and static compensation, regulation reserve, secondary regulation, which are subject to payment.

Ancillary services refer to a variety of functions which are contracted so that they can assurance system security. Among them, it is especially important the frequency-power regulation. To keep the grid frequency, frequency regulation is executed by the Transmission System Operator (TSO) through balancing supply and demand.

The frequency control methods are listed below. There are three classification of reserves: primary, secondary, and regulation reserve [117].

- **Primary regulation** – associated with the ability of power generations sets to respond to unexpected imbalances in a short duration, by preserving speed and minimizing the frequency fluctuation, in order to maintain frequency as close as possible to the reference. It is an unpaid ancillary service that is obligatory for all generators in operation [117].
- **Secondary regulation** – related to the remote regulation of generator sets. It is seen as the generator or load that is able to provide and absorb the electricity in response to the frequency variation in 5 to 10 min It is a paid ancillary service according to market mechanisms [117].
- **Regulation reserve** – an additional service paid by market mechanisms. It consists on guarantee the normal operation of the system when facing incidences that may result in disparities between production and demand capable of exhausting primary and secondary regulation [117].

As mentioned above, ancillary services are indispensable to guarantee that adequate resources are available to reliably generate and transmit electricity so that there will be sufficient generation to meet the demand. Based on this process, several electricity markets present payments to power generators for their available capacity—independent of the cost of the energy produced, known as capacity payment. These payments offer an incentive for generators to locate in that market and they help guarantee that there will enough power supply to meet the demand of the market at all times.

In Portugal in 2017, a new regime of remuneration of the security reserve, provided by electric power producers and other market agents was established. The remuneration of the security reserve is established through a competitive auction mechanism that exclusively remunerates the availability services provided, supporting low carbon technologies [117], [118]. This study mainly focuses on the participation of the EVs in the secondary reserve market and capacity payments.

3.6.3. Public middle school parking lot

To test the methods above, the parking lot from a public middle school in *Senhora da Hora* (41°11'08.1"N 8°38'37.6"W), Portugal, a city located north of Porto (Figure 3.9, and Figure 3.10), was chosen. This school's parking lot is located in a municipality of 175 478 inhabitants [119], and serves professors, employees and local residents.

For the study, the parking lot occupation data from an entire day was gathered. It consists of hourly records of the number of arrivals and departures. This PL has a capacity for a maximum of approximately 41 spaces and, as it can be observed in Figure 3.9 it is not covered with any type of structure. Each parking space uses around 9.64 m^2 of area, which accounts for nearly 400 m^2 of available for car shading. The layout is mainly of perpendicular parking spaces.

Figure 3.9 – The parking lot and the area where it is located.

a.

b.

c.

Figure 3.10 – Public middle school's parking lot. (a) At 10:00h; (b) At 13:00h; (c) At18:00h.

3.6.3.1. Parking Lot Occupation Data

Real data for vehicle's arrival and departures were collected on a weekday (Tuesday 2 April 2019) from 8:00 am until 19:00 pm. It was assumed that the PL is monitored only during the class period; therefore occupation data after this period is not considered. The occupation pattern of the parking lot is dependent on the classes schedule.

The arrival/time schedule is presented in Figure 3.11-Blue markets denote the arrival time of an EV and, red markets denote the departure time.

Figure 3.12 indicates the number of vehicles that arrive and departure at a certain time. In order to analyze the data occupation during the day, a probability function of the parking duration was constructed, as shown in Figure 3.13. As it can be observed, the most likely parking duration is six hours and, the probability of an EV staying less two hours is relatively low. Figure 3.14 present the total number of EVs in the PL in each hour. As it is illustrated, the number of vehicles is higher between hours 11 and 12 and hours 15 and 16.

Additionally, at 15:00 pm the PL nearly reaches its maximum capacity. Moreover, the least occupied hour is 19. Figure 3.15 presents parking lot's occupation from a different perspective. It illustrates the percentage of the parking lot that is occupied in each hour.

The maximum parking lot's occupation is 40 vehicles, which represents a maximum occupation of nearly 98%. During the rest of the day, the parking lot's occupation is less than 80% As the PL is located in a school, the EVs that enter the PL follow class schedule.

Therefore, the total EVs can be divided into different groups based on their stay duration. Figure 3.16 shows the number of EVs in each class. For the state of charge of each EV, it is considered a random variable between 0.2 and 0.8.

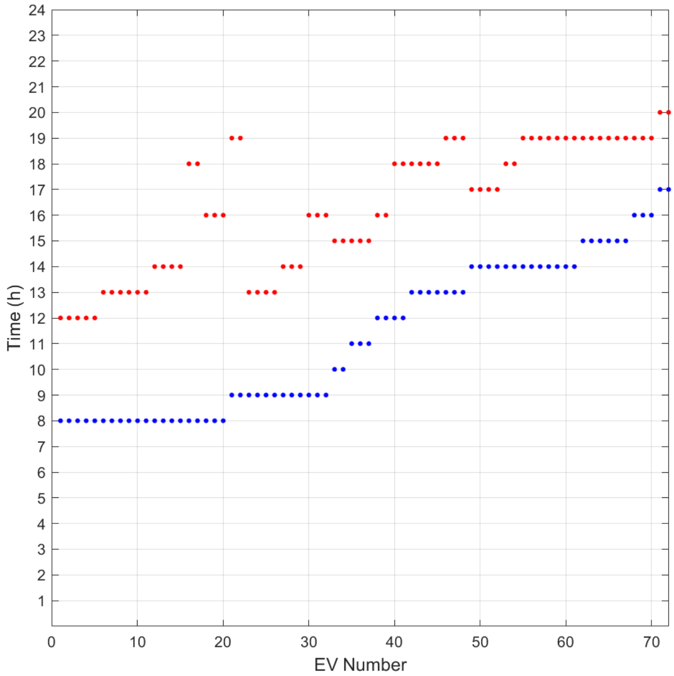
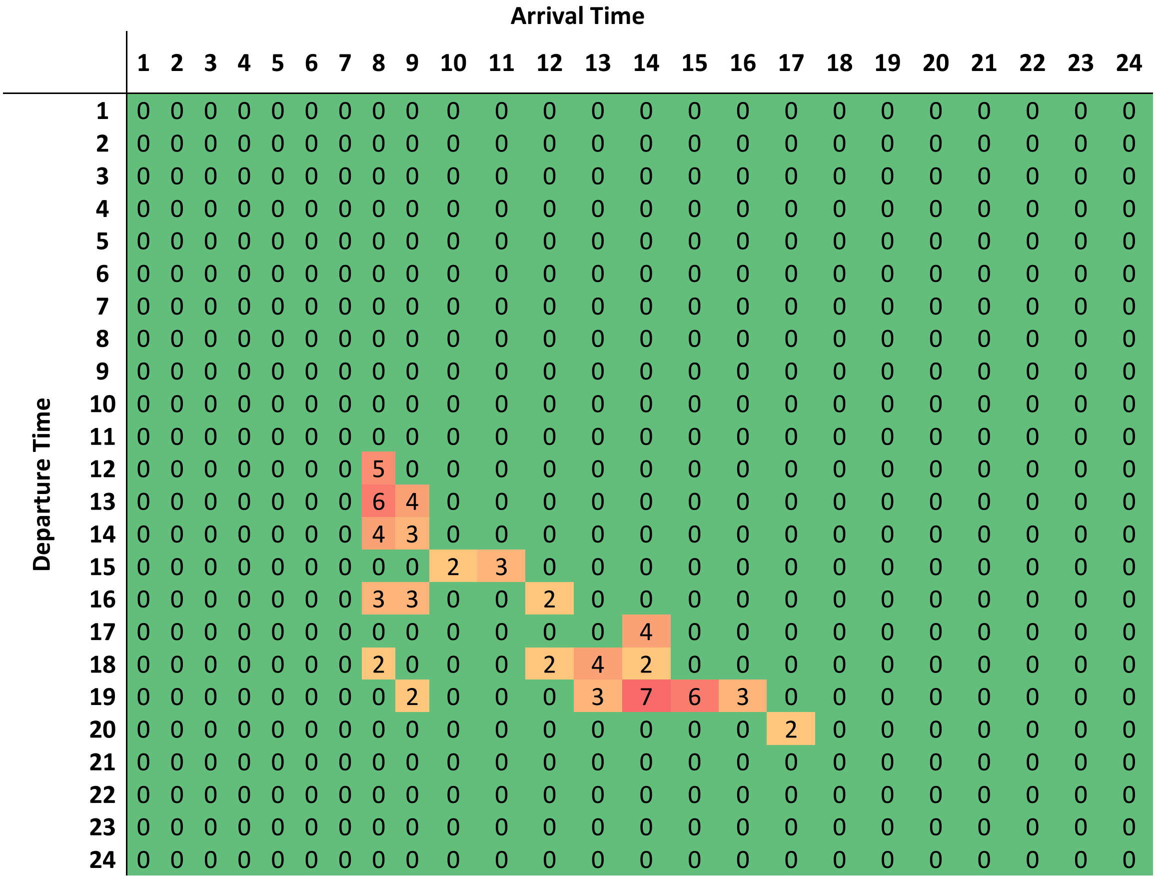


Figure 3.11 – Arrival and departure times of EVs at the PL's middle school.



	Arrival Time																							
Departure Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	6	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	3	3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	2	0	0	0	2	4	2	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	2	0	0	0	3	7	6	3	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3.12 - Number of EVs based on the arrival/departure schedule corresponding to - Public middle school's parking lot.

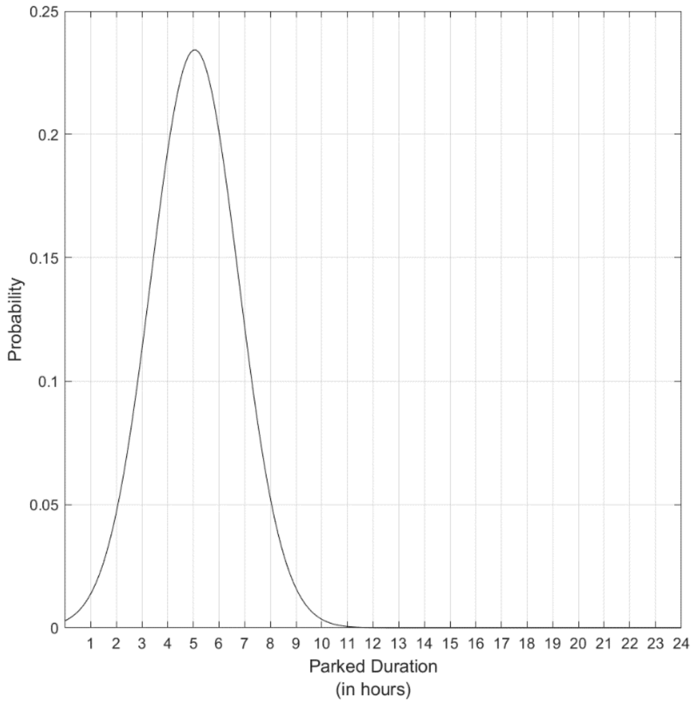


Figure 3.13 - Probability distribution of parked duration at the PL's middle school.

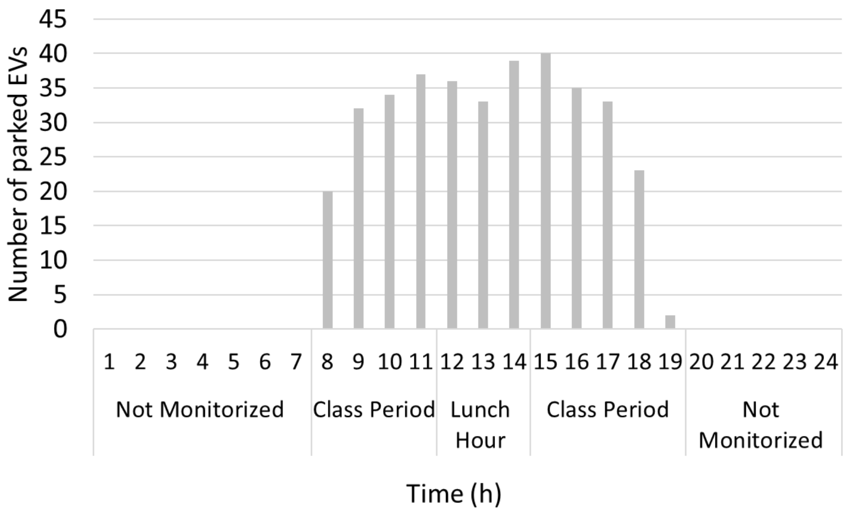


Figure 3.14 - Number of EVs in the PL's middle school in each hour.

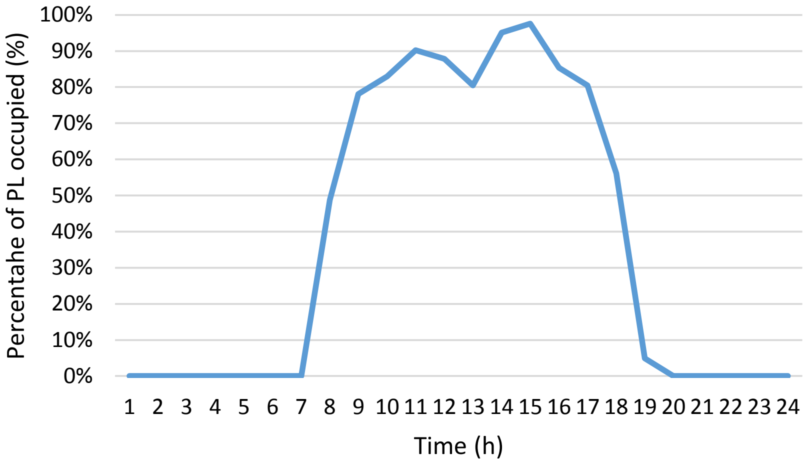


Figure 3.15 - Public middle school's parking lot occupancy during a day.

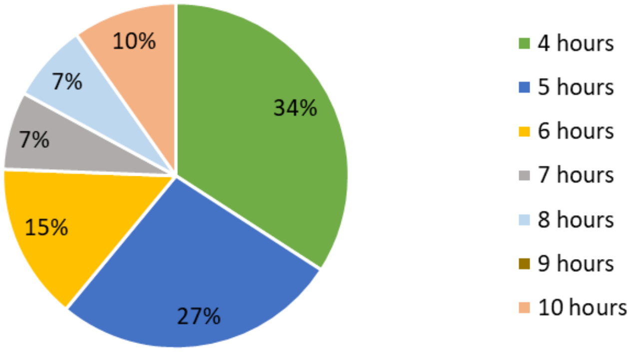


Figure 3.16 - Classification of EVs based on their stay duration.

3.6.3.2. *Rooftop PV*

Based on the conditions and methods explained in Section 0, two seasonal PV power curves were obtained, due to the fact that PV power generation actually is dependent on weather condition and is variable. Through the real solar irradiance and ambient temperature data (Figure 3.17), the daily power PV generation for both a typical winter and summer days is presented in Figure 3.18. As it can be observed, higher solar irradiance levels result in greater amounts electricity generated.

A good correlation between the photovoltaic generation and the parking lot's occupation data is essential to directly use photovoltaic for EV charging; for this parking lot, that correlation is of 78% and 94% on the typical considered winter and summer days, respectively. Figure 3.30 presents the rooftop PV production profile along with the occupation data from the public middle school's parking

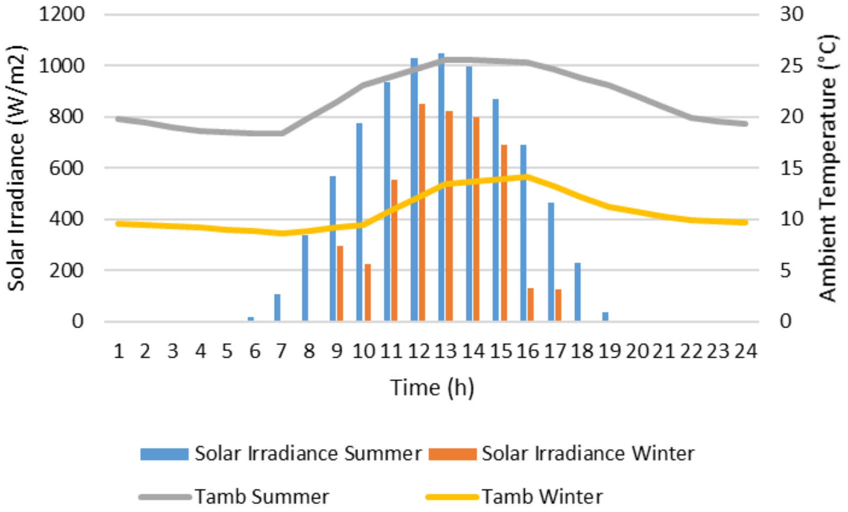


Figure 3.17 – Solar irradiance and ambient temperature for a typical winter and summer days corresponding to public middle school's case study.

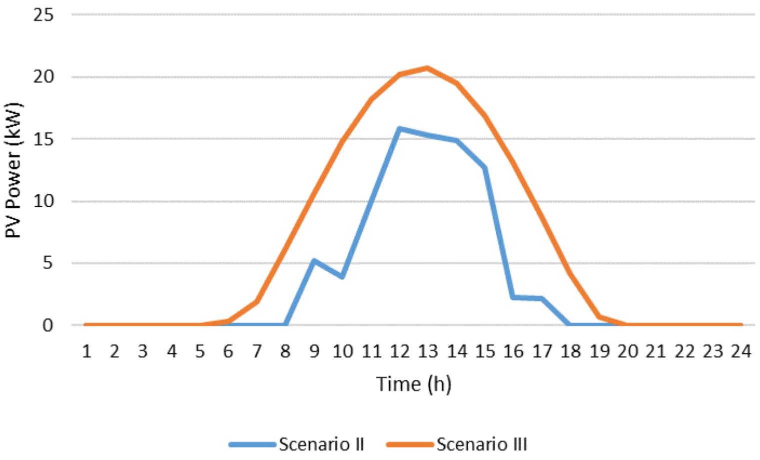


Figure 3.18 – PV Power Output (Public Middle School).

According to (3.7), the PV power output that is transferred to the parking lot is constrained. Figure 3.20 presents the maximum injection that is allowed from the rooftop PV to the public school’s parking at each hour.

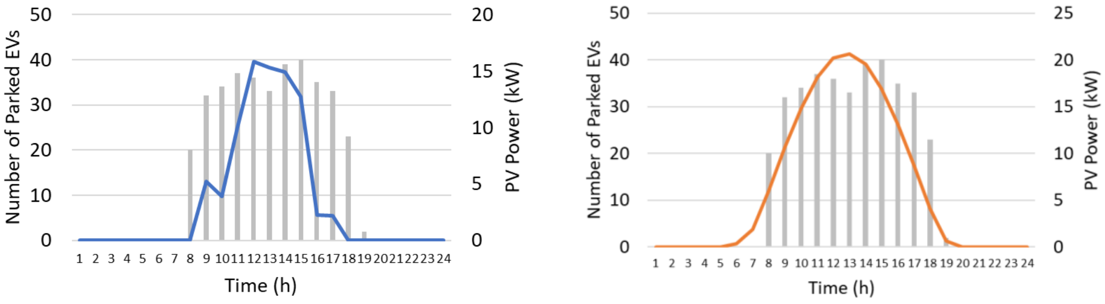
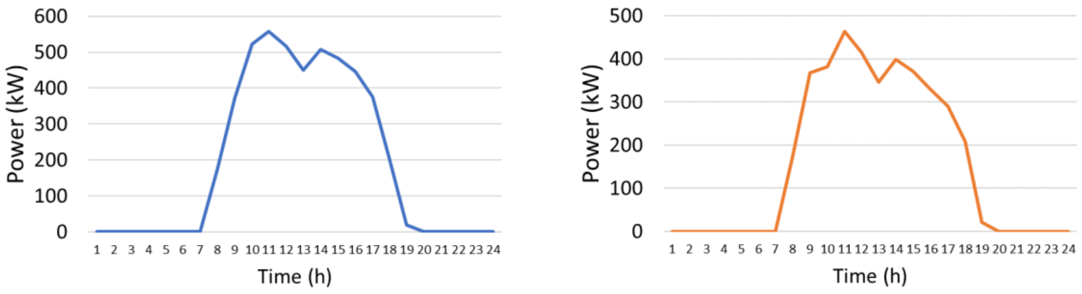


Figure 3.19- Seasonal PV production profile and public school’s parking lot occupation corresponding to (a) Typical winter day; (b)Typical summer day.



a. **b.**

Figure 3.20 - Maximum injection from the rooftop PV to the public school’s parking lot corresponding to (a) Typical winter day; (b)Typical summer day.

3.6.4. *Faculdade de Engenharia da Universidade do Porto* (FEUP)

The second case study focus on the student’s parking lot from FEUP, in Porto (41° 10’ 40.8’’ N, 8° 35’ 52.8’’ W), Portugal (Figure 3.21). The faculty serves 6730 students and 1218 employees, and has five parking lots, as it can be observed in Figure 3.22 [120].

For the study, only the permanent staff parking lot (P1) was considered. This PL has a capacity for a maximum of approximately 450 “official” parking spaces, and as it can be observed in Figure 3.5 it is not covered with any type of structure. For the numerical study, the occupation data of six rows, highlighted in red, of the parking lot occupation data was gathered, as it can be observed in Figure 3.21. These four rows make up a total of 108 parking spaces.

Figure 3.21 – FEUP’s parking lot and the area where it is located.

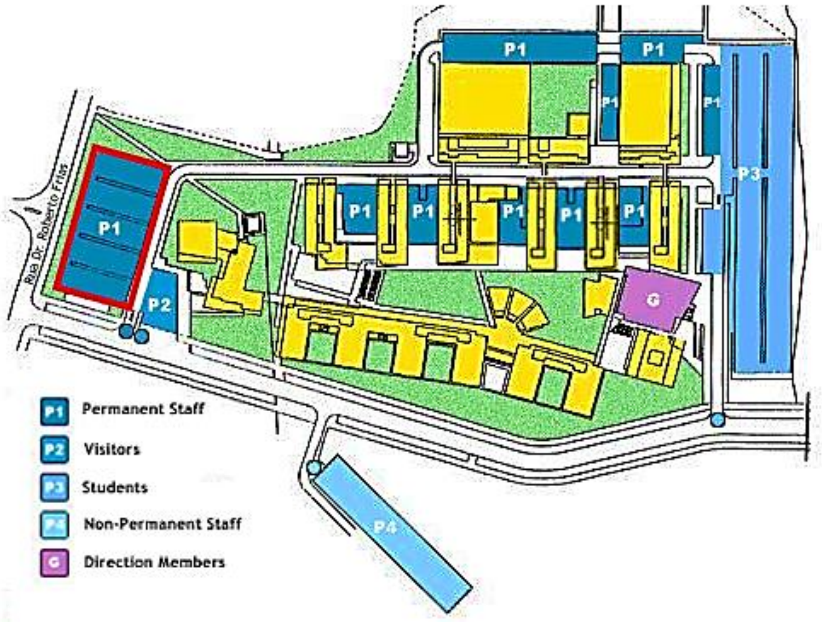


Figure 3.22 – Map of the parking lot.

3.6.4.1. Parking Lot Occupation Data

According to a study of the parking lot, the arrival and departures times of EVs are randomly distributed based on a normal distribution- The distribution of arrival times is divided into two groups, as indicated in Table 3.4.

It is assumed that the PL it is not monitored during night time and weekend. Therefore, EVs are not registered. The arrival/departure patterns of the EVs are shown in Figure 3.23. Blue markers denote the arrival time of an EV and, red markets denote the departure time. Figure 3.12 indicates the number of vehicles that arrive and departure at a certain time.

In order to study the data occupation during the day, a probability function of the parking duration was constructed, as shown in Figure 3.25. As it can be observed, the most likely parking duration is 9 hours.

Figure 3.26 illustrate the total number of EVs in the PL in each hour. As it is presented, the number of vehicles is higher between hours 14 and 16. Moreover, the least occupied hour is 22. Figure 3.27 illustrates the classification of EVs based on their duration. As it can be observed, the majority of the EVs stays in the PL between 7 and 9 hours. The SOC of each EV is considered a random variable between 0.2 and 0.8.

Table 3.4 – EVs probability distribution parameters

		Mean	Standard deviation	Max
Type 1	Arrival Time	9	0.83	11.5
	Departure Time	18		-
Type 2	Arrival Time	14	0.83	16.5
	Departure Time	21		-

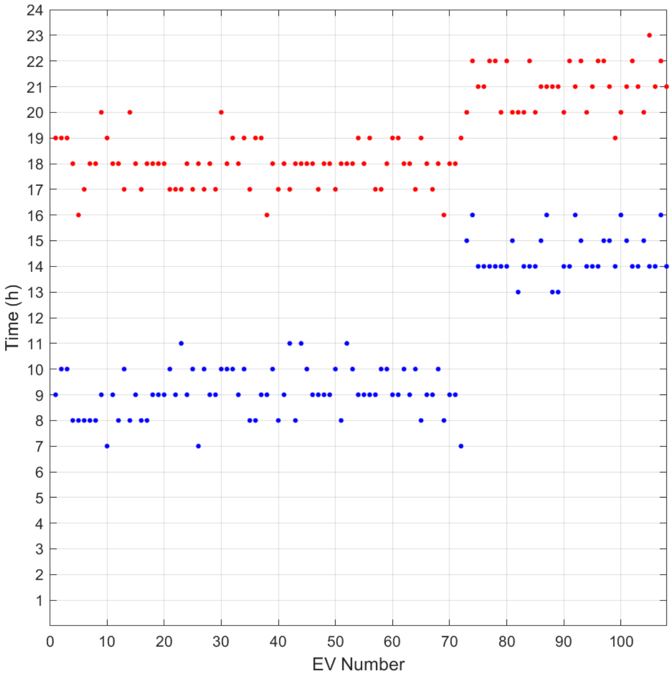
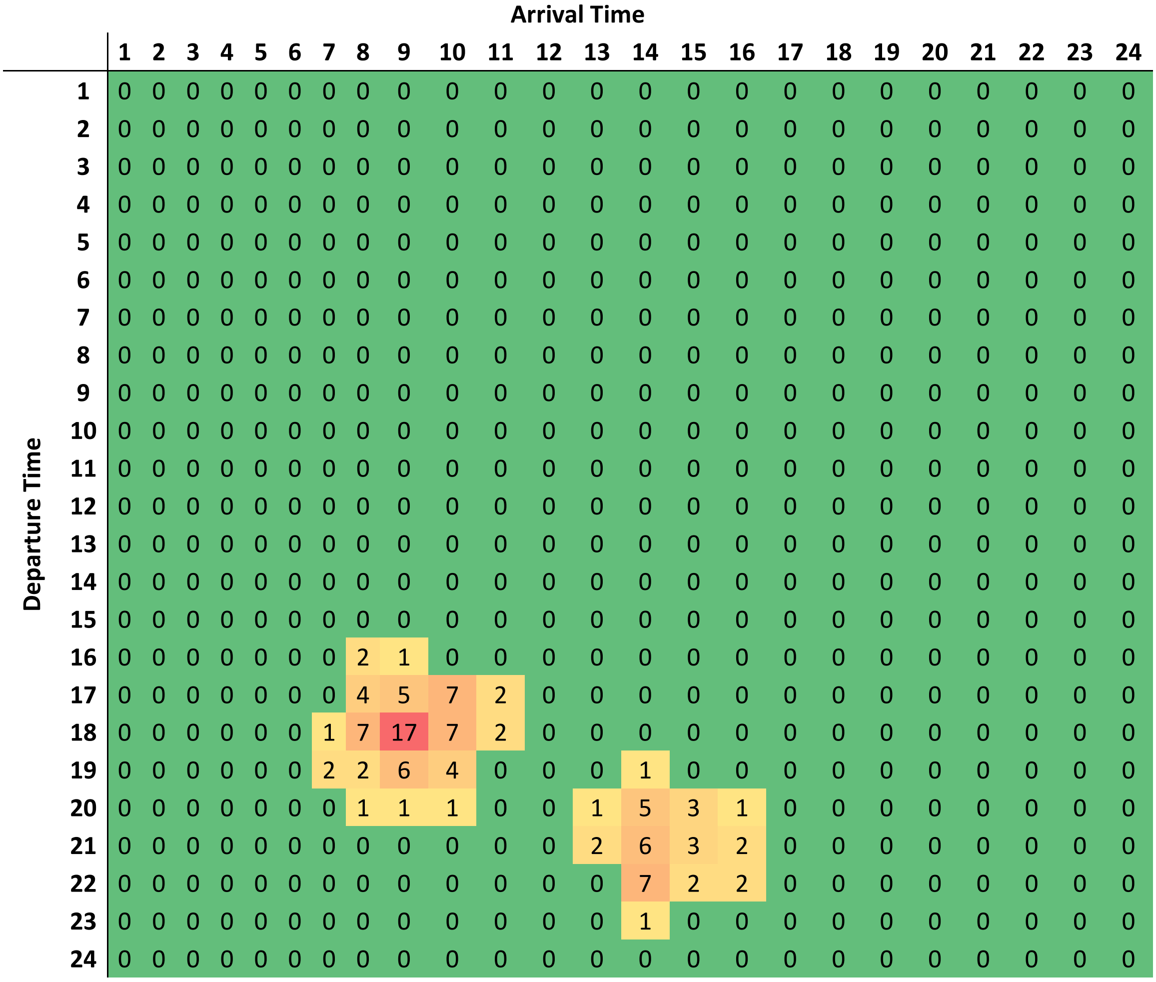


Figure 3.23 - Arrival and departure times of each EV at FEUP's parking lot.



	Arrival Time																							
Departure Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	4	5	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	1	7	17	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	2	2	6	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	1	1	1	0	0	1	5	3	1	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	2	6	3	2	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	7	2	2	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3.24 - Number of EVs based on the arrival/departure schedule corresponding to FEUP's parking lot.

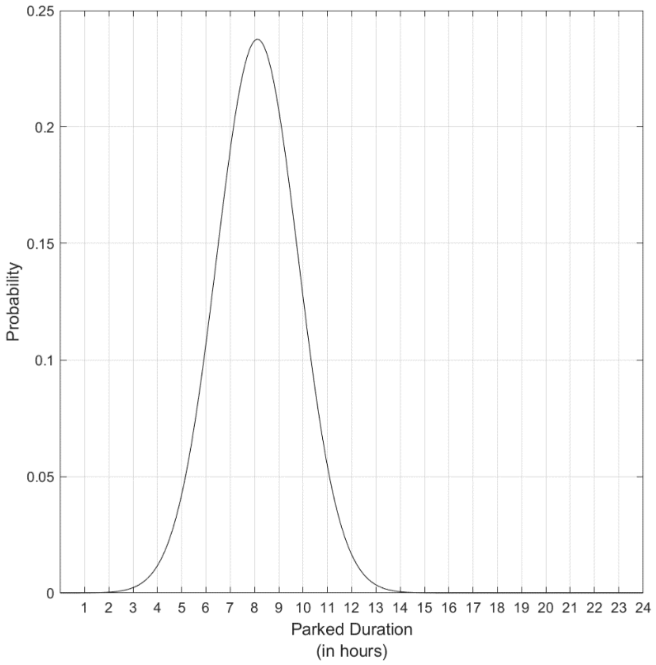


Figure 3.25 - Probability distribution of parked duration at FEUP's parking lot.

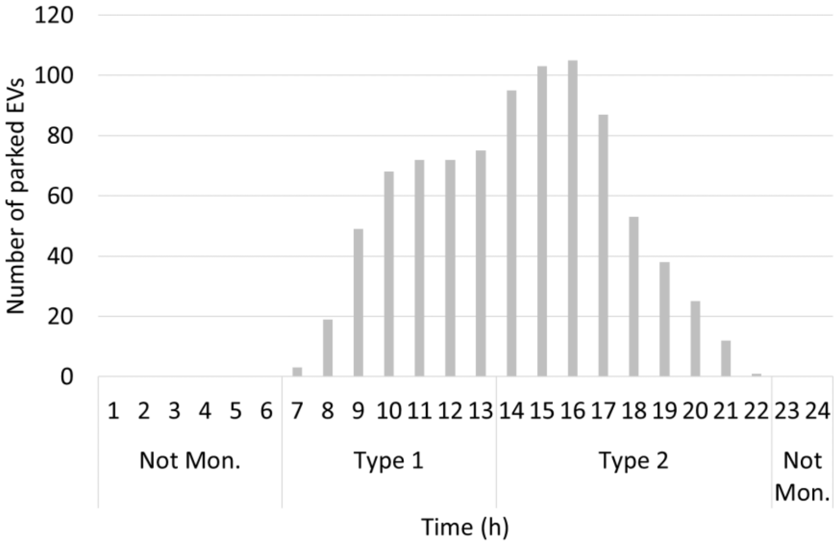


Figure 3.26 – Number of EVs at FEUP's parking lot in each hour.

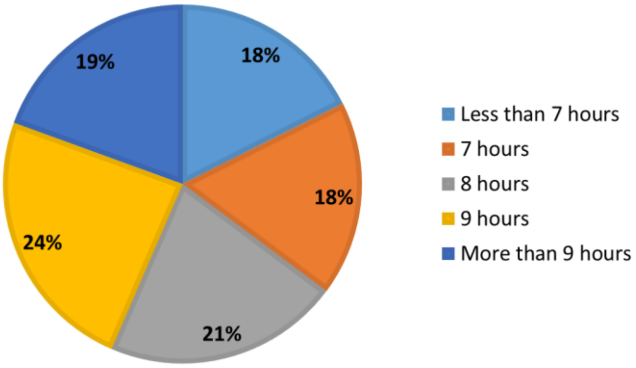


Figure 3.27 - Classification of EVs based on their stay duration corresponding to FEUP's numerical study.

3.6.4.2. Rooftop PV

Similar to the previous case study two seasonal PV power curves were obtained. Through the real solar irradiance and ambient temperature data (Figure 3.28), the daily power PV generation for both a typical winter and summer days is presented in Figure 3.29.

A good correlation between the photovoltaic generation and the parking lot's occupation data is essential to directly use photovoltaic for EV charging; for this parking lot, that correlation is of 71% and 88% on the typical considered winter and summer days, respectively.

Compared to the previous case study, these correlation present lower values due to the presence of vehicles in the evening, which does not occur in the public middle school, combined with a low/null PV generation. Figure 3.30 presents the rooftop PV production profile along with the occupation data from FEUP's parking lot

According to equation (3.7) from Section 3.2, the PV power output that is transferred to the parking lot is constrained.

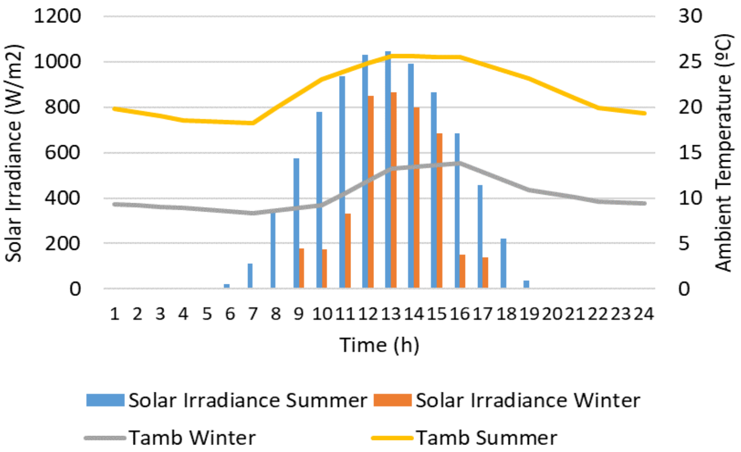


Figure 3.28 – Solar irradiance and ambient temperature for a typical winter and summer days.

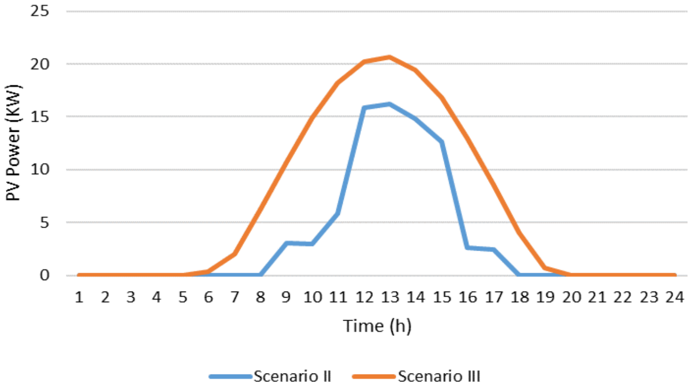


Figure 3.29 – PV Power Output (FEUP).

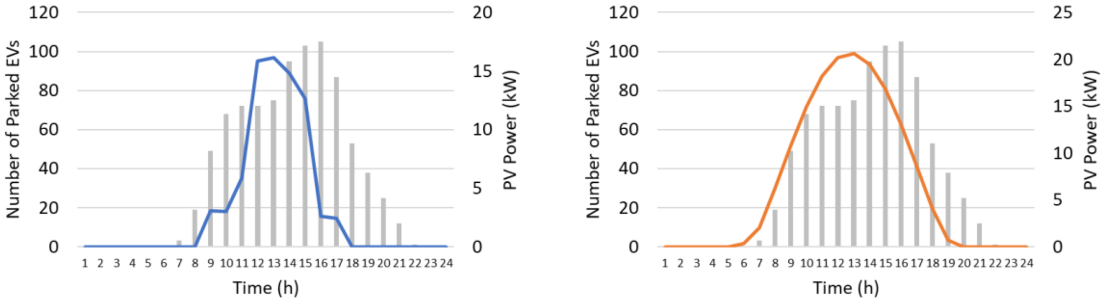


Figure 3.30- Seasonal PV production profile and public school's parking lot occupation corresponding to (a) Typical winter day; (b)Typical summer day.

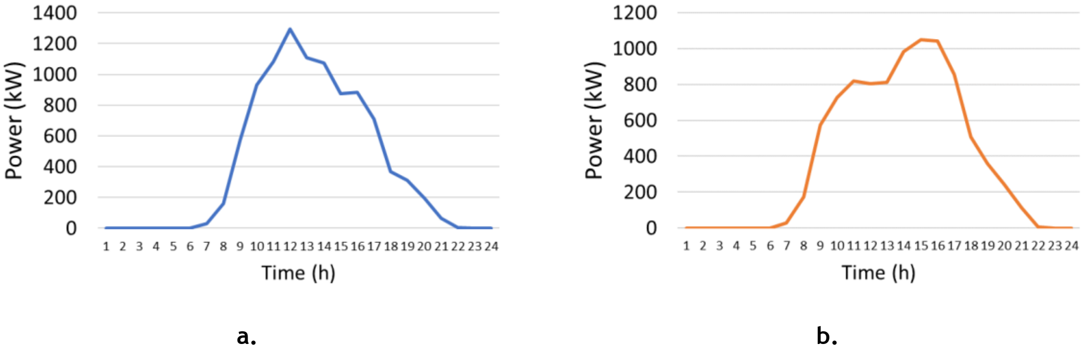


Figure 3.31 – Maximum injection from the rooftop PV to the FEUP's parking lot corresponding to (a) Typical winter day; (b)Typical summer day.

Chapter 4

Results and Discussion

This section shows and analyzes the obtained results for both case studies, with the purpose of analysing the participation in different power markets. Three approaches were conducted: no capacity payment for both reserve and regulation market is considered, the consideration of capacity payment and, an increase of the capacity payment.

4.1. Analysis Results from Public School Parking Lot

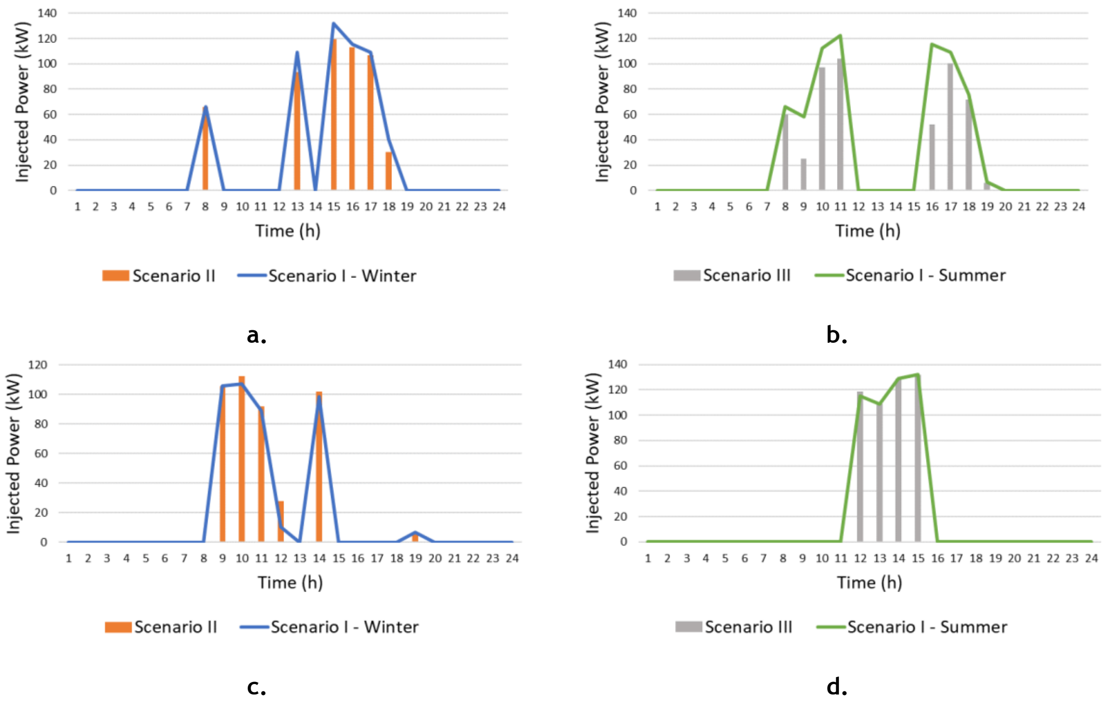
4.1.1. Without capacity payment

In this section the simulation results are presented. A total of three case scenarios were defined, considering different weather conditions, as listed in Table 4.1. Scenario I was defined as a reference/base case with no rooftop PV system. It is divided in two scenarios: winter and summer in order to compare with the remaining scenarios. In Scenario II, a 100 kW rooftop PV was formulated for a typical winter day. Scenario III considers a 100 kW rooftop PV for a typical summer day.

The traded energy between the grid and the parking lot is presented in Figure 4.1. The winter scenarios are illustrated on the left, while the summer scenarios are demonstrated on the right. In Scenario II, the parking lot buys energy from the grid only about for one hour in the morning, while the presence of a higher solar irradiance levels causes the energy's exchange to the parking lot for extended hours in the morning hours.

Table 4.1 – Public middle school's scenarios description without considering a capacity payment

Scenario	Season	rooftop PV	Capacity Payment
I (base case)	Winter	-	×
	Summer	-	×
II	Winter	100 kW	×
III	Summer	100 kW	×



a.

b.

c.

d.

Figure 4.1 - Injected power from grid to public school's parking lot (upwards) and from public school's parking lot to grid (downwards) without considering a capacity payment.

In the middle of the day, when PV generation is high the parking lot draws more energy from the grid. However, the total amount of energy drawn from the grid in winter scenarios is higher than the summer cases.

Another point that can be observed is that the parking lot purchases energy from the grid when the energy price is lower. An example is hour 10, with an energy price equal to 0.0539€/kWh and 0.042€/kWh for Scenario II and Scenario III, respectively. While in Scenario II (with the highest energy price), the parking lot does not buy energy from the grid, in Scenario III the parking lot purchases nearly 100 kW from the grid. This fact equally occurs in hour 11.

Moreover, in hours 9 and 16, in Scenario III, the parking lot buys a considerably lower amount of energy than its corresponding base scenario. On one hand, in hour 9, the parking lot buys approximately 58 kW and nearly 25 kW and, in Scenario I (Summer) and Scenario III, respectively. On the other hand, in hour 16, the parking lot buys approximately 115 kW and around 52 kW and, in Scenario I (Summer) and Scenario III, respectively.

These two facts reflect the presence of the PV generation, confirming that is not necessary to buy a great amount of energy considering a rooftop PV system.

As for the injection from the parking lot back to the grid, in Scenario III, the parking lot transfers a higher amount of energy from 12:00h to 15:00h (when electricity prices are relatively high), compared to Scenario II. This means that in the presence of a higher solar irradiance, the parking lot has a higher capability to benefit from selling energy to the grid at solar peak hours.

Another fact that can be pointed out is that the grid does not sell and buy energy at the same time. In scenario II, in hour 8, there is not enough energy generated from the rooftop PV to satisfy the charge requests of the charging EVs, thus the parking lot buys a higher amount of energy from the energy market. In contrast, in hour 14, there is an excess generation. Therefore, this surplus generation is sold back to the grid. Similarly, in Scenario III, the parking lots becomes more active in late morning and at early afternoon, while in morning and evening hours it buys a higher amount of energy from the grid.

Moreover, it can be observed that in Scenario II, in specific hours, more particularly from 10:00 am to 12:00 pm and 14:00 pm, the parking lot sells a higher energy to the grid than its respective base scenario. This fact would be expectable since in Scenario II there are two power sources that can satisfy the EV charging requirements (grid and rooftop PV), which leads to the transfer the excess of energy back to the grid.

Figure 4.2 demonstrates the participation of the parking lot in the regulation down market. By comparing Figure 4.2 with Figure 4.1 can be observed that, the EV parking lot prefers to participate in the regulation market than in the energy one. As can be seen, the parking lot has a higher potential to participate in regulation markets in a typical summer day, compared to the cases where a winter day is considered. This is due to the higher PV power uncertainty into the system at peak hours. Thus, the parking lot can benefit from supplying the regulation up/down to compensate the intermittency at these hours.

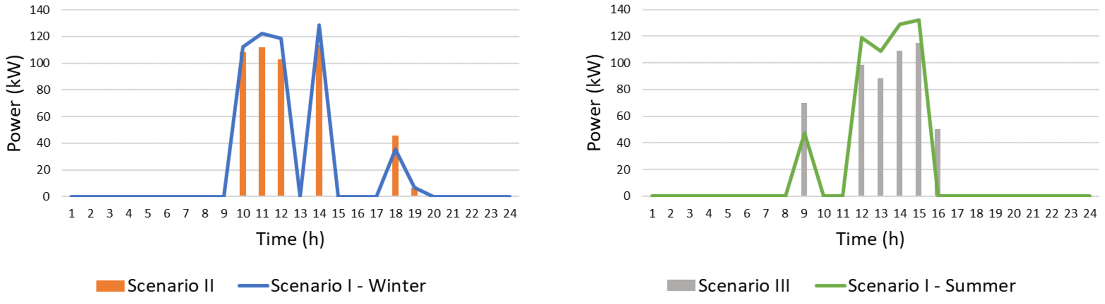
While in Scenario II, the contribution in the regulation down market occurs mainly in the morning (7:00 am to 11:00 am) and in the beginning of the afternoon, including a pause at “lunch hour”, in Scenario III the parking lot participates in the regulation down market for an extended period, including from 12:00 pm to 14:00 pm.

Moreover, despite the fact that both scenarios have the potentiality for contributing in the regulation market, Scenario III presents a higher potential to participate in regulation markets when compared to cases where a winter day is considered (Scenario II)

For PL2G, regulation down corresponds to decrease the power output or power flowing from the grid to the parking lot (battery charging). As it can be observed from Figure 4.2a, the injection from the grid to the parking lot is considerably higher (nearly 50%) at 18:00 pm when considering the integration of the rooftop PV system. Contrasting, according to Figure 4.2b, the power flow from the grid to the parking lot in Scenario III is significantly higher at 9:00 am when comparing the two summer scenarios.

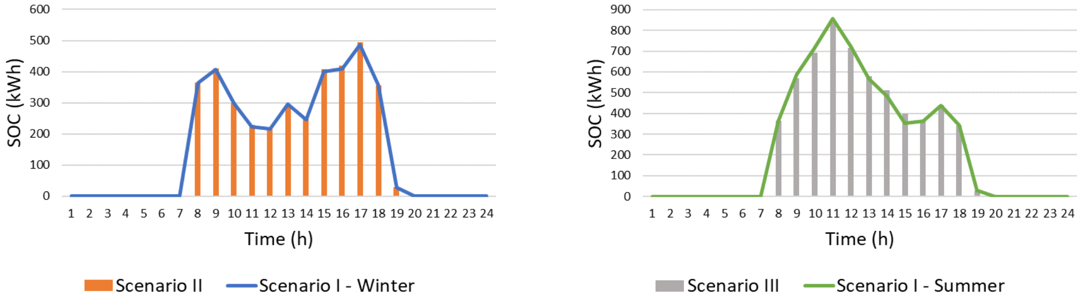
Comparing the two scenarios with different weather conditions, the mentioned fact occurs due to the price’s differences. While at 9:00 am, it is more attractive price to participate in the regulation up in the summer, at 18:00 pm it is more economically viable to participate in regulation up market in winter.

The SOC of the parking lot in each hour is presented in Figure 4.3.As it can be observed, the highest amount of changing in the SOC occurs in morning peak hours.



a. **b.**

Figure 4.2 - Public school parking lot's offer to the regulation down market without considering a capacity payment corresponding to (a) Scenario I – Winter and Scenario II (b) Scenario I – Summer and Scenario III.



a. **b.**

Figure 4.3- SOC of the public middle school's parking lot without considering a capacity payment corresponding to (a) Scenario I – Winter and Scenario II (b) Scenario I – Summer and Scenario III.

As for Scenario III, the highest commutative amount of SOC of EVs in the parking lot, occurs between 14:00 pm and 16:00 pm. In addition, in Scenario III, the SOC of parking lot is higher than the other scenarios in the majority of the hours, despite that in Scenario II a relatively higher amount of more energy is purchased from the grid than in Scenario III. Therefore, the distinction in the SOC of the parking lot does not come from the amount of energy that is bought from the grid but from the PV power output from the rooftop.

The different terms of EV parking lot's profit are presented in Figure 4.4. In all the results that are reported here, the income from parking lot usage tariff has been excluded. The reason is that although the main revenue of PLs is from entrance tariffs, the results only indicate the revenue from electrical transactions. It can be observed that Scenario I (both for winter and summer cases) is the one with the lowest profit and the most profitable is Scenario III.

Moreover, the income from charging EVs represents the largest contribution for the overall profit in Scenario III, confirming that this scenario represents a higher level of PV power generation. Moreover, Scenario II presents the highest income from electricity market. This fact would be not be expectable since in Scenario III the parking lot transfers a higher amount of energy to the grid than in Scenario II. However, this is mainly due to the considered energy prices that are higher in the winter day than the summer day.

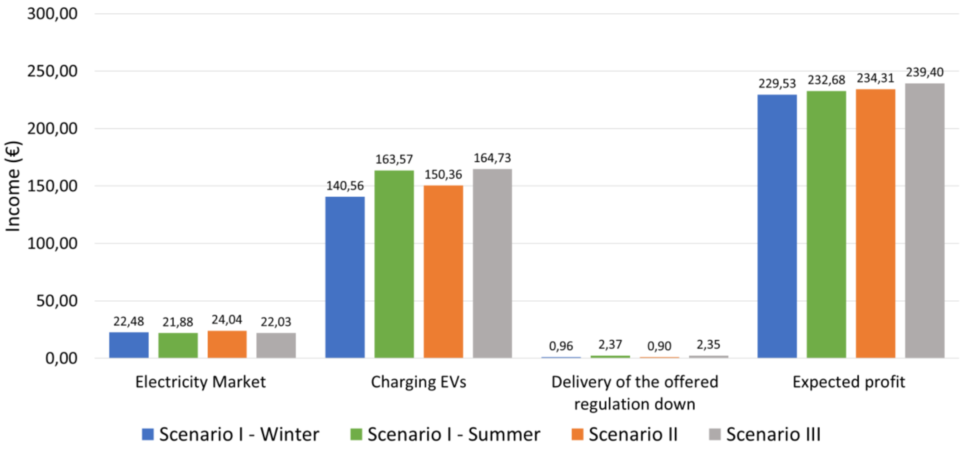


Figure 4.4 - A breakdown of public school EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) without considering a capacity payment.

The contributions of each term for the total income in each scenario are presented in Figure 4.5. As it can be observed, the largest contribution in all scenarios is the income from charging EVs, due not only to the presence of PV generation, more particularly in Scenario II and Scenario III, but also due to the high interaction from the grid and the parking lot (G2PL).

The lowest income is represented by the delivery of the offered regulation down. The reason is that the income from delivering the offered regulation is related to the probability of being called by the system operator to generate the offered regulation.

Another point that can be observed from the results is that the parking lot with and without the rooftop PV system participates practically equally in both electricity market and in the EVs charging. Therefore, the distinction in the expected profit does not come from the incomes but from costs.

However, by comparing scenarios with different weather conditions, it can be observed that the participation in the electricity market in winter is 2% higher than in summer, suggesting that the parking lot injects a higher amount of energy to the grid in winter than in summer. Despite that, the contribution for EVs charging is 2% higher in summer scenarios, which was expected due to a higher PV power production in summer.

The different terms of EV parking lot's costs are presented in Figure 4.6. The results show that Scenario III is the most expensive scenario, followed by its corresponding base scenario and Scenario II, and the cheapest is the base winter scenario.

It can be observed that in scenarios that consider the rooftop PV, the parking lot pays a higher cost for EVs to discharge. In the presence of PV power generation, EVs tend to discharge in early morning and in the evening, when market prices are high, increasing the cost associated with EVs discharging and consequently, the total cost. Moreover, the presence of PV generation leads to a higher participation in the energy market, which implies that EVs are discharged in order to inject energy to the grid.

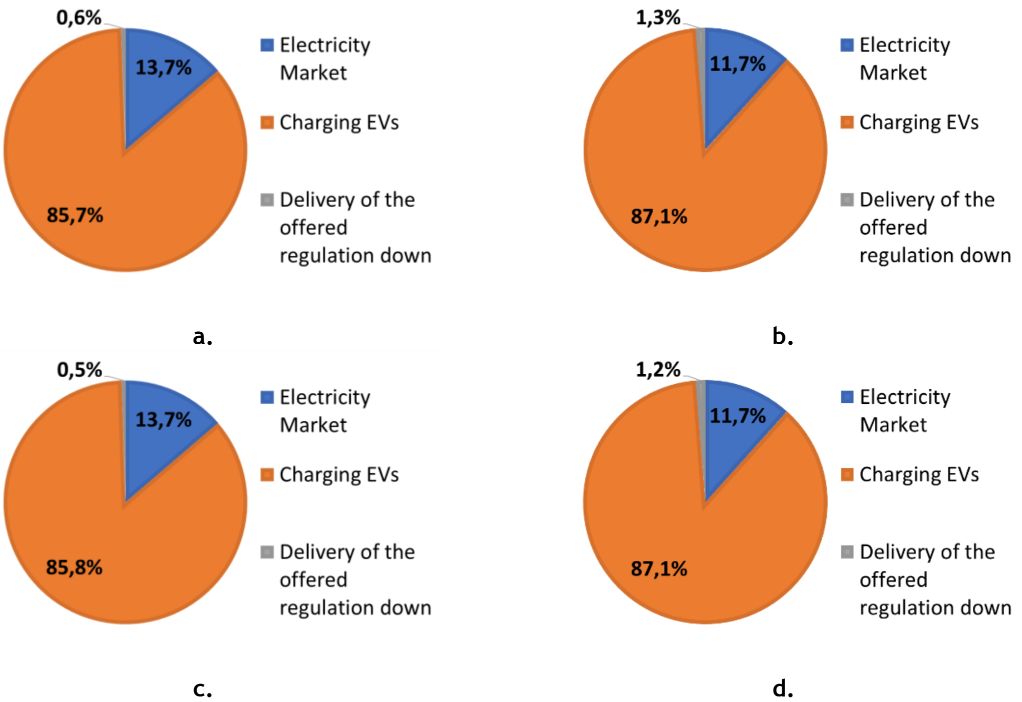


Figure 4.5 - Contribution of each income for the global public school EV PLO's profit corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer) without considering a capacity payment.

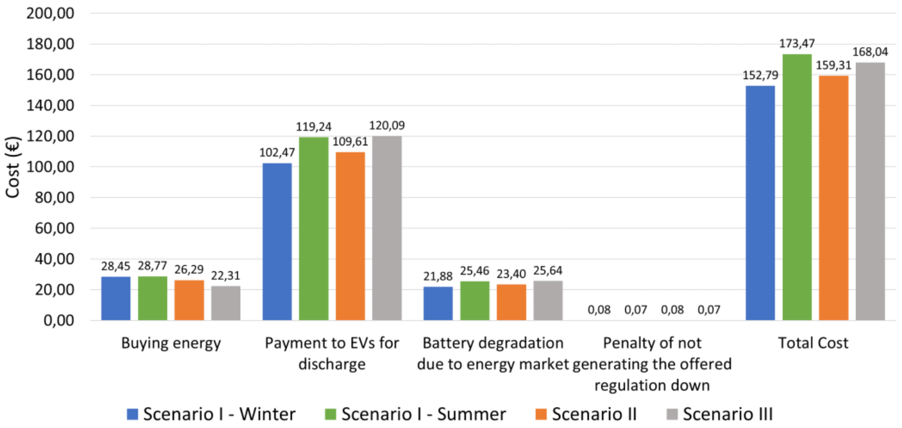


Figure 4.6 - A breakdown of public school EV PLO's cost corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) without considering a capacity payment.

The largest difference between base scenarios and the scenarios that involve the rooftop PV system is detected in the cost of buying energy from grid. While in winter scenarios there is a difference of approximately 2€, in summer scenarios it increases up to around 6€. This fact would be predictable since in the presence of higher solar irradiance levels and consequently, more PV power generation available, the parking lot is able to fulfill the charging requirement without buying a larger amount of energy from the grid. Therefore, it can be concluded that as the PV power generation increases the cost of buying energy decreases. As for the battery degradation costs, it can be observed that as the interaction between the parking lot and the grid increases, this cost also increases.

However, it is not a significant increase. On one hand, in winter scenarios, there is an increase of about 1.5€. On the other hand, in summer scenarios, this increase is even lower, not reaching 1€. In Scenario I (Winter), with the lowest impact on battery degradation cost, EVs owners do not have as much as interest in participate in PL2G activities as in Scenario III, where the cost is higher.

For a detailed analysis of each scenario, Figure 4.7 demonstrates the contributions of each cost for the total cost. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge, while the lowest is represented by the battery degradation costs due to the presence in the energy market.

By comparing the winter scenarios, it can be concluded that when considering a rooftop PV system, the parking lot buys a lower amount of energy, which was expected. Consequently, since there are two EV charging sources, i.e., grid and rooftop PV, the parking lot is more willing to participate more dynamically in the energy market, by selling energy to grid, increasing not only the battery degradation costs but also the cost payment to EVs for discharge. The same circumstances occur in summer scenarios, however with a higher difference since there is higher solar irradiance levels and consequently a larger PV output.

As an example, while in winter scenarios there is a difference of 2% in the cost of buying energy, in summer scenarios, the parking lot with the rooftop PV system buys less 3% than scenario where no rooftop PV is considered.

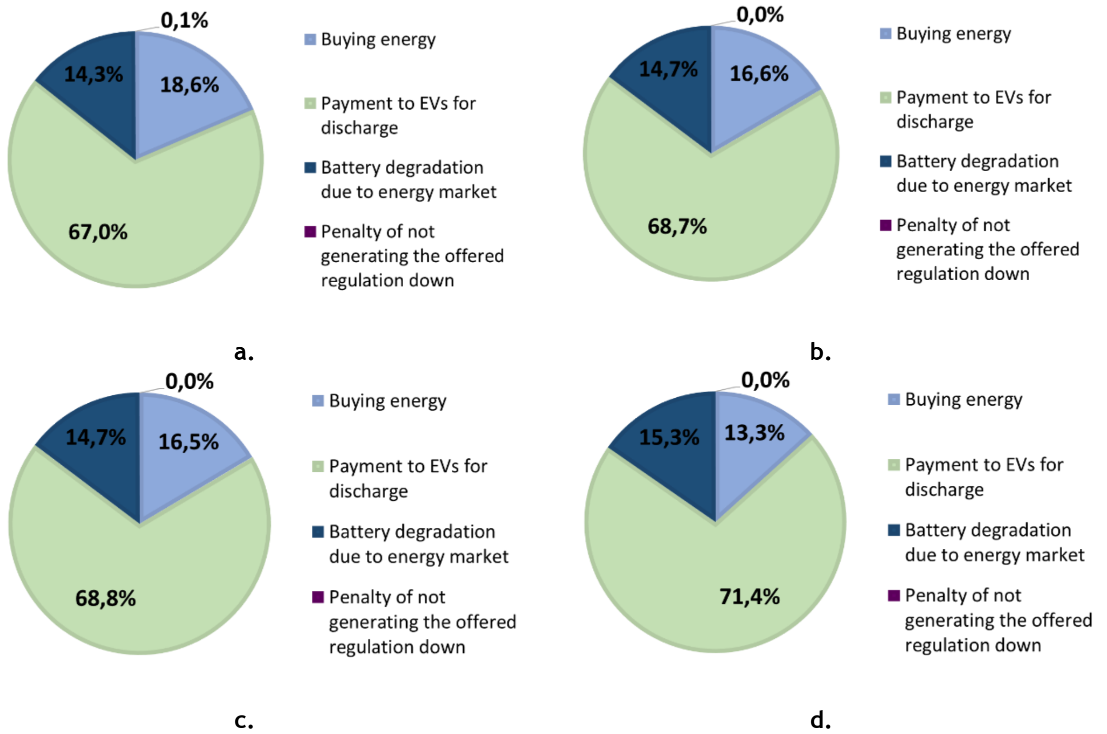


Figure 4.7 - Contribution of each cost for the global public school EV PLO's profit corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer) without considering a capacity payment.

4.1.2. With capacity payment

In this section the simulation results are presented. In accordance with the previous section, a total of three case studies were defined, considering different weather conditions, as listed in Table 4.2. However, in this section the capacity payment is considered. Scenario I was defined as a reference/base case with no rooftop PV system. It is divided in two scenarios: winter and summer in order to compare In Scenario II, a 100 kW rooftop PV was formulated for a winter day. Scenario III considers a 100 kW rooftop PV for a typical summer day.

Analogous to the previous section, the results from winter scenarios are presented on the left while summer scenario's results are illustrated on the right. The traded energy between the grid and the parking lot is presented in Figure 4.8. On one hand, in Scenario II, the parking lot buys energy from the grid only about for three hours, more specifically from 12:00 pm to 14:00 pm. On the other hand, in Scenario III, the parking lot does not buy energy from the grid at any hour. This means that either the PV generation or the regulation market is able to meet the EV charging requirements, thus it is not necessary to purchase energy from the grid.

An interestingly fact that can be deducted from the results is that even in base summer scenario, the parking lot does not buy any amount of energy from the grid. This would not be expected since the reference scenario does not involve PV generation. Considering that in this section it is assumed a capacity payment for regulation market, the EVs charging requirements are not met via the injection of energy from the grid to the parking lot but from the regulation market.

Regarding the energy injection from the parking lot back to the grid, in Scenario II the parking lot exchanges a higher amount of energy from 8:00 am to 9:00 am, occurring two peaks later at 11:00 am and 18:00 pm. It can be deduced that in this scenario, the parking lot has a higher capability to profit from selling energy to the grid at peak hours.

Contrasting, in Scenario III there is only one hour (11:00 am) when occurs the exchange of energy back to the grid. This means that the parking lot only participates in the energy market in periods that the energy price can compensate the costs of operating in V2G mode.

Table 4.2 - Public school's scenarios description considering a capacity payment

Scenario	Season	rooftop PV	Capacity Payment
I (base case)	Winter	-	✓
	Summer	-	✓
II	Winter	100 kW	✓
III	Summer	100 kW	✓

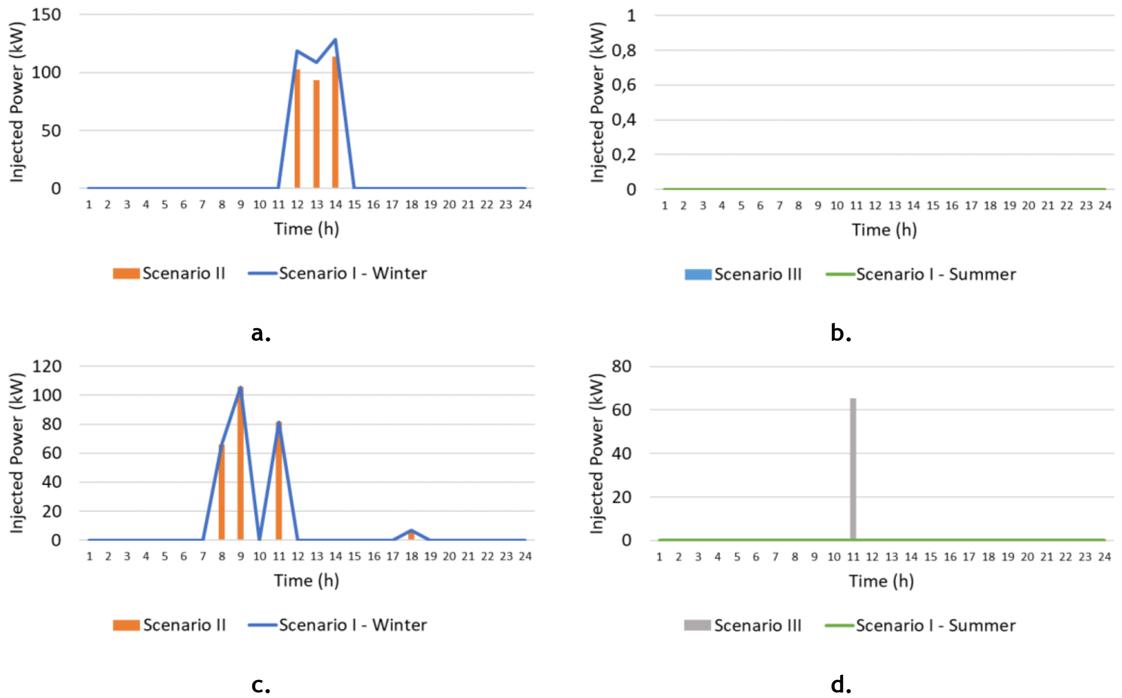


Figure 4.8 – Injected power from grid to public school's parking lot (upwards) and from public school's parking lot to grid (downwards) considering a capacity payment.

In Figure 4.9 is illustrated the participation of the parking lot in the regulation market. By comparing this with Figure 4.8 it can be concluded that, the EV parking lot prefers to participate in the regulation market than in the energy market. This preference is especially evident it in Scenario III there is only one hour that presents interaction with the grid, i.e., participation in the energy market.

While in Scenario II, the contribution in the regulation down market occurs in the morning (8:00 am to 11:00 am) and in the beginning of the afternoon until evening, including a pause at "lunch hour", in Scenario III the parking lot participates in the regulation down market for an extended period, including from 12:00 pm to 14:00 pm. This fact means that the considered price and capacity payment for the regulation down, at these specifically hours, are more attractive in summer than in winter.

Despite the fact that both scenarios have the potentiality for contributing in the regulation market, Scenario III presents a higher potential to participate in regulation markets in compared to the cases where a winter day is considered (Scenario II) This is due to the higher PV power unpredictability into the system at peak hours.

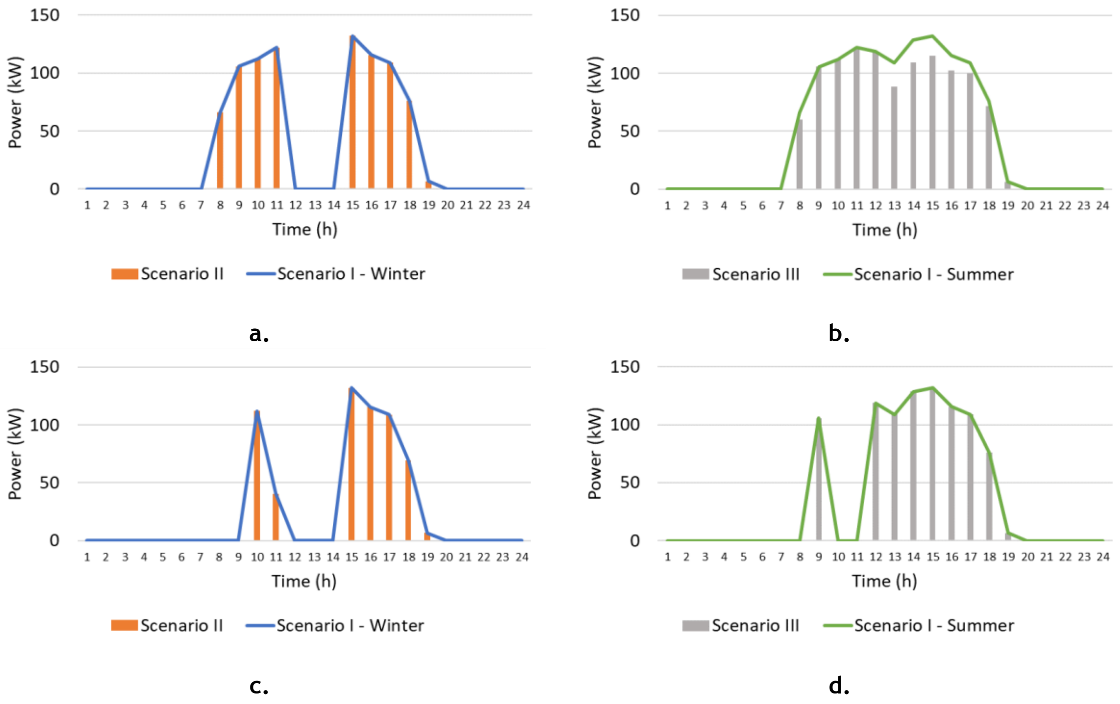
Thus, the parking lot can benefit from supplying the regulation up/down to recompense the uncertainty at these hours. Another point that can be observed is that the parking lot participates in the regulation up market only in periods that the capacity payment can compensate the costs of contributing to regulation market. As an example, as can be observed in Figure 4.9 (downwards), in the hour 9, in Scenario II there is no participation in the market, while in Scenario III the parking lot contributes to this market.

Therefore, the capacity payment for the regulation up in this hour is higher in the considered typical summer day than in the winter day. Contrasting to what occurs in the previous section (in which the capacity payment is not considered), these results show that the capacity payment significantly influences the presence in the regulation up market.

As can be observed in Figure 4.9 , more specifically in Figure 4.9c and Figure 4.9 d, the parking lot participates in the regulation up market mainly after midday. On one hand, in Scenario I the parking lot is most willing to increase its output in hour 10 during the morning (in around 112 kW), while in the afternoon; the parking lot participates in the regulation up market with 132 kW.

On the other hand, in Scenario III, the parking lot participates more intensively in the regulation up market in hour 15 and 16, in which the parking lot is almost totally occupied. As an example, as it can be observed from Figure 4.10, the participation in the regulation up occurs in hours that can always compensate the costs, more particularly the battery degradation costs. This fact is more evident in hours 14 and 15, where the offset is higher.

The SOC of the parking lot in each hour is presented in Figure 4.11. As for Scenario II, the highest amount of changing in the SOC occurs in between 14:00 pm and 16:00 pm, when the parking lot buys energy from the grid. Regarding Scenario III, the highest commutative amount of SOC of EVs in the parking lot, occurs between 14:00 pm and 16:00 pm. In addition, as it can be observed a higher SOC is achieved in Scenario III (where a typical summer day is considered) in the majority of the hours. Despite the fact that in Scenario II more energy is purchased from the grid, in Scenario III, a higher PV power output is presented in Scenario III and, hence, a higher SOC is achieved.



a.

b.

c.

d.

Figure 4.9 – Public school's parking lot offers to the regulation down (upwards) and regulation up (downwards) markets considering a capacity payment.

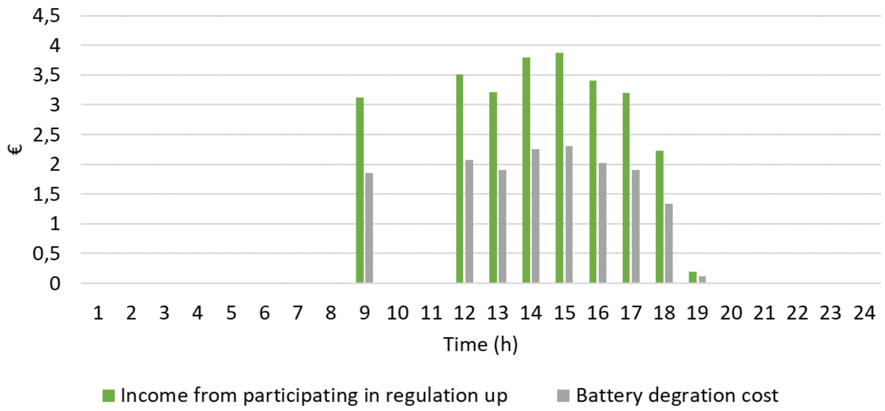
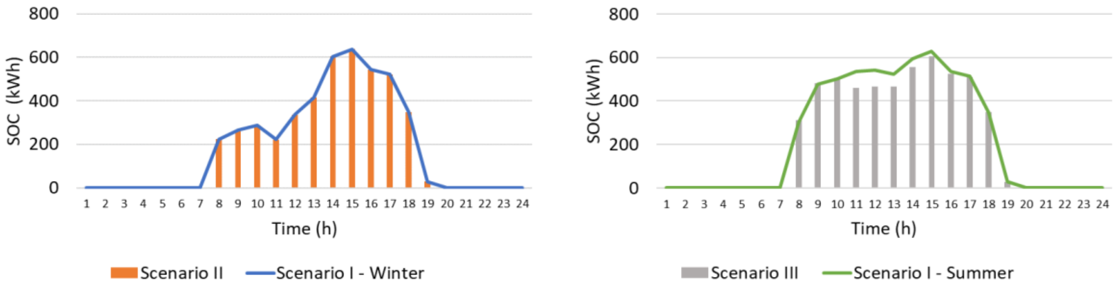


Figure 4.10 – Income and cost from the participation in the regulation up market corresponding to Scenario III from public school's parking lot.



a. **b.**

Figure 4.11- SOC of the public middle school's parking lot considering a capacity payment corresponding to (a) Scenario I – Winter and Scenario II (b) Scenario I – Summer and Scenario III.

The different terms of EV parking lot's profit are presented in Figure 4.12. It can be observed that Scenario I concerning a typical winter day is the one with the lowest profit, followed by Scenario II and Scenario I concerning a typical summer day. The most lucrative scenario is Scenario III. In this case, the parking lot has the highest income from charging the EVs.

Even though Scenario I (Summer) presents a relatively high income, this does not come from charging EVs, but from providing services to the grid, more specifically by participating in regulation up/down. This means that in the presence of a capacity payment for both reserve and regulation up/down the parking lot prefers rather contribute to these markets than purchasing energy from the grid in order to charge EVs.

Regarding electricity market income, Scenario II presents it the highest. This fact would be expectable since Scenario II presents a higher interaction between the grid and the parking lot, when compared with Scenario III, in which there is injection from grid to parking lot only for one hour.

Furthermore, Scenario III presents a smaller income from charging EVs, when compared with Scenario II, since it does not purchase energy to the grid, thus the rooftop PV is the only that meets EVs charging requirements. As for the costs, the contributions of each term for the total income in each scenario are presented in Figure 4.13.

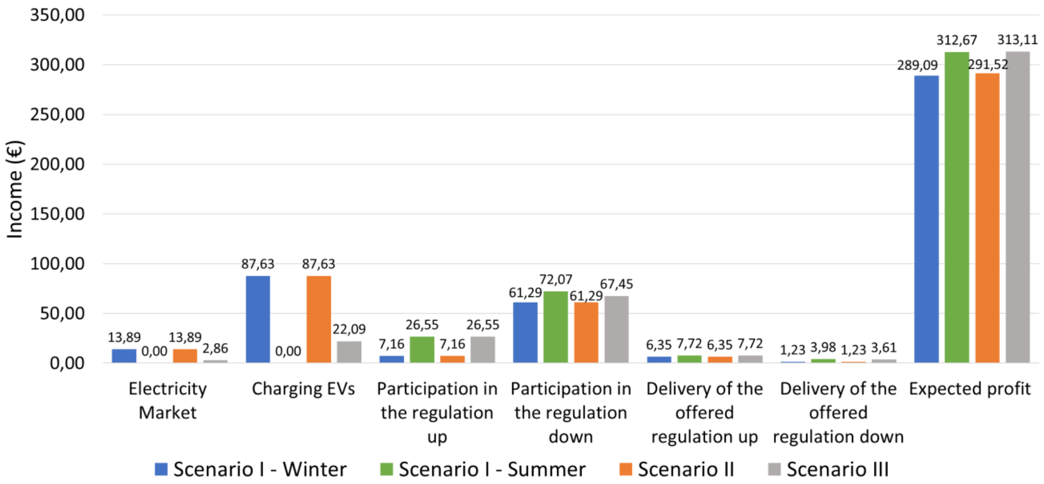
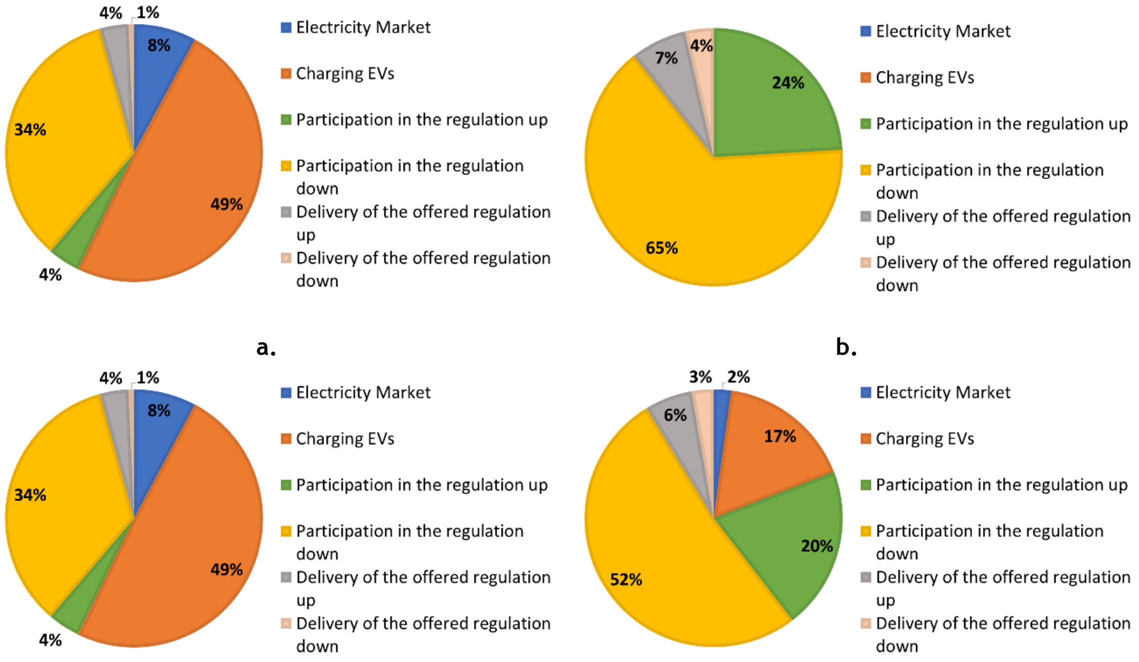


Figure 4.12 - A breakdown of public school EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering a capacity payment.



a.

b.

c.

d.

Figure 4.13 -Contribution of each income for the global public school EV PLO's profit corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer) considering a capacity payment.

As it can be observed, the largest contribution in Scenario I (Winter) and Scenario II is the income from charging EVs, while in Scenario I (Summer) is the income resulted from participating in the regulation down market. The results also show that in Scenario III, the highest income outcomes from contributing in the regulation down market, as in Scenario I (Summer), however with a lower share. Another point that can be observed from the results is that there are no differences regarding incomes between the base winter Scenario and Scenario II.

Therefore, the distinction in the expected profit does not come from the incomes but from costs. Even though, the parking lot participates actively in the regulation up and down market, the income resulted from being called by the operator system to deliver the offered regulation represents a relatively small fraction in the global profit, both in Scenario II and Scenario III, since this income is related to the probability of activated quantity of regulation by the operator system.

On one hand, in Scenario II, the total income for deliver the offer regulation represents 5% in the overall profit. On the other hand, in Scenario III, this income represents a fraction of 9% in the total expected profit.

The different terms of EV parking lot's costs are presented in Figure 4.14. As it can be observed, the base case (winter) is the one with the highest cost, while the base case regarding summer presents the lowest cost. By comparing scenarios with rooftop PV system, Scenario III is the most expensive scenario.

Regarding the cost of purchasing energy from the grid, scenarios involving winter season represent the highest costs, when compared with scenarios considering a typical summer day. In fact, scenarios involving higher levels of solar irradiance present a null cost of buying energy from the grid, confirming that the EVs charging requirements are not fulfilled through by purchasing energy and/or the rooftop PV but from the participation in the regulation market.

As for the payment cost to EVs for discharge, the winter scenarios present equal costs. This fact would be expectable since in these scenarios the parking lot transfers back to the grid the same amount of energy, at the same hours. Excluding the summer base scenario, Scenario III presents the lower cost due to the payment for EVs to discharging since the parking lot only interacts with the grid only for one hour. An evident difference is detected between Scenario II and Scenario III, regarding battery degradation costs both in energy and regulation market.

Something that can be deducted from the results is that as the participation in these markets increases, the costs increase. On one hand, Scenario II presents the highest impact on battery degradation cost. This is due to the fact that EVs owners are interested in participating in the different markets. On the other hand, Scenario III presents a lower effect on battery degradation cost, meaning that EVs owners do not have as much as interest in contributing to both energy and regulation markets, when compared with Scenario II.

When considering a capacity payment, these costs have decreased since the parking lot participates not only in the energy market but also in regulation market, which presents a lower cost of battery degradation. Another point that can be observed from the results is that the parking lot pays a penalty due to the unavailability to generate the offered regulation up and down, even though this cost represents a very lower contribution for the total cost (0.2 % in Scenario II and 1% in Scenario III).

The contributions of each term for the total cost in each scenario are presented in Figure 4.15. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge, except for the Scenario I (Summer) where the cost of battery degradation due to the participation in the regulation market is the most expensive term.

The lowest costs are represented by the cost penalties of not generating the offered regulation (both up and down). As for the winter scenarios, the distinction in the contributions of each cost results from buying energy from the grid. In Scenario II the parking lot buys a maximum of approximately 114 kW at hour 14, while in its respective base scenario it purchases a maximum of 130 kW. Regarding summer scenarios, there is a considerably higher disparity in the cost's distribution between base scenario and Scenario III.

Regarding Scenario I (Summer), the total cost is practically caused by the battery degradation cost due to the participation in the regulation market. This fact would be expectable since the parking lot does not charge EVs by buying energy from the grid but from participating in regulation market, more specifically in regulation down. Therefore, by taking part in ancillary services, the battery degradation costs increase.

Scenario III is a considerably more balanced scenario since the parking lot participates not only in the energy market but also in regulation market, leading to a contribution of each market for the battery degradation. The total battery degradation costs represent 54% of Scenario's III total cost. The contribution of approximately 45% due to payment to EVs for discharged is caused by the interaction with the grid at hour 11, with an injection back to the grid of around 66 kW.

By participating in the regulation market, the parking lot is at risk of not being able to generate the offered regulation, which may lead to costly penalties. As can be observed in Figure 4.15 this fact occurs in all scenarios. However, these penalties represent an extremely small fraction of the total cost, reaching a maximum of 2% in Scenario I (Summer).

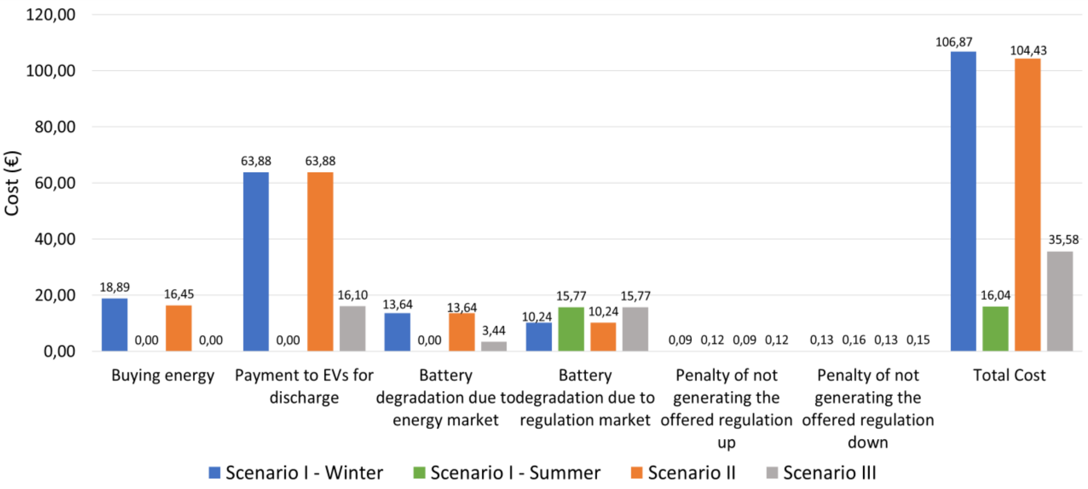
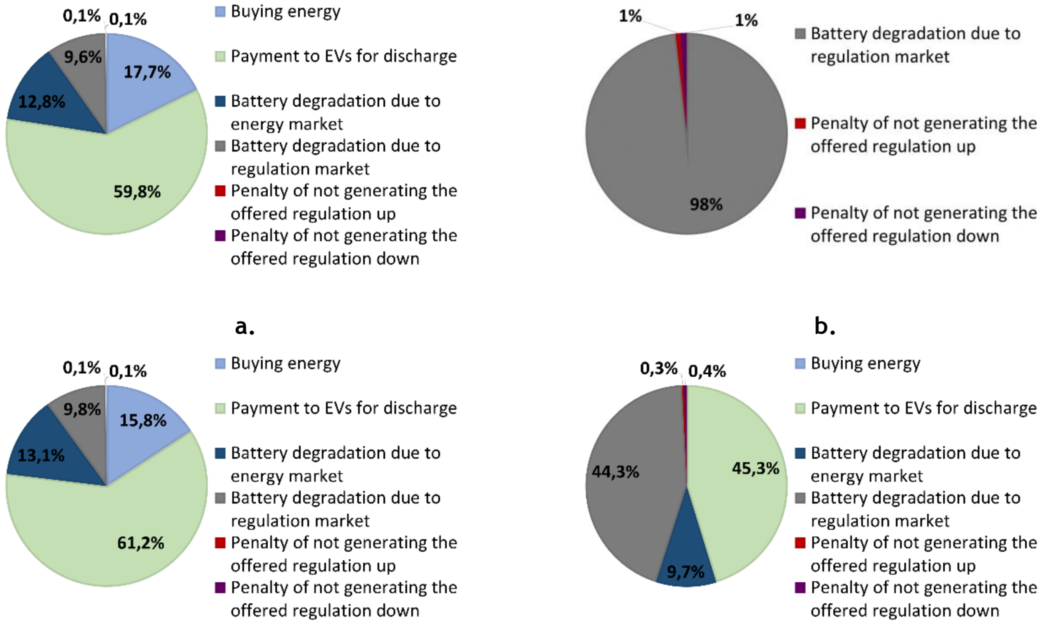


Figure 4.14 - A breakdown of public school EV PLO's costs corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering capacity payment.



a. b.

c. d.

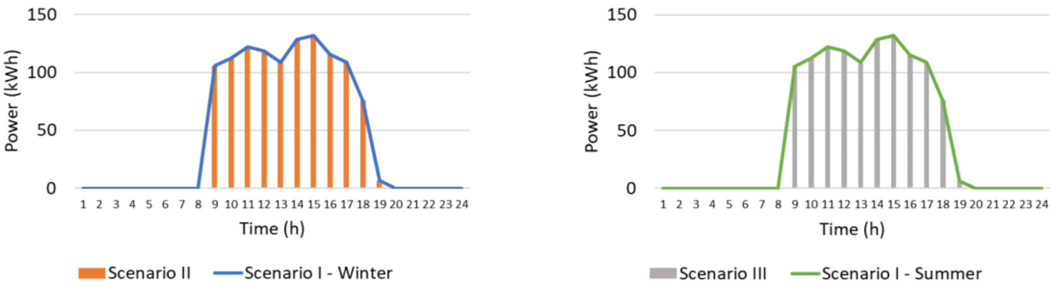
Figure 4.15 - Contribution of each income for the global public school EV PLO's profit corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer) considering a capacity payment.

As the previous results showed, the capacity payment meaningfully influences the participation of the parking lot in the reserve market. In order to evaluate the presence in the market, a tenfold increase of the capacity payment was investigated.

The reserve market participation is illustrated in Figure 4.16. As can be confirmed, the amount of the capacity payment meaningfully influences the presence in the reserve market. Something that can be denoted from the results is that the parking lot only contributes in the reserve market when the capacity payment is higher. This fact means that the parking lot participates in this market only in periods that the capacity payment can compensate the costs of operating in the energy market, i.e., in V2G mode.

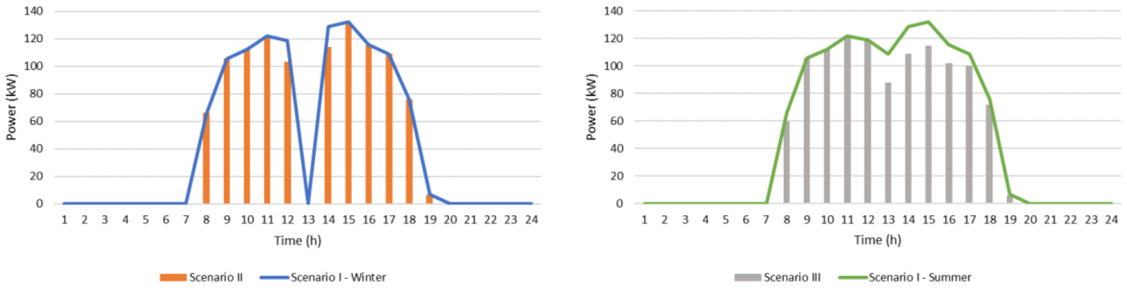
By comparing the scenarios with the different weather conditions, it can be concluded that the participation in reserve market is equal for both winter and summer, suggesting that the capacity payment of reserve in winter and summer are not considerably different to imply different contributions in these markets.

However, as it can be observed in Figure 4.17, the increase of the reserve capacity payment also significantly influences the participation in regulation down market, more particularly at 13:00 pm. While in winter, the parking lot prefers to purchase around 45 kW, in hour 13, illustrated in Figure 4.18, in summer it contributes with approximately 88 kW to the regulation. This means that despite the purchase of energy from the grid implies a cost, the regulation capacity payment and its price are not enough attractive to participate.



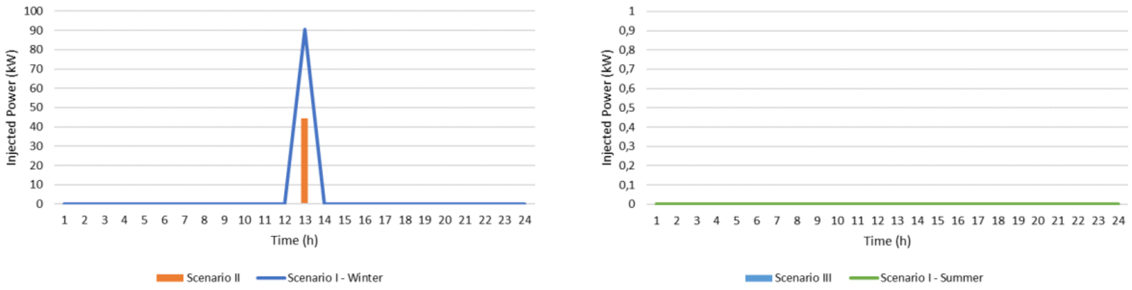
a. b.

Figure 4.16 – Public school's parking lot reserve market participation considering an increase of reserve capacity payment corresponding to (a) Scenario I – Winter and Scenario II (b) Scenario I – Summer and Scenario III.



a. b.

Figure 4.17 – Public school's parking lot offers to the regulation down market considering an increase of the reserve capacity payment.



a. b.

Figure 4.18 – Injected power from the grid to the public school's parking lot considering an increase of reserve capacity payment corresponding to (a) Scenario I – Winter and Scenario II (b) Scenario I – Summer and Scenario III.

The different terms of EV parking lot's profit are presented in Figure 4.19. As it was expected from the increasing of the capacity payment, the results show that there is a participation in the capacity payment of reserve and consequently, an increase in the expected profit.

An interestingly detail that can be pointed out is the fact that the total expected profit from Scenario I (Summer) is higher than Scenario II. This is due to not only the higher income from participating in capacity payment of reserve in Scenario II but also because the EVs are less discharged than in Scenario II, which consequently leads to a higher cost.

The contributions of each term for the expected profit in each scenario are presented in Figure 4.20. As it can be observed, the largest contribution in Scenario I (Winter), Scenario II is the income from charging EVs, while in Scenario I (Summer) is the income from participating in the capacity payment of reserve.

The results also show that in Scenario III the highest income outcomes from contributing in the capacity payment of reserve, as in Scenario I (Summer), however with a lower percentage. Another point that can be observed from the results is that the incomes do not modify either considering the winter base scenario or Scenario II. Therefore, the dissimilarity in the expected profit does not come from the incomes but from costs.

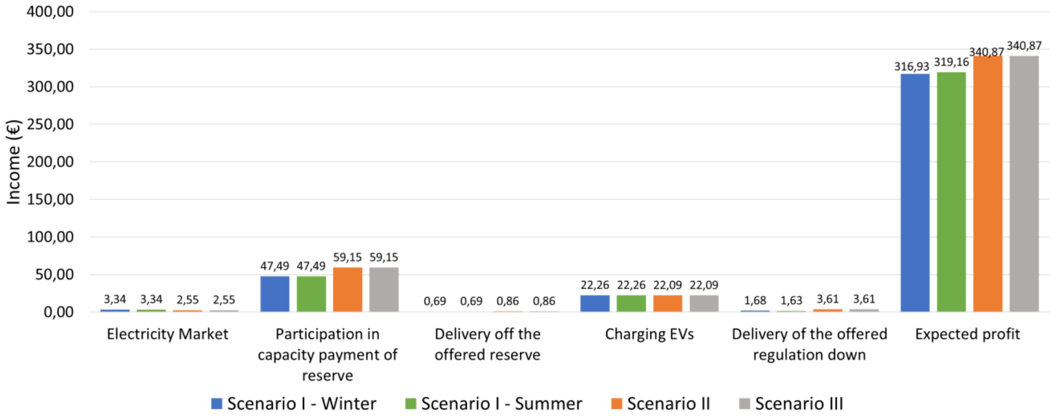
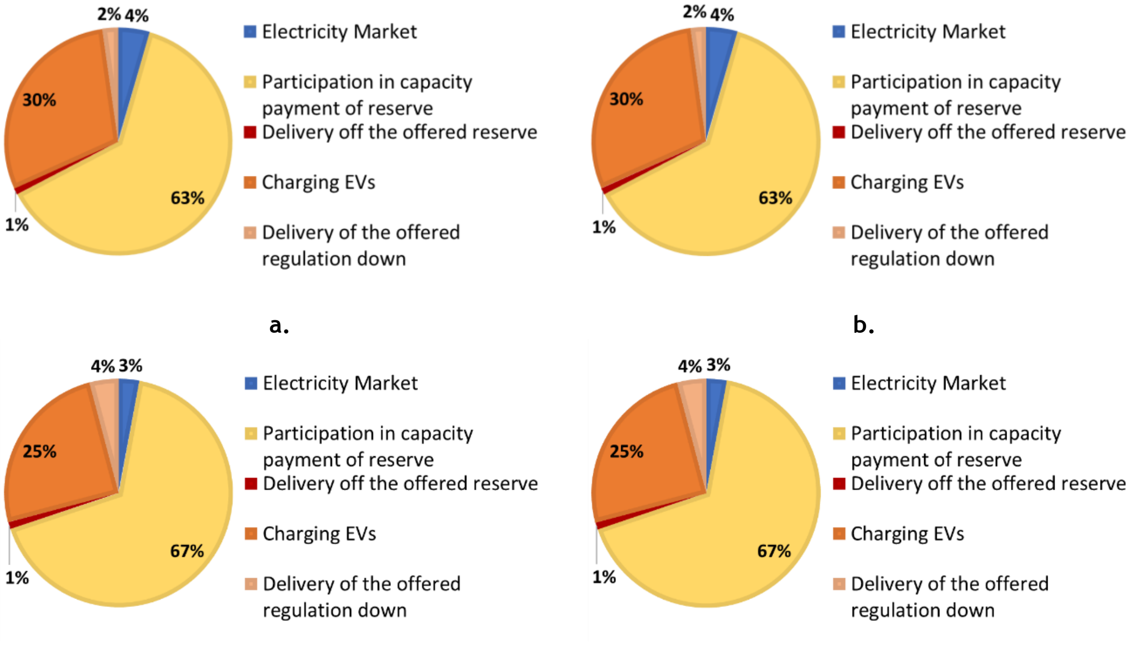


Figure 4.19 – A breakdown of public school EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering an increase of the capacity payment.



a.

b.

c.

d.

Figure 4.20 – Contribution of each income for the global public school EV PLO's profit considering an increase of the capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

The different terms of EV parking lot's costs are presented in Figure 4.21. As it can be observed, the base scenarios are the most expensive when comparing with scenarios with rooftop PV system. Scenario I (Winter) presents the highest cost, followed by Scenario I (Summer) and Scenario III, and Scenario II denotes the lowest cost.

As for the cost of purchasing energy from the grid, scenarios involving winter season represent the highest costs, when compared with scenarios considering a typical summer day. In fact, Scenario III present a null cost of buying energy from the grid, analogous to the base scenario from the previous section, which confirms that the EVs are charged via the rooftop PV system and/or regulation down market.

Therefore, it is not necessary to buy any amount of energy from the grid. Regarding the payment cost to EVs for discharge, winter scenarios present equal costs. This fact would be expected since in these scenarios the parking lot exchanges back to the grid the same amount of energy, at the same hours. Regarding the payment cost to EVs for discharging, summer base scenario presents the lower mentioned cost since the parking lot does not interact with the grid. In winter scenarios, the parking lot pays the same amount to EVs for injecting energy to the grid. Moreover, these cost in winter are higher when compared with summer, due to a lower level of PV generation that implies that EVs are more discharged.

As for battery degradation costs, winter scenarios present the highest cost both in energy, suggesting that as the market participation increases, the costs also increase. While winter scenarios, present the highest impact on battery degradation cost due to the fact the parking lot is interested in selling energy to the grid, in Scenario III there is a lower effect on battery degradation cost, meaning that the parking lot injects a lower amount of energy to the grid, when compared with Scenario II.

In addition, the summer base scenario presents a null battery degradation cost since it does not interact with the grid at any hour. Moreover, there is no battery degradation cost related to regulation market, which was expected since the parking lot does not contribute to the regulation up market.

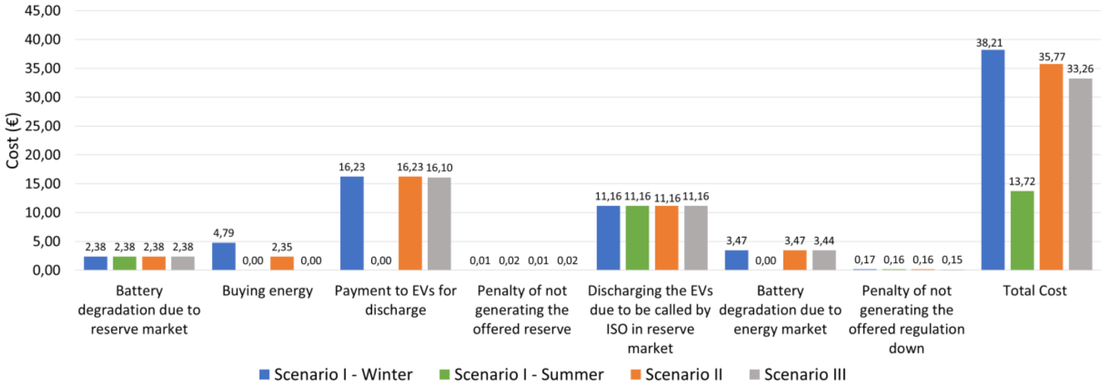


Figure 4.21 – A breakdown of public school EV PLO's cost corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering an increase of the reserve capacity payment.

As a result of the participation in the reserve market, a new term emerges related to the battery degradation costs due to the contribution for this market. However, these costs are relatively uniform in all scenarios, not surpassing the small amount of 2.38€. This cost's consistency is due to the similarity in the participation in this market. In other words, in all scenarios the parking lot participates with an equal amount of energy in the majority of the hours.

Consequently, if necessary, EVs may be called by the operator system for discharging in order to deliver the offered reserve. This operation leads equally to a cost. Analogous to the regulation market, in case of the parking lot does not generate the offered reserve, a cost penalty is introduced. Even though that all the scenarios present this cost, it constitutes an extremely small fraction in their overall cost.

Another point that can be observed from the results is that the parking lot pays a penalty due to the unavailability to generate the offered regulation down, even though this cost represents a very low contribution for the total cost, reaching a maximum of 0.3% in the base summer scenario.

The contributions of each term for the total costs in each scenario are presented in Figure 4.22. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge while the lowest costs are represented by the cost penalties of not generating the offered regulation.

As for the winter scenarios, the distinction in the contributions of each cost results from buying energy from the grid. In Scenario II the parking lot buys a maximum of approximately 91 kW at hour 13, while in its respective base scenario it purchases a maximum of around 45 kW.

Regarding summer scenarios, the distinction in the cost's distribution is mainly to the payment to EVs for discharging. Since the parking lot in Scenario III injects an amount of energy to the grid, around 66kW, it pays a higher cost to EVs, when compared with its corresponding base scenario. Therefore, its contribution for the total cost is also higher.

As a result of these distinctions, the EVs discharging due to be called by the operator system and the battery degradation costs in the reserve market are two parameters that are affected, despite the fact that the reserve participation is equal in all scenarios.

Through the participation in the regulation market, the parking lot may not be able to generate the offered regulation, which may lead to costly penalties. As can be observed in Figure 4.22 this fact occurs in all scenarios. However, these penalties represent an insignificant fraction of the total cost, reaching a maximum of 1.2% in Scenario II.

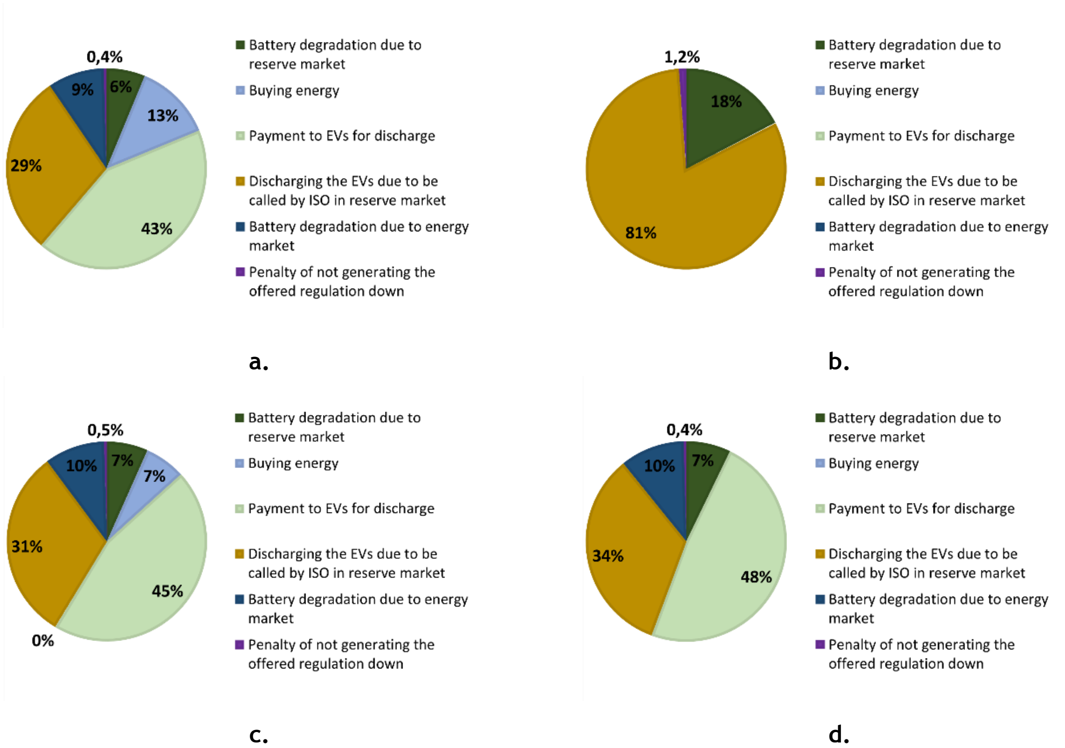


Figure 4.22 - Contribution of each cost for the global public school EV PLO's profit considering an increase of the capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

For an overall analysis of the system, Figure 4.23 demonstrates the results for the three different assumptions, i.e., with the capacity payment, without the capacity payment and considering an increase of the capacity payment. Even though the income from parking lot usage tariff is equal to all the considered scenarios, the results reported here include this term in order to fully investigate the operation of the parking lot.

As it can be observed from Figure 4.20 (upwards), the charging income, i.e., charging EVs through the rooftop PV and/or from the energy bought to the grid gains interest without considering a capacity payment for both reserve and regulation. In other words, the parking lot considers that is more attractive to buy energy from the grid or to exploit the PV generation for charging EVs rather than participate in the regulation and reserve market. Consequently, the cost of buying energy increases when considering a capacity payment. When taking into account a capacity payment, the participation in regulation market increases, since this can compensate the costs for participating in a V2G mode.

Another interesting point that can be observed assuming a capacity payment is that in the base Summer Scenario there is no injection from the grid to the parking lot, i.e., the parking lot does not buy energy from the grid. Consequently, there is neither income from charging EVs nor cost for buying energy from the grid. However, there is a higher participation in the regulation down, meaning that EVs are charged through this contribution. Accordingly, the mentioned scenario presents only costs related to the regulation market, leading to the lowest overall cost when compared with the other scenarios.

As it can be concluded, there is only participation in the reserve market when occurs an increase of the capacity payment. This means that the considered prices were too low for the parking lot provides services to the grid. The results show that the parking lot prefers to participate in the capacity payment of reserve rather than in electricity market. Moreover, it can be denoted that the parking lot prefers to participate in the reserve market rather than in the regulation. As it was expected, since the parking lot contributes to the reserve market, this situation, i.e., increasing the reserve capacity payment, is the only one that presents costs regarding battery degradation in the reserve market and EVs discharge due to be called by the operator system in the reserve market.

As for the battery degradation costs, it can be concluded that they are higher without considering a capacity payment. In this case, despite the fact that the parking lot does not benefits from participating neither in reserve nor regulation market, it has a larger interaction with the grid, by injecting energy to the grid. When considering a capacity payment, the total battery degradation costs in both energy and regulation markets are even lower than without considering it. Since in this situation the parking lot participates in the both markets, the costs are distributed, being the regulation battery degradation cost lower than energy battery degradation. Moreover, in this case, the parking lot has profits from taking part into the regulation market, which compensate the costs for providing ancillary services to the grid. With the increase of the capacity payment, the total battery degradation costs are the lowest (around 6€).

As it can be denoted, when assuming an increase of the capacity payment, there is a consistency on scenario's costs. This is mostly due to the equal reserve market participation in all scenarios, which leads to present the same cost for example for discharging the EVs due to be called by operator system in this market.

Another fact than be observed is that the presence of the EVs discharging cost in all scenarios, with the exception of the base Summer Scenario. This is due to the interest of the parking lot in participating in PL2G activities, which leads to discharge EVs. According to Figure 4.23, Scenario III without considering a capacity payment presents the highest cost for discharging.

Since there is a higher presence of PV power generation, EVs tend to discharge in early morning and in the evening, when market prices are high, increasing the cost. Contrastingly, the same scenario but considering a capacity payment presents the lowest mentioned cost. Moreover, when the parking lot participates in the energy market the capacity payment can compensate the costs of operating in PL2G activities, decreasing the cost of discharging EVs.

Regarding the expected profit, on one hand, when not taking in consideration the capacity payment, the revenue is almost constant. However, the scenarios considering the rooftop PV system presents the highest profit.

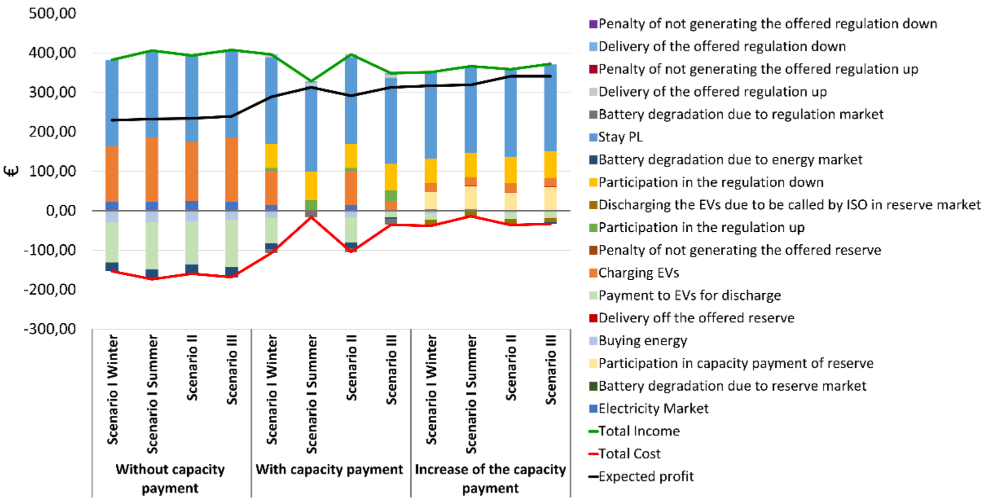


Figure 4.23 – A breakdown of public school EV PLO's profits and costs corresponding to three assumptions: without capacity payment, with capacity payment and an increase of the capacity payment.

On the other hand, when assuming a capacity payment, relatively higher differences are observed when considering different weather conditions, within the summer scenarios presenting the largest profits. These differences are also observed when increasing the capacity payment, where the summer scenario considering the rooftop PV generation (Scenario III) reports the most profitable scenario.

4.1.3. Additional study

The impacts of the behavior of the parking lot operator are also investigated considering different cases built based on the size of the rooftop PV. Table 4.3 and Figure 4.24 shows how the different incomes and cost are affected as the number of roof-top PV panels increases.

It is assumed the same EV traffic patterns and prices in all cases, not considering the capacity payment for the different markets. Moreover, is taken into account the worst weather conditions, i.e., the winter case (Scenario II). It can be observed that the case with 50 panels brings the lowest profit for the parking lot. A higher number of solar PV panels leads to a higher profit for the EV parking lot, since it allows the EV parking lot to participate more actively in energy market.

Based on the results Figure 4.24 the case with 600 PV panels is the most profitable one for the parking lot. In this case, the parking lot has the lowest cost of buying energy from the grid. As can be seen, the parking lot prefers to take part in the energy market rather than in the regulation and reserve markets, due to the low amount of regulation and reserve price and, the lack of the of capacity payment. The cost to EVs for discharge increases, as the number of solar panels increases.

Furthermore, as can be seen from Figure 4.24 the battery degradation cost increases, as the number of solar panels increases. This is due to the high interaction between the PL and the grid. A perceptible change is noticed in the cost of buying energy from the grid.

As shown Figure 4.24 as the number of solar PV panels increases, the cost of buying energy from the grid decreases. This fact would be expectable since there is a higher PV generation from the rooftop system as the number of PV panels increases, thus the rooftop PV is able to meet the charging requirements without buying a larger amount of energy from the grid.

Table 4.3 - Change of the incomes and costs with the change in the number of PV panel on the rooftop corresponding to public school's case study

	50 PV Panels	100 PV Panels	200 PV Panels	300 PV Panels	400 PV Panels	600 PV Panels
Electricity Market (€)	22.72	22.95	23.41	23.88	24.34	25.27
Charging EVs (€)	142.03	143.50	146.43	149.36	152.30	158.17
Stay PL (€)	218.40	218.40	218.40	218.40	218.40	218.40
Delivery of the offered regulation down (€)	0.95	0.94	0.93	0.91	0.89	0.85
Buying energy (€)	28.12	27.80	27.15	26.51	25.86	24.57
Payment to EVs for discharge (€)	103.54	104.61	106.75	108.89	111.03	115.30
Battery degradation due to energy market (€)	22.11	22.34	22.79	23.25	23.71	24.62
Penalty of not generating the offered regulation down (€)	0.08	0.08	0.08	0.08	0.08	0.07
Total Income (€)	384.10	385.79	389.17	392.55	395.93	402.69
Total Cost (€)	153.85	154.83	156.78	158.72	160.67	164.57
Expected profit (€)	230.25	230.96	232.39	233.82	235.25	238.12

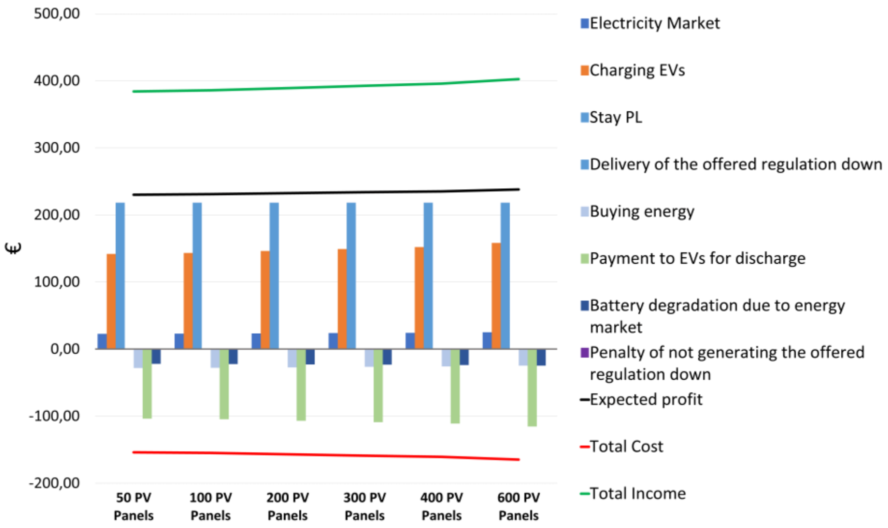


Figure 4.24 - Change of the incomes and costs with the change in the number of PV panel on the rooftop corresponding to public school's case study.

4.2. Analysis Results from FEUP Parking Lot

4.2.1. Without capacity payment

In this section the simulation results are presented. A total of three case studies were defined, considering different weather conditions, as listed in Table 4.4. Scenario I was defined as a reference/base case with no rooftop PV system. It is divided in two scenarios: winter and summer in order to compare In Scenario II, a 100 kW rooftop PV was formulated for a winter day. Scenario III considers a 100 kW rooftop PV for a typical summer day.

The traded energy between the grid and the parking lot is presented in Figure 4.25. As can it be observed, the parking lot receives a smaller amount of energy in those cases involving the PV power generation compared to the base case. In Scenario II, the parking lot buys energy from the grid only about for one hour in early morning (8:00 am), while the presence of higher solar irradiance levels causes the transfer of energy to the parking lot for extended hours in the morning (from 7:00 am to 12:00) and evening hours (from 17:00 pm to 20:00 pm).

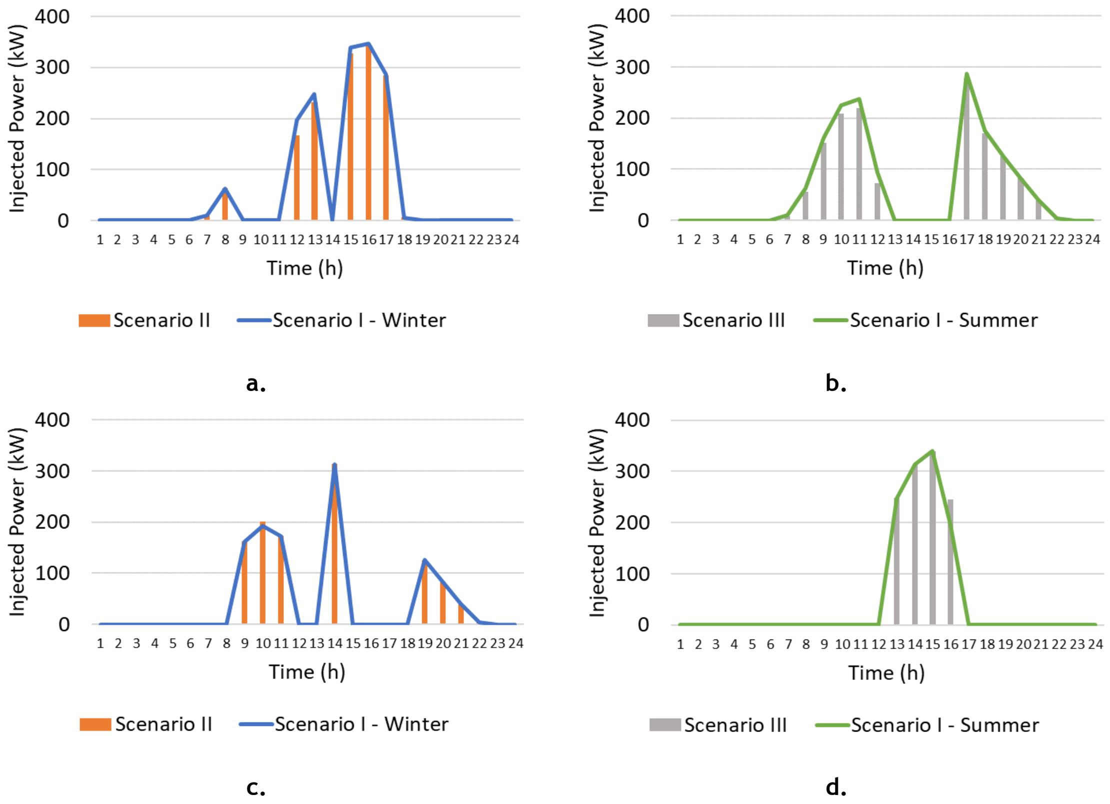
Furthermore, while in Scenario II, the parking lot injects to the grid a larger amount of energy (around 314 kW) at hour 14, in Scenario III, the parking lot transfers a higher amount of energy for a prolonged period, more particularly, from 13:00 pm to 16:00 pm compared to Scenario II.

This means that in the presence of a higher solar irradiance, the parking lot has a higher capability to benefit from selling energy to the grid at solar peak hours. It can be noticed that the grid does not sell and buy energy at the same time. In scenario II, in hour 8, there is not enough energy generated from the rooftop PV to satisfy the charge requests of the charging EVs, thus the parking lot buys a higher amount of energy from the energy market.

As can be observed in Figure 4.25, in the middle of the day, when PV generation is high the parking lot draws more energy from the grid. Another factor that influences the amount of energy that is bought from the energy market is the number of vehicles in the parking lot. When comparing these results with the corresponding results from the previous numerical study, where a parking lot with a significantly smaller dimension is considered, it can be concluded that there is a considerably larger amount of energy injected from the grid to the parking lot.

Table 4.4 – FEUP's case studies description without considering a capacity payment

Scenario	Season	rooftop PV	Capacity Payment
I (base case)	Winter	-	×
	Summer	-	×
II	Winter	100 kW	×
III	Summer	100 kW	×



a. b. c. d.

Figure 4.25 - Injected power from grid to FEUP's parking lot (upwards) and from FEUP's parking lot to grid (downwards) without a capacity payment

In contrast, in hour 14, there is an excess generation. Therefore, this surplus generation is sold back to the grid. Similarly, in Scenario III, the parking lots becomes more active from 13:00 pm to 16:00 pm, while in morning and evening hours it buys a higher amount of energy from the grid.

Figure 4.26 demonstrates the participation of the parking lot in the regulation down market. It can be concluded that the EV parking lot prefers to participate in the energy market rather than in the energy one. As can be seen, the parking lot has a higher potential to participate in regulation market in a typical summer day, compared to the cases where a winter day is considered. This is due to the higher PV power uncertainty into the system at peak hours. Thus, the parking lot can benefit from supplying the regulation up/down to compensate the intermittency at these hours.

While in Scenario II, the contribution in the regulation down market occurs during three periods: 10:00 am to 12:00 am, a peak at 14:00 am and from 18:00 pm to 20:00 pm, in Scenario III the parking lot participates in the regulation down market for a continuous period of five hours, more particularly from12:00 pm to 16:00 pm. Moreover, despite the fact that both scenarios have the potentiality for contributing in the regulation market, Scenario III presents a higher potential to participate in regulation markets when compared to the cases where a winter day is considered (Scenario II).

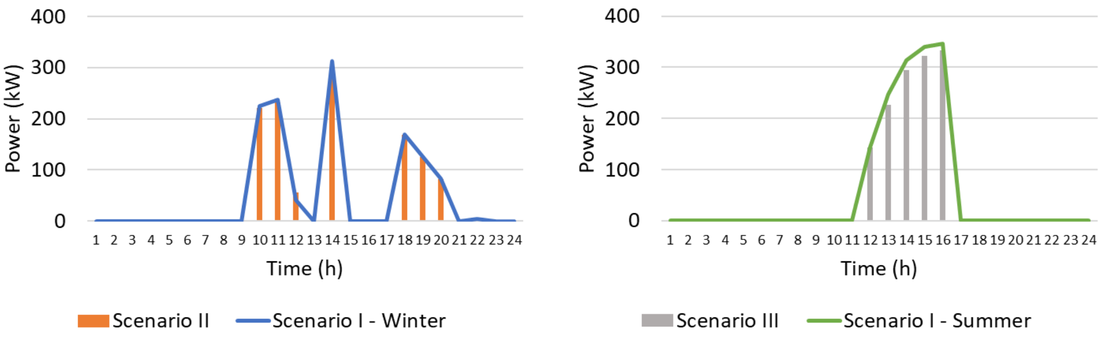


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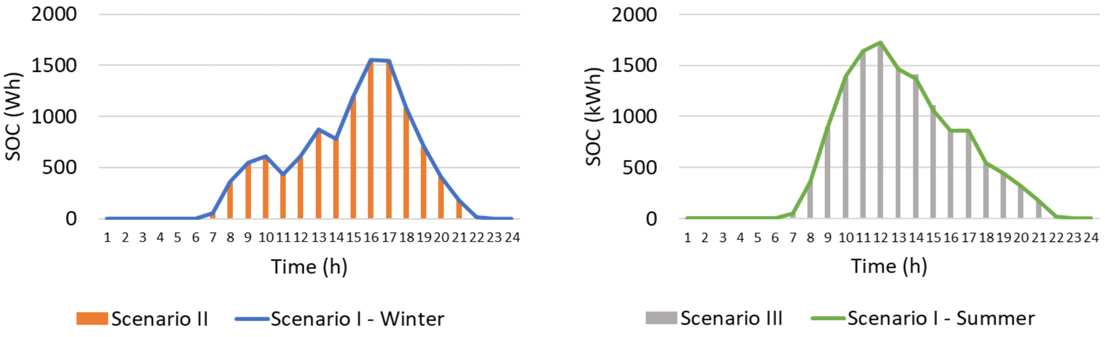
Figure 4.26 -FEUP's offer to the regulation down market without considering a capacity payment corresponding to (a) Scenario I - Winter and Scenario II (b) Scenario I - Summer and Scenario III

The total SOC of the parking lot in each hour is presented in Figure 4.27. As for Scenario II, the highest commutative amount of SOC of EVs in the parking lot, occurs between 16:00 pm and 17:00 pm. In Scenario III, the highest amount of changing in the SOC occurs at hour 11 and 12.

In addition, in Scenario III, the SOC of parking lot is higher than the other scenarios in the majority of the hours, despite the fact that in Scenario II a relatively higher amount of energy (around 1432 kW) is purchased from the grid than in Scenario III, which buys a total amount of approximately 1417 kW. Therefore, the distinction in the SOC of the parking lot does not come from the amount of energy that is bought from the grid but from the PV power output from the rooftop, since that the traffic conditions are equal to both scenarios.

The different terms of EV parking lot's profit are presented in Figure 4.28. Similar to the previous case study, all the results that are illustrated here do not report the income from parking lot usage tariff has. Scenario III is the most profitable one for the parking lot, while the winter base scenarios is the less lucrative scenario.

Such as the income resulted from the electricity market, Scenario II presents highest income. This fact would be expectable since Scenario II presents the highest interaction between the parking lot and the grid.



a. b.

Figure 4.27- SOC of the FEUP student's parking lot corresponding to (a) Scenario I - Winter and Scenario II (b) Scenario I - Summer and Scenario III

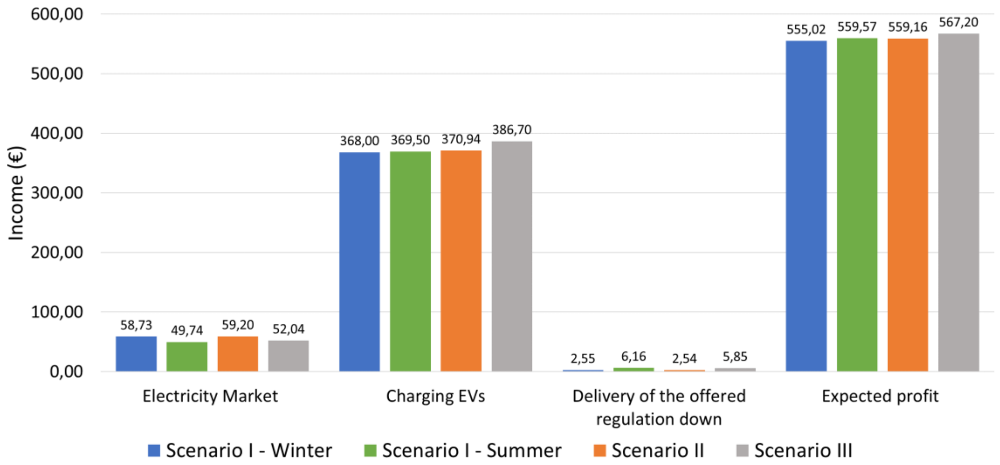


Figure 4.28 - A breakdown of FEUP EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) without considering capacity payment.

Contrasting, the summer base scenario presents the lowest income from generating in the electricity market, even though it presents a higher energy injection from the parking lot to the grid. Furthermore, Scenario II presents a smaller income from charging EVs, when compared with Scenario III, despite the fact that the parking lot buys a higher amount of energy from the grid in Scenario II (around 1432 kW) than Scenario III, with a total of approximately 1417 kW.

In order to better investigate the difference in the income resulted from charging EVs between scenarios that consider the rooftop PV system, Figure 4.29 represent this term in each hour. As it can be observed, the distinction in this income comes from the charging in the morning, more particularly from 9:00 am to 11:00 am and from charging the EVs at evening hours, from 18:00 pm to 21:00 pm.

On one hand, in hours 15 and 16, Scenario II is the scenario that benefits more from charging EVs; however, this process not occurs via the rooftop PV system but from purchasing from the grid. On the other hand, at the same mentioned hours, Scenario III has a significantly higher PV power generation, thus the parking lot does not need to buy energy from the grid, leading to a considerably lower income when compared with Scenario II.

Through the participation in the regulation market, the parking lot may be required by the system operator to deliver the offered regulation, benefiting from delivering it. However, this income represents a relatively small fraction in the global profit, when compared with the remaining terms.

The contributions of each term for the total income in each scenario are presented in Figure 4.30. As it can be observed, the lowest contribution in all scenarios is the income from the delivery of the offered regulation, while the largest is the income from charging EVs. Another point that can be observed from the results is that on one hand, in winter, the parking lot with and without the rooftop PV system participates equally in both electricity market and in the EVs charging. Therefore, the distinction in the expected profit does not come from the incomes but from costs.

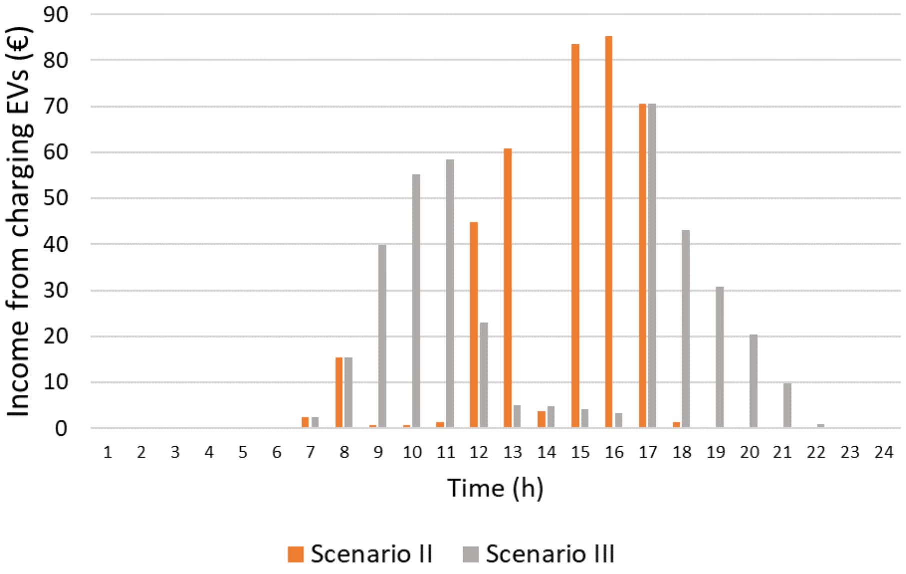


Figure 4.29 - Income from charging EVs in each hour corresponding to Scenario II and Scenario III without considering a capacity payment

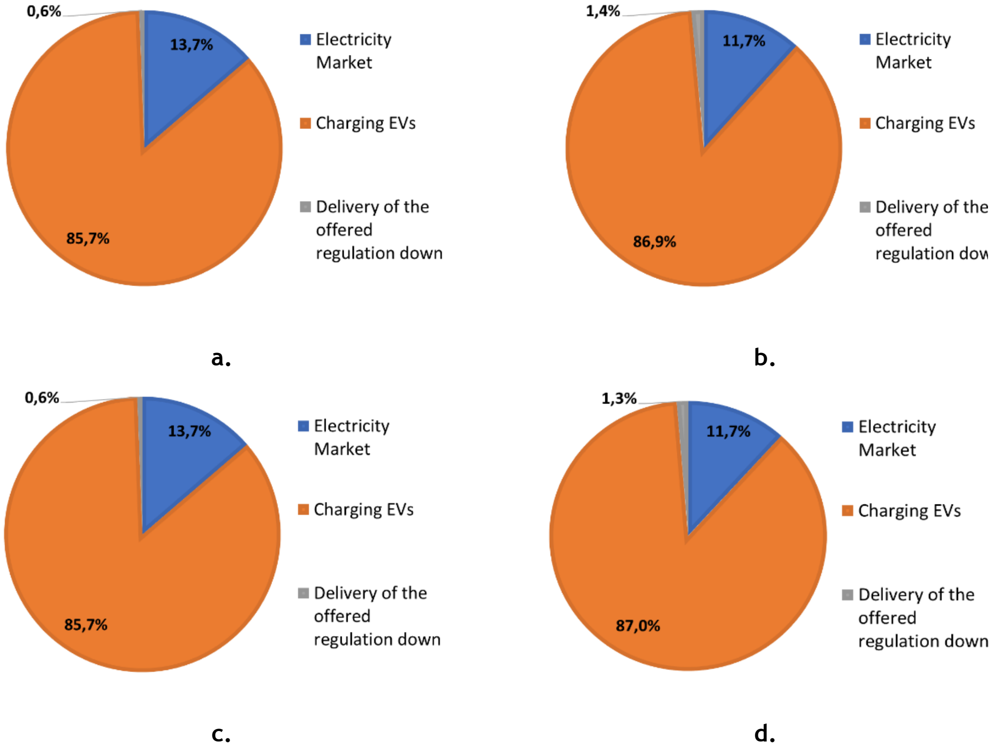


Figure 4.30 - Contribution of each income for the global FEUP EV PLO's profit without considering a capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer)

On the other hand, in summer, there is a difference of 0.1% in both the income from charging EVs and the income resulted by deliver the offered regulation. In Scenario III, charging EVs results in a higher income since it involves the rooftop PV. As for the offered regulation, Scenario III participates with a less amount of energy than its corresponding base scenario.

Consequently, the parking lot delivers a smaller amount of energy if called by the operator system. By comparing scenarios with different weather conditions, it can be observed that in winter, the parking lot benefits more from the electricity market than in summer. Despite that, the contribution for EVs charging is 1.2% higher in summer scenarios, which was expected due to a higher PV power production in summer.

The different terms of EV parking lot's costs are presented in Figure 4.31. As it can be observed, Scenario III represents the highest cost. The main reason is the higher cost related to the payment to EVs for discharge. Since there is a higher presence of PV power generation, EVs tend to discharge in early morning and in the evening, when market prices are high. A clear change is observed in the cost of energy bought from the grid. As shown in Figure 4.31, as the PV power generation increases (from Scenario II to Scenario III), the cost of buying energy decreases. This means with more PV power generation available, the parking lot is able to fulfill the charging requirements; thus, it is not necessary to buy a high amount of energy from the grid, as in Scenario I. Further, since the PL's operator is interested in minimizing its cost, (or maximizing its profit), it increases its income for sale to the grid.

Moreover, a significant difference is detected in the cost of degradation of batteries. It can be observed that a large interaction between the PL and the grid has a negative effect on the battery degradation cost. In Scenario I, with the lowest impact on battery degradation cost, EVs owners do not have as much as interest in participate in PL2G activities as in Scenario III, where the cost is higher.

Another point that can be observed from the results is that the parking lot pays a penalty due to the unavailability to generate the offered regulation up and down, even though this cost represents a very lower contribution for the total cost, not reaching an impact of 0.05% in the global cost. The reason is that this cost is related to the probability of being called by the system operator generate its offered regulation. Moreover, the parking lot's main objective is the EVs charging, therefore it can basically choosing not participate in the regulation market, without suffer high cost penalties.

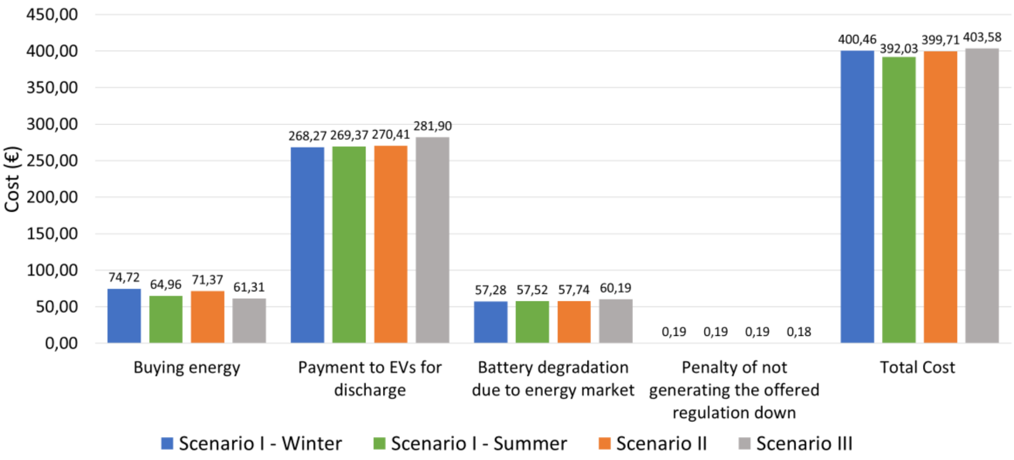


Figure 4.31 - A breakdown of FEUP EV PLO's cost corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) without considering capacity payment.

For a comprehensive analysis of each scenario, Figure 4.32 demonstrates the contributions of each cost for the total cost. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge, while the lowest is represented by the battery degradation costs due to the parking lot’s participation in the energy market.

By comparing the winter scenarios, it can be concluded that in the scenario involving a rooftop PV system (Scenario II), the parking lot buys a lower amount of energy, which was predictable. Consequently, since there are two EV charging sources, i.e., grid and rooftop PV, the parking lot is more willing to participate more actively in the energy market, by selling energy to grid, increasing not only the battery degradation costs but also the cost payment to EVs for discharge. The same circumstances occur in summer scenarios. By comparing winter and summer scenarios, it can be denoted that there is a lower purchase of energy from the grid, implying a smaller cost of buying energy.

However, the battery degradation costs and the cost of paying to EVs for discharging are higher. This is mostly due to a higher injection of energy from the parking lot back to the grid between 13:00 pm and 16:00 pm.

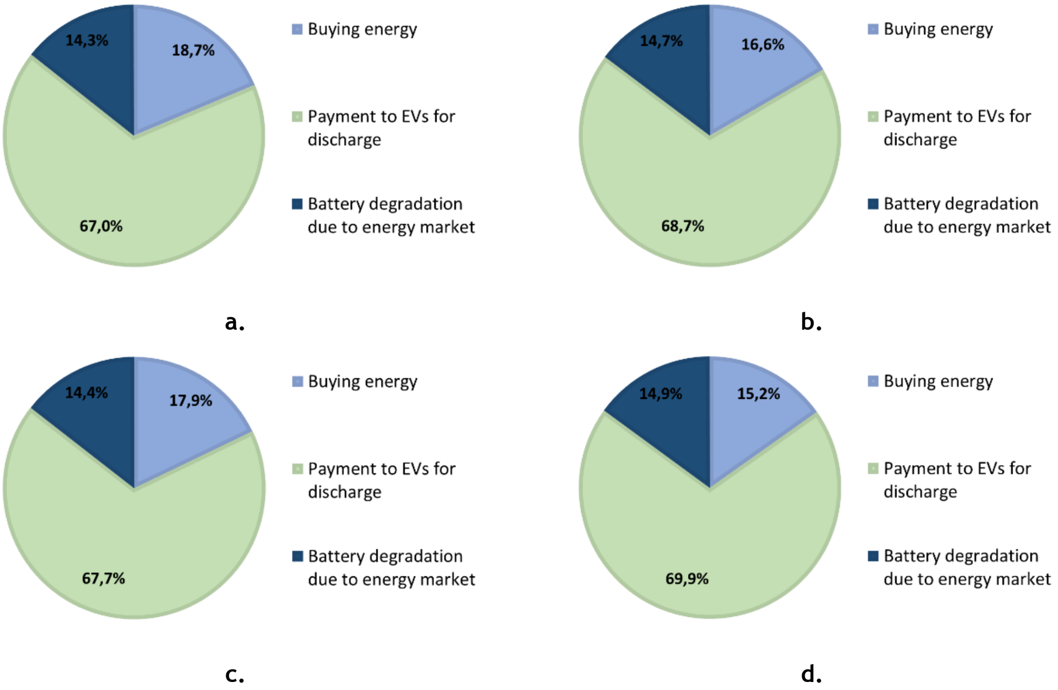


Figure 4.32 – – Contribution of each cost for the FEUP’s EV PLO’s cost without considering capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer). With capacity payment

4.2.2. With capacity payment

In this section the simulation results are presented. In accordance with the previous section, a total of three case studies were defined, considering different weather conditions, as listed in Table 4.5. However, in this section the capacity payment is considered. Scenario I have been defined as a reference/base case with no rooftop PV system. It is divided in two scenarios: winter and summer in order to compare the results between each other. In Scenario II, a 100 kW rooftop PV was formulated for a winter day. Scenario III considers a 100 kW rooftop PV for a typical summer day.

The traded energy between the grid and the parking lot is presented in Figure 4.33. On one hand, in Scenario II, the parking lot buys energy from the grid only about for three hours, more specifically from 12:00 pm to 14:00 pm. On the other hand, the parking lot does not buy energy from the grid at any hour.

This means that with the implementation of a capacity payment, the parking lot is willing to participate in the regulation down market, meeting the EVs charging requirements through this participation. Moreover, it can be denoted that the scenario involving the rooftop PV system purchases a lower amount of energy than its respective scenario.

Moreover, as it can be observed, the parking lot exchanges back to the grid a higher amount of energy from 8:00 am to 11:00 am in a winter day (when occurs an increase of the number of parked EVs from 19 to 72, making up a growth on the parking lot's occupation of proximately 279%) occurring two peaks later at 18:00 pm and 21:00 pm. Therefore, in this scenario, the parking lot has a higher capability to benefit from selling energy to the grid at peak hours, preferring to sell the energy that is not used for EVs charging, rather than participating in regulation market. In Scenario III there are only two hours in which occurs the energy transfer back to the grid (11:00 am and 22:00 pm).

In hour 11, since the regulation down price does not compensate because it presents a null value combined to the fact that is PV power available, the parking lot is able to inject energy back to grid, more particularly approximately 63 kW in hour 11 (at an electricity price of 0.0437 €/kWh). In hour 22, despite the fact that there is not PV power available and the regulation down price remains null, there is only one vehicle parked at the parking lot, which allows the parking lot to transfer to the grid an amount of 3.3 kW in hour 22 (at a electricity price of 0.044 €/kWh)

Table 4.5 – FEUP's scenarios description considering a capacity payment

Scenario	Season	rooftop PV	Capacity Payment
I (base case)	Winter	-	✓
	Summer	-	✓
II	Winter	100 kW	✓
III	Summer	100 kW	✓

In Figure 4.34 is illustrated the participation of the parking lot in the regulation market. The results show that with the introduction of a capacity payment, the parking lot is able to participate in the regulation up market, contrasting to the results from the previous section.

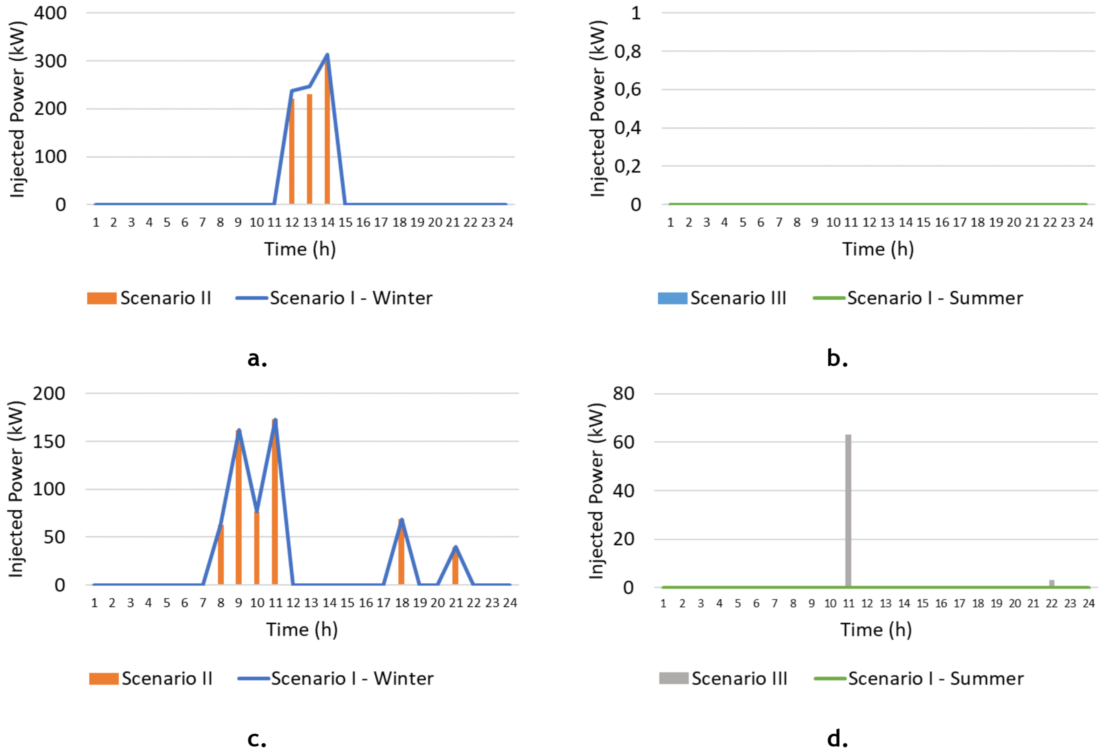


Figure 4.33 - Injected power from grid to FEUP's parking lot (upwards) and from FEUP's parking lot to grid (downwards) considering a capacity payment

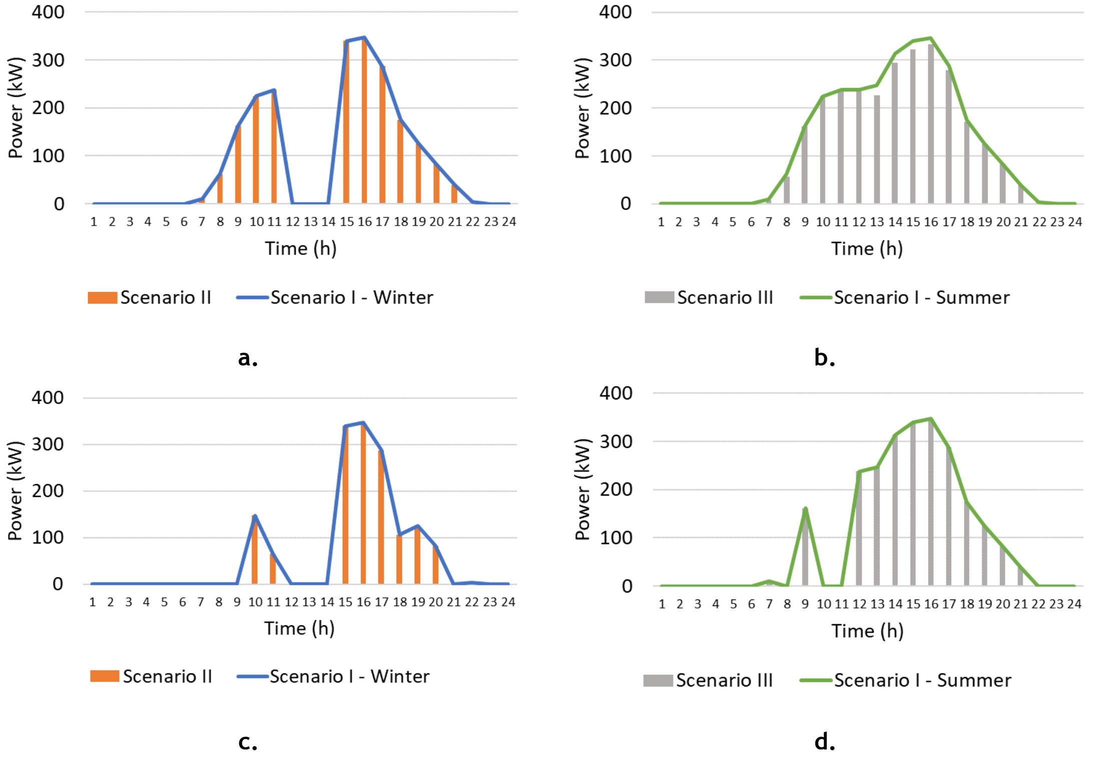


Figure 4.34 - FEUP's offers to the regulation down (upwards) and regulation up (downwards) market considering a capacity payment.

On one hand, in Scenario II, the contribution in the regulation down market occurs mainly in the morning (8:00 am to 11:00 am) and during the afternoon. However, it includes a pause at “lunch hour”. On the other hand, in Scenario III the parking lot participates in the regulation down market for an extended period, including from 12:00 pm to 14:00 pm. This fact means that the considered price and capacity payment for the regulation down, at these specifically hours, is more rewarding in summer than in winter.

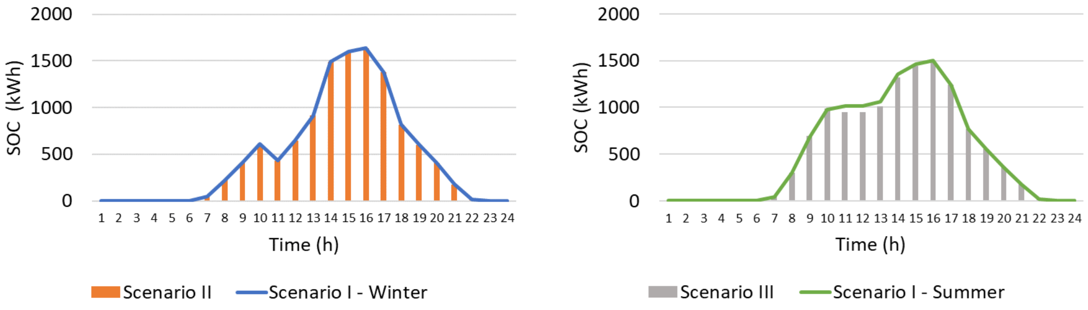
Despite the fact that both scenarios have the potentiality for contributing in the regulation market, Scenario III is seen as the most promising in terms of participating in regulation markets This is due to the higher PV power uncertainty into the system at peak hours. Thus, the parking lot can benefit from supplying the regulation up/down to recompense the unpredictability at these hours.

Another point that can be observed is that the parking lot participates in the regulation up market only in periods that the capacity payment can compensate the costs of contributing to regulation market. As an example, in hour 10, in Scenario II the parking lot participates in the regulation market, while in Scenario III the parking lot does not contributes to this market. Therefore, the capacity payment for the regulation up in this hour is higher in the considered typical winter day than in the summer day.

The SOC of the parking lot in each hour is presented in Figure 4.35. As for the Scenario II, the highest amount of changing in the SOC occurs in between 14:00 pm and 16:00 pm, when the parking lot buys energy from the grid. Regarding Scenario III, the highest commutative amount of SOC of EVs in the parking lot, occurs between 14:00 pm and 16:00 pm.

In addition, as it can be observed a higher SOC is achieved in Scenario III in the majority of the hours. Despite the fact that in Scenario II more energy is purchased from the grid, in Scenario III, a higher PV power output is presented in Scenario III and, hence, a higher SOC is achieved.

The different terms of EV parking lot’s profit are presented in Figure 4.36. It can be observed that Scenario I (winter) is the lowest profitable, followed by Scenario II and, Scenario I (summer). The most lucrative is Scenario III. In this case, the participation in the regulation down represents the largest contribution for the overall profit in Scenario III.



a. **b.**

Figure 4.35- SOC of FEUP’s parking lot considering a capacity payment corresponding to (a) Scenario I - Winter and Scenario II (b) Scenario I - Summer and Scenario III

As for the electricity market income, Scenario II presents a higher income, when compared with Scenario III. This fact would be expectable since Scenario II presents a higher interaction between the grid and the parking lot, when compared with Scenario III, in which there is no injection from grid to parking lot. Moreover, the mentioned income is equal for both Scenario I (Winter) and Scenario II.

This means that the parking lot injects an equal amount of energy to the grid at the same hours, which was predictable since it is considered equal prices for both scenarios. Therefore, the profit's distinction does not come from this income term.

Regarding income from charging EVs, Scenario III presents a smaller income when compared with Scenario II. Even though Scenario III presents a higher level of PV generation, EVs are charged via the regulation down market due to the presence of a capacity payment, which is more attractive than purchase energy from the grid.

Consequently, the income from participating in the regulation down market is the highest in Scenario III, when compared with the remaining scenarios. Moreover, since the parking lot does not purchase energy from the grid in Scenario III, the rooftop PV is the only that meets EVs charging requirements, decreasing the income from EVs charging.

Furthermore, the results demonstrate a null income from charging EVs in summer base scenario, confirming that there is neither injection from the grid to the parking lot nor PV generation (base scenario).

Even though Scenario I (Summer) presents a relatively high income (when compared with winter scenarios) this does not come from charging EVs, but from providing services to the grid, more specifically by participating in regulation up/down. This means that in the presence of a capacity payment for both reserve and regulation up/down the parking lot prefers rather contribute to these markets than purchasing energy from the grid in order to charge EVs.

In regulation market, there is no assurance that the capacity reserved will be actually activated; creating an income resulted from being called by the system operator to deliver the offered regulation (up and down. On one hand, in Scenario II, the mentioned income represents a small fraction (5%) in the overall profit- On the other hand, in Scenario III this income represents a fraction of 11% in the total expected profit, 3% higher than the contribution of EVs charging.

The contributions of each term for the expected profit in each scenario are presented in Figure 4.37. As it can be observed, the largest contribution in Scenario I (Winter), and Scenario II is the income from charging EVs, while in Scenario I (Summer) is the income resulted from participating in the regulation down market.

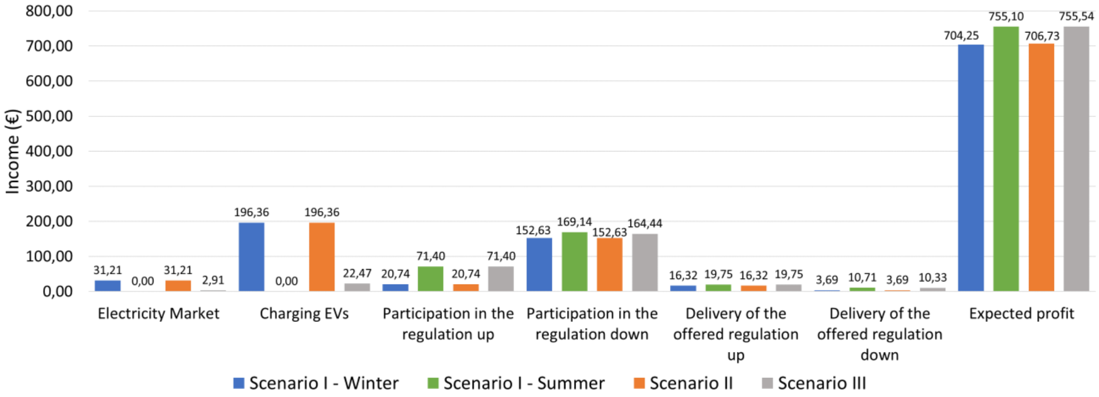


Figure 4.36 – A breakdown of FEUP's EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering capacity payment.

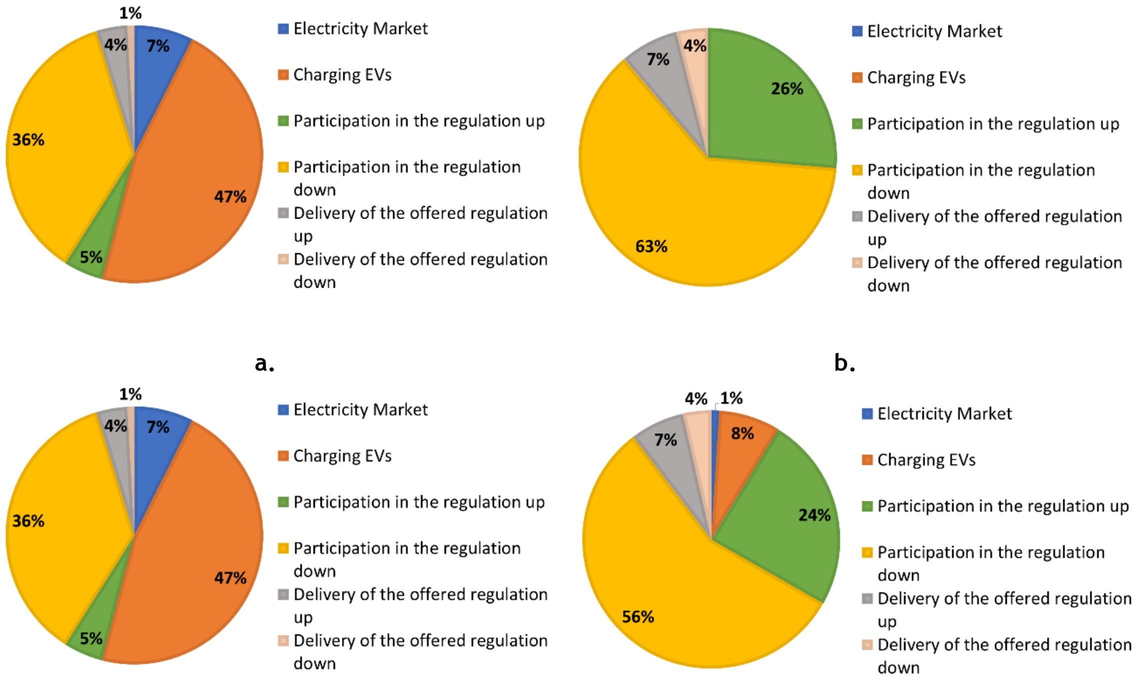
The results also show that in Scenario III, the highest income outcomes from contributing in the regulation down market, as in Scenario I (Summer), however with a minor share, a decrease of 7%. Another point that can be observed from the results is that there are no differences regarding incomes between the base winter Scenario and Scenario II.

Therefore, the distinction in the expected profit does not come from the incomes but from costs. Furthermore, it can be observed that the electricity market represents a contribution of 1% in Scenario III, while in base Summer Scenario, there is no contribution of this market. This is due to the injection of the parking lot in hour 11, implying that at this particular hour there was a PV surplus that allied with the attractive energy price was injected into the grid. This specific transaction leads to an income around 3€.

The different terms of EV parking lot's costs are presented in Figure 4.38. As it can be denoted the base case (winter) is the one with the highest cost, while the base case concerning summer presents the smallest cost. As for scenarios that involve rooftop PV system, Scenario III presents the most expensive scenario, with a total cost of approximately 62€.

Regarding the cost of purchasing energy from the grid, scenarios involving winter season represent the highest costs, when compared with scenarios considering a typical summer day. In fact, summer scenarios denote a null cost of buying energy from the grid, confirming that the parking lot meets EV charging requirements via regulation down market and not through the energy's purchase from the grid.

As for the second illustrated cost, it can be concluded that in winter scenarios the parking lot pays a higher amount to owners for discharging their EVs than in summer scenarios. This fact would be expectable since in these scenarios the parking lot participates more actively in PL2G activities than in summer scenarios. Moreover, winter scenarios present an equal cost due to paying to EV's drivers for discharging their vehicles. This result shows that the parking lot regardless the presence of the rooftop PV, it generates the same amount of energy to the electricity market at the same hours.



a. b.

c. d.

Figure 4.37 - Contribution of each income for the global FEUP EV PLO’s profit considering a capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

An evident difference is verified between Scenario II and Scenario III, regarding battery degradation costs both in energy and regulation market. On one hand, Scenario II presents a total battery degradation cost of nearly 57€. On the other hand, in Scenario III the mentioned cost contributes with approximately 45€ to the global cost of the parking lot, a difference of closely 27%.

Scenario III presents a lower effect on battery degradation cost when compared with Scenario II, meaning that EVs owners do not have as much as interest in contributing to both energy and regulation markets. The results also demonstrate that as the participation in the energy and regulation increases, the costs increase. Furthermore, as it was expected, winter scenarios present an equal battery degradation total cost. This is due to an equal participation not only on the electricity market, as mentioned above, but also in the regulation up market.

The contributions of each term for the total cost in each scenario are presented in Figure 4.39. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge, except for the Scenario I (Summer) where the cost of battery degradation due to the participation in the regulation market is the most expensive term. The lowest costs are represented by the cost penalties of not generating the offered regulation (both up and down).As for the winter scenarios, the distinction in the contributions of each cost results mainly from buying energy from the grid, since the parking lot in winter base scenarios buys a higher of amount of energy from the grid lot in all hours than in Scenario II.

For instance, in Scenario II the parking lot buys a maximum of approximately 299 kW at hour 14, while in its respective base scenario it purchases a maximum of nearly 314 kW, leading to a higher cost. Regarding summer scenarios, there is a considerably higher disparity in the cost's distribution between base scenario and Scenario III.

In Scenario I (Summer), the total cost is essentially caused by the battery degradation cost due to the participation in the regulation market. This fact would be expectable since the parking lot does not charge EVs by buying energy from the grid but from participating in regulation market, more exactly in regulation down. Consequently, by taking part in ancillary services, the battery degradation costs increase.

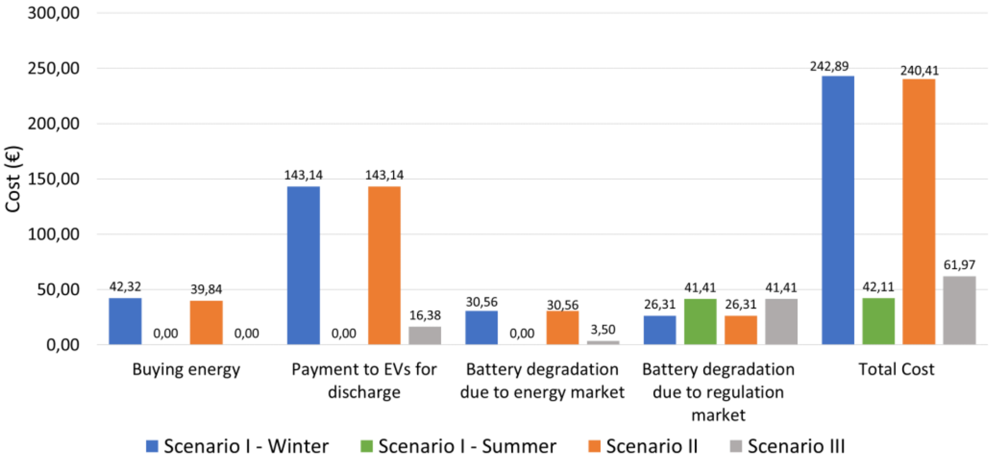


Figure 4.38 – A breakdown of FEUP's EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering capacity payment.

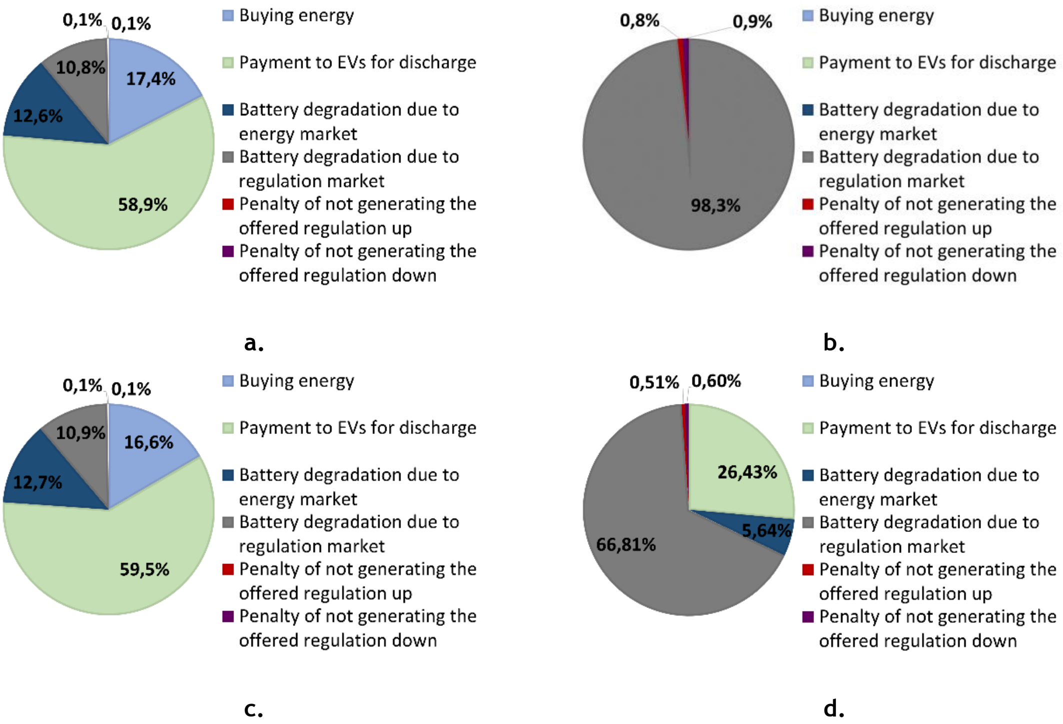


Figure 4.39 – Contribution of each cost for the global FEUP EV PLO's profit considering a capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

Scenario III is a considerably more balanced scenario since the parking lot participates not only in the energy market but also in regulation market, leading to a contribution of each market for the battery degradation. The total battery degradation costs represent 72% of Scenario's III total cost. The contribution of approximately 26% due to payment to EVs for discharged is caused by the interaction with the grid at hours 11 and 22, with an injection back to the grid of around 63.3kW and 3.3 kW, respectively.

By participating in the regulation market, the parking lot is at risk of not generating the offered regulation, which may lead to costly penalties. As can be observed in Figure 4.15 this fact occurs in all scenarios. However, these penalties represent an extremely small fraction of the total cost, reaching a maximum of 1.7% in Scenario I (Summer).

In order to better investigate the costs penalties due to not generate the offered regulation, Figure 4.40 represent this term in each hour. As it can be observed, both scenarios pay a higher penalty in hour 15 and 16, when the parking lot presents the highest occupation, more specifically, 103 and 105 vehicles, respectively.

Moreover, Scenario III is the only that pays the penalty for both regulation up and down during the "lunch hour", i.e., from 12:00 pm to 14:00 pm. Similarly, Scenario II is the only that pays the penalty for the regulation up. Similar to the previous case study, an increase of the capacity payment was considered in order to fully analyze the parking lot's participation in the reserve market. The reserve market participation is illustrated in Figure 4.41. As can be confirmed, the amount of the capacity payment significantly influences the presence in the reserve market.

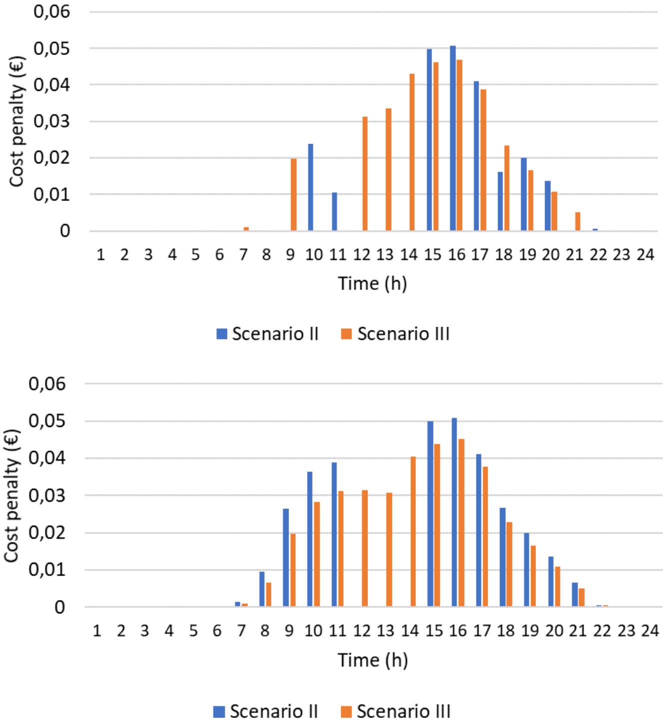


Figure 4.40 – Cost penalty in each hour of not generating the offered regulation up (upwards) and the offered regulation down (downwards) corresponding to Scenario II and Scenario III (FEUP's parking lot).

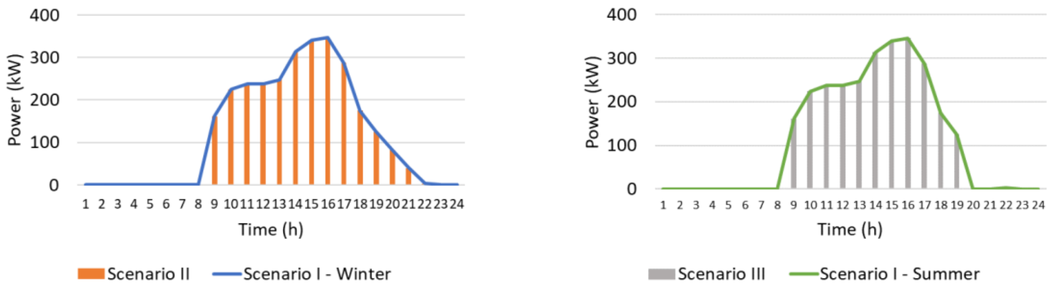
Something that can be denoted from the results is that the parking lot only contributes in the reserve market when the capacity payment is higher. This fact means that the parking lot participates in this market only in periods that the capacity payment can remunerate the costs of operating in the energy market, i.e., in V2G mode.

According to Figure 4.41, it can be denoted that regardless of the season (winter or summer), the parking lots practically participates equally in the reserve market, excluding hours 20 and 21. While in winter scenarios, the parking lot injects an amount of approximately 83 kW and 40 kW at 20:00 pm and 21:00 pm, respectively, in summer scenarios the parking lots does not contribute to this market. This result suggests that at these hours there is a larger difference between the winter and summer capacity payment, which leads to choose the reserve market rather than regulation or energy market.

This fact can be confirmed by Figure 4.42, more particularly Figure 4.42d, in which is demonstrated that the parking lot is more interested in the regulation up, by increasing its output by around 83 kW and 40 kW, at 20:00 pm and 21:00 pm, respectively.

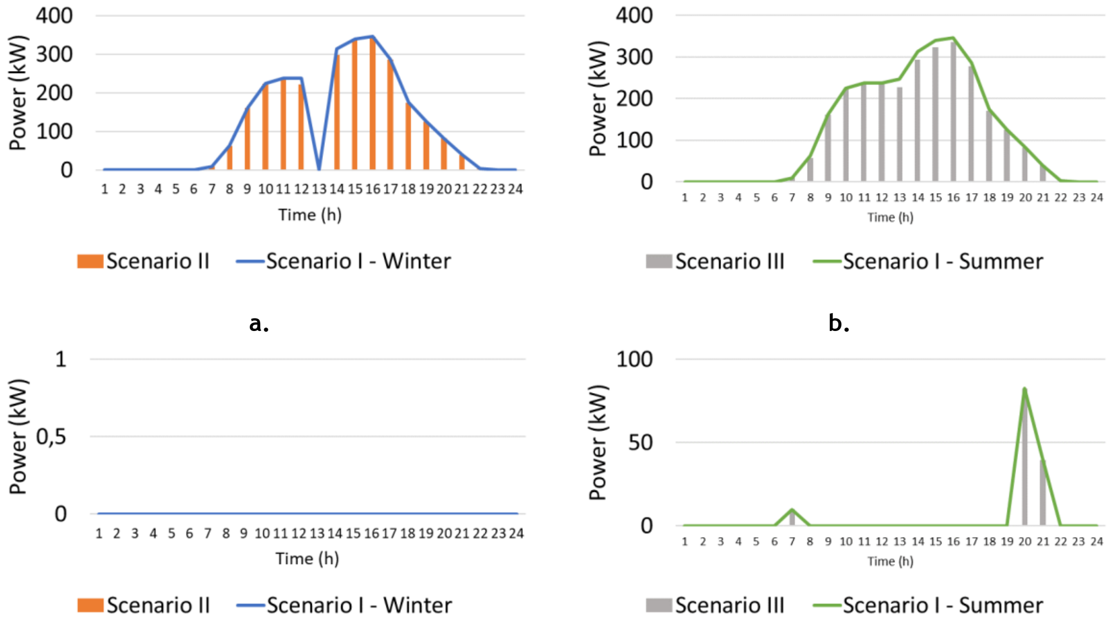
Another fact that can be deducted from Figure 4.42 is that, in hour 13, there is no offer to the regulation down in winter scenarios, contrasting to what occurs in summer. This is because at this hour, the parking lot buys energy from the grid, as it can be observed in Figure 4.43, despite this implies the incur in additional costs. Additionally, Figure 4.43 shows that the parking lot buys a lower amount of energy (53 kW) than its respective base scenario, which counts with approximately 100 kW. This means that in the presence of the rooftop PV system it is not necessarily resorting to grid.

The different terms of EV parking lot's profit are presented in Figure 4.44. The results illustrate that there is a participation in the capacity payment of reserve with the introduction of a higher capacity payment, and therefore, an increase in the expected revenue.



a. b.

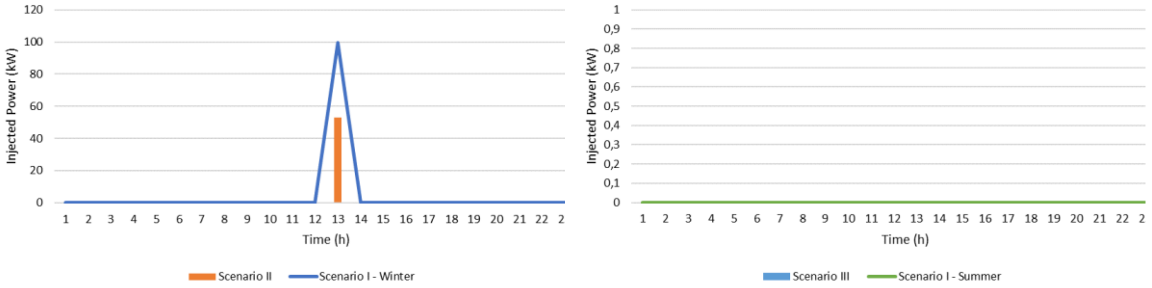
Figure 4.41 - FEUP's reserve market participation considering an increase of the capacity payment corresponding to (a) Scenario I - Winter and Scenario II (b) Scenario I - Summer and Scenario III.



a. b.

c. d.

Figure 4.42 – FEUP's offers to the regulation down (upwards) and regulation up (downwards) market considering an increase of the reserve capacity payment.



a. b.

Figure 4.43 – Injected power from FEUP's parking lot to grid considering an increase of the reserve capacity payment.

Scenario III presents the highest cost, whereas the winter base scenario denotes the lowest. First of all, winter scenarios denote higher income from generating in electricity market than summer scenarios. Moreover, winter scenarios benefit more for selling energy back to the grid, since it injects energy to the grid in hours, more specifically, in hour 7, that are more price-attractive in winter than in summer.

Comparing to Scenario III, while the parking lot sells a total amount of approximately 73 kW, in summer scenarios there is an exchange of 63 kW from the parking lot to the grid, leading to a difference of around 1.17€ in the income resulted from the energy market.

The participation in the reserve market results in the emergence of two new income terms: the income from participating in the capacity payment of reserve and the income from deliver the offered reserve through the call of the operator system. Contrasting to the above-mentioned income, summer scenarios denote the highest income than winter scenarios.

This is mainly due to the fact that the summer reserve capacity payment is more remunerative than the winter capacity payment, in the majority of the hours, leading to higher incomes, as it can be observed in Figure 4.45. As mentioned above, if the system operator requires, the parking lot is called for delivery the offered reserve. However, this income represents a considerably low fraction in the total profit, reaching a maximum of approximately 10.7€ in summer base scenario.

According to Figure 4.44, winter scenarios denote also the highest income from charging the EVs. Even though this scenario presents a lower PV output level than Scenario III, it interacts more with the grid, by purchasing energy, which helps to increase charging income. This fact can be confirmed by Figure 4.46, which presents the charging energy and charging income. As the charging energy, i.e., the PV power generation and the injected energy from grid to the parking lot, increases, the charging income also increases.

In addition, it can be concluded that the parking lot participates in the regulation down market with approximately 2.6 MW and 2.8 MW in winter and summer scenarios, respectively, which leads to a high income. Regarding regulation up, contrasting to what occurs in the previous section, the parking lot is willing to increase its output only in summer scenarios during three hours (7:00 am, 20:00 pm and 21:00 pm), leading to an income of nearly 6€.

Due to the participation in the regulation market, the parking lot may be required by the system operator to deliver the offered regulation, benefiting from delivering it. This income represents a relatively high fraction in the global profit, when compared with the remaining terms.

Another detail that can be pointed out is the fact that the total expected profit from Scenario I (Summer) is higher than winter scenarios. This fact would not be expectable since the winter base scenario does not consider a rooftop PV system.

This result confirms that summer prices are more attractive for providing ancillary services to the grid than winter prices. The contributions of each term for the expected profit in each scenario are presented in Figure 4.47.

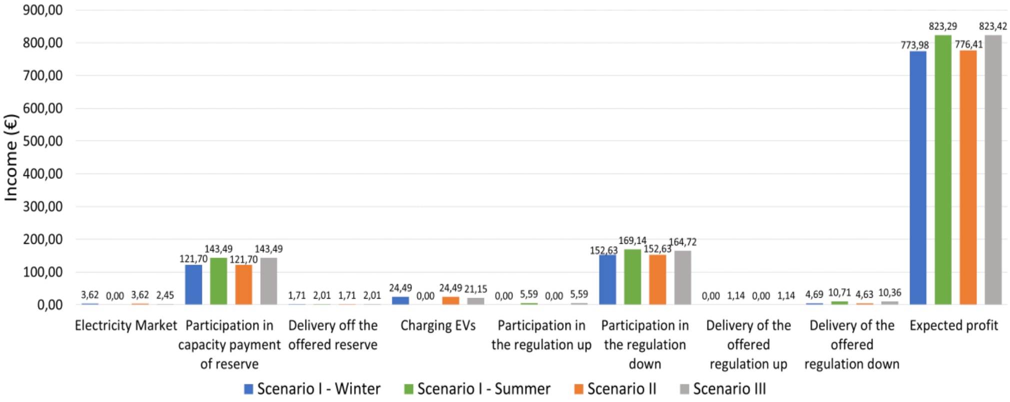


Figure 4.44 - A breakdown of FEUP EV PLO's profit corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering an increase of the reserve capacity payment.

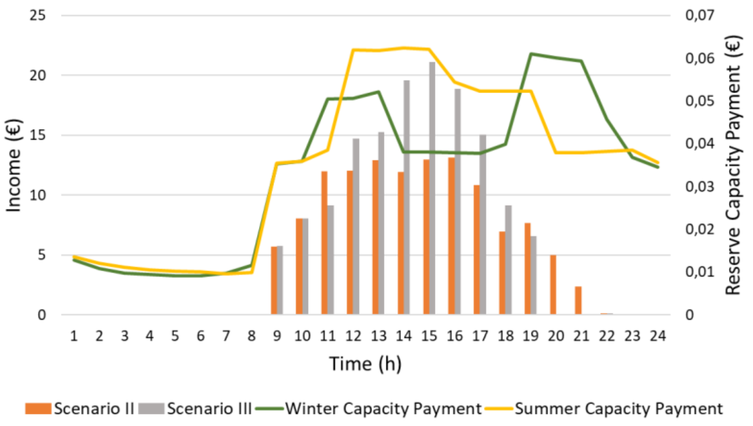


Figure 4.45 -Income from participating in the capacity payment of reserve corresponding to Scenario II (Winter) and Scenario III (Summer) considering an increase of the capacity payment.

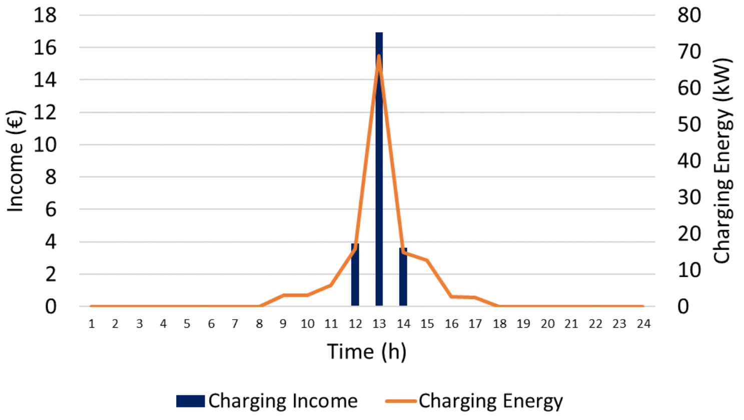


Figure 4.46 -Income from charging EVs and charging energy corresponding to Scenario II (Winter) considering an increase of the capacity payment

As it can be observed, the main contribution in all scenarios is the income resulted from participating in the regulation down market, however with different percentages. While the summer base scenario presents the highest share, winter scenarios report the lowest, implying not only that the parking lot participates more actively in regulation market in summer but also that the summer capacity payment can compensate more the costs of providing ancillary services.

Another point that can be observed from the results is that there is an equal income allocation between Scenario II and its corresponding base scenario, suggesting that the distinction in the expected profit does not come from the incomes but from the costs. This fact would not be predictable since in Scenario II the EVs charging requirements are met via two terms: the energy purchased from the grid and from the rooftop PV system; while, in the reference scenario, this income results only from the injected energy from the grid to the parking lot. Contrastingly, an equal income distribution does not occur in summer scenarios, mainly due to the participation in the electricity and regulation down market.

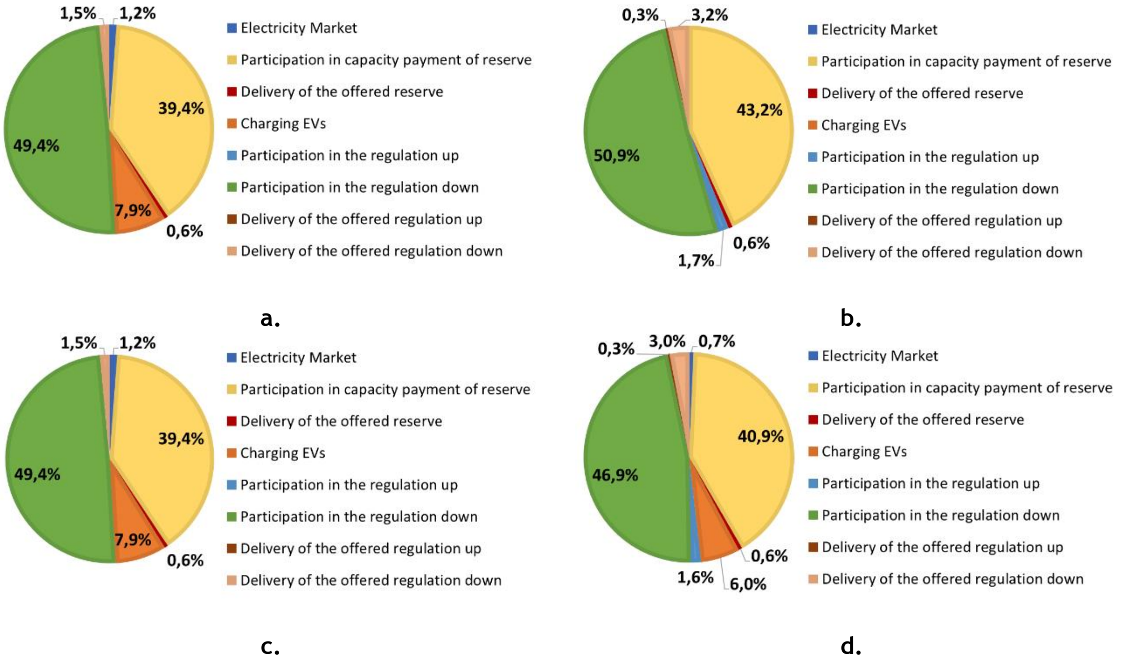
While in base summer scenario, there is no participation neither in electricity nor regulation market, the parking lot in Scenario III participates with 63 kW and 2.8 kW, respectively, which leads to a total cost of approximately 167€.

Another factor that affects this disparity in income's distribution, is the profit resulted from charging EVs, with Scenario III presenting a revenue around 21€, compared to a null profit in the corresponding base scenario. This result clears evidence the impact of the rooftop PV system, since in neither case the parking lot does not purchase energy from the grid, i.e., it meets EVs charging requirement through PV power from the rooftop.

The different terms of EV parking lot's costs are presented in Figure 4.48. As it can be observed, winter scenarios are the most expensive when comparing with scenarios that involve a typical summer day. Scenario I (Winter) presents the highest cost, followed by Scenario II (Winter) and Scenario III, and Scenario I (Summer) denotes the lowest cost.

In the first place, there are no significant differences in costs related to battery degradation due to the reserve market, meaning that the parking lot has a similar participation in the reserve market in all scenarios. When comparing scenarios that involving renewable generation, it is observed a 0.4% difference in this income. This difference results mainly from hours 20 and 21, where the parking lot in Scenario III prefers to contribute with approximately 132 kW rather than in reserve market. This difference in the hourly battery degradation cost is illustrated in Figure 4.49, making up a total cost of around 0.25 in 20:00 pm and 21:00 pm.

As for the cost of purchasing energy from the grid, scenarios involving winter season represent the highest costs, when compared with scenarios considering a typical summer day. In fact, summer scenarios present a null cost of buying energy from the grid, which confirms that one of the EVs charging sources is the rooftop PV system. Therefore, it is not necessary to buy any amount of energy from the grid.



a.

b.

c.

d.

Figure 4.47 – Contribution of each income for the global FEUP EV PLO's profit without considering a capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

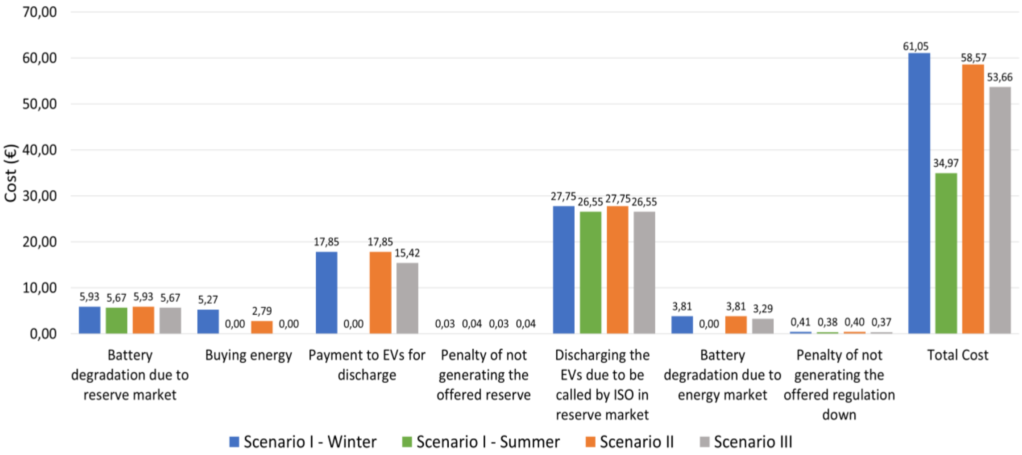


Figure 4.48 – A breakdown of FEUP EV PLO's cost corresponding to Scenario I (base case), Scenario II (Winter) and Scenario III (Summer) considering an increase of the capacity payment.

Regarding the payment cost to EVs for discharging, Scenario II (Summer) presents the lowest, excluding base summer scenario, since the parking lot only interacts with the grid only for one hour, with a total of nearly 63 kW. Base scenarios present lower costs when compared with summer that integrate the rooftop PV.

This is because, in the presence of PV generation, the parking lot discharges some EVs in early morning, when PV power generation is low and market prices are high, as it can be observed in Figure 4.50. When comparing scenarios that involve PV generation, in winter, the parking lot pays a higher cost to EVs for injecting energy to the grid due to discharge them during the morning, more specifically between 7:00 am and 8:00 am.

This is due not only to the fact that EVs batteries discharge faster in cold weather but also because the PV generation is lower than in summer, even more during the morning, which leads to a higher interaction between the parking lot and the grid.

As a result of the participation in the reserve market, a new term emerges related to the generation because of discharging the EVs due to be called by the operator system in reserve market. This term develops as significant factor contributing with a relatively higher percentage for the general cost. Analogous to the regulation market, in case of the parking lot does not generate the offered reserve, a cost penalty is introduced. Even though that all the scenarios present this cost, it constitutes an extremely small fraction in their overall cost.

A relatively low difference (around 0.26€) is detected between Scenario II and Scenario III, regarding battery degradation costs in energy market. Something that can be deducted from the results is that as the market participation increases, the costs also increase. On one hand, Scenario II presents the highest impact on battery degradation cost.

This is due to the fact the parking lot is interested in selling energy to the grid. On the other hand, Scenario III presents a lower effect on battery degradation cost, meaning that the parking lot injects a lower amount of energy to the grid, when compared with Scenario II.

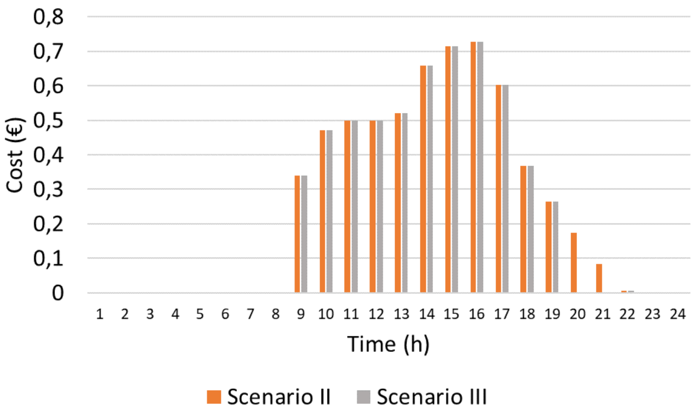


Figure 4.49 - Hourly cost due to battery degradation in reserve market corresponding to Scenario II (Winter) and Scenario III (Summer) considering an increase of the capacity payment.

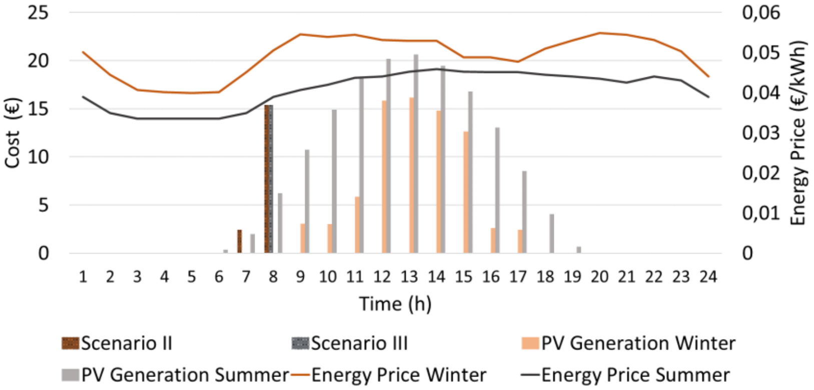


Figure 4.50 - Hourly cost due to discharging EVs corresponding to Scenario II (Winter) and Scenario III (Summer) considering an increase of the capacity payment.

Another point that can be observed from the results is that the parking lot pays a penalty due to the unavailability to generate the offered regulation down, even though this cost represents a very low contribution for the total cost, reaching a maximum of 0.41€ in base winter scenario.

The contributions of each term for the total costs in each scenario are presented in Figure 4.51. As it can be observed, the highest cost in all scenarios results from paying to EVs for discharge due to be called by the operator system in the reserve market, reaching approximately half of the total cost in winter scenarios and Scenario III. In the summer base scenario, this cost represents a higher percentage, contributing with almost 80% of the total cost. The lowest costs are represented by the cost penalties of not generating the offered regulation.

As for the winter scenarios, the main distinction in the contribution of each cost is caused by the energy's purchase from the grid. This is because, in the presence of PV generation, it is not needed a so high amount of energy than without considering the solar power. This fact specifically occurs at hour 13, where the PV power is particularly high, evens as it is considered a typical winter day. Another distinction that can be pointed out is the influence of the cost from buying energy from the grid.

Regarding summer scenarios, the distinction in the cost's distribution is equally mainly to the payment to EV's drivers for discharging. While in Scenario III the parking lot transfers a total amount of energy back to the grid of approximately 63 kW, in its respective base scenario, it sells a total of nearly 73 kW, reflecting in a difference of around 29% between these scenarios. As a result, the battery degradation cost due to the participation in the electricity market is lower, leading to a 0.5% difference between summer scenarios.

As a consequence of the participation in the reserve market, the battery degradation costs in this market, is an additional factor that influences the cost's allocation. While in Scenario III there is a participation in the reserve market of around 2.7 MW, in Scenario II, the parking lot injects to the reserve market approximately 2.8 MW, leading not also to an increase of payment to discharging the EVs due to be called by the operator system in reserve market, as mentioned above, but also it influences negatively the battery degradation Therefore, as it can be denoted, a total difference of 0.4% between summer and winter scenarios is verified on the battery degradation cost.

Through the participation in the regulation market, the parking lot may not be able to generate the offered regulation, which may lead to costly penalties. As can be observed in Figure 4.51, this fact occurs in all scenarios. However, these penalties represent an insignificant fraction of the total cost, reaching a maximum of 1.1% in Scenario I (Summer).

For a global analysis of FEUP's case study, Figure 4.52 illustrates the results for the three different assumptions, i.e., with the capacity payment, without the capacity payment and considering an increase of the capacity payment. Similar to the previous case study, the results reported here include the income from parking lot usage tariff in order to fully investigate the operation of the parking lot.

It can be denoted that scenarios that assume an increase of the reserve capacity payment present the highest profit, reaching a maximum of around 823€ in Scenario III, while scenarios that do not consider a capacity payment denote the lowest profit, reaching a maximum of approximately 567€ in the same scenario, making up a difference of about 45%.

As it can be observed from Figure 4.52 (upwards), the charging income, is more interesting without considering a capacity payment for both reserve and regulation market. In other words, the parking lot considers that is more attractive to purchase energy from the grid or to exploit the PV generation for charging EVs rather than participate in the regulation and reserve market. Consequently, the cost of buying energy increases when considering a capacity payment. When taking into account a capacity payment, the participation in regulation market increases, since this can offset the costs for performing in a V2G mode.

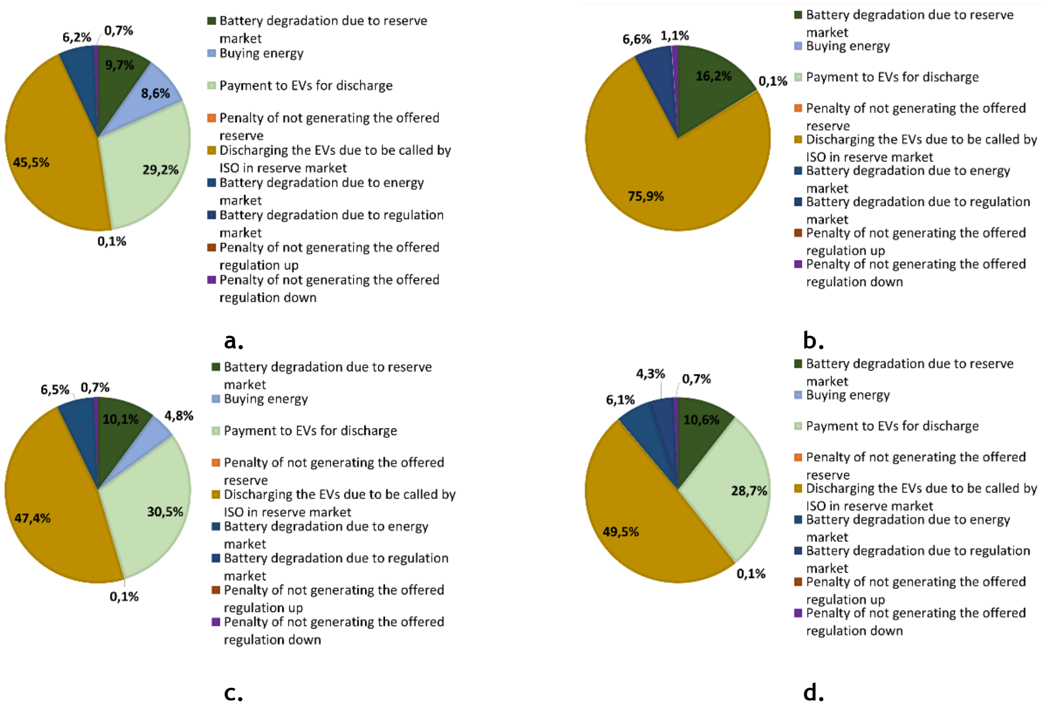


Figure 4.51 -Contribution of each cost for the global FEUP EV PLO's profit without considering a capacity payment corresponding to (a) Scenario I (Winter). (b) Scenario I (Summer). (c) Scenario II (Winter). (d). Scenario III (Summer).

However, the participation in regulation down market is higher than in regulation up, i.e., the parking lot is less willing to increase its output for grids benefit. Furthermore, the parking lot also benefits from delivery the offered regulation up and down, via being called by the operator system.

Another curiously point that can be observed when assuming a capacity payment is that in the base Summer Scenario the grid does not transfers energy to the parking lot. Consequently, there is neither income from charging EVs nor cost for buying energy from the grid. Nevertheless, there is a higher participation in the regulation down, meaning that EVs are charged through this contribution. Based on this the mentioned scenario presents only costs related to the regulation market, leading to the lowest global cost, around 42€.

Moreover, there is only participation in the reserve market when occurs an increase of the capacity payment, suggesting that the assumed prices were too small for the parking lot provide services to the grid. As a consequence, the results show that the parking lot prefers to participate in the capacity payment of reserve rather than in electricity market.

As it was expected, since the parking lot contributes to the reserve market, this case, i.e., increasing the reserve capacity payment, is the only one that presents costs regarding battery degradation in the reserve market and EVs discharge due to be called by the operator system in the reserve market, reaching a maximum of approximately 6€ and 28€ in summer base scenario.

According to Figure 4.52, Scenario III without considering a capacity payment presents the highest cost for discharging (around 282€). Since there is a higher presence of PV power generation, EVs tend to discharge in early morning and in the evening, when market prices are high, increasing the cost.

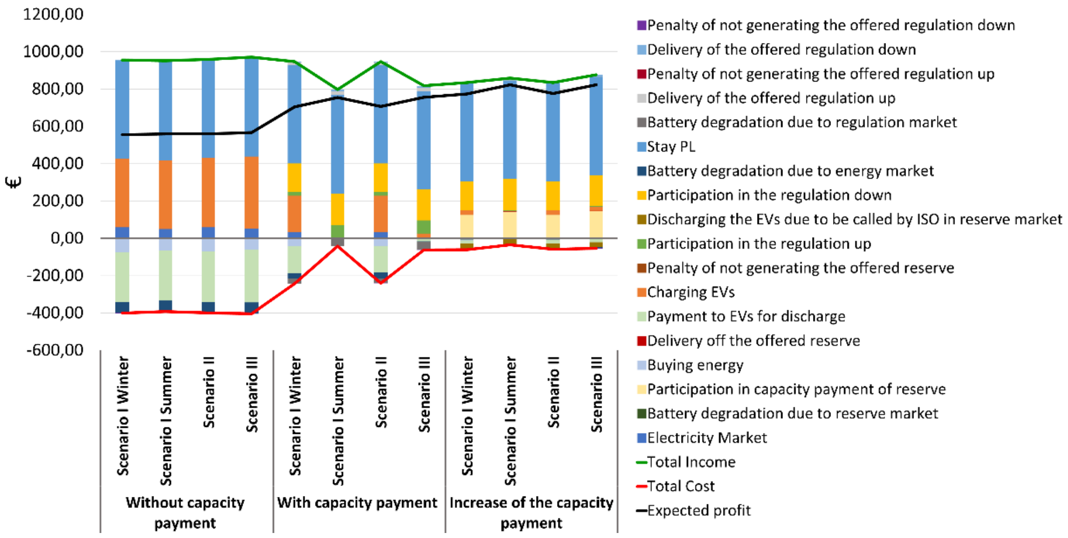


Figure 4.52 - A breakdown of FEUP EV PLO's profits and costs corresponding to three assumptions: without capacity payment, with capacity payment and an increase of the capacity payment

Contrasting, the same scenario when considering a capacity payment, it presents the lowest cost (approximately 16€). This means that in the presence of a capacity payment, the parking lot prefers to participate in regulation market since the capacity payment can compensate the costs of operating in PL2G activities, decreasing the cost of discharging EVs.

Concerning the expected profit, on one hand, when not taking in consideration the capacity payment, the revenue is practically constant. However, the scenarios considering the rooftop PV system presents the highest profit. On the other hand, when assuming a capacity payment, relatively higher differences are observed when considering different weather conditions, within the summer scenarios presenting the largest profits. These differences are also observed when increasing the capacity payment, where the summer scenario considering the rooftop PV generation (Scenario III) reports the most profitable scenario.

4.2.1. Additional study

The effects on the behavior of the parking lot operator are also investigated considering different cases built based on the size of the rooftop PV. Table 4.6 and Figure 4.53 shows how the different incomes and cost are influenced as the number of roof-top PV panels increases. It is assumed the same EV traffic patterns and prices in all cases, not considering the capacity payment for the different markets.

Moreover, is taken into account the worst weather conditions, i.e., the winter case (Scenario II). It can be observed that the case with 50 panels brings the lowest profit for the parking lot. A higher number of solar PV panels leads to a higher profit for the EV parking lot, since it allows the EV parking lot to participate more actively in energy market. The scenario that integrates 600 PV panels is the most profitable one for the parking lot. In this case, the parking lot has the lowest cost of buying energy from the grid.

Table 4.6 - Change of the incomes and costs with the change in the number of PV panel on the rooftop

	50 PV Panels	100 PV Panels	200 PV Panels	300 PV Panels	400 PV Panels	600 PV Panels
Electricity Market (€)	31.21	31.21	31.21	31.21	31.21	31.21
Charging EVs (€)	196.36	196.36	196.36	196.36	196.36	196.36
Stay PL (€)	20.74	20.74	20.74	20.74	20.74	20.74
Delivery of the offered regulation down (€)	152.63	152.63	152.63	152.63	152.63	152.63
Battery degradation due to reserve market (€)	526.20	526.20	526.20	526.20	526.20	526.20
Buying energy (€)	16.32	16.32	16.32	16.32	16.32	16.32
Payment to EVs for discharge (€)	3.69	3.69	3.69	3.69	3.69	3.69
Battery degradation due to energy market (€)	41.95	41.58	40.84	40.09	39.35	37.86
Penalty of not generating the offered regulation down (€)	143.14	143.14	143.14	143.14	143.14	143.14
Total Income (€)	30.56	30.56	30.56	30.56	30.56	30.56
Total Cost (€)	26.31	26.31	26.31	26.31	26.31	26.31
Expected profit (€)	0.23	0.23	0.23	0.23	0.23	0.23

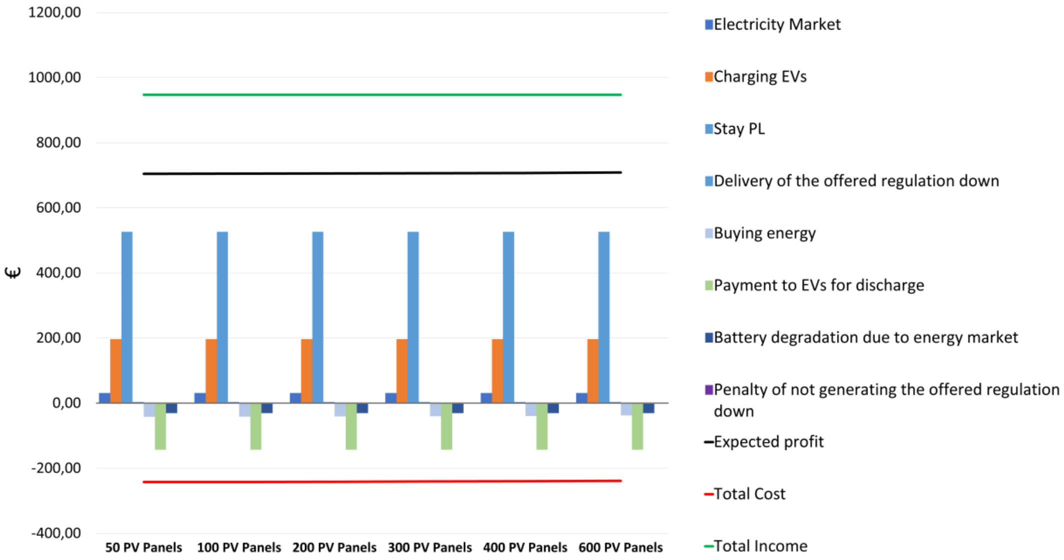


Figure 4.53 - Change of the incomes and costs with the change in the number of PV panel on the rooftop corresponding to FEUP's case study

As can be seen, the parking lot prefers to take part in the energy market rather than in the regulation and reserve markets, due to the low amount of regulation and reserve price and, the lack of the of capacity payment.

The cost to EVs for discharge rises, as the number of solar panels increases. Furthermore, as the battery degradation cost increases, as the number of solar panels increases. This is due to the high interaction between the parking lot and the grid. A perceptible change is noticed in the cost of buying energy from the grid.

Another point that can be pointed out is as the number of solar PV panels increases, the cost of buying energy from the grid decreases. This fact would be expectable since there is a higher PV generation from the rooftop system as the number of PV panels increases, thus the rooftop PV is able to meet the charging requirements without buying a larger amount of energy from the grid.

Chapter 5

Conclusions and Future work

5.1. Main Conclusions

EVs can become an important part for power systems, with consequent air pollution, system reliability and economic benefits. The economic value of some V2G modes appear high, plenty to counterweight the initial high cost of electric vehicles, therefore having the potential to accelerate their market integration. To accomplish this potential, some harmonization of vehicle and infrastructure planning will be required.

Allying this to the fact that vehicles are parked during a considerable period of time during the day being exposed to solar irradiance and that a considerably high fraction of worldwide EVs charging stations are located in parking lots, a convenient and viable solution emerges in terms of EV charging, through the equipment of parking lots with photovoltaic rooftops. It is a feasible mechanism to charge electric vehicles at heavily populated areas such as workplaces and shopping centers.

This thesis presents a model to reflect the impacts of photovoltaic generation on the profits and behavior of an EV parking lot, considering different weather conditions (a typical winter and summer days). The profit was calculated considering the interaction of parking lot in three power markets (electricity, reserve, and regulation services) and, contracts with EV drivers that show interest in operate in V2G mode. Additionally, the effect of a capacity payment is discussed. Therefore, each case study is divided according three assumptions: without considering a capacity payment, considering a capacity payment and considering an increase of the capacity payment.

This work analyzes the traffic patterns of two parking lots located in different areas: the first, from a public middle school, and the second from a university, both from Porto, Portugal. Assuming that all parked vehicles are electric, it is analyzed the possibility of charging them via photovoltaic energy, while their owners are working. Several conclusions can be made for both case studies.

Regarding the expected profit, when not taking in consideration the capacity payment, the revenue is almost constant, being Scenario III the most profitable (accounting with 239€ and 567€ for the public school and FEUP's parking lot, respectively), followed by Scenario II and Scenario I (Summer), and the less gainful is Scenario I (Winter), with 230€ and 555€ for the public school and FEUP's parking lot, respectively.

However, the scenarios considering the photovoltaic rooftop system presents the highest profit. On the contrary, scenarios that assume an increase of the reserve capacity payment present the highest profit, reaching a maximum of around 823€ in Scenario III and a minimum of approximately 774€ in base winter scenario.

It was also observed that the participation in the reserve market was mainly influenced by the price, being only economically viable when an increase of the capacity payment occurs. By participating in the reserve market, the parking lot is remunerated for having available and synchronized a given capacity as well as it receives an additionally compensation for deliver the offered reserve.

However, in the case that parking lot is not able to generate enough energy to participate in reserve; it can merely decide to not participating without paying high cost penalties. These costs penalizations are only observed when assuming an increase of the capacity payment, reaching a maximum of approximately 0.017€ in base summer scenario.

Another ancillary service, regulation, appears to be a particularly valuable application of V2G power, more especially in the presence of a capacity payment. At this circumstance, similar to what occurs in regulation market, the parking lot is paid not only for having available and synchronized a given capacity but it receives additionally payment for energy delivery. If the parking lot has not enough energy to participate in regulation, it can simply choose not participate without suffering high penalties. The maximum penalty that the parking lot suffers for not deliver the offered regulation is approximately 0.38 € and 0.32€ in regulation down and up market, respectively.

When comparing the two case studies, it can be concluded that FEUP's parking lot is more profitable than the public school's parking lot at both days with different weather conditions. For instance, while FEUP's reaches a profit of approximately 756€ in a typical summer day (considering a capacity payment), the school achieves a profit of around 313 € considering the same assumptions, attaining a difference of approximately 141%. These results show that parking lots with higher dimensions seem to lead to higher profits.

However, this assumption should not be taken into account for each and every case because there is a major factor that determines the parking lot's profit: its dynamic nature. In other words, if the parking lot was more static, that is, all the electric vehicles are parked all day long, for instance, from 8:00 am to 18:00 pm, it will lead to lower participation in the several markets since electric vehicles remain the same during all day, which does not allow major modifications. Therefore, in this case, profits will be lower.

5.2. Future work

Some useful perspectives exist for future development and research, specifically:

- The study of different electric vehicle models/brands to estimate the effects of different specifications such as battery capacity on the operation of the parking lot;
- The study of parking lots with different traffic patterns such as shopping centers or airports in order to evaluate the impact of electric vehicle's uncertainties (arrival and departure time) on the parking lot's participation on multiple markets;
- The integration of the distribution network according to the parking lot considered. Instead of be inserted into a standard distribution network, this work could be adapted to the distribution network where the parking lot is allocated;
- The application of a constraint regarding the charging level, i.e., consider the most suitable charging level according to the parking duration of the electric vehicle;
- The study of new operating strategies combining more renewable integration, i.e., a combination of solar and wind power, for instance, proposing new market interactions.

5.3. Contributions

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