Faculdade de Engenharia da Universidade do Porto

Coordinated Operation of Electric Vehicle Solar Parking Lot as a Virtual Power Plant

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Resumo

Com o crescimento da capacidade dos recursos distribuídos de energia (DERs), e a ampla diversidade das tecnologias complementares inerentes ao processo DER, é possível a expansão dos meios pelos quais os consumidores de eletricidade podem interagir ativamente com a rede elétrica. A descentralização resultante da operação e a tomada de decisões inerentes ao processo DER gera várias oportunidades e desafios. Se a abordagem adotada não for a mais adequada, a diminuição da robustez resultante do sistema elétrico afetará adversamente todas as partes interessadas.

No entanto, se as redes de eletricidade existentes se adaptarem com êxito à transição DER, na qual os consumidores ativos de pequena escala participam simultaneamente no fornecimento e procura de eletricidade, são esperadas perspetivas ilimitadas para futuros sistemas de energia sustentáveis, e mercados de eletricidade mais eficientes. Portanto, os operadores elétricos devem desenvolver novas estruturas de gestão da eletricidade que aproveitem o potencial de participação do pequeno consumidor e, ao mesmo tempo, garantam a confiabilidade, a robustez, a eficiência e a minimização dos custos no sistema elétrico. Nos últimos anos, as *Virtual Power Plants* (VPPs) surgiram como uma estrutura eficaz para agregar o potencial coletivo dos DERs, onde se incluem a geração distribuída (DG) e os sistemas de armazenamento de energia (ESS), por meio da implementação de programas de *Demand Response* (DR).

No presente trabalho é apresentado a operação de dois ativos indispensáveis dos DERs: os veículos elétricos (VEs) e os estacionamentos equipados com sistemas fotovoltaicos (PVPLs), permitindo assim a análise sobre a coordenação de uma estratégia ótima de gestão de eletricidade, permitindo a possível agregação do sistema proposto numa VPP. Com efeito, o sistema de gestão de energia (EMS) proposto foi desenvolvido utilizando as ferramentas de otimização e modelação GAMS e MATLAB, com a expectativa para uma futura utilização por parte dos operadores de rede, no contexto de cidades inteligentes, permitindo a coordenação das operações dos PVPLs e os sistemas de gerenciamento de energia doméstico (HEMSs). O modelo desenvolvido foi validado e testado considerando casos de estudo reais na cidade do Porto, Portugal.

Palavras-chave: *Demand response;* Parque de estacionamento fotovoltaico; Operação coordenada; Recursos distribuídos de energia; Sistema doméstico de gestão de energia; Veículos elétricos; *Virtual power plant*.

Abstract

The growth in distributed energy resources (DERs) capacity and the broad diversity of complementary technologies has expanded the means by which electricity consumers can engage with the power grid. The resulting decentralization of operation and decision-making gives rise to several opportunities and challenges. If poorly addressed, the resulting weakening of power systems will adversely affect all stakeholders.

However, if existing power grids successfully adapt to this transition in which small-scale consumers participate simultaneously in supply and demand of electricity with their DERs, limitless prospects for sustainable energy systems and more efficient energy markets are anticipated. Therefore, operators must develop new energy management frameworks which harness the potential of consumer participation while ensuring system reliability and cost-efficiency.

In recent years, virtual power plants (VPPs) rose as one such effective framework to aggregate the collective potential of DERs, including distributed generation (DG) and energy storage systems (ESS), through demand response (DR) program implementation.

In this work, the operation of two indispensable DER assets, electric vehicles (EVs) and photovoltaic-equipped parking lots (PVPLs) is coordinated in an optimal energy management framework, in order to study their possible aggregation in a VPP. The proposed energy management system (EMS) was developed using the optimization and modulation tools like GAMS and MATLAB, and is intended for use by grid operators to coordinate the operation of PVPLs and home energy management systems (HEMSs) in the context of smart cities. The developed model was validated and tested by considering real-life case studies in the city of Porto, Portugal.

Keywords: Coordinated operation; Demand response; Distributed energy resources; Domestic energy management system; Photovoltaic parking lot; Virtual power plant.

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Finally, I must express my very profound gratitude to my parents, for their loving support throughout my years of study, and throughout the process of conducting research and writing this thesis. This accomplishment would not have been possible without them.

Thank you.

Sincerely,
Tiago Poças de Almeida

"Good ideas are always crazy until they're not."

Elon Musk

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Nomenclature

List of Acronyms

AC	Alternating Current
AGC	Automatic Generation Control
AS	Ancillary Services
CHP	Combined Heat and Power
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DSO	Distribution System Operator
DR	Demand Response
EMS	Energy Management System
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
EVSPL	Electric Vehicle Solar Parking Lot
G2H	Grid-to-Home
G2V	Grid-to-Vehicle
H2G	Home-to-Grid
HEMS	Home Energy Management System
PV	Photovoltaic
RES	Renewable Energy Sources
SH	Smart Home
SOC	State-of-Charge
SOE	State-of-Energy
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
VRE	Variable Renewable Energy
VPP	Virtual Power Plant

List of Symbols

i	Index for home appliances
j	Index for EES devices
$\eta_j^{Ch.}$	Charging efficiency of ESS *j*
$\eta_j^{Disch.}$	Discharging efficiency of ESS *j*
$I_{j,t}^{Ch.}$	Charging status of ESS *j* at time slot *t*
$I_{j,t}^{Disch.}$	Discharging status of ESS *j* at time slot *t*
$P_{j,t}^{Ch.}$	Charging Power of ESS *j* at time slot *t*
$P_{j,t}^{Disch.}$	Discharging Power of ESS *j* at time slot *t*
E_j^{max}	Maximum acceptable energy stored at ESS *j*
E_j^{min}	Minimum acceptable energy stored at ESS *j*
λ_t^{buy}	Price of energy bought from the grid (house)
λ_t^{sell}	Price of energy sold back to the grid (house)
P_i	Rated power of appliance *i*
NA	Set of shiftable home appliances
NT	Scheduling period
$S_{i,t}$	Binary status of operation appliance *i* at time slot *t*
$B_{i,t}$	The preferred usage status of the appliance *i* at time slot *t*
$LB_{i,b}$	The lower band of baseline operation
$UB_{i,b}$	The upper band of baseline operation
$LB_{i,s}$	The lower band of allowable operation
$UB_{i,s}$	The upper band of allowable operation
T_i	Total number of time intervals for operation
γ^{charge}	Rate of charge EV
$\gamma^{discharge}$	Rate of discharge EV
n_t^{PL}	Number of EVs in the parking lot at hour t
Γ^{R-up}	Penalty for not distributing the offered regulation up
Γ^{R-down}	Penalty for not distributing the offered regulation down
λ_t^{En}	Energy price
λ_t^{Res}	Reserve price
λ_t^{R-up}	Regulation-up price
λ_t^{R-down}	Regulation-down price
Cd^{En}	Battery degradation cost due to energy market
Cd^{Reg}	Battery degradation cost due to regulation
$\pi^{unvail.}$	Scenario Probability of being unavailable
π^{call}	Scenario Probability of being called
η^{charge}	Charge efficiency of battery (EV)
$\eta^{discharge}$	Discharge efficiency of battery (EV)
$\lambda^{Tariff,stay}$	Parking usage tariff
p.u.	Per-unit system

Chapter 1

Introduction

1.1 Background

1.1.1 Proliferation of Distributed Energy Resources

Not enough emphasis can ever be made on how much people's well-being, industrial competitiveness and even the overall functioning of human society all greatly depend on safe, reliable, sustainable, and affordable energy systems. With that being said, Greenhouse Gas (GHG) emissions from fossil fuels reached a record 36.79 Giga tons of carbon dioxide equivalent ($GtCO_2e$) in 2017, increasing between 0.8% and 3% over the previous year. It is estimated that GHG emissions will double by 2050 if immediate and decisive actions are not taken [1].

Due to such limitations and environmental drawbacks of conventionally used fossil fuels for electricity generation, the ever-growing demand in energy markets, and concerns on security of supply, it became mandatory to consider other forms of sustainable and environmentally friendly energy sources during the past few decades. Renewable energy sources (RES), such as photovoltaic (PV) solar power generation, are environmentally friendly and can help to meet the fast-growing load demand.

However, given the unpredictable and intermittent nature of RESs, certain challenges still need to be addressed. Since PV power is to a great extent non-dispatchable and time-varying, it becomes necessary to couple them with other geographically distributed energy resources (DERs) to mitigate these effects.

Typically, Energy Storage Systems (ESS) have been used alongside RES to compensate for their non-dispatchable nature and provide more control for the grid operators. One such example is the use of hydroelectric ESS with wind farms to store unforeseen surplus generation and feed it back into the grid when unforeseen shortage of generation is encountered. In the case of PV systems, batteries are commonly used as the ESS.

1.1.2 The Rise of Electric Mobility and Electric Vehicles

EV sales (both purely battery-electric and plug-in hybrids) surpassed 2 million units in 2018, a 58% growth over the previous year [2]. The exponential rise of electric mobility in general and consumer-owned electric vehicles (EVs) in particular made the latter attractive candidates as a DER which could be used as semi-dispatchable DER which simultaneously serves as an ESS, leveraging the overall sustainability and cost-efficiency of power systems.

Consequently, the world is likely to witness a similar rise of smart charging solutions. As opposed to uncontrolled charging as soon as it is plugged in, the EV or charger will examine conditions such as local and national demand, price, signals, time of day, the customer's charging preferences and battery state-of-charge (SOC), and then decide on the most optimal time to charge. Customers who are most flexible at the time of such conditions will probably pay a lower price for the electricity, whereas those who want to be able to recharge their vehicle immediately will be able to do so albeit at a higher cost.

Continuing from smart charging, one can talk about the vehicle-to-grid technology (V2G). V2G describes a system whereby plug-in EVs, including battery electric vehicles (BEVs), hydrogen fuel cell electric vehicles (FCEVs), or plug-in hybrids (PHEVs) have the ability to export electricity to the utility provider. With the EV owner's consent, a utility provider could effectively draw electricity from V2G connected cars.

Owing to the variable output of all sources of electricity generation, especially RESs, the grid operators are increasingly looking for providers of balancing services that can either absorb power when generation outstrips demand, or supply power when demand is higher than generation. The batteries in EVs are ideal to provide such balancing, assuming power can flow in either direction in a controllable manner.

Since PV represents non-dispatchable and time-floating energy supply whereas EVs could represent controllable loads and energy storage, it clearly makes sense to couple the two. On one hand, EVs can help the power grid maintain the supply-demand balance, thus allowing a larger penetration of renewable energy. On the other hand, PV production could also enable a larger penetration of EVs, since they do not cause a significant net-load increase if charging directly from local PV sources [3].

However, integrating EVs and PV with the grid has to be done with due care; otherwise it might instead compromise the grid reliability. For the grid operator, the main concern over PV generation is its uncertainty. As for the EVs, they might trigger a surge in demand, causing grid overload. Both situations could lead to power quality degradation and stability issues [4, 5]. In this context, decentralized on-grid PV power plants and EVs charging directly from them are of less concern to the grid. This happens because the grid would not have to integrate a large PV capacity and would not need a big reinforcement to satisfy the increasing EV demand.

Moreover, this solution does not imply GHG emissions and the charging infrastructure promotes the EV adoption. It could be implemented via solar arrays installed as shade structures over parking lots to charge EVs during the day, i.e., EV solar parking lots (EVSPLs).

Worldwide, there is plenty of parking space that can be converted to EVSPLs without requiring the use of new land. They may be installed practically anywhere: at workplaces, shopping centers, supermarkets, hotels, hospitals, airports, universities, and so on. To take advantage of EVSPLs, cars need to be parked for long enough during daytime, since to fully charge an EV from empty or to top it up one may need several hours, depending on the connection type.

Smart EVSPLs may also act as an aggregator of EVs, easing the interaction between the players, in a virtual power plant (VPP) approach. The concept of VPP is a solution which has been developed to address the need for the effective integration of DERs in the electricity grid regarding both technical and economic aspects.

1.1.3 Virtual Power Plants

The VPP is a virtual architecture that uses software and smart devices for decentralized control and optimal dispatch of DERs. In this way, VPPs effectively provide services to the grid while maximizing customers' and utilities' performance objectives and ensuring that power system constraints are duly enforced. The main actors in a VPP are called aggregators. As the name suggests, they utilize this powerful framework to perform the aggregation of DERs to act collectively as a "virtual" dispatchable unit which can interact with different players in the power system.

Figure 1.1 provides a short overview about DER aggregation and VPP connection. A non-exhaustive list of potential benefits of DER aggregation under VPP architecture includes:

- Mitigating RES uncertainty effects by having a diversity of sources in different locations;
- Balancing energy supply and demand locally and decreasing the need to re-dispatch large conventional power plants;
- Breaking the capacity limit for entering the electricity market. In other words, many DERs have insufficient capacity, output controllability and flexibility necessary for participating in the electricity market directly.

The main actors in a VPP are called aggregators. A Supplier/Aggregator (S/A) is a company responsible for the VPP's operation which sells electricity to the users and aggregates and manages their load demand with the purpose of offering demand side management (DSM) and other possible ancillary services to the system operator. The S/A can use the VPP concept as a tool for performing this aggregation to form a single group of resources which can interact with the Distribution System Operation (DSO), with the Transmission System Operator (TSO), and the market [6].

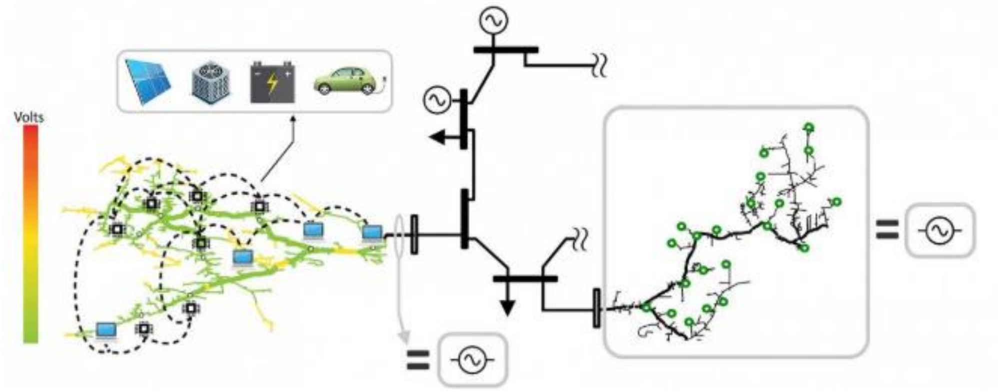

Figure 1.1 - DER aggregations in distribution feeders to emulate a VPP [7].

In fact, VPPs are already being employed as real-life technologies, evolving past being merely conceptual models. Actually, for instance, *Kraftwerke GmbH* manages one of the Europe's largest VPPs with more than eight thousand units. Moreover, Tesla is establishing an aggregation of residential and commercial storage systems in the USA and Australia. Hence, AGL, an electricity provider and gas supplier, manages a project that comprises the installation and orchestration of a 5MW VPP consisting of up to 1000 residential ESSs installed behind the meter, and capable of dispatching up to 12 MWh of stored energy.

All the aforementioned projects were established to demonstrate the role of VPPs in enabling higher penetrations of distributed renewable generation in the grid and help further understanding about the role of distributed smart storage in supporting grid resilience and reliability [8]. Those are only a few of many examples of worldwide adoption of VPPs as an effective framework for energy management.

1.2 Motivation

The sustainable use of RESs is not possible without reviewing current market models and some renewable energy policies. As elaborated, one effective method for dealing with the challenge of RES integration in existing electricity market structures is the deployment of VPPs. When integrated in a VPP, the power and flexibility of the aggregated assets can be managed collectively.

Thus, even small units get access to the lucrative markets, like the balancing reserve market, that they otherwise would not be able to participate in individually. Any decentralized unit that consumes, stores or produces electricity can become a part of a VPP. In this thesis, a methodology is proposed, implemented, and tested for techno-economically optimal energy management within a VPP-based framework.

In this sense, the VPP is composed of an EVSPL and several prosumers whose assets include EVs and Smart Homes (SH) equipped with Home Energy Management Systems (HEMS). Both the technical and economic impacts of the coordinated operation of the EVSPL and the SHs are assessed through different case studies.

1.3 Objectives

This work tries to propose a global energy management framework for smart grid operators, which builds upon the fundamental concept of VPPs. The optimal operation of PVPLs and smart homes is coordinated such that the maximum benefit of EVs can be harnessed for the grid while also maximizing the benefit for the owners.

HEMSs are coordinated with EMSs of PVPLs and the resulting effect on grid operation and economic gains (or lack thereof) for all players (PL owners, EV owners, grid operators, among others) is investigated in a full techno-economic analysis of the feasibility of the proposed approach as a next-generation VPP model.

In the majority of the existing studies on the integration of EV parking lots and RESs, the main function of the control algorithm has been to decrease the operational cost or, in other words, maximize the operational profit.

To evaluate the electric impacts of such entities and their possible aggregation in a VPP, an energy management methodology is presented which allows an organized and economic planning of energy consumption and production.

The main goal of this work is to provide a management solution that facilitates the integration of DERs based on a VPP concept, where the objective is to improve the power grid performance while simultaneously maximizing the economic benefit of all participants.

1.4 Thesis Structure

This dissertation is divided into five chapters. The first chapter is an introductory chapter where the context of the problem is presented, and the objectives and the structure of the study are listed.

The second chapter includes a literature review of relevant works on the subject area of the present dissertation. The third chapter describes the methodology applied to formulate the proposed model mathematically, the software tools used for implementation, and the constructed case studies used for validation and analysis.

The fourth chapter presents the results obtained from the conducted case studies and provides a discussion thereof. Finally, the fifth and last chapter lists the main conclusions of this work, discusses the limitations of the performed analyses, and suggests future prospects which can build upon the reached frontiers.

Chapter 2

State-of-the-Art Review

In this chapter, a comprehensive review of the state-of-the-art scientific literature pertaining to relevant topics is presented. The survey starts with EVs and continues to cover VPP definitions and components, highlighting the different techniques that can be used for VPP optimal operation. It is also presented a spectrum of works on technologies which are relevant to the current thesis and its objectives.

2.1 Literature Review on Electric Vehicle Technologies

The search for efficient alternatives to replace fossil fuels has become one of the most important challenges facing the transportation and logistics sector. Since transportation sector is one of the major sources of CO_2 emissions within the European Union (EU), the need to reduce emissions in this sector is inevitable. Thus, for transportation sector, the European Commission (EC) stated the goal to reduce the greenhouse gas emissions by 20% until 2030 compared to emissions in 2008, and by 60% until 2050 compared to 1990. Recently, the EC has reinforced the 2050 goal, and expressed the expectation that transportation sector should "*be firmly on the path towards zero*" [9].

The electrification of the transportation sector means on one hand an increase in the energy demand which must be served. On the other hand, this offers the opportunity to make use of those additional mobile energy sources for energy market participation and power system operation.

This context has led to an increased awareness of the public for EVs, with car manufactures investing massively to make EVs an industrially viable and cost competitive product which will lead, in the next years, to a noticeable change in the automotive portfolio. An exemption of this observation is the number of passenger plug-in electric car registrations in Europe amounted in May 2019 to around 37,400, which is 28% more than a year ago, as shown in Figure 2.1.

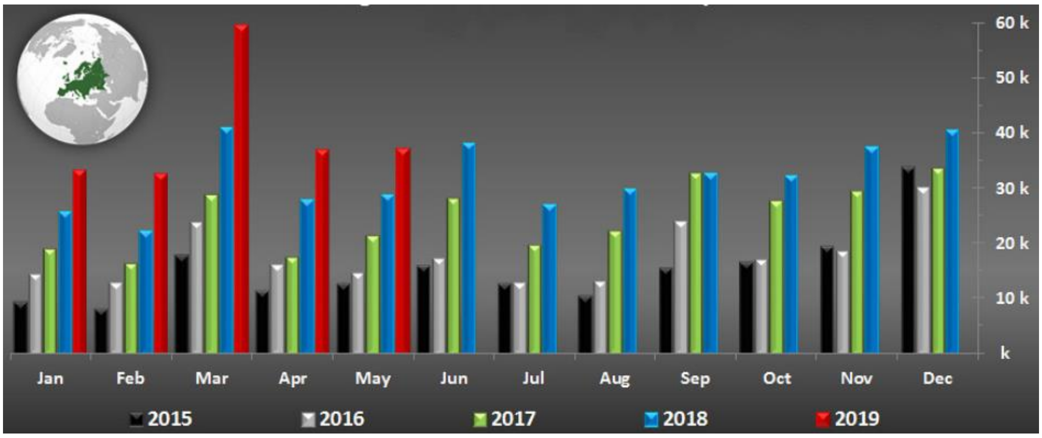

Figure 2.1 - Plug-in electric car sales in Europe [10].

Almost two-thirds of the segment (63%) is all-electric cars around 24,000 [10]. China has the largest number of EV sales worldwide, followed by Europe and the United States. The current EVs can be classified into two main categories:

- All-electric vehicles (AEVs) that include Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs);
- Hybrid electric vehicles (HEVs) that include Plug-in Hybrid Electric Vehicles (PHEVs) and Full Hybrid Electric Vehicles (FHEV).

Battery EVs, also called BEVs and more frequently EVs, are fully electric vehicles with an electric motor instead of an internal combustion engine. The vehicle uses a large traction battery pack to power the electric motor and must be plugged in to a charging station or a wall outlet to charge. Because it runs on electricity, the vehicle emits no exhaust from a tailpipe and does not contain the typical liquid fuel components, such as a fuel pump, fuel line or fuel tank. Some of the key components of a fully EV can be addressed and are briefly expressed on the Figure 2.2:

- Traction battery pack: Stores electricity for use by the electric traction motor;
- Electric traction motor: Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions;
- Onboard charger: Takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction batteries. It monitors battery characteristics such as voltage, current, temperature and state of charge while charging the pack;
- Power Electronics controller: It manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces;

- DC/DC converter: This device converts the higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery;
- Transmission (electric): The transmission transfers mechanical power from the electric traction motor to drive the wheels;
- Charge port: It allows the vehicle to connect to an external power supply in order to charge the traction battery pack.

2.1.1 Types of Charging

EV charging is classified by power levels or modes. References [11,12] have deal with an overview on different types of EVs charging stations and a comparison between the related European and American Standards. Charging an EV in Europe differs by country. Some European countries primarily use 1-phase connections to the grid, while other countries are almost exclusively using a 3-phase connection.

For the current work, all EVs are assumed to be Nissan Leaf with batterie capacity of 30kWh. The Figure 2.3 shows all possible ways that the Nissan Leaf 30kWh can be charged, but some modes of charging might not be widely available in certain countries. The Nissan Leaf uses two charging standards for its inlets Type 1 and CHAdeMO [13]. The Type 1 inlet is used when charging at home or at public slow and fast AC points. The CHAdeMO inlet is used to carry high power during rapid DC charging from a CHAdeMO connector.

The Nissan Leaf is fitted with a 3.3 kW on-board charger for Type 1 AC charging, in addition to rapid 50 kW DC capability. Often the optional 6.6 kW on-board charger is fitted though to make greater use of public charger points. This means that even when connected to a fast charger with a rated output above 3.3 kW or 6.6 kW, the Leaf will only be able to charge at its on-board charger capacity.

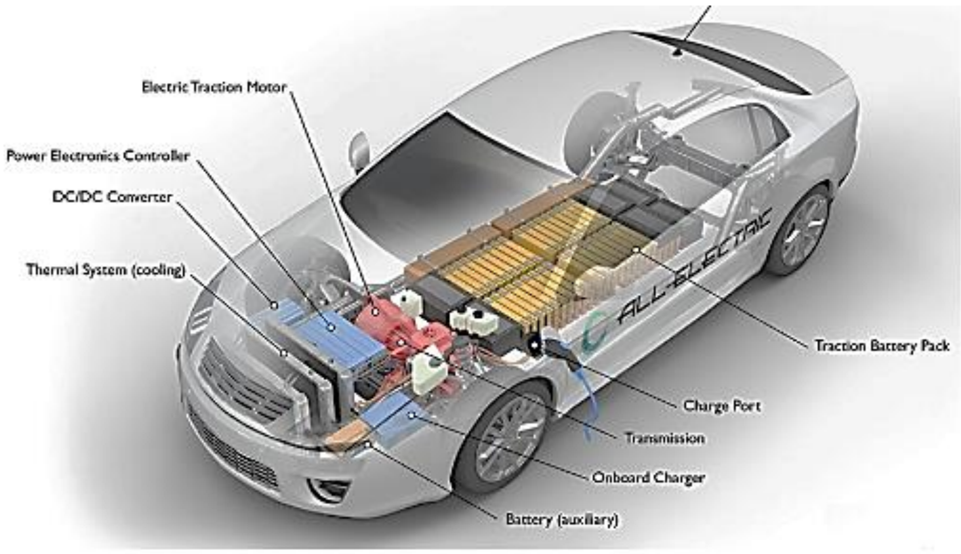

Figure 2.2 - Key components of a BEV [14].

Type 1 (Yazaki - SAE J1772)

Charging Point	Max. Power	Power	Time	Rate
Standard 3.3 kW On-Board Charger				
Wall Plug (2.3 kW)	230V / 1x10A	2.3 kW	14h30m	12 km/h
1-phase 16A (3.7 kW)	230V / 1x14A	3.3 kW †	10 hours	17 km/h
1-phase 32A (7.4 kW)	230V / 1x14A	3.3 kW †	10 hours	17 km/h
3-phase 16A (11 kW)	230V / 1x14A	3.3 kW †	10 hours	17 km/h
3-phase 32A (22 kW)	230V / 1x14A	3.3 kW †	10 hours	17 km/h
Optional 6.6kW On-Board Charger				
Wall Plug (2.3 kW)	230V / 1x10A	2.3 kW	14h30m	12 km/h
1-phase 16A (3.7 kW)	230V / 1x16A	3.7 kW	9 hours	19 km/h
1-phase 32A (7.4 kW)	230V / 1x29A	6.6 kW †	5 hours	34 km/h
3-phase 16A (11 kW)	230V / 1x16A	3.7 kW †	9 hours	19 km/h
3-phase 32A (22 kW)	230V / 1x29A	6.6 kW †	5 hours	34 km/h

CHAdeMO

Charging Point	Max. Power	Avg. Power	Time	Rate
CHAdeMO (50 kW DC)	47 kW †	45 kW †	28 min	250 km/h

Figure 2.3 - Ways of charge - Nissan Leaf 30kWh [13].

2.1.2 Interaction between Electric Vehicles and the Power Grid

Smartly charged EVs can help reduce variable renewable energy (VRE) curtailment, improve local consumption of VRE production, avoid investment in peaking generation capacity and mitigate grid reinforcement needs [15].

By adjusting their charging patterns, given that EVs currently are idle in parking for most of the time, (90-95% of the time for most cars), so, EVs can become grid-connected storage units and contribute for both system and local flexibility, as illustrated in Figure 2.4.

Therefore, the grid potentially uses the EV's batteries for regulation, in which will ensure that the overall supply and demand remain in balance during a time period. This is typically practiced using spinning reserve power generation, as well as the practices of peak shaving, demand response and valley filling [16], that is discussed in the next section.

Spinning reserve is the mechanism by which extra power generation is provided when peak demand requires it. It is currently provided by off-line power generation plants that are running but not sending power to the grid until required. These plants can deliver power on short notice but at relatively high cost.

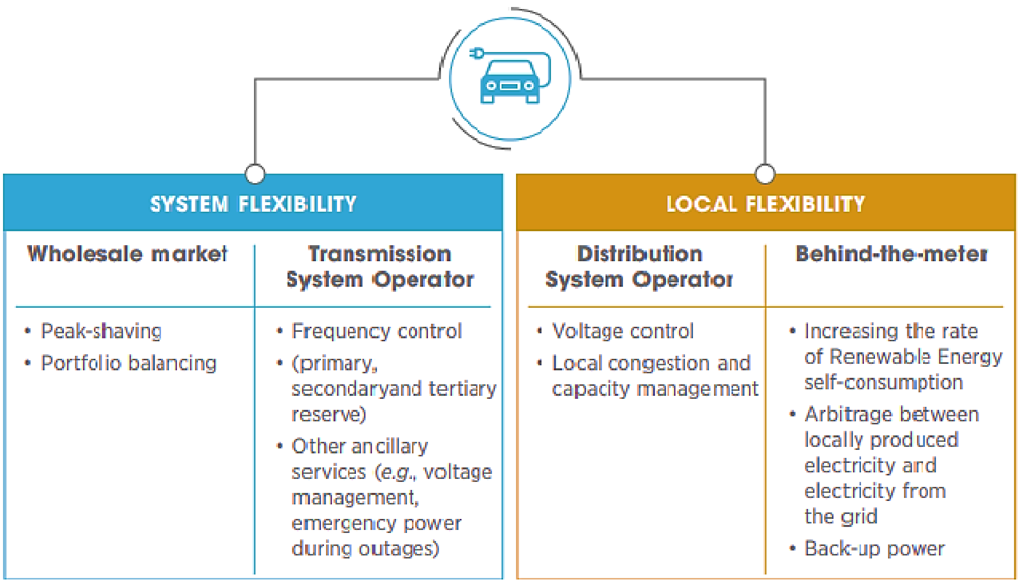

Figure 2.4 - Services EVs can provide to the power system [15].

Ancillary services (system and local levels / TSO and DSO) involve supporting real-time balancing of grids by adjusting the EV charging levels to maintain steady voltage and frequency. It is well understood that an EV with an enough large battery size can be charged and also discharge its electricity to provide the fast response needed for some ancillary services.

However, the ability of a single EV to supply or draw power has little or no effect on the grid, as well as virtually no economic power to negotiate on price. Therefore, the concept of EV aggregation was conceived, in which many EVs can be grouped together by a single entity known as an aggregator. Representing a sufficiently large population of EVs, the aggregator wields economic clout in negotiating for better electric rates and payback during peak times, as well as allowing collections of EVs to benefit the grid in terms of ancillary services.

The aggregator acts as a VPP with a fast response and the ability to provide services for the needed period. In this sense VPP Operator Next Kraftwerke and Jedlix, a smart charging platform provider, have launched an international pilot project which uses EV batteries to deliver secondary control reserve to TenneT, the TSO in The Netherlands [17].

2.1.2.1 Charging Control Strategies

The integration of high EV numbers cannot be done by the traditional “fit-and-forget” approach as great grid reinforcement would be needed, resulting in an overall high cost for the society. Instead, different control strategies need to be designed and implemented, which represents one of the biggest challenges for the successful transition to electric mobility. EV charging strategies can be divided in three categories, based on the level of control, as shown in Figure 2.5 [18].

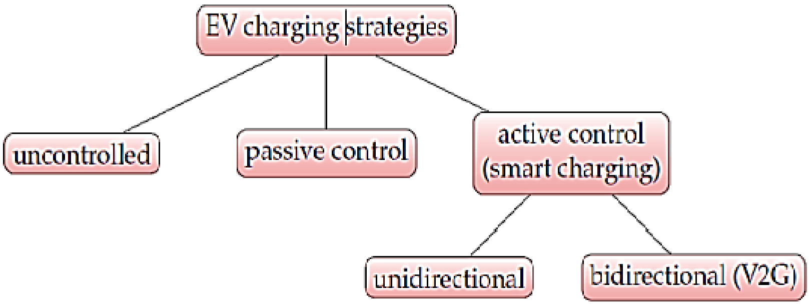

Figure 2.5 - Classification of possible charging control strategies for EV adoption [18].

Uncontrolled charging represents charging where the EV charges at maximum power as soon as it is connected to the grid. If EVs were charged in an uncontrolled way, they could increase the peak on the grid since charging trends could match existing load peaks and thus contribute to overloading and the need for upgrades at the distribution and transmission levels.

Additionally, this extra load would result in upgrade needs in the generation capacity. Passive control includes situations, where the EV owners are encouraged to charge their EV at a certain time, for example by having lower price tariffs during the night [18]. Smart charging means adapting the charging cycle of EVs to both the conditions of the power system and the needs of vehicle users.

The active smart charging is divided in two: unidirectional and bidirectional (V2G). With unidirectional charging, the EVs can modulate the charging power by increasing or decreasing the rate of charging. With bidirectional charging (V2G), the EVs can also inject power back to the grid when it's most needed and provide balancing and flexibility services [15].

In addition, vehicle-to-home (V2H) and vehicle-to-building (V2B) are forms of bidirectional charging where EVs act as supplement power suppliers to the home during periods of power outage or for increasing self-consumption of energy produced on-site (demand charge avoidance).

The time at which EV charging (or discharging) occurs, and its power level, could have significant implications for the electricity system. Without smart charging, EV charging is likely to happen during existing electricity system peak times (such as between 5pm and 7pm) when many people arrive home from work. This would require significant levels of additional investment in both the networks that transport the electricity and in electrical generation capacity to meet demand, with the costs borne ultimately by consumers. The uncontrolled charging situation can be improved by off-peak charging or smart "valley filling".

The Figure 2.6 shows how peak shaving can be part of a smart charging approach. Peak shaving is a complementary technology in which overall demand is reduced at peak times, reducing the need for spinning reserve. Valley filling is an opposing mechanism by which excess grid capacity is used during low demand hours. These techniques can be employed to mitigate the potential additional demand on the grid.

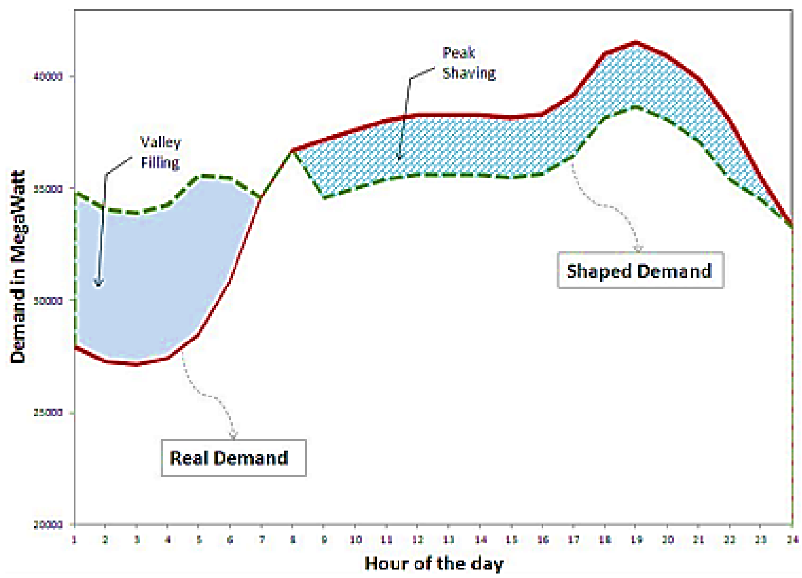

Figure 2.6 - Peak Shaving and Valley Filling [16].

2.1.2.2 Vehicle-to-Grid (V2G) Technology

V2G is a new emerging technology which came into existence because a large number of EVs can be used as load as well as an energy storage system to support the grid. Proper communication, between the power grid and the EV battery, is an essential part of the V2G system, as it is necessary for controlling the power flow. Figure 2.7 shows the energy transfer between the vehicle and the grid termed as V2G and G2V.

In [19], the authors have presented the advantages of the V2G technology for PHEVs. Improvement of short-term voltage stability are one of the potential benefits of the V2G mode. A number of advantages, to the EV owners, charging station and grid, are seen using V2G capability in several countries in the world. Some of them are the following [20]:

- Ancillary services that includes the spinning reserve and the power grid regulation. EVs can help support the balancing act between electricity demand and supply by adjusting their charging levels in order to maintain a steady voltage and frequency. Moreover, EVs are often able to respond more quickly than existing power sources;
- Active power support that includes the flattening of the grid load profile by “peak load shaving” and “load levelling”. At the time of peak-off demand, the EV users can purchase electrical energy at a lower price from the grid and at the time of peak-on demand, the EV users can sell electrical energy at a higher price to the grid. Thus, EVs act as movable storage units;
- Backup energy for home where the excess energy, from RES, is stored in EVs and used when the demand is higher;
- Reactive power compensation that provides voltage regulation in the grid.

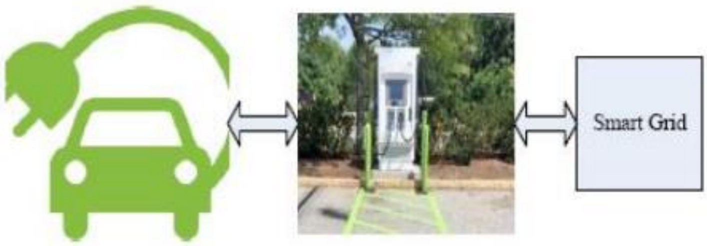

Figure 2.7 - Vehicle-to-Grid and Grid-to-Vehicle [20].

In [21] is presented the current scenario, the latest development, and barriers in the implementation of EVs infrastructural and charging systems considering the international standards. Despite, V2G implementation has a number of advantages and services to the power grid, and it has also many barriers including economic, social and technical challenges. Some of them are the following [20]:

- Degradation of the battery. Although the production cost of batteries continuously decreases, it still contributes to more than 1/3rd of the total cost of an EV. Charging and discharging actions result in the reduction of battery capability to store energy and to provide a certain amount of power over the battery lifetime. In V2G services, more charging/discharging cycles occur. Hence, the battery degradation might be more severe than no-V2G service cases;
- High investment cost is one of the major challenges coming in the way of V2G technology. For the V2G implementation, hardware and software infrastructure should be improved. Each EV which is participating in the V2G system will have a need of a bidirectional battery charger, which has a complex controller and high-tension cable with a need for safety associated;
- Social barriers are another challenge that V2G system needs to overcome and is related with the public acceptance. EV users will store an amount of energy for the emergency purpose and unpredictable journey. Sharing energy by the grid system can create the problem of the range anxiety which can become worse due to the lack of a charging facility.

There are several running V2G projects around the world. For example, in [22], a pilot project conducted by Mitsubishi in cooperation with the Netherlands/Germany-based operator TenneT, the electric vehicle smart-charging solutions provider *NewMotion* and the V2G tech and grid-balancing services provider *Nuvve* is presented.

The project is based around the use of the battery packs outfitted in the Outlander PHEVs and the aim is to provide capacity reserve services through the connection of the vehicles plugged to the grid, whether at home or at one of *NewMotion*'s plug-in EV charging stations.

2.2 Ancillary Services

Ancillary services (AS) are required to operate a power system under adequate levels of security, stability and quality of service [23]. The AS can be divided in four main categories to maintain the system operation stability: voltage control, frequency control, stability control and restarting system [24].

Voltage control constitutes an essential service for maintaining voltage in the power system within the recommended boundaries during regular operation and disturbances, assuring the balance of injection and absorption of reactive power. Voltage control can be provided by the dynamic sources (generators, synchronous compensators) and static sources (capacitor banks, static voltage controllers) [25].

Frequency control helps the system to maintain the frequency within the allowed margins by continuous modulation of power using the operational reserves. It includes automatic (primary and/or secondary) and manual (tertiary) frequency regulation. This service is mainly provided by generators but can also be provided by flexible loads and storage units [25].

A certain amount of active power, usually called system reserve, is kept available to perform frequency control: - when the system frequency tends to decrease it is necessary to inject more active power or reduce load (positive reserve), while when the frequency tends to rise it is necessary to reduce active power generated or increase load (negative reserve). Reserve services can be divided in three categories: Primary reserve, Secondary reserve and Tertiary reserve.

Figure 2.8 illustrates the timeline for the activation of these reserves where the first line after the disturbance shows the frequency deviation. Primary reserves are activated within seconds after the disturbance and are typically unable to bring frequency back to the nominal value. Secondary reserves are then activated by the AGC within minutes to bring frequency back to the nominal value and to keep the power interchanges between control areas in scheduled values. Finally, tertiary reserves replace and complement secondary reserves, and this can also involve rescheduling generators already in operation [23].

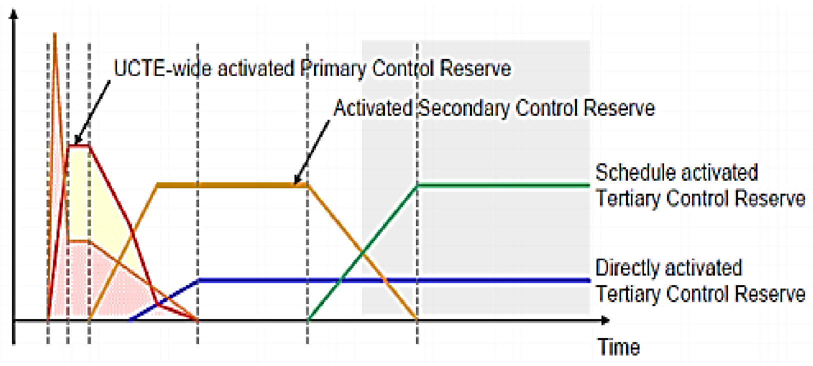

Figure 2.8 - Timeline for the activation of reserves [23].

2.2.1 Ancillary Services Provided by Demand Response Strategies

When a large online generator stops producing electricity unexpectedly, the balance between supply and demand on the system is thrown out of whack and system frequency dives below 50 Hz. In this circumstance, the system has a matter of seconds to restore the balance by either increasing generation or reducing demand. Failure to restore the balance quickly enough can result in involuntary load shedding or, in the worst-case scenario, a blackout system. This is briefly expressed on the Figure 2.9.

As one of the featured initiatives in smart grids, demand response is enabling active participation of electricity consumers in the supply/demand balancing process, thereby enhancing the power system's operational flexibility in a cost-effective way. The main objectives of the application of a DR scheme are summarized as follows [26]:

- Reduction of the total power generation. Under the successful implementation of a DR scheme, the need of activating more expensive power plants and build new ones to meet peak demands is mitigated;
- Change of the demand pattern, optimizing the end-user consumption, in order to follow the available supply, especially in regions with high penetration of renewable energy sources, such as solar panels and wind turbines, to maximize the overall power-system's reliability;
- Reduction or even elimination of overloads in the distribution system.

The adjustment of the customers' electric usage is realized as a response to changes in electricity price over time or when system reliability is threatened. This function is executed through the cooperation of three main participants [27]:

- End-users (residential, commercial or industrial) loads that take part in the DR program;
- A DR aggregator that is connected to the end-user's EMS and executes the DR program;
- A System Operator (SO) that manages the system.

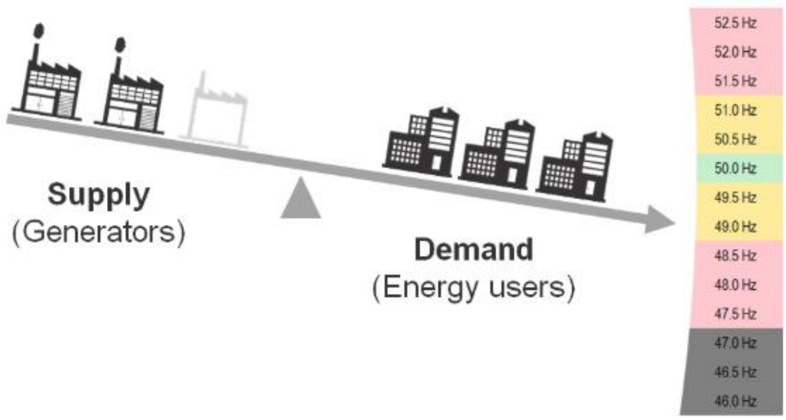

Figure 2.9 – Drop in frequency due to an unexpected event.

In general, the process of a DR scheme begins at the SO, which determines the demand volume that should be reduced or increased in a certain period. This information is submitted to the DR aggregators, who then select the participating end-users based on their availability.

Considering the number of end-users that agree with the proposed DR scheme, the aggregator calculates the total load flexibility that can be offered and reports back to the SO [26]. In this new paradigm, frequency control ancillary services can be provided by resources like batteries and DR that do not “spin” the way a synchronous generator does. Thus, DR can help re-balance supply and demand, as it can help to maintain the frequency of power system.

2.2.2 Demand Response Programs

In order to motivate customers, DR programs should increase end-user’s understanding of the benefits deriving from DR and improve their capability to take part in DR programs using control technologies, such as smart meters and thermostats. DR programs can be roughly classified into three groups according to the party that initiates the demand reduction action [28]:

- Price-based DR: In this program type, DR is implemented through approved utility tariffs or contractual appointments in deregulated markets according to which the price of electricity varies over time in order to motivate customers to adjust their consumption patterns. Customers would pay the highest prices during peak hours and the lowest prices during off-peak hours. The prices can be established a day in advance on a daily or hourly basis or in real time and the customer would react to the fluctuations in the electricity prices. Examples of programs in this category are shown in Figure 2.10;
- Incentive or Event-based DR: This category of DR programs rewards customers for reducing their electric loads upon request or for giving the program administrator some level of control over the customer's electricity-using equipment. A set of demand reduction signals, in the form of voluntary demand reduction requests or mandatory commands, is sent by the utility or the DR service provider (aggregator) to the participating customers. Incentive-based programs can be further categorized into classical and market-based programs, and they can be offered at both retail and wholesale market;
- Demand reduction bids: In this program, customers initiate the DR request and send demand reduction bids to the utility by offering an available demand reduction capacity and the requested price. This program mainly stimulates large customers to deliver load reductions at prices for which they are willing to be curtailed, or to recognize the load quantity they would be willing to curtail at the announced price.

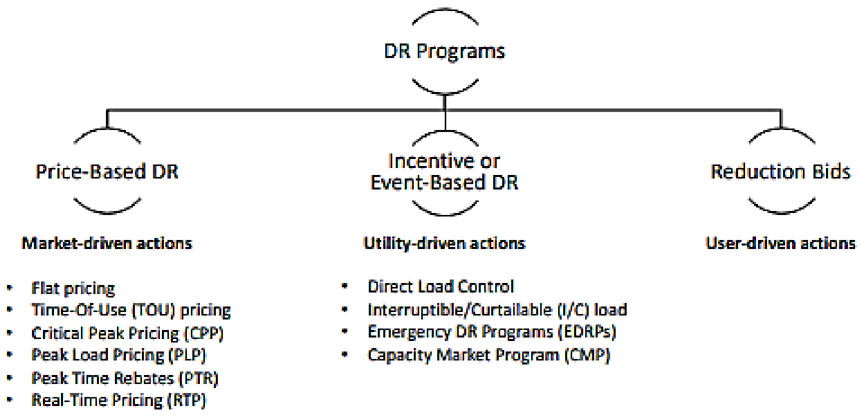

Figure 2.10 - Common types of DR programs [29].

DR programs are therefore a key concept not only to reduce the electricity bill, but also to decrease CO_2 emissions by reducing the need for polluting peaking power plants. As a consequence, DR provides benefits for both the end-users and the utility. On the customer side, end-users can change their consumption patterns so that their electricity expenses are reduced. On the utility side, DR programs can reduce the stress of operation on grid asset, decrease outage risk, provide efficient utilization of the RES, and secure grid reliability and stability [30].

2.3 Photovoltaic-Equipped Electric Vehicle Parking Lots

A fast-growing renewable energy sector, an increasing shift towards electric energy in the transport sector, and an expected increase in the sales of EVs asks for an improved infrastructure for charging EVs using renewable energy. As it is known, integrating EVs and PV with the grid, either individually or together, must be done with due care, otherwise it might instead compromise the grid reliability.

So, combining decentralized on-grid PV power plants and EVs charging directly from them are less of concern to the electric system because, with this solution, the grid would not have to integrate a large PV capacity and would not need a big reinforcement to satisfy the increasing EV demand. Electric vehicles are parked for a considerable time during the day being exposed to sunlight.

Additionally, 26% of worldwide EVs charging stations are located in parking lots mostly located near urban populations' hubs. In this context, there is a move towards designing solar-powered EV charging stations that provide clean electricity.

With the reduction in solar costs and improvement in solar efficiency, building solar-powered EV charging station presents an excellent opportunity to "greenify" our transportation needs, making EVs end-to-end environmentally positive. Combining these factors to PV power generation, i.e., covering PLs with rooftop PV systems, presents an opportune and reasonably priced solution for EV charging requirements [31].

The concept of solar parking lots aims at coupling the development of clean solar electricity and electric mobility. Solar panels provide shade and generate electricity to charge parked electric vehicles. In a vehicle-to-grid approach, the vehicles may also feed the grid and support it with ancillary services [32].

2.3.1 Benefits and Challenges

In reference [32], an overview of the benefits that EVSPLs is provided, as well as challenges that must be overcome in the short future. They are categorized in the usage of renewable energy, balance of energy, infrastructure, awareness of electric driving, and the stimulation of local economies. One of the main challenges is related with the coordination between the RES production and the charger demand of the EVs, due to the PV generation uncertainty.

To maximize solar EV charging, PV production must therefore be matched as closely as possible with the EV load profiles. Another challenge to account in the operation of the parking lot is related to the uncertain behavior of EVs such as arrival and departure times together with state-of-energy of EVs when they reach the parking lot.

2.3.2 Smart Electric Vehicle Parking Lots

An EV smart parking lot is described in reference [32] which makes use of RESs of its own and is able to control the parked EVs charging/discharging arrangement. Electric cars are parked most of the time during the day, and due to their batteries, they represent energy storage systems. So, in a network that allows bidirectional energy fluxes, they can act as a new player providing services to the electrical grid.

In an EVSPL there are unidirectional and bidirectional energy fluxes, as shown in Figure 2.11. In the presence of a battery that supports a local storage in the EVSPL, the PV arrays generate energy which must be distributed unidirectional to the EVs, BESS, or the electrical grid. The other type of energy flows in the EVSPL occurs in both directions and it is called vehicle-2-grid (V2G) and vehicle-2-vehicle (V2V). V2G implies that EVs discharge the energy stored in the battery to the grid, which is accompanied with a financial compensation to the EV owners.

Vehicle owners will thus have an asset which, due to its storage capacity, can be used in several situations, such as supporting building grids at peak hours or even stabilizing national electrical system parameters. V2V energy fluxes are defined by vehicles that donate part of their stored energy to other vehicles.

For example, if the PV output is not enough, instead of using the grid because the electricity spot price at that time is high, it may be better to transfer energy from one vehicle that will be parked for a longer time period and will have enough time to (re)charge to one that needs to leave in a short time frame. Therefore, pricing is a key element to establish which way energy should flow.

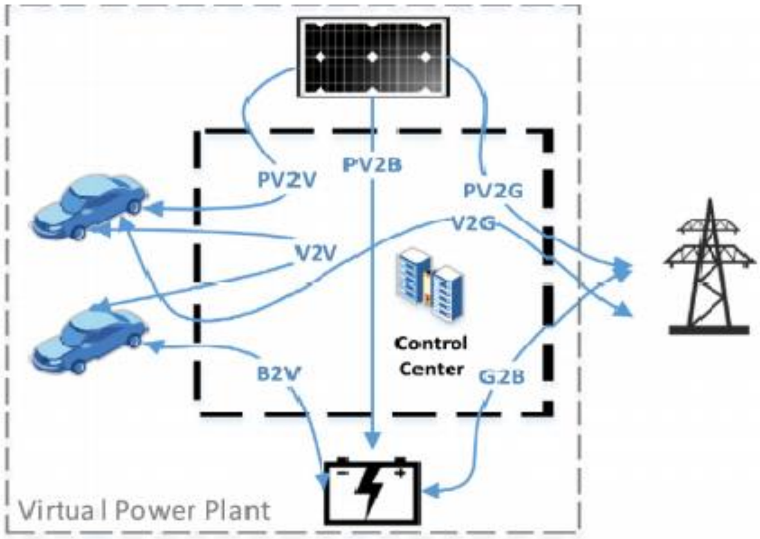

Figure 2.11 - Types of energy fluxes in a smart EVSPL with central energy storage [32].

There are several parties involved in an EVSPL which are associated with decision-making. The operator of the EVSPL whose goal is to maximize profit by creating revenues from parking fees, charging fees and fees to stabilize the utility grid. The operator can manage EVs charging, according to the preferences establish by EVs owners, such as the final SOC desired.

In addition, the EVs owners will be able to make decisions regarding maximum charging price, regarding length of charging time, whether discharging is an option, and maximum energy which can be discharged. Lastly, the system operators (DSO and TSO) will determine the electricity pricing and the capacity of the utility grid. Especially DSOs will be in contact with EVSPL operators as it will be mainly focused on the day-ahead market and local grid stabilization in short time frames [32].

In [31] was proposed a model to optimize the parking lot from the operator's point of view, while maximizing the parking lot's profit from owner/operator perspective that outcomes from market participations and from the process of EV charging, i.e., the amount that EV owners pay to charge their EV batteries.

2.4 Smart Homes

Over the past few years, classical residential building technologies have evolved to include more advanced features so as to enable the transformation of traditional structures into so called "smart homes". Smart homes have been researched over the last 30 years. The pioneering work in this area are the Smart Rooms implemented by the MIT Media Lab (Pentland, 1996) [33]. Thereafter, several researches have investigated this topic with a wide range of prospective applications.

According to reference [33], the smart home enables the management and control of different areas of a residence. The evolution of modern smart homes allows for a new level of control and automation.

Home automation can include a broad of sensors, actuators and control devices, and the application software [34]. There are selected functions of smart home so as to cover the greatest range of users. The functions can be distributed by four main groups: energy efficiency and management; security; entertainment and health.

2.4.1 Home Energy Management Systems

The combination of the smart grid and the incentives offered by DR programs has led to the development of HEMS. The HEMS concept have been studied for many researchers over the past few years. Moreover, there are several recent studies dealing with DR strategies for the optimum appliance operation of smart houses.

In reference [35], has developed an optimization strategy to evaluate the real-time price-based DR management for residential appliances. Although the real-time pricing incentive may introduce financial risks to end customers as compared to the flat rate or time-of-use (TOU) rate, it brings additional benefits to enhance the operational security and economics of power systems.

In [36], a multi-objective optimization for a smart house applying real-time pricing (RTP) as DR was proposed. For the assumed smart house, PV in addition to controllable loads, like a Heat Pump and a fixed battery, are introduced. Furthermore, the electricity is purchased at the RTP price, and the surplus power of renewable energy is sold at the RTP price.

In [37], incentive rewards were used with battery and PV management for controlling household are consumption. The used method considers the stochastic behavior of price, PV generation and loads. Incentive rewards are offered based on the participation of the consumer to the DR event. Results show that the proposed DR scheme can decrease the customer electricity bill by 18%.

The central task of the home energy management system (HEMS) is to reduce costs for the provision of energy without compromising the owner's wellbeing. This system can also optimize the operational schedule of home appliances and simultaneously manage the distributed energy resources and storage [38]. The overall architecture of a typical HEM with DR is shown in Figure 2.12.

The Figure 2.12 shows the flow of information from the HEMS to the various devices, including the EV and the ESS, and the bidirectional flow of electricity between the smart meter and the smart house. A smart meter is commonly installed at home and constantly in communication with a grid via the Internet, which links customers and utilities.

In [39] a MILP model of the HEM structure was provided to investigate a collaborative evaluation of a dynamic price-based DR strategy, a distributed small-scale renewable energy generation system, the V2H capability of an EV together with two-way energy trading of EV (using V2G option) and ESS.

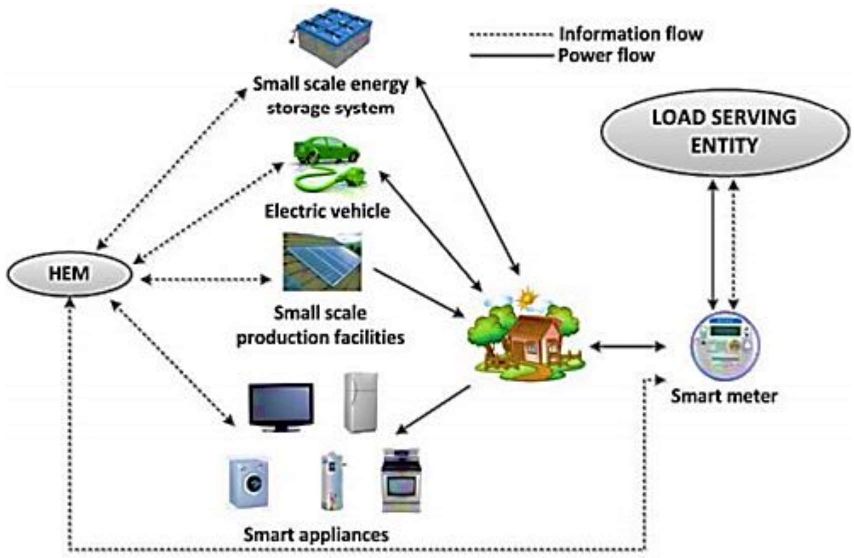

Figure 2.12 - Block diagram of a fundamental DR strategy for smart households [39].

A HEMS is made up of a number of appliances which has different characteristics. The load profile of each appliance (and thus the load profile of the house) will depend on a number of factors such as the size of the house, number of inhabitants, the climate conditions of the area where the house is located, and so on. Household appliances are often divided into three categories, according to their operational characteristics and controllability: baseline loads, burst loads and regular loads [40].

Baseline loads, also called must-run appliances, are not controlled meaning that their usage is entirely dependent on end-user behavior and there are exactly no operation time intervals for them. Some examples of baseline loads are lighting, ovens and televisions.

Burst loads, also called shiftable loads, can be shifted in time, and may also be paused at specific predefined cycle times. This ability enables significant energy consumption flexibility. This category includes clothes washing machines and clothes washing machines. Regular loads are those whose load profiles change according to the environment conditions and generally include thermal loads such as electric water heaters.

2.5 Virtual Power Plants

Global energy markets are facing major changes. We move from a model with centralized electricity generation in power plants operated by large utilities towards a mix of decentralized and often renewable energy production in small facilities. Those small-scale plants are typically owned by small companies or households, who become 'prosumers': consumer and producer at the same time.

Worldwide is experiencing a paradigm shift. The fast-increasing penetration of distributed energy resources (DERs) requires new technologies as well as new energy strategies and policies to handle the technical and the economic issues emerging due to this upward penetration. Business models have to be reinvented and our grids redesigned.

Moreover, distributed generation (DG) plays an important role in reinforcing the main generating power plants to satisfy the growing power demand. Properly planned and operated DG installations have many benefits such as economic savings due to the decrement of power losses, higher reliability, and improved power quality. However, the increased penetration of DG without harmony between the generating units, may lead to undesirable voltage profiles and unreliable operation of the protection devices, and unbalance between the real consumption and the production.

The negative aspects of increased uncoordinated DG penetration are the basic motivation for the introduction of virtual power plant (VPP) concept. A VPP is an aggregation of DERs, controllable loads and possible storage devices, besides allowing access to national markets, and to provide energy and auxiliary services [41]. Conventional as well as renewable resources are used in the VPP but mostly plants of renewable resources such as photovoltaic power plants, wind turbines or small hydro are aggregated in order to operate a unique VPP [42].

In a VPP, decentralized units in a power network are linked and operated by a single, centralized control system. When integrated into a VPP, the power and flexibility of the aggregated assets can be traded collectively. Thus, even small units get access to the lucrative markets (like the market for balancing reserve) that they would not be able to enter individually.

2.5.1 Literature Review of the Virtual Power Plants

The VPP has been presented in the literature by several researchers. The idea of aggregation of distributed energy resources emerged in the 1990s when the deregulation of electricity markets was taking place. The main reason for the aggregation was the increase of renewable power generation, which could not enter the electricity market because of its intermittency and small generation capacity due to limited efficiency. Representing a group of renewable generators as a virtual utility would assist in breaking the capacity threshold for entering the electricity market.

Shimon Awerbuch in 1997 has introduced the origin of the terminology VPP in his book entitled the Virtual Utility for the first time [43]. The virtual utility in their perspective could be a new business model for electricity generation that would not only allow DERs to enter the market but would also lower electricity prices and increase market transparency.

Subsequently, the virtual utility transformed into a virtual power plant. The main goal of this entity is to maximize the benefits of the participants to take advantage of a lager capacity in the energy markets [41]. In [44], the concept and architecture of a complex VPP was introduced and discussed. The operation and control of a VPP was analyzed as a case study and its optimal capacity was determined. Hence, in [45] has presented a literature review for different VPP definitions, components and operation systems.

2.5.1.1 VPP Classification

In [41, 45, 46], the authors summarized the concept of the VPP and introduced two different types of VPPs – commercial virtual power plant (CVPP) and technical virtual power plant (TVPP). CVPP considers DERs as commercial entities offering the price and amount of energy that it can deliver, optimizing economical utilization of VPP portfolio for the electricity market.

CVPP performs bilateral contracts with both the DG units and the customers. Small-scale DG units are not able to participate in the electricity market individually. Therefore, CVPP makes these units visible to the electricity market. These contracts information is sent to the TVPP in order to take the amount of the contracted power into consideration during the performance of technical studies. Some of the CVPP's functionalities are summarized as follows:

- Scheduling of production based on predicted needs of consumers;
- Trading in the wholesale electricity market;
- Balancing and/or trading portfolios;
- Production and consumption forecasting based on weather forecasting and demand profiles;
- Constructing DER bids and submitting them to the electricity market;
- Scheduling of generation and daily optimization;
- Selling DER power in the electricity market.

On the other hand, TVPP is responsible for the correct operation of the DERs and the ESSs in order to manage the energy flow inside the VPP cluster, and execution of ancillary services. Based on the information received from CVPP, about the contractual DGs and the controllable loads, in addition to the detailed information about the distribution network topology, TVPP ensures that the power system is operated in an optimized and secure way taking physical constraints and potential services offered by VPP into account.

Based on the control scheme and operational strategy, three main groups of VPP approaches are categorized by authors in [47] and briefly shown in Figure 2.13:

- Centralized controlled virtual power plant – the VPP has the complete knowledge of involved DER units under its control and sets the operating points to meet the varying requirements of the local power system. However, such an architecture cannot easily integrate new components, e.g. generators or loads;
- Decentralized controlled virtual power plant – a hierarchical architecture with a central controller, which ensures economical operation and security of the system, and distributed local controllers that ensure optimal DER operation. This structure provides scalability, but it still relies heavily on the central controller. A hierarchical model is described in reference [48], by defining VPPs on different levels.

A local VPP supervises and coordinates a limited number of DERs while delegating certain decisions upwards to a higher level VPP. This design requires communication between different neighboring VPPS;

- Fully decentralized controlled virtual power plant – an extension of the previous architecture, wherein central controllers are replaced by information exchange agents which only provide valuable services (e.g. market price signal, weather forecasting, data logging, etc.). It has a relatively higher scalability and openness than the other architectures as it relies on plug and play ability.

It should be noted that the suitability of each of the VPP approaches is dependent of the market structure, standards and rules in the area where the VPP is going to be implemented as an aggregator tool.

2.5.1.2 Components of the Virtual Power Plant

In [49], the VPP components are introduced, including the wind power plants (WPPs), PVs, conventional gas turbines (CGTs), ESSs and demand resource providers (DRPs). A two-tier robust scheduling model is established. The upper layer uses the VPP operating revenue as the maximum objective function and the lower layer uses the minimum system payload and operating cost as objective functions.

VPP is a large entity that involves a huge number of DGs, controllable loads, and storage elements under a layer of Information and Communication Technologies (ICT). VPP is responsible for controlling the supply and manages the electrical energy flow not only within its cluster but also in exchange with the main grid. In addition, VPP can also offer ancillary and power quality services.

In Figure 2.14 is represented a schematic structure of a VPP, which is composed by conventional power plants (CPPs), wind power plants (WPPs), photovoltaic generators (PVs), ESSs and EVs. It's worth mentioning that the VPP's structure is not fixed, and DERs can be inserted or deleted dynamically based on alliance contract.

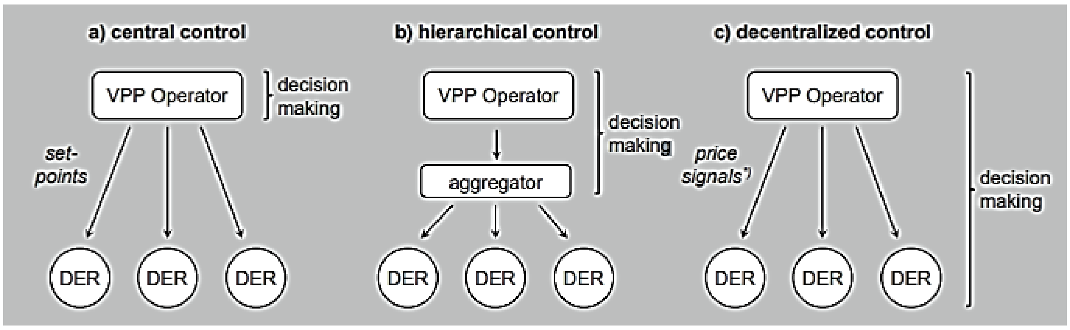

Figure 2.13 - Operational strategy for VPP to coordinate distributed energy sources by central, hierarchical and decentralized control approaches.

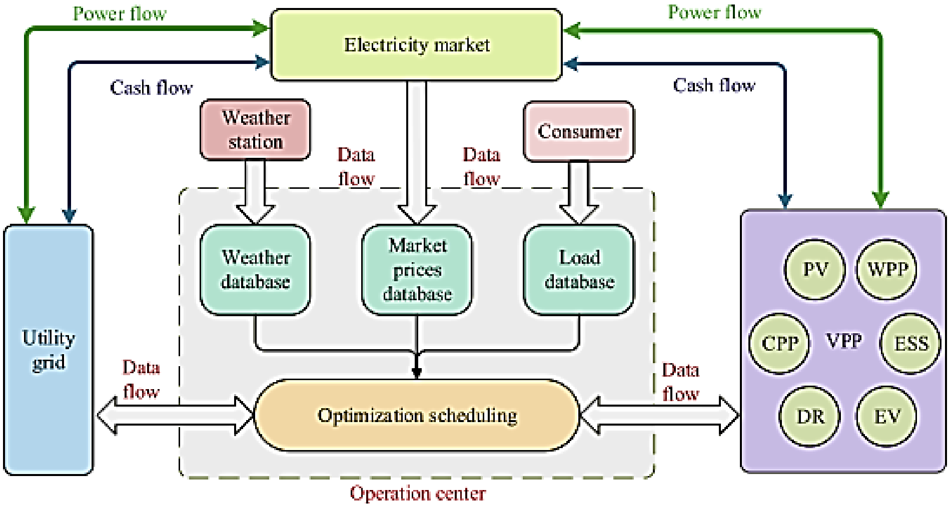

Figure 2.14 - Operational framework of VPP [50].

Moreover, in Figure 2.14 is illustrated a typical three bidirectional flows, which occurs within the VPP's environment: data flow, power flow and cash flow. VPP consists of three main parts including: distributed energy resources, energy storage systems and information and communication technologies.

A. Distributed Energy Resources

DERs can be either distributed generators or controllable loads connected to the network. From the author's point of view [46], DGs within the VPP assumptions can be classified according to:

A.1. Type of the primary energy source

According to the primary energy source type, DGs can be classified into two categories:

- Generators utilizing RES (such as wind-based generators, photovoltaic arrays, small hydro-plants);
- Generators utilizing non-RES (such as Combined Heat and Power (CHP) plants, biogas, diesel generators, gas turbines).

A.2. Capacity of distributed generation units

According to unit capacity, DGs can be classified into two categories:

- Small-scale capacity DGs that must be connected to the VPP in order to gain access to the electricity market; or they could be connected together with controllable loads to form micro grids that may or may not participate in the VPP based on their capacities;
- Medium and large-scale capacity DGs that can individually participate in the electricity market, but they may choose to be connected to VPP to gain optimal steady revenue.

A.3. Ownership of distribution generation units

DGs within the VPP premises may be [51]:

- Residential, Commercial, and Industrial-owned DGs used to supply part/all of its load in its own premises. They can be referred to as Domestic DGs (DDG);
- Utility-owned DGs that are used to support the main grid supply shortage. They may be called Public DGs (PDG);
- Commercial company owned DGs that aim to gain profits from selling power production to the grid. They can be named Independent Power Producers DGs (IPPDG).

A.4. Distributed generation operational nature

DGs operational nature can be classified into two cases:

- Stochastic nature: In case of wind-based and photovoltaic DG units, the output power is not controllable as it depends on a variable input resource. To overcome this nature, this type of DG must be equipped with battery storage in order to be able to control the output power;
- Other DG technologies such as FCs and micro-turbines have an operational dispatchable nature. They are capable of varying their operation quickly. Therefore, in general, VPP should include controllable loads, energy storage elements and dispatchable DGs in order to compensate the vulnerability of the stochastic nature-DG type.

B. Energy Storage Systems

ESS and its elements play a pivotal role in bridging the gap between the generation and demand, especially in the presence of high penetration of stochastic generation. Energy storage elements can store energy during off-peak periods and feed it during the peak periods. It also can optimally redistribute the output power of wind turbines and photovoltaic arrays throughout the day. ESS can be classified according to their applications; i.e. supplying power or energy, as follows:

- Energy supply class includes:
    - Hydraulic Pumped Energy Storage (HPES);
    - Compressed Air Energy Storage (CAES).
- Power supply class includes:
    - Flywheel Energy Storage (FWES);
    - Super Conductor Magnetic Energy Storage (SMES);
    - Supercapacitor energy storage (SCES);
    - Battery energy storage system (BESS).

C. Information and Communication Systems

The energy management system (EMS) represents the heart of the information and communication system. It manages the operation of other VPP components through communication technologies in bidirectional ways. The EMS has the following responsibilities:

- Receiving information about the status of each element inside the VPP;
- Forecasting renewable energy sources and output power;
- Forecasting and management of loads;
- Coordinating the power flow between the VPP elements;
- Controlling the operation of DGs, storage elements, and controllable loads;

The EMS's aim is to achieve one of the following targets:

- Minimization of: {generation cost; energy losses; greenhouse gases emissions};
- Maximization of profit;
- Improvement of voltage profile;
- Enhancement of power quality.

2.5.1.3 Operation of the Virtual Power Plant

In this section, it is presented some methods for modelling the operation and optimizing the schedule and the bidding of the VPPs in electricity markets. Centralized VPP operation can be viewed as an optimization problem, and we can use different optimization methods to solve for the optimal schedule and to obtain bidding strategies of the VPP.

In [52] the generation scheduling for a VPP was used considering the cost of degradation of the energy storage system. Using piecewise linearization methods, the VPP model with battery degradation cost, uncertain renewable generations, and market price is formulated as a two-stage stochastic mixed-integer linear programming (MILP).

In [53] a MILP model for the optimal dispatching problem in the VPP was established, with an objective of maximizing the total profit of the VPP considering the costs of power generation and carbon emission trading as well as charging/discharging of EVs. Appropriate price subsidies will be provided by the concerned agents in order to incentivize EV owners to register their EVs as schedulable devices. The general dispatch framework of the VPP is depicted in Figure 2.15.

Based on the predicted results of renewable energy generation outputs, load demands, day-ahead submitted information of EVs and the prices of electricity and carbon trading, the EMS of the VPP determines generation outputs of gas turbines at each time period of the next day, charging/discharging schedules of EVs, DR schedules and carbon emission trading outcomes. The electrical demands in the VPP can be satisfied by the DGs as well as the power supply from the connected distribution network.

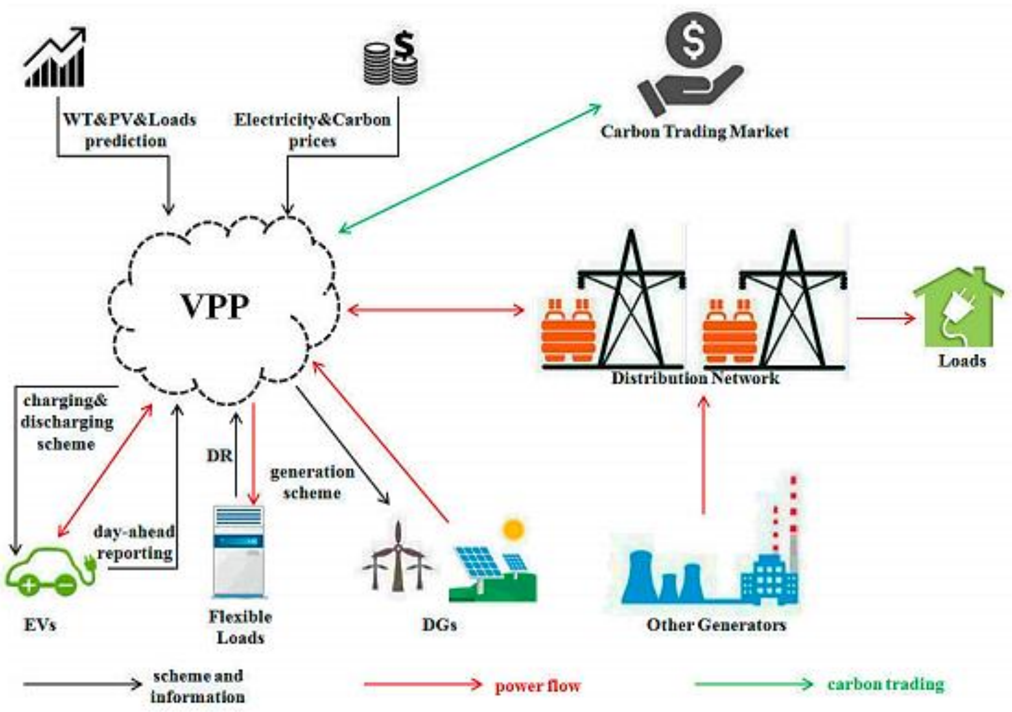

Figure 2.15 - Dispatching procedure in a VPP [53]

The VPP can gain economic profits by transmitting redundant power to the distribution network and buy/sell carbon emission credits in the carbon trading market. In [54], a coordinated control method of VPP, which includes photovoltaic systems (PVs) and controllable loads was proposed so that the aggregated power output of the VPP can be flexibly adjusted in a wide range.

Others optimization techniques, beyond MILP, have been applied to the VPP scheduling like fruit fly optimization algorithm (FOA) [55], fuzzy optimization [56], and different stochastic techniques [57, 49, 58, 59]. In [60], a modified particle swarm optimization approach has been applied to the schedule of several energy resources, minimizing the operation costs from the point of view of a VPP.

In [61] firstly, in order to reduce the number of decision variables, the decision area of VPP was divided. Then, a multi-objective optimization model, which considers the average daily cost, load characteristics, degree of DG consumption and the degree of resource aggregation were established. Finally, the improved Bat algorithm, which is a new heuristic algorithm, based on priority selection was used to solve the model to obtain an optimal compromise solution.

In [62], a meta-heuristic algorithm, the Imperialist Competitive Algorithm was used as VPP control strategy to minimize the total system costs of a collection of several DERs, including RES generators, storage units, and controllable loads, over a time horizon of 24h. The aim is to optimize the operation costs of DERs installed at different points of the distribution network by collecting resources which are owned by different stakeholders and that are usually dispersed throughout the grid.

In [63] a robust optimization formulation was proposed to model the price uncertainty and manage the VPP participation in the electricity market. This approach can be considered as a substitution for stochastic programming to address uncertainty in the mathematical programming model.

In [58] was investigated the control and bidding problem of VPPs, consisting of Renewable Distributed Generators (RDGs) and consumers with inelastic demand. As both renewable generation and inelastic demand cannot be scheduled and accurately forecasted, a novel coordinated strategy on renewable power usage is proposed. The idea is to accomplish a much more capable way of handling the situations with high forecast uncertainties in both supply and demand sides.

VPPs with wind power, photovoltaic generation and combined heat and power plants, as well as flexible demands were modelled and concluded that self-supply VPPs can achieve very high rates of self-sufficiency in the local load supply, which makes them much less exposed to sudden price changes [64].

In [47] was discussed a market-based fully decentralized VPP and proposed two operating scenarios. The first scenario consists of general bidding where each DER has to develop its own optimal operation schedule for the next day based on the VPP forecasted information. The VPP acts as an intermediary: it passes information between agents and submits the aggregated bid to the wholesale market.

In this case, the VPP does not take part in decision making and can live on the brokerage fees it charged from every participant leaving the risk to the DER owners. The second scenario is a price signal scenario where the VPP sends a price signal to all DERs and establishes the optimal operating point through an iterative algorithm.

However, these two scenarios are extremes regarding the presumed intelligence: either the agents are intelligent, and the VPP only acts as an intermediary, or vice versa, i.e., the VPP is intelligent and steers the system to the desired behavior while the DERs perform secondary control.

Additionally, the DER owners and the dispatchable generators should consider the risks of participating in electricity markets because of uncertain generation/demand and highly volatile real-time prices. References [65, 66, 67] have presented the procedure of including risk measure techniques such as the conditional value-at-risk (CVaR) in the formulation of the stochastic programming.

In [66] the CVaR management method was used to model and control the risks of low profit scenarios. The uncertain parameters, including the PV power output, wind power output and day-ahead market prices are modelled through scenarios. The proposed formulation investigated both day-ahead and balancing energy markets.

In [68, 69] the proposed model was divided in two steps. The first presents the formulation of the problem, while the second step demonstrates the numerical analysis. In detail, in the first stage it was explained the bidding problem faced in a VPP and the second stage demonstrated that a VPP may have a share in the energy market and can export power to the main network or the energy can be injected into the VPP.

Moreover, EVs have received significant attention as an emerging energy storage form for the VPP. In [70] the focus was to enable wind power generators to fully participate in electricity markets by forming VPP with EVs that can store the energy to overcome the intermittent nature of the energy supply. In order to analyze the cost and emission impacts caused by plug-in hybrid EVs (PHEVs) application in the VPP, in [71] has developed an energy management model for a VPP including PHEVs and distributed energy resources. In [72] the VPP was established through bilateral incentive contracts with vehicle owners, in order to aggregate the EVs.

In [73] was presented a multi-agent system for simulating and operating a hierarchical energy management of a power distribution system with focus on EVs integration. The algorithm is based on a negotiation:

- Each VPP produces a schedule of EV charging and submits it to the distribution system operator (DSO) agent;
- The DSO agent checks whether there is congestion with the submitted schedules or not. If there is congestion, it calculates congestion price and sends it to the VPPs, which recalculate the schedules with the new prices, and the process continues until it converges to a schedule without congestion;
- VPPs optimize the schedule using mixed-integer non-linear programming whereas the DSO agent solves a convex optimization problem.

2.5.2 Market Operation

Market participation opportunities for VPP may vary from one electricity market to another and depend on the regulations and requirements set in the specific are where VPP is going to operate. In most cases, the VPP is able to engage the day-ahead, intraday, and the reserve and regulations markets.

Based on the information about the VPP internal components and the market status, the VPP control center can make an estimate bid for each hour of the next day in the day-ahead market. The difference between the contracted power in the day-ahead market and the real-time demand and power generation of the VPP resources can be handling in two ways:

- Internal energy management of VPP resources including generation resources, storage systems and responsive loads;
- Additionally, VPP trades in the intraday market when more exact information about generation capacity and load demand within the VPP is available.

When deciding VPP's optimal bids, the VPP control center, in addition to the data associated with the market price forecasts, VPP should consider the data associated with the behavior of its internal components, including:

- Generation forecast for its generating resources;
- Demand forecast for its loads, including EVs;
- Flexibility of responsive loads including EVs for DSM and other services considering their preferences.

The above factors enable the VPP control center to determine its internal requirements, limitations, and possible services which can be offered to the market [6].

2.5.3 Benefits and Challenges of the VPP Implementation

According to the literature review, there are many advantages arising from the adoption of the concept of a virtual power plant:

- High efficiency: VPP manages internal DERs and controllable loads effectively, improving the safety of the system operation;
- Environmental protection: Through the use of renewable energy and energy-savings technologies, VPP reduces the use of conventional fossil energy, so as to reduce pollution and protect the environment;
- Aggregation: VPP integrates several kinds of DERS in different areas and achieves coordinated dispatching through the connection of DERs;
- Balance: The emergence of VPP makes power consumers become active participants in the power system. VPP can balance supply and demand by replacing the traditional energy generation at the peak period;

Hence, VPPs establishing and operating has proven to be challenging. Issues have occurred on most fronts – from the technology itself, to the quality and cost of installation, to the sales and marketing efforts to get customers engaged [74].

An example of the technology challenges that can occur was described by AGL during their VPP trial in South Australia [8]. AGL reported technical challenges associated with grid conditions declaring that high voltage levels in many parts of the distribution network regularly affect some customers by making their ESS systems inoperable. During voltage excursions, customer's inverters disconnect from the grid, making them unavailable to the VPP.

Moreover, a common issue with VPP technology is the loss of connectivity with the assets due to telecommunication limitations [75]. Another challenge is the low acceptance amongst residential customers for third parties to control their household assets, like batteries. Many customers seek to distance themselves from energy companies by purchasing a battery, so to then make a deal with an energy company to be part of a VPP is misaligned with their objectives.

2.5.4 Examples of Virtual Power Plants Usage

The world's electricity economy is shifting from an almost-total dependence on large, centralized power stations to a much more diverse and diffuses electricity supply system. Over the past decade, the technologies driving this shift have made the concept of the VPP possible [76]. Two of the most significant European projects that in some way used the concept of VPP and integrated DER are:

- Fenix Project – The goal of the project is to move away from traditional management of small units in a power system. Thus, the 'fit and forget' principle must be rejected. Through the Fenix Project all sources will be integrated in an active way with the system. The new approach uses the concept of VPP to tie together distributed microgenerators and loads into a single system visible to the rest of the network. The Fenix Project tests two types of VPP: technical VPP (TVPP) and commercial VPP (CVPP) [77].

  TVPP is a local power management system which gives detailed information about all aspects of the local system. CVPP has functions which contain information about the costs and characteristics of distributed power sources. CVPP does not deal with the technical delivery of loads.

  It is a system which enables trading in the energy market and the balancing of trading. TVPP can contain more than one CVPP in FENIX. VPP were implemented in two networks. The first of them was the real power network of Iberdrola in Spain (Southern Scenario) and the second was the EDF Energy network in the UK (Northern Scenario). The Northern scenario is dedicated to small scale generation: in households and municipal facilities.

  The main parts of the devices are CHP and PV, connected to a low voltage network. In contrast, the Southern scenario focuses on generators which are connected to a medium voltage network. They might serve as an ancillary service to DSOs and TSOs.

  VPP was used to show its usefulness in: Voltage Control - support for maintaining a determined voltage level by providing reactive power to the network; Tertiary reserve - power reserves that can be put into the network and help to cope with imbalances; Participation in the Day-Ahead energy market. Figure 2.16 shows in brief the VPP Fenix concept.

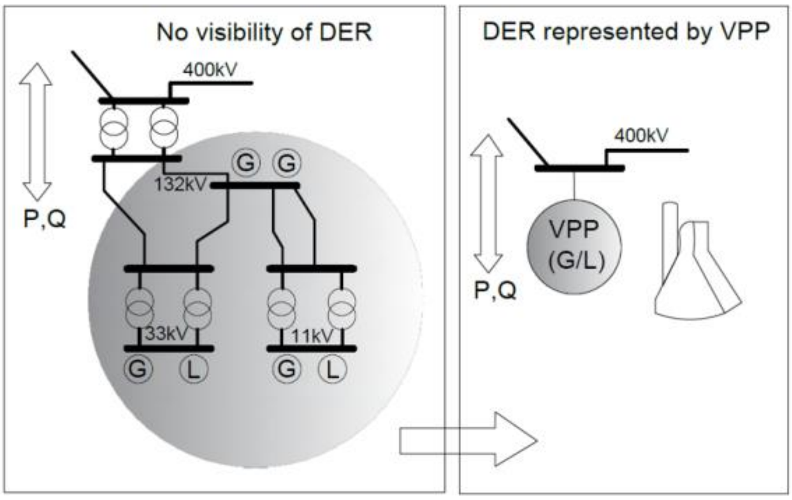

Figure 2.16 - VPP concept in FENIX [77]

- EDISON Project – The Danish project aims has been launched to investigate how a large fleet of electric vehicles (EVs) can be integrated in a way that supports the electric grid while benefitting both the individual car owners and society through reductions in CO_2 emissions.

  The consortium partners include energy companies, technology suppliers and research laboratories and institutes. The Danish island of Bornholm has been selected as simulation scenario for EDISON WP3 because it represents a small grid with the option of operating in island mode 5 and with a high wind power penetration.

  The ØSTKRAFT Company is the distribution system operator (DSO) as well as the generating company on the island, supplying more than 27,000 customers [78]. One aspect which differentiates the EDISON Project VPP from other VPP is the common usage of electric vehicles as active energy storage units. Most VPPs concentrate only on intelligent management of generation units.

Moreover, projects worldwide are being developed underneath the concept of VPP. For example, the South Australian Government is working with Tesla and electricity retailer Energy Locals to develop the world's largest VPP.

Tesla has designed/developed the VPP and is managing the installation of the solar panels and battery storage in South Australia homes. Energy Locals is the retailer that is arranging residents' supply contracts and is customers' main point of contact about their electricity supply and their bills. The South Australia Government is providing grant and loan funding, through the Renewable Technology Fund, to support the trials.

The VPP is composed by a network of potentially 50,000 homes across South Australia and has already reached 1100, each comprising a solar PV system, a Tesla Powerwall battery system and a smart meter. When the VPP is operating at full scale, it will generate 250 MW and store 650 MWh [79].

Chapter 3

Methodology

This chapter describes the problem formulation and the mathematical models that have been used for the optimal energy management of the VPP participants (SHs and EVSPL). The feasibility of this approach is examined through four case studies, using real PV power generation data, the corresponding electricity market prices, and commercially available EV specifications.

3.1 Smart House Operation

The HEMS used in the SHs, in this study, is based on the system presented in [80]. The objective of the proposed self-scheduling model for HEMS is to minimize the total daily cost of electricity bill. The cost is the difference between the energy bought from the grid and the energy sold back to the grid by the house-owned assets that are able to provide energy (PV and ESS). In the presented EMS, the energy provided by the ESS is used directly to cover a portion of the house needs and is never injected into the grid. The main function (Z) can be stated as below:

$$Minimize\ Z = \sum_{t} \left(\frac{P_t^{G2H}}{\Delta t} \cdot \lambda_t^{buy} - \frac{P_t^{H2G}}{\Delta t} \cdot \lambda_t^{sell} \right) \tag{3.1}$$

In the equation (3.1), the (P_t^{G2H}) is the variable that represents the total power bought from the grid at time t, and the (P_t^{H2G}) represents the total power sold to the grid, which is due to the excess energy produced by the PV system.

3.1.1 House Demand Characterization

To evaluate the electricity bill cost reduction with and without the proposed EMS, two numerical studies have been considered:

- Before the implementation of the EMS where is considered the baseline operation intervals based on the end-user preferences;

- After the implementation of the EMS where the flexible loads are optimally schedule based on the predefined tariffs.

The baseline operation intervals are subjected to the binary parameters, $B_{i,t}$, and the bounds for each home appliance are available based on the end-user preferences. Equation (3.2) set that the operation status of the corresponding appliance would be '1' during the baseline intervals and '0' before and after the considered operation bounds.

$$B_{i,t} = \begin{cases} 0 & t < LB_{i,b} \\ 1 & LB_{i,b} \leq t \leq UB_{i,b} \\ 0 & t > UB_{i,b} \end{cases}, \qquad B_{i,t} \in \{0,1\} \tag{3.2}$$

where the lower and upper bounds are respectively $(LB_{i,b})$, and $(UB_{i,b})$.

With the implementation of the EMS, the flexible loads can be shifted before or after the baseline operation intervals, in order to reduce the daily bills. Since the hourly tariffs affect the total operation cost, the end-users can benefit from the optimal self-scheduling based on the predefined tariffs.

In this regard, the end-user can set the allowable time intervals for plunging in the appliances to the grid, as shown by equation (3.3).

$$S_{i,t} \leq \begin{cases} 0 & t < LB_{i,s} \\ 1 & LB_{i,s} \leq t \leq UB_{i,s} \\ 0 & t > UB_{i,s} \end{cases}, \qquad S_{i,t} \in \{0,1\} \tag{3.3}$$

Self-scheduling of the appliances within the HEMS allows the owners to view the impact of each appliance to the total electricity bill and thus can help to modify their behavior to optimize the bill within their own preference ranges.

It is evident that, for each home appliance, the operation duration should be the same for both cases, as shown by equation (3.4). In other words, it means that the end-user just changing the operation time intervals does not change the daily energy consumption that should remain the same after task scheduling implementation.

$$\sum_{t=1}^{NT} S_{i,t} = \sum_{t=1}^{NT} B_{i,t} = T_i , \qquad \forall_i = 1,2, \dots, NA \tag{3.4}$$

The total demand of the house is presented in equation (3.5). The first part of the equation is related with the energy consumption of 10 shiftable appliances whereas the second part is related with the non-shiftable loads. The appliances will be deepened later in this work.

$$P_t^D = \sum_{i}^{NA} \sum_{t}^{NT} \left(\frac{S_{i,t} \cdot P_i}{\Delta t}\right) + \sum_{t}^{NT} \frac{P_f}{\Delta t} \tag{3.5}$$

The usage status of appliance i at time t is a binary variable, represented by $(S_{i,t})$, and the rated power of the corresponding appliance is (P_i). On the other hand, (P_f) represent the fix demand in the house at each time slot.

Moreover, in this study, the time slots are considered to be in terms of 30 minutes. So, for a 30-min interval the (Δt) coefficient, number of intervals in 1 hour, must be 2 and the total time slots are set as 48 for daily operation.

3.1.2 Energy Storage System Modelling

Constraint (3.6) shows the binary variables which aims to restrict the ESS to be in either a charging or discharging mode at any one time as it is impossible for the ESS to operate in both modes simultaneously.

Constraints (3.7) and (3.8) impose a limit on the charging ($P_{j,t}^{Ch.}$) and discharging ($P_{j,t}^{Disch.}$) power of the ESS. The energy stored in the ESS at a specific interval is a function of the energy stored in the previous interval plus the actual amount of energy that is transferred to the battery if it is charging at that interval minus the energy that is subtracted if the battery is discharging during that interval.

This is shown in equation (3.9) which also includes an efficiency factor for charging and discharging. It is considered that the state of energy in ESS at the end of the operation horizon should be equal to the initial stored energy in ESS at the beginning of the operation horizon. Moreover, the energy within the ESS is constrained by upper and lower limits that are captured by constraint (3.10).

$$0 \leq I_{j,t}^{Ch.} + I_{j,t}^{Disch.} \leq 1 \tag{3.6}$$

$$P_{j,t}^{Ch.} \leq I_{j,t}^{Ch.} . P_j^{Ch.max} \tag{3.7}$$

$$P_{j,t}^{Disch.} \leq I_{j,t}^{Disch.} . P_j^{Disch.max} \tag{3.8}$$

$$E_{j,t} = E_{j,t-1} + \eta_j^{Ch.} . P_{j,t}^{Ch.} - \frac{1}{\eta_j^{Disch.}} . P_{j,t}^{Disch.} \tag{3.9}$$

$$E_j^{min} \leq E_{j,t} \leq E_j^{max} \tag{3.10}$$

The ESS devices have their associated constraints in terms of a daily operation in this study.

3.1.3 Photovoltaic Power Modelling

Equation (3.11) enforces the fact that the actual power provided by the house-owned PV system (PV_t), in each time slot, can be used to cover a portion of the house needs and in case of an excess of generation, injected to the grid.

$$PV_t = P_t^{PV,used} + P_t^{PV,sold} \tag{3.11}$$

3.1.4 Power Balance

Equation (3.12) states that the total residential load plus the charging needs of the ESS is either satisfied by the grid (P_t^{G2H}) or by the combined energy supply by the PV and the ESS. Adding to this equation, there is the energy sold back to the grid (P_t^{H2G}). Mathematically, the power balance for each time slot is as follows:

$$PV_t + P_t^{G2H} = P_t^D + P_{j,t}^{Ch.} - P_{j,t}^{Disch.} + P_t^{H2G} \tag{3.12}$$

3.2 Parking Lot Operation

The optimal strategy for the operation of the EVSPL is adapted from the work developed in [31]. The proposed EVSPL scheme which allows bidirectional power is described in the Figure 3.1. The energy exchanges between the parking lot and the grid are possible because of the V2G and G2V technologies that allow EVs to cooperate in two different ways with the grid: either through the sell or the purchase of power when needed. The inputs to the model can be divided into four parts:

- EV – Arrival time, departure time, SOE at the arrival time, battery capacity;
- PV panels – Hourly PV power output consider the season and location;
- Electricity market – Day-ahead energy price, reserve price and regulation up/down price;
- Finance – Energy tariff, parking usage tariff;

3.2.1 Mathematical Model of Parking Lot

On one hand, the limit of power injection from the grid to parking lot is limited by constraint (3.13) in consonance with the rate of charge of EVs. On the other hand, constraint (3.14) presents the limit of power injection from the parking lot to the grid, based on the rate of discharge of the EVs.

$$P_t^{En,G2PL} + P_t^{PV2PL} + P_t^{R.down} \leq \gamma^{charge}.n_t^{PL} \tag{3.13}$$

$$P_t^{En,PL2G} + P_t^{Res.Act} + P_t^{R.up} \leq \gamma^{discharge}.n_t^{PL} \tag{3.14}$$

One additional constraint, presented in (3.15), in order to limit the injection of power from the PV rooftop to the parking lot (PV2PL), has been added. The maximum power that can be injected to the parking lot depends on the SOC from the previous hour and the state-of-energy from arrived/departed EVs.

$$P_t^{En,PV2PL} \leq SOC^{max} \times PLCapcom_t - (SOC_{t-1} + PLSOEnet_t) \tag{3.15}$$

where $PLCapcom_t$ is the sum of EVs capacity in the parking lot and $PLSOEnet_t$ consist on the difference between $PLSOEin_t$ and $PLSOEout_t$.

The SOC of the parking lot at each hour t, presented in (3.16), is based on the SOC from the previous hour, the energy exchanges with the grid in both directions and the SOC from both arrived and departure EVs.

$$\begin{aligned} SOC_t = {} & SOC_{t-1} + SOC_t^{arrival} - SOC_t^{departure} \\ & + \left(P_t^{En,G2PL} + P_t^{PV2PL} + P_t^{R.down}\right).\eta^{charge} \\ & - \frac{P_t^{En,PL2G} + P_t^{Res.Act} + P_t^{R.up}}{\eta^{discharge}} \end{aligned} \tag{3.16}$$

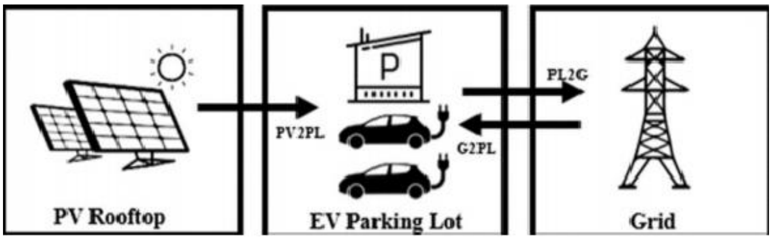

Figure 3.1 - EV parking lot equipped with a rooftop PV [31].

The limits of the total SOC of the parking lot are presented in equation (3.17). It has been considered a minimum state of charge of 20% and a maximum of 80%, for each EV.

$$\sum SOC^{EV,min} \leq SOC_t \leq \sum SOC^{EV,max} \tag{3.17}$$

The SOC of departure EVs is presented in (3.18) and (3.19). On the one hand, in (3.18) 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. On the other hand, in (3.19) is represented the amount of energy that is absorbed from an EV.

$$SOC_t^{up} = \begin{cases} 0, & SOC_t^{departure} \leq SOC_t^{scenario} - SOC_{t-1}^{scenario} \\ SOC_t^{departure} - SOC_t^{scenario} - SOC_{t-1}^{scenario}, & Otherwise \end{cases} \tag{3.18}$$

$$SOC_t^{down} = \begin{cases} 0, & SOC_t^{scenario} - SOC_{t-1}^{scenario} \leq SOC_t^{departure} \\ SOC_t^{departure} - SOC_t^{scenario} - SOC_{t-1}^{scenario}, & Otherwise \end{cases} \tag{3.19}$$

where ($SOC_t^{scenario}$) is represented by (3.20):

$$SOC_t^{scenario} = \sum Cap_t^{EV}.SOC_t^{EV} \tag{3.20}$$

3.2.2 Optimization Model

The objective function aims to maximize the profit from the parking lot's operator point of view. The profit results from the difference of several incomes and costs terms, that are elaborated below in (3.21) to (3.34). The first income term results from providing energy, parking lot to grid, to the electricity market.

$$Income1 = \sum_t P_t^{En,PL2G}.\lambda_t^{En} \tag{3.21}$$

The second income term results from the probability of the activation of reserve by the operator system.

$$Income2 = \sum_t P_t^{Res,PL2G} \times \pi^{call} \times \lambda_t^{Res} \tag{3.22}$$

The third income term is caused by the process of EV charging, i.e., it represents the amount paid by EV owners to charge their EV batteries.

$$Income3 = \sum_t \left(P_t^{En,PV2PL} + P_t^{En,G2PL}\right) \times \lambda_t^{Tariff,G2V} \tag{3.23}$$

where ($\lambda_t^{Tariff,G2V}$) represents the charging tariff of one of the Portuguese networks and it has been extracted from [81].

The fourth and the fifth term are related with the probability of being called by the operator system to generate the offered regulation up and down, respectively.

$$Income4 = \sum_{t} P_t^{Reg.PL2G} \times \pi^{call} \times \lambda_t^{R-up} \quad (3.24)$$

$$Income5 = \sum_{t} P_t^{Reg.G2PL} \times \pi^{call} \times \lambda_t^{R-down} \quad (3.25)$$

The sixth term represents the parking usage tariff, i.e., the amount that EV owners pay to the parking lot for staying in the parking lot.

$$Income6 = \sum n_t^{PL} \times \lambda^{Tariff,stay} \quad (3.26)$$

where $\lambda^{Tariff,stay}$ corresponds to a parking usage tariff from Porto and has been extracted from [82].

The first cost term is due to the battery degradation, caused by the operation in V2G mode, in reserve market.

$$Cost1 = \sum P_t^{Res,PL2G} \times \pi^{unvail.} \times Cd^{En} \quad (3.27)$$

The second term results from the purchase of energy from the grid.

$$Cost2 = \sum P_t^{En,G2PL} \times \lambda_t^{En} \quad (3.28)$$

The third term results from the amount paid to the EV owners due to discharge their EVs, caused by the operation in V2G mode.

$$Cost3 = \sum P_t^{En,PL2G} \times \lambda_t^{Tariff,G2V} \quad (3.29)$$

The fourth term is caused because of discharging the EVs due to be called by the operator system for participate in reserve market.

$$Cost4 = \sum P_t^{Res,PL2G} \times \pi^{unvail.} \times \lambda_t^{Tariff,G2V} \quad (3.30)$$

The fifth and sixth terms, presented in (3.31) and (3.32), respectively, are due to the battery degradation, caused by the operation in V2G mode, in the energy and regulation market.

$$Cost5 = \sum P_t^{En,PL2G} \times Cd^{En} \quad (3.31)$$

$$Cost6 = \sum P_t^{Reg,PL2G} \times Cd^{Reg} \quad (3.32)$$

where (Cd^{En}) and (Cd^{Reg}) are the battery degradation cost due to the operation in V2G mode, in energy and regulation market, respectively.

The seventh and eighth term, presented in (3.33) and (3.34), respectively, result for the parking lot's unavailability to deliver the offered energy in the regulation market.

$$Cost7 = \sum P_t^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-up} \quad (3.33)$$

$$Cost8 = \sum P_t^{Reg,PL2G} \times \pi^{unvail.} \times \lambda_t^{En} \times \Gamma^{R-down} \quad (3.34)$$

3.3 Virtual Power Plant Control Strategy

The proposed VPP is schematically illustrated in Figure 3.2. A hierarchical control approach is adopted in the present work, where a local VPP supervises and coordinates a limited number of DERs while delegating certain decisions upwards to a higher level VPP. It is a design that requires communication between different neighboring VPPs but, in this work, this will not be addressed.

The VPP control center is responsible for the supervision of the local VPPs and implements the coordination with market and utility operators. Each local controller has its own energy management system, which is what this work focuses on.

One of the local VPP controllers, which aggregate the total number of houses, is responsible for the management and dynamic integration of prosumers participating in DR programs. For this propose, the implemented EMS manages and optimizes all the prosumer's energy assets, that includes the controllable loads and DERs. This includes, in a first stage, the computation of the power profiles of all of the DER units and loads, for the different houses, and, in a second stage, the computation of the optimal working point of the VPP.

Each power profile is defined as the active power produced or consumed by the specific physical entity over a given time horizon of 24h with a system-defined time step of 30 minutes. For each physical entity, one or more profiles can be generated depending on the possible different configurations of the resource.

Air conditioning systems, for instance, may have different feasible demand profiles, based on the given weather forecasts, expected room occupancy, desired comfort level and time schedules defined by the end-user. Moreover, in this control strategy, the RES generators, i.e. the house's PV systems, produce as much as they can throughout the day and no active and reactive power constraints are needed, that can lead to the curtailment of PV generation, as it achieves the desired requirements set by DSO.

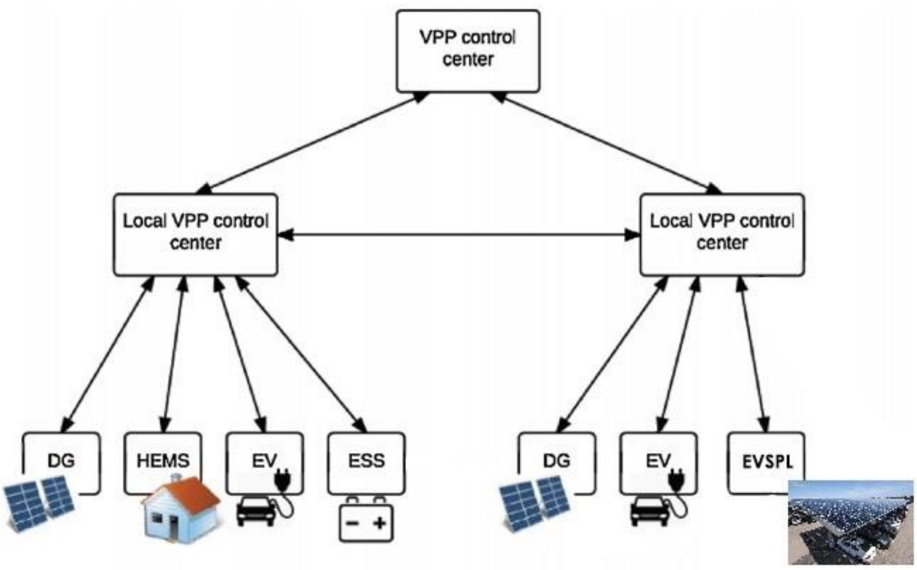

Figure 3.2 - Proposed VPP architecture.

By establishing a clear revenue stream for demand response, the VPP can achieve notably savings on the electricity bill of the houses and thus maximize its profit. Moreover, there is a large amount of energy, produced by the PV systems that can be traded in the energy market and will increase the profit of the VPP.

The other local controller, that manages the EVSPL, aims to generate the optimal energy exchanges between the parking lot and the grid, based on an hourly simulation, in order to minimize costs and maximize services provided to the grid.

3.4 Numerical Studies

For the purpose of evaluate a possible aggregation of an EVSPL and several smart homes, as a virtual power plant, four case studies have been considered:

- No EVSPL and no HEMS considered;
- The existence of the HEMS and no EVSPL;
- The existence of the EVSPL and no HEMS;
- The existence of the EVSPL and HEMS;

The first case study was defined as a reference/base case, where neither the HEM system nor the EVSPL were considered. In the first and third case studies, the EVs and the other loads, belonging to the houses, are supplied without adopting any energy management methods while in the second and fourth case studies, the proposed HEMS is adopted for optimally planning of energy consumption/production. Moreover, in the third and fourth case studies, the existence of an EVSPL, with the respective energy management system, is considered.

The number of smart homes matches the capacity of electric vehicles in the parking lot, which are equal to 108, for the proposed study. In other words, each EV is related with a different house. Moreover, the smart homes are grouped in two neighborhoods, located in distinct regions and with different driving distances from the parking lot.

The network used for the proposed model, illustrated in Figure 3.3, is based on a modified IEEE 33-bus distribution test system and includes renewable and non-renewable generation. As it shown, the parking lot is located on bus 33 and the two neighborhoods on bus 22 and 25, respectively. For the other buses it was considered some Portuguese residential low voltage profiles, BTE and BTN C, respectively, which were constructed based on the information from the Portuguese Energy Regulation Services Entity (ERSE) [83].

3.4.1 Photovoltaic Rooftop Generation

The output PV power through an entire specific day was determined considering a house located in Gondomar (41°06'45.8"N 8°32'02.3"W), as shown in Figure 3.4. For the present study, a summer day was chosen, more specifically the first day of July 2019.

This house has a photovoltaic production unit of 16 panels with an energy storage system installed (small batteries).

The data was collected from the service Victron Remote Management provided by Victron Energy to their users to remotely monitor their installations all over the world [84].

To obtain the PV Rooftop generation profile, first the normalization of the PV production profile from ERSE [83] is done, so that values fall between 0 and 1. In other words, all the values, during a specific day, from the ERSE profile, are divided by the maximum value registered in p.u., so that the value 1 corresponds now to the maximum value observed. Finally, the normalized data is transformed according to the hourly PV production values coming from the house in order to create a more realistic profile.

The PV power outputs for each house and for the EVSPL are shown in Figure 3.5. As it can be noted, the maximum power output occurs at hour 9, which corresponds to the period between 14:00h and 15:00h. In this work, the 24-hour period starts at 06:00h (1 July 2019) and it ends at 06:00h of the next day.

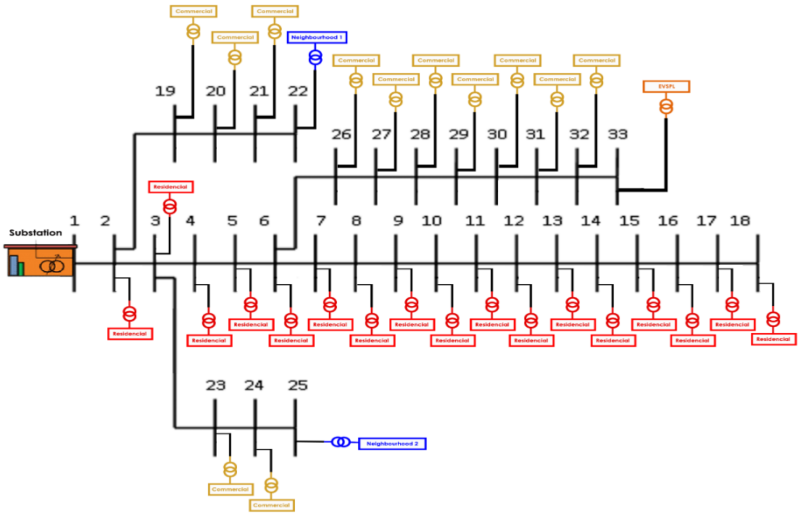

Figure 3.3 – Modified IEEE 33-bus test system used for power flow analysis.

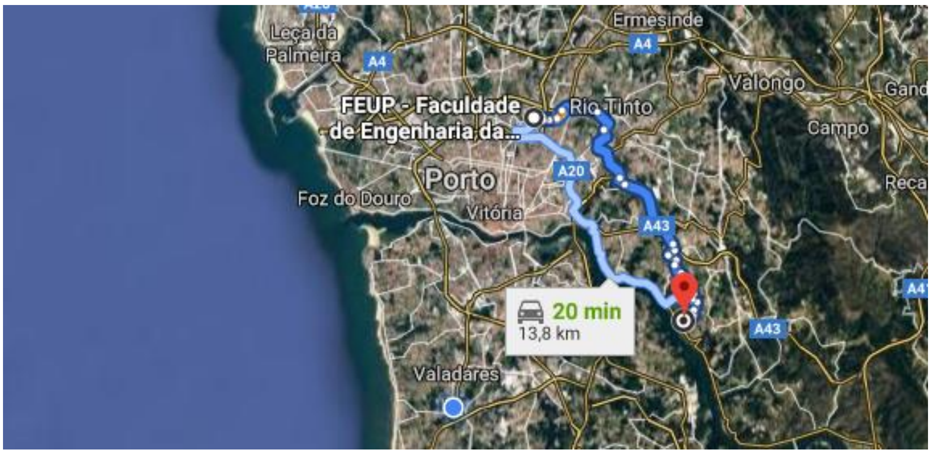

Figure 3.4 - Area where the house is located (real-data PV generation).

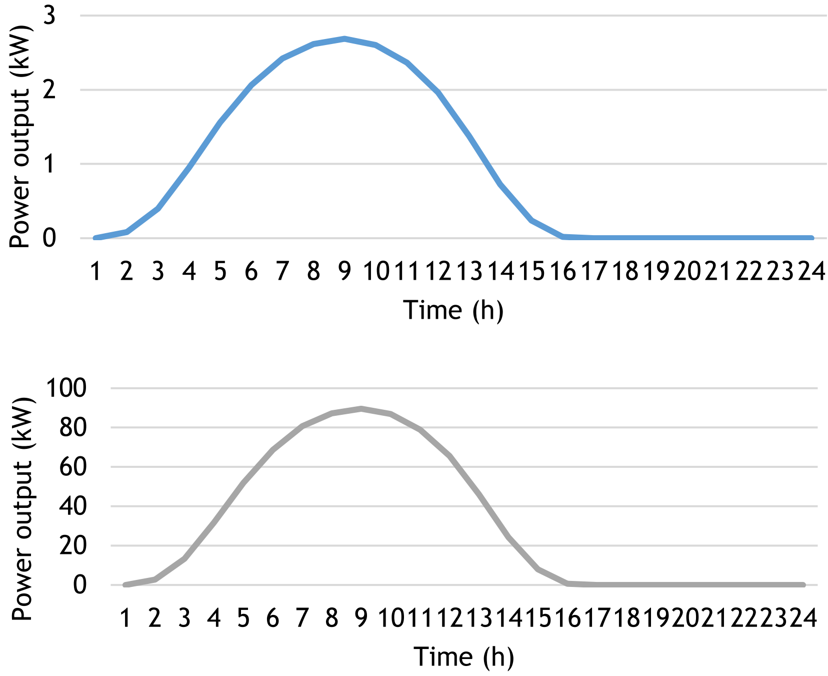

Figure 3.5 - House PV system output (head) and EVSPL PV system output (bottom).

3.4.2 Home Energy Management System

The proposed HEMS was implemented in General Algebraic Modeling System (GAMS), applying the Mixed Integer Programming (MIP) solver. The total numbers of houses, analyzed in this work, are distributed by 2 different neighborhoods. The first one is inhabited by students/researchers and the second one by teachers, that share the same parking lot at University. Moreover, the first neighborhood has a total of 72 houses and the second one 36.

Each house has an installed PV system of 3 kW and 48V lithium-ion storage battery, and the same number of home appliances, including one EV. The panel and battery data are shown in Tables 3.1 and 3.2, respectively. In order to evaluate the proposed model, the self-scheduling of 10 different appliances is analyzed to show the effect of a price-based demand response program on the daily bill before and after implementation of HEMS.

Although the home appliances are common to all the houses, their specifications, like the duration, the baseline time intervals and the allowable operation ranges, can be different according to the end-user’s preferences and needs. These are detailed explained in Sections 3.4.2.1 and 3.4.2.2, considering one of the houses. The same study was applied to the other houses, taking into account the different specifications of each one of them.

The prices, available in Table 3.3, are fixed for a specific period, being higher at peak hours and cheaper in off-peak hours, with the aim to incentivize the end-user to reduce the consumption in peak-hours and increase the consumption in off-peak hours in order to allow a more efficient use of the generation, transmission and distribution resources [29]. The effectiveness of this scheme depends on attractive off-peak prices and relatively high prices in peak-demand hours.

Table 3.1 – Home PV Panel data [85].

Panel Model	P_{MPP}	V_{MPP}	I_{MPP}	V_{OC}	I_{SC}
SPP042702000	270 W	31.70 V	8.52 A	38.04 V	9.21 A

Table 3.2 – Home battery specifications [86].

Battery Model	Usable Energy	Round-trip η	Max Ch. / Disch. Power
LG RESU 6.5kWh	5.9 kWh	95.0 %	4.2 kW

Table 3.3 - Hourly prices for the considered day [87].

Hour	EUR/kWh	Hour	EUR/kWh
00:00-01:00	0.1025	12:00-13:00	0.2287
01:00-02:00	0.1025	13:00-14:00	0.1704
02:00-03:00	0.1025	14:00-15:00	0.1704
03:00-04:00	0.1025	15:00-16:00	0.1704
04:00-05:00	0.1025	16:00-17:00	0.1704
05:00-06:00	0.1025	17:00-18:00	0.1704
06:00-07:00	0.1025	18:00-19:00	0.1704
07:00-08:00	0.1025	19:00-19:30	0.1704
08:00-09:00	0.1704	19:30-20:00	0.2287
09:00-10:00	0.1704	20:00-21:00	0.2287
10:00-10:30	0.1704	21:00-22:00	0.1704
10:30-11:00	0.2287	22:00-23:00	0.1025
11:00-12:00	0.2287	23:00-00:00	0.1025

3.4.2.1 Base Case: Without the Energy Management System

The specifications of 10 shiftable home appliances regarding 1 of the 108 smart houses are shown in Table 3.4. Where (Pi) is the rated power of the corresponding appliance and (Ti) the total operation time, in time intervals of 30 minutes. LBb and UBb are the lower and upper bound for the baseline time intervals, respectively. LBs and UBs are the lower and upper bound of the allowable time intervals, respectively.

The total time slots are set as 48, covering 24 hours, and starting at 6:00 am of the first day of July 2019. In other words, the first hour (time slot 1 and 2) comprises the time between 6:00 and 7:00 am. The intervals for some appliances, like the EV, are related with the daily work schedule of its owner, which is illustrated in Section 3.4.3.

The total energy demand of the shiftable loads is 27.15kWh. The EV with the demand equal to 14.85kWh, i.e. about 55% of the total demand, has the highest contribution to the energy demand while shifting its operation can promote a sharp cost reduction. Figure 3.6 illustrates the total demand of the house, during the entire day, considering the loads presented in Table 3.4 in addition to non-shiftable loads (Refrigerator, TV, and lighting system).

Although the small battery behaves like a load when charging, its energy demand is not characterized in the Figure 3.6.

Analyzing the Figure 3.6, it is noted that a considerable percentage of the total demand occurs in the peak hours, i.e. hours 5-7 in the morning (time slots 10-14) and hours 14-15 in the evening (time slots 28-30).

From the remaining demand, just a small percentage occurs at off-peak hours, i.e. hours 1-2 in the morning (time slots 1-4) and hours 17-24 (time slots 33-48). Moreover, the EV, which represents the load that has the highest contribution to the daily electricity bill, starts the charging process immediately when it arrives home, at hour 14, with a total duration of 4.5 hours (time slots 28-36).

3.4.2.2 Incorporating the Energy Management System

The total house demand, after applying the HEM system, is shown in Figure 3.7. As it expected, the total cost has a reduction of over 30%, by optimally shifting the load demand of the home appliances presented on Table 3.4. This value does not consider the revenue due to the sale of the excess energy from the house PV system.

Table 3.4 - Specifications of shiftable home appliances

Appliance	Pi	Ti	LBb	UBb	LBs	UBs
Dishwasher (1)	1.8	4	5	8	5	10
Washing Machine (2)	0.5	3	6	8	6	10
Clothes Dryer (3)	3.0	2	11	12	11	15
Living Room AC (4)	1.5	2	29	30	28	31
Microwave (5)	1.2	1	29	29	29	30
Laptop (6)	0.1	4	31	34	31	38
Cooker Hob (7)	1.5	1	29	29	29	30
Vacuum Cleaner (8)	1.4	2	9	10	9	12
Room AC (9)	1.0	1	33	33	33	36
Electric Vehicle (10)	3.3	9	28	36	28	47

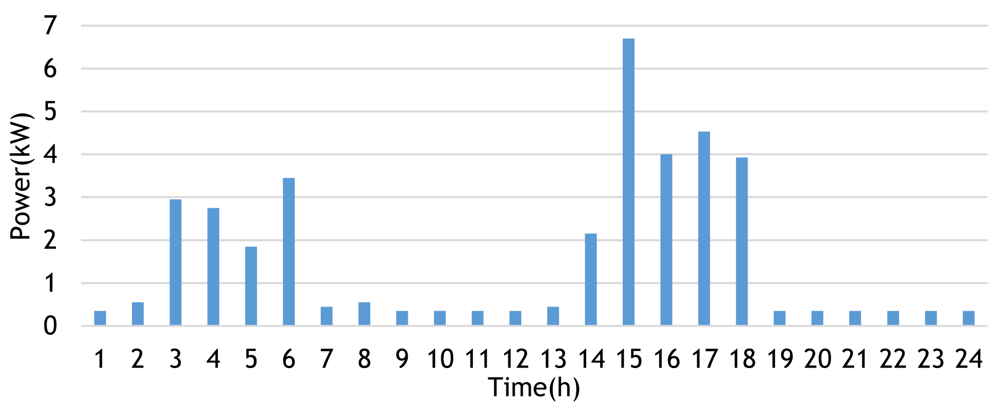

Figure 3.6 - Total house demand without the HEMS.

The demand in the peak hours has a significant reduction when comparing with the base scenario, without the HEM system. This reduction is more pronounced in the evening peak hours. In contrast, the demand in the off-peak hours, after midnight, has increased because the HEM system automatically shifts the charging of EV to lower price periods. As can be seen, the EV only starts to charge at hour 20.

The generation data of the house's PV system is the normalized version of a measured daily solar production profile, as illustrated in Section 3.4.1. When the available energy from the household-owned resources, like the PV system and the small ESS, is sufficient to cover the total of the needs, the excess of energy can be sold back to the grid and vice-versa. The energy purchased from the grid can be directly consumed by the home appliances or to charge the ESS system.

In Figures 3.8 and 3.9 are illustrated the total amount of energy that is purchased from the grid, G2H power injection, and the amount of surplus energy that can be sold, H2G power injection, respectively, during the considered day. As opposed to the traditional grid setup where a giant power plant provides energy to several smaller homes, in a VPP all those homes generate and store energy.

As seen in the Figure 3.8, in the morning period, the combined energy usage from the PV system production and discharging of the ESS almost covers the demand of the house. In this period, a little over half a kW is bought from the grid in hours 4:00 – 5:00. In these hours the battery is not capable of supplying the whole demand since the maximum charging/discharging capacity defined for the ESS is 1.1 kW per hour.

As illustrated in Figure 3.9, from 11:00 to 20:00 (hours 6:00 -14:00) the PV production is higher than the needs of home appliances or the charging of ESS, and there is an excess of energy that is injected into the grid. Moreover, in hour 14:00 there is a bidirectional exchange between the grid and the home. This occurs because the time slots are considered to be in terms of 30 minutes.

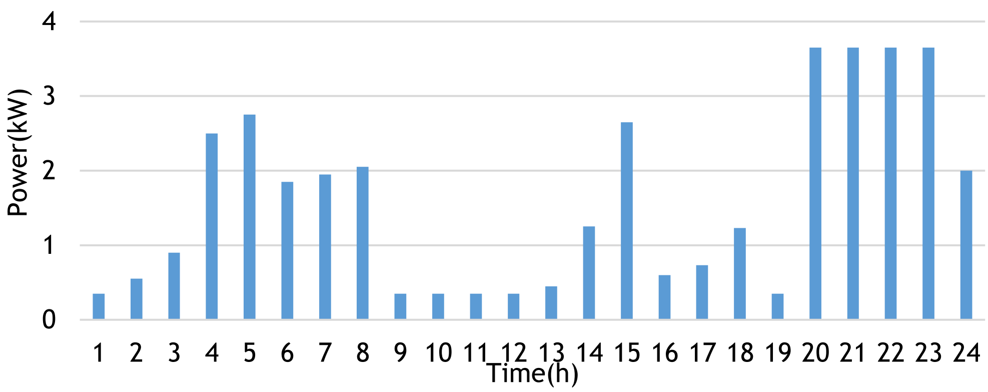

Figure 3.7 - Total house demand with the HEM system.

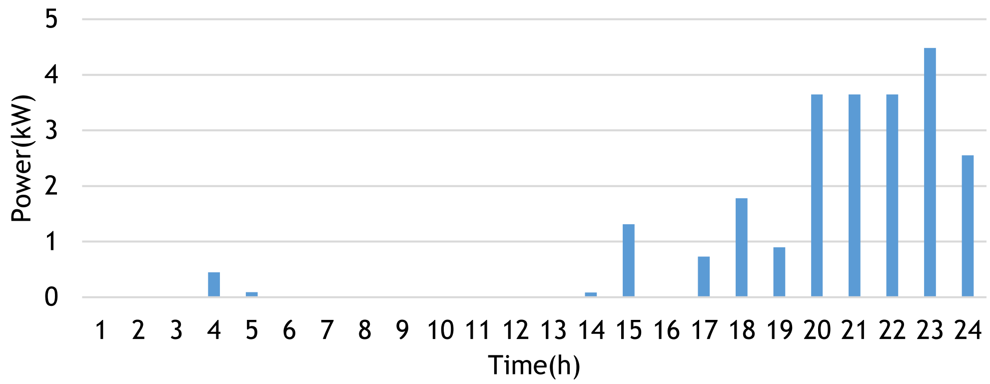

Figure 3.8 - Injected power from G2H.

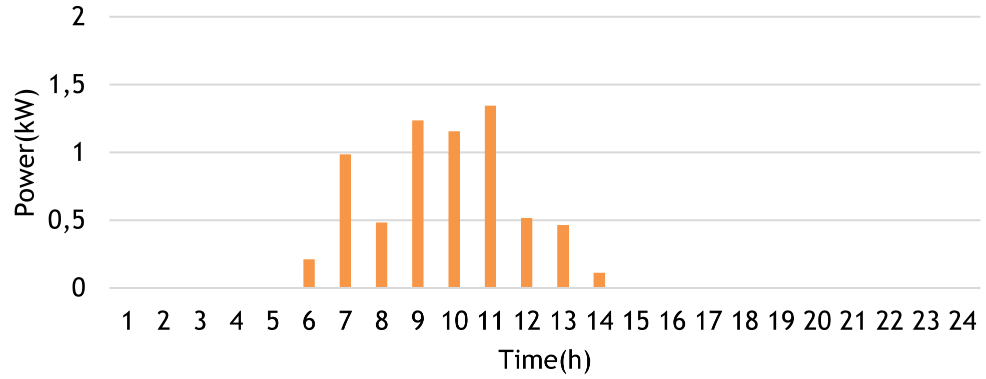

Figure 3.9 - Injected power from H2G.

So, in the first half of the hour (time slot 27) the house demand is very low and there is an excess of energy that is injected into the grid. On the other hand, in the second half of the hour (time slot 28), the PV system together with the ESS are not capable of supply the demand, and the house has to buy a small amount of energy from the grid.

Regarding the ESS, it is assumed that there is a strict constraint on the initial and final energy storage, at 5.9 kWh (the total usable capacity of the battery). Analyzing the Figure 3.10, the battery starts discharging in the first hour, of the morning period, and supplies a fraction of the load over some hours, avoiding the purchase of energy from the grid, when the prices are higher.

Moreover, at hour 7:00 the battery starts charging until it reaches the maximum value, 5.9kWh, at hour 13:00. The energy to charge the battery is exclusively supplied by the PV system, in this period. In hours 14:00 and 15:00 a discharging event occurs to minimize the supplied energy from the grid and contain the second peak period. Moreover, it can be observed that the battery only starts the charging process at hour 17:00 when the prices are at the lower value.

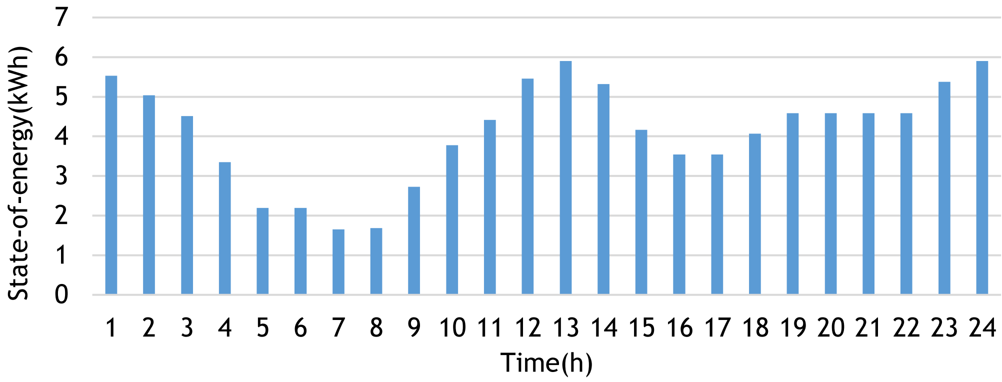

Figure 3.10 - House battery state-of-energy variation.

Apparently, there should not be an interruption in the charging process of the battery, in hour 19, but the reason is related with an increase of house demand in hour 20 that stays until hour 23:00, seen in Figure 3.7. So, when the HEM system, during of the monitoring of the house demand, detects an increase of the demand in hour 20 it tries to shift the charge of the battery to a period with a lower demand. As the battery has to be fully charged in the hour 24 and with the considered charging rate it's not possible in one hour, it starts the charging process at hour 22.

3.4.3 Electric Vehicle Solar Parking Lot

The proposed model was implemented in General Algebraic Modeling System (GAMS), applying the MIP solver. In order to evaluate the model, the parking lot from Engineering Faculty of the University of Porto (FEUP), in Porto (41° 10' 40.8'' N, 8° 35' 52.8'' W), has been considered. The faculty has 5 parking lots, as it can be observed in Figure 3.11 [88]. For this study, only the parking lot (P1), highlighted in red, was considered.

Furthermore, in order to fully analyze the bidirectional energy exchanges between the EVSPL and the grid, a distinct pattern between the prices of energy, reserve and regulation has been considered (different electricity markets). The 100kW rooftop PV output power, presented in Figure 3.5, of a typical summer day has been investigated. All the EVs are supposed to be Nissan Leaf with a battery capacity of 30 kWh [13]. With regards to EV charging the following assumptions were made:

- Charging efficiency is 90 % for all EVs;
- Discharging efficiency is 81 % for all EVs;
- Minimum and maximum SOC is 20 % and 80 %, respectively;
- Rate of charge and discharge of the parking lot is 3.3 kWh;

It is also assumed that the EV owners pay 0.246 EUR/kWh to charge their cars, which represents the charging tariff from one of the Portuguese networks and it has been extracted from [81]. As for the energy prices, the data obtained from the first day of July 2019 of the Portuguese market have been used [89], expressed in the Figure 3.12.

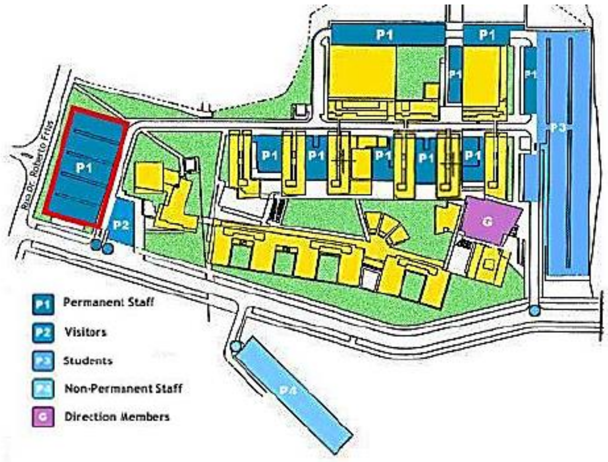

Figure 3.11 - Map of the FEUP parking lots.

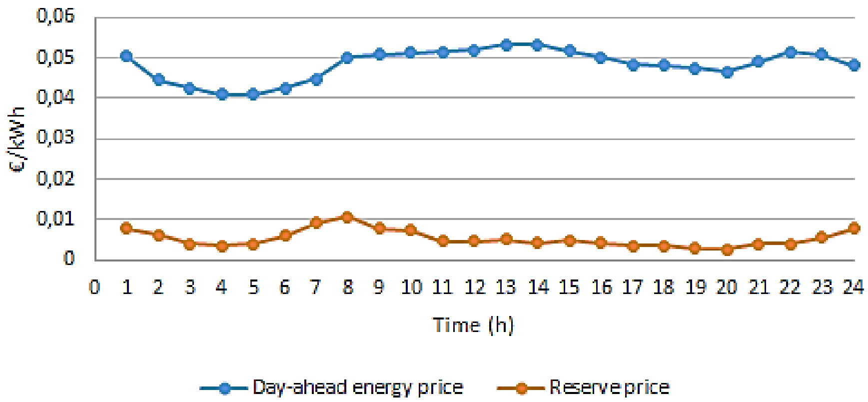

Figure 3.12 - Considered prices (July 2019).

3.4.3.1 Parking Lot Occupation

The arrival and departure times of EVs are randomly distributed according to on a normal distribution based on a study of the FEUP parking lot [31]. The distribution of arrival times is divided into two groups, depending on the work schedule of the EV owners (morning or afternoon), as shown in Table 3.5.

It is assumed that the parking lot is not monitored during night-time. Moreover, the SOC lost in the trip home to university and vice-versa, for the 2 neighborhoods are arbitrarily distributed according to on a normal distribution, as shown in Table 3.6. In Figure 3.13 is illustrated the number of EVs that arrive (departure) in each hour of the day.

Figure 3.14 illustrates the probability function of the FEUP's parking lot duration. As it can be observed, the most likely parking duration is 8 hours. The total number of EVs in the parking lot in each hour based on their expected stay duration is shown in Figure 3.15. Since the time scale was shifted by 6 hours, the hour 2 corresponds to the hour 8 of the Figure 3.13 and so on.

Table 3.5 - EVs probability distribution parameters (Arrival/Departure times).

		Mean	Std. 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		-

Table 3.6 - EVs probability distribution parameters (Trip SOC lost).

		Mean	Std. Deviation
N1	SOC Lost	20 %	2 %
N2	SOC Lost	30 %	3 %

Departure Time \ Arrival 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	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	3	7	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	6	19	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	6	7	4	0	0	0	3	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	2	1	0	0	4	7	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	2	2	5	2	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	3	4	2	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	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 3.13 - Arrival/Departure schedule corresponding to parking lot.

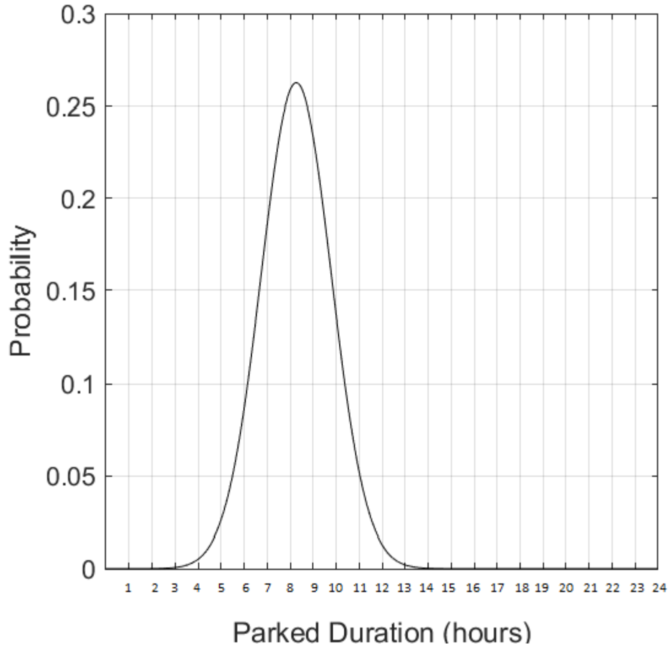

Figure 3.14 - Probability distribution of parked duration at FEUP's parking lot.

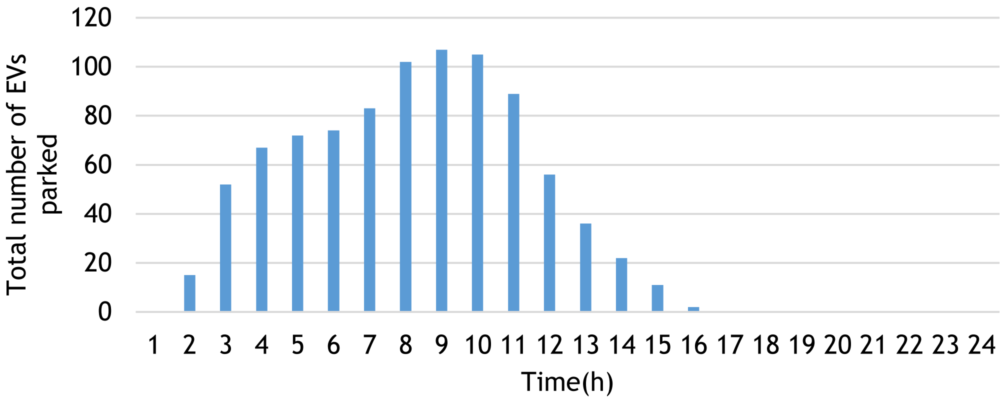

Figure 3.15 - Number of EVs at FEUP's parking lot in each hour.

Chapter 4

Results and Discussion

In this section the simulation results are presented. The case studies defined in Section 3.4, for the purpose of analyze the electric impacts that the possible aggregation of EVSPLs and smart houses, in a VPP, can have on the distribution power systems are discussed. Also, it is analyzed the characteristics of energy supply in smart distribution networks change with the presence of distributed and renewable energy sources.

Reverse power flows and unpredictable generation profiles can cause voltage overshoots and fast voltage changes. As a result, the power system integration is limited by technical and operational constraints. By aggregating the several houses and the parking lot in a VPP community, with a coordinated control, it allows them to operate as a single dispatchable power plant.

The system network, presented in Section 3.4, has been compared, for the different case studies, in a multi-period AC optimal power flow analysis using a simulation tool called MATPOWER.

4.1 Economic Analysis

4.1.1 Smart Homes

The neighborhoods 1 and 2 of SHs are located on buses 22 and 25, respectively. The set of houses have the same home appliances and systems integrated (PV system, inverter, small batteries and so on). Nevertheless, the demand of each house is different through the day and is related to the different owners' habits and work schedules. As can be seen by Figure 3.13, the EVs owners, associated to different houses, have different working schedules at the University.

By applying the same methodology of Section 3.4.2, to all the houses, it's possible to calculate the amount of energy that can be taken from (fed to) the grid, on different hours of the day, under the optimally operation of the proposed energy management system.

The VPP control center strategy optimizes the solar power and ESS output to minimize the power purchase cost and increase the power sale income, over a time horizon of 24h. The total amount of traded energy between the grid and the cluster of smart houses, Neighborhood 1 and 2, it can be seen in Figures 4.1 and 4.2, respectively.

According to Figure 4.1, the optimization model for the operation of all the houses can meet the internal load demand and sell electricity to the distributed power grid during a prolonged period, more particularly, from 9:00h to 20:00h (hour 4 to 14).

It can be noticed that from 8:00 to 12:00h (hours 3-6), there is a bidirectional flow of energy, or, in other words, the grid sells and buys energy at the same time. Hours 5 and 6, in the plot at the top of the Figure 4.1, have very small values, although they appear to be null in the illustration. This occurs because in the optimization model the hour is divided in two time slots, as explained in Section 3.1.1. So, in one time slot there is a surplus of energy, while in the other the total energy from installed PV systems and batteries discharging is not capable of meeting the houses demand.

Moreover, in this period, despite of the small amount of electricity needed from the distributed power grid, the purchase rate is obviously reduced when comparing with the situation in what the HEM system is not considered, which contains the peak load period in the morning. The energy needs in the second peak period, between 19:00 and 21:00 (hours 14 and 15), are also reduced by optimally re-scheduling the several home appliances to off-peak periods, after midnight.

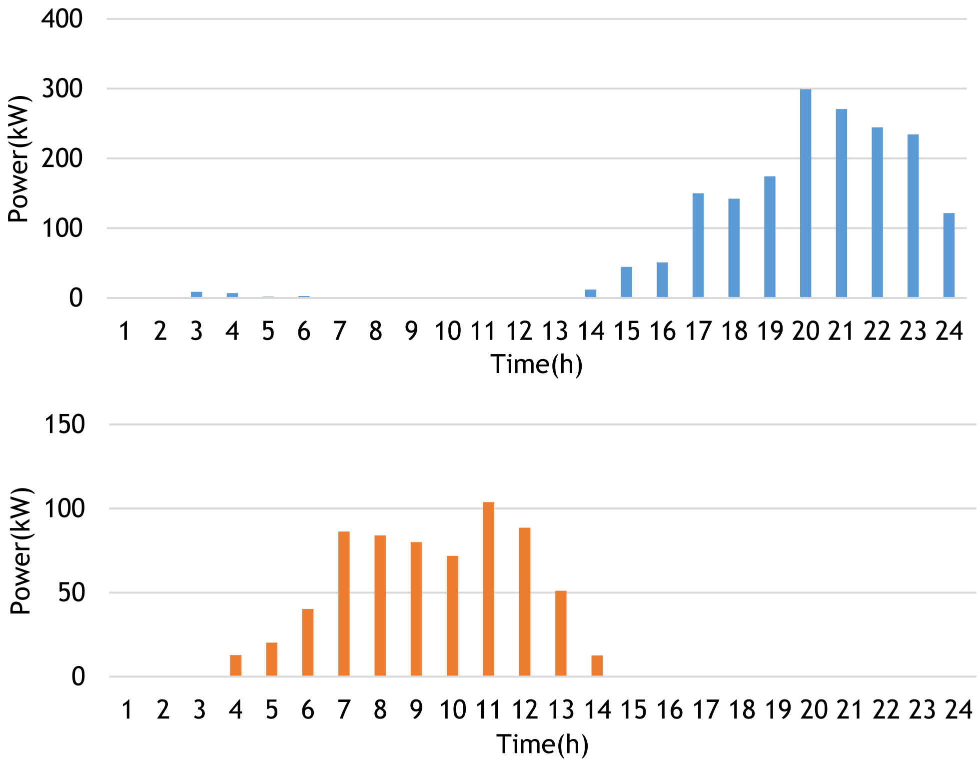

Figure 4.1 - Injected power from grid to neighborhood 1 (head) and from neighborhood 1 to grid (bottom).

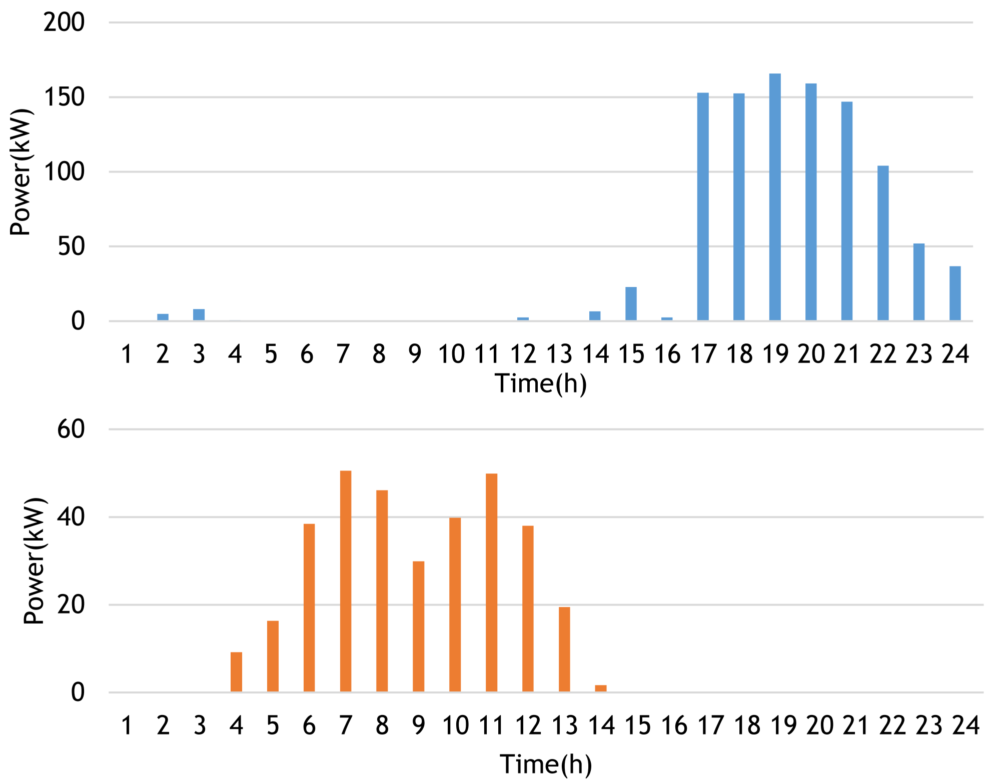

Figure 4.2 - Injected power from grid to neighborhood 2 (head) and from neighborhood 2 to grid (bottom).

As it can be seen in the Figure 4.2, the bidirectional power flow between the grid and neighborhood 2 is lower when compared with the other neighborhood. This is expected since the neighborhood 2 has half of the houses. Moreover, although the PV generation output is the same for all the houses, it is observed that in neighborhood 1 the maximum injection into the grid occurs between 16:00h and 17:00h (hour 11), while in neighborhood 2 the maximum injection into the grid occurs between 12:00h and 13:00 (hour 7).

Also, the maximum PV generation output occurs in hour 9, between 14:00h and 15:00h, as illustrated in Figure 3.5, which does not match with none of the aforementioned injection periods. This is explained by the different appliances' specifications, presented in Table 3.4, that each of the houses can have.

For example, while one house can have a peak demand in hour 7, another house may have a demand equal to zero at the same hour, which makes the result of the optimization performed by the EMS different for each house. Thus, the houses may have different consumption/production patterns based on the end-user's preferences and work schedule, which directly influences the results depicted in Figures 4.1 and 4.2.

Some assumptions were made regarding the biding strategy of the VPP controller that aggregates the neighborhoods. It is assumed that the VPP controller participates in the energy market based on the initial estimation of the electric demand of the houses and the forecast of the generated energy of installed PV systems, which really correspond to the values actually consumed/produced, or, in other words, the prediction error is equal to zero.

Part of the total electric power generated by the PV systems is for supplying the houses and the surplus energy can be offered by the VPP controller to the electricity market, benefiting from delivering it. Another income comes from the selling of electricity to the houses where is applied a tri-period tariff of one of the Portuguese energy traders [87], as shown in Figure 4.3.

As it can be seen in Figure 4.3, the income of selling energy to the houses is much higher than the income resulting from the excess solar generation injected to the grid, for the two neighborhoods. Moreover, the cost related with the amount of energy bought from the grid to supply the energy needs of the two neighborhoods is presented in Figure 4.4. As it expected, the cost is lower for the neighborhood 2 since it has half of the houses when compared to the other neighborhood.

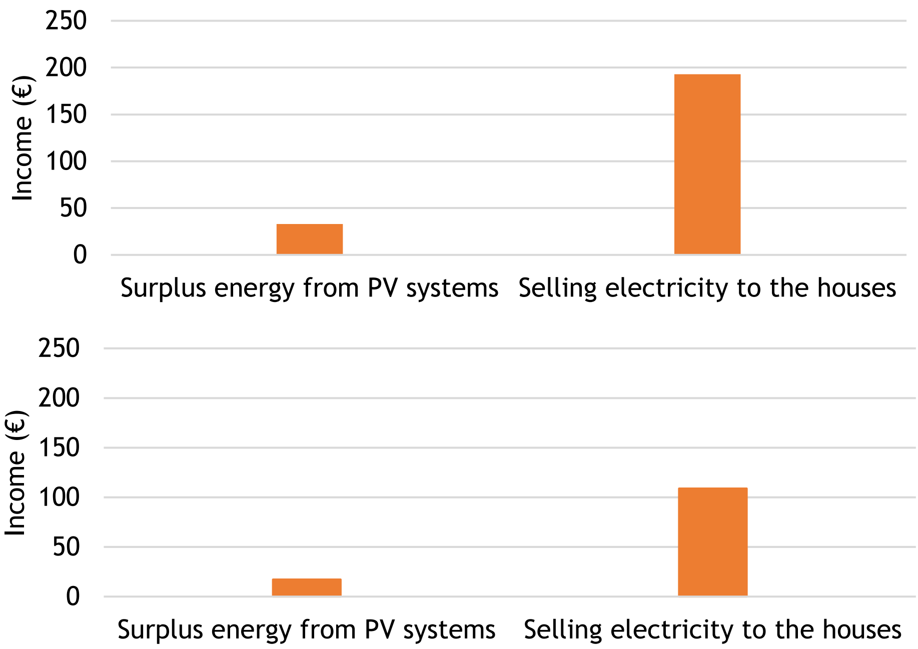

Figure 4.3 - Analysis of the neighborhood 1 incomes (head) and neighborhood 2 incomes (bottom).

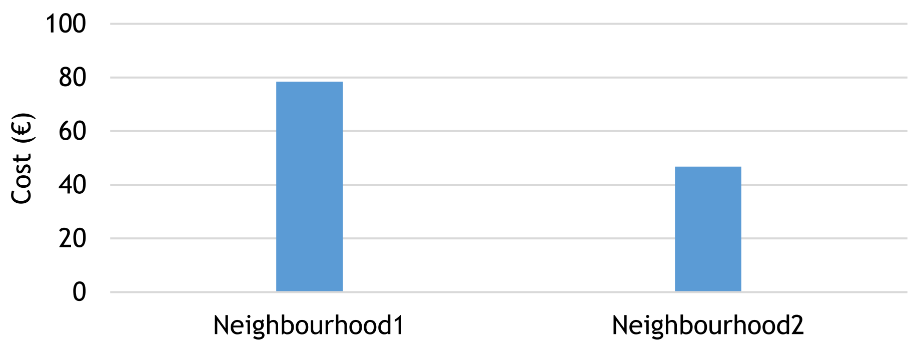

Figure 4.4 - Analysis of the cost related with the purchase of electricity.

4.1.2 Electric Vehicle Solar Parking Lot

The traded energy between the grid and the parking lot is presented in Figure 4.5. As it can be observed, the parking lot injects to the grid a large amount of energy between 10:00h and 11:00h (hour 5) and between 12:00h and 15:00h (hours 7-9).

Therefore, the parking lot has a higher capability to benefit from selling energy to the grid at solar peak hours. From 11:00h to 12:00h (hour 6), although the PV generation is high, there is not enough energy generated from the rooftop PV to satisfy the charge requests of the charging EVs, which leads the parking lot to buy a large amount of energy from the energy market. Moreover, there is a transfer of energy to the parking lot for extended hours in the evening, more particularly, from 15:00h to 20:00h (hours 10-14).

Figure 4.6 demonstrates the participation of the parking lot in the regulation-down market. By comparing the Figure 4.6 with the Figure 4.5, the EVSPL prefers to participate in the regulation market. As can be seen, the parking lot participates in the regulation market for an extended period in the morning between 07:00h and 11:00h (hours 2-5) and in the beginning of the afternoon between 12:00h and 16:00h (hours 7-10). The regulation-down corresponds to the power flowing from the grid to the parking lot, used to charge the EVs.

The different incomes and costs related to the VPP controller that manages the EVSPL operation are presented in Figure 4.7 and Figure 4.8, respectively. Through the participation in the regulation market, the parking lot may be required by the system operator to generate the offered regulation, illustrated in Figure 4.6, benefiting from delivering it. However, as illustrated in the Figure 4.7, this income has the lower influence in the global profit because it is related to the probability of being called by the system operator.

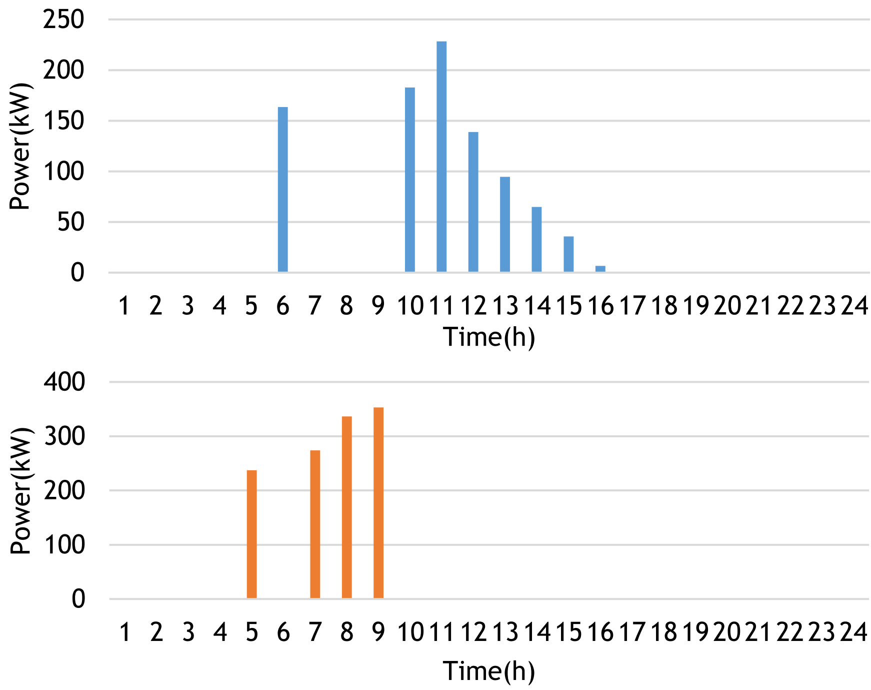

Figure 4.5 - Injected power from grid to parking lot (head) and from parking lot to grid (bottom).

The highest incomes are, on one hand the amount that EV owners pay to the parking lot for staying in the parking lot and on the other hand, the amount that is paid by EV owners to charge their vehicles. Finally, there is an income that results from the amount of energy transferred from the parking lot to the grid in the electricity market.

As it can be observed, the higher cost term is related to the payment to EV owners for discharge the batteries of their vehicles. By investigating this term, in each hour, the EVs discharge from 10:00h to 11:00h, hour 5, and between 12:00h and 15:00h, hours 7-9. Since there is a high PV power generation, at these hours, the EVs tend to discharge when the market prices high.

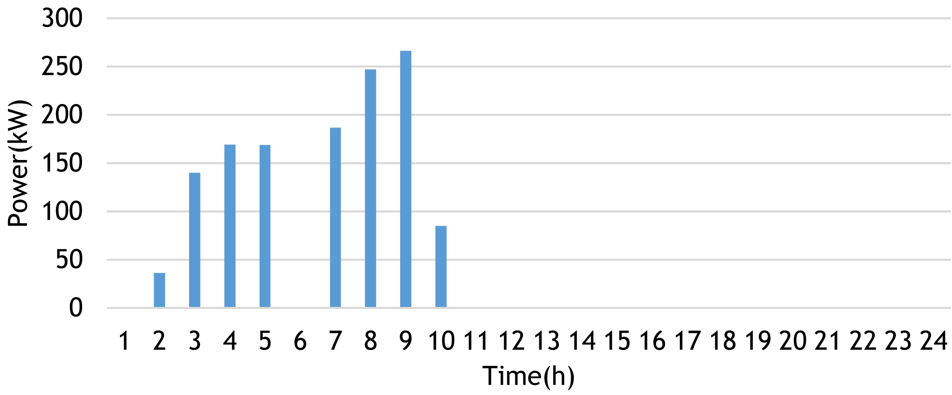

Figure 4.6 - Parking Lot’s offer to the regulation down market.

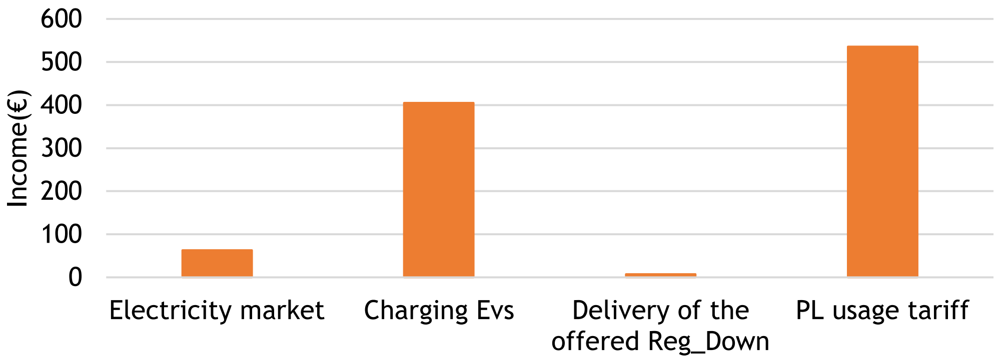

Figure 4.7 - Analysis of the parking lot's incomes.

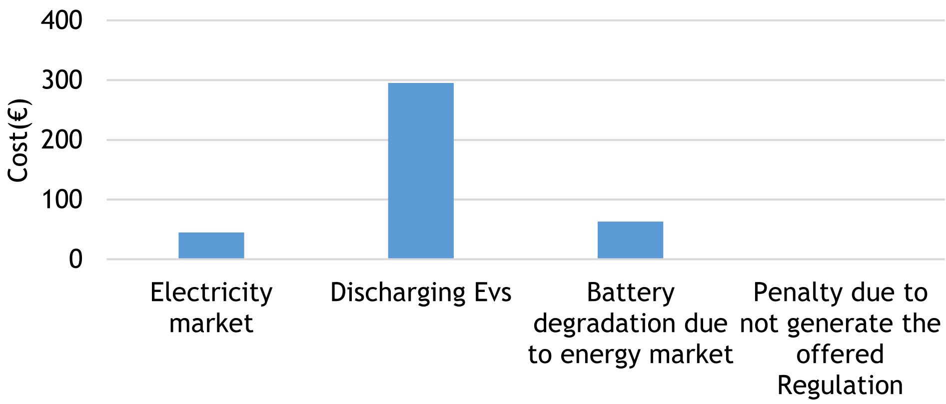

Figure 4.8 - Analysis of the parking lot's costs.

The battery degradation cost is related with the participation of the parking lot in the energy market (PL2G activities). When the interaction between the parking lot and the grid increases, this cost also increases. The electricity cost is related with the amount of energy bought from the grid. This means that, although the PV power generation is available, the parking lot is not able to fulfil the charging requirements without buying a portion of energy from the grid.

Moreover, it is noted that the parking lot pays a penalty in case of an unavailability to generate the offered regulation, even though this cost represents an insignificant contribution to the total cost. In the Figure 4.9 is illustrated the expected profit for the VPP controllers, regarding each of its participants, smart houses and EVSPL, for the considered day. As observed, the EVSPL contribution for the total profit is much higher than the 2 neighborhoods.

This is partly due to the fact that the VPP controller, responsible for the optimal operation of the smart houses, is not only concerned with maximizing its profit, but also getting the homeowners/prosumers to minimize their cost. The proposed EMS can lead to significant electricity bill savings of up to 30 per cent, in some houses, by optimally shifting the demand off the allowable appliances through time and managing the PV/ESS systems, making it easier for homes to become more self-sufficient.

4.2 Case Studies: Network Simulation and Analysis

One of the main advantages of distributed generation is its impact on grid losses and increasing voltage level on distant buses. In future distribution systems characterized by time-varying power generation and demand, it is assumed that normal voltage conditions are required to guarantee security of supply and operation of power electronic equipment.

The European standard EN 50160, for example, defines an allowable voltage deviation of ±10%, maximum, of the nominal voltage to keep the service voltage to customers within acceptable voltage ranges [90]. The same applies to undesirable conditions which can be caused by unpredicted changes in demand or generation, failure of system devices or the incapacity to compensate the reactive power demand [91].

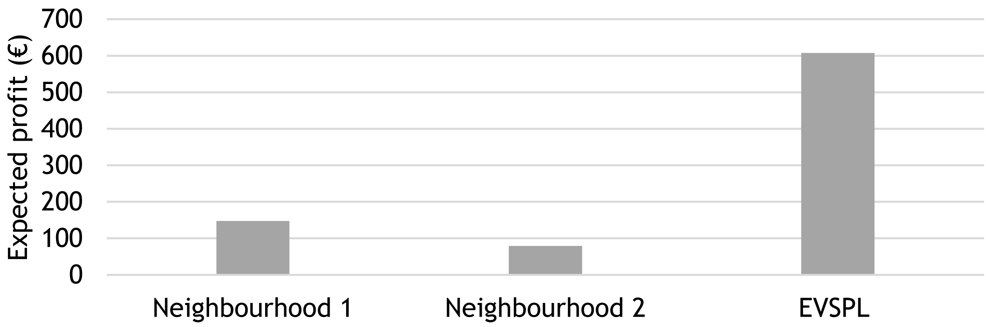

Figure 4.9 - Expected profit due to each VPP participant.

In order to keep the power system voltages at all buses in acceptable ranges in both normal and atypical conditions, voltage control solutions are used in distribution systems, which are not part of the scope of this work.

4.2.1 No EVSPL and No HEMS (Base Case)

Figure 4.10 depicts the active power losses that have been calculated for all lines, for the base case. The total value, over the 24-hour period, is 1.784 MW. Moreover, the reactive power losses totalize 1.218 Mvar. As it was expected, significant voltage drop exist on some buses, especially the ones that are located far away from the main substation, for example bus 18. The obtained voltage profiles for the 3 buses, where the EVSPL and the neighborhoods are located, can be seen in Figure 4.11.

In Figure 4.12 is described the active energy supplied to the neighborhoods 1 and 2, without the implementation of the energy management system. Since in this case study there is no EVSPL at bus 33, the active power flow in the aforementioned bus is zero.

4.2.2 HEMS with no EVSPL

In this case study it was introduced the optimal management of Distributed Energy Resources (DERs) owned by different prosumers, participating in DR programs. Figure 4.13 shows the comparison of the active power flow at buses 22 and 25, where the neighborhood 1 and 2 are located, respectively, between the previous case study and this one, where a control and management strategy was conceived for planning the energy consumption/production of the VPP local controller.

After the implementation of the EMS, it can be seen a reverse power flow between 09:00h and 19:00h (hours 4-13). This is caused by the optimal management of the household owned assets (PV system and ESS), that allows the VPP controller to offer the excessive energy in the electricity market, during the hours with high solar irradiation.

The proposed EMS also produced significant improvements in the daily peak periods, morning and evening, as it can be observed by the resulting active power that presents a much flatter behavior than in the previous case study. Moreover, a peak arises in the off-peak hours between 01:00h and 06:00h (hours 20-24).

However, this situation is not necessarily harmful to the electrical network. In fact, by shifting the demand from peak to off-peak hours can facilitate the real-time balance off supply and demand, which can contribute to an increase in network reliability and quality of supply. With regard to power losses, there was a reduction in total active and reactive line losses with the EMS implementation.

Figure 4.14 illustrates the comparison of the results obtained in this case study with those obtained in the base case, regarding the active power losses. Although, over the 24-hour period, there was a reduction in total active power losses, 1.749 MW, between 00:00 and 06:00h (hours 19-24) there is a slight increase in losses. This is due to the fact that in these hours there is a large amount of energy consumed caused by the load shifting to the off-peak hours.

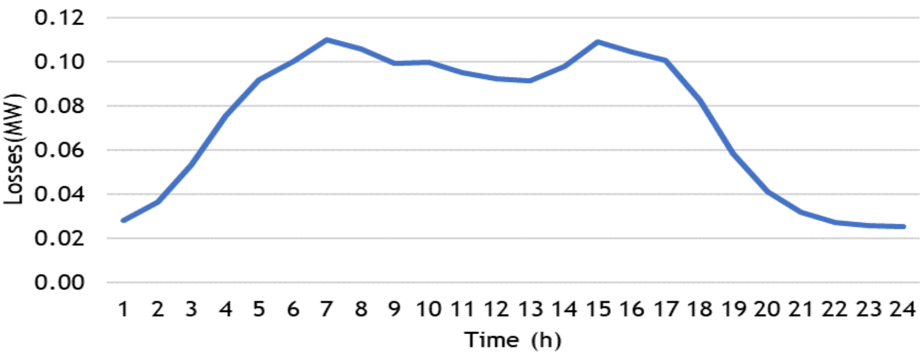

Figure 4.10 - Case study 1 - Total line losses in MW.

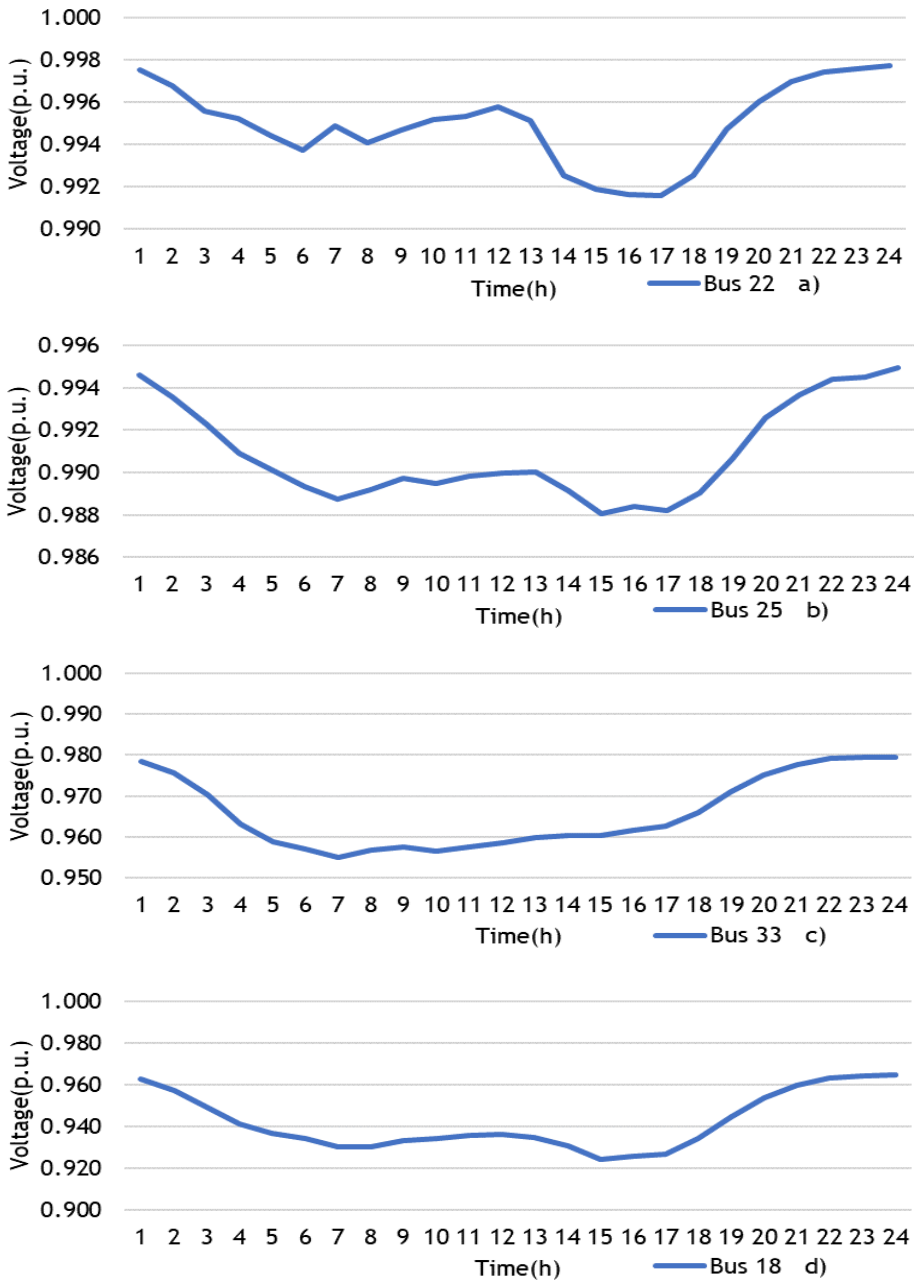

Figure 4.11 - Voltage profiles: (a) Neighborhood 1; (b) Neighborhood 2; c) EVSPL; (d) Farthest network bus.

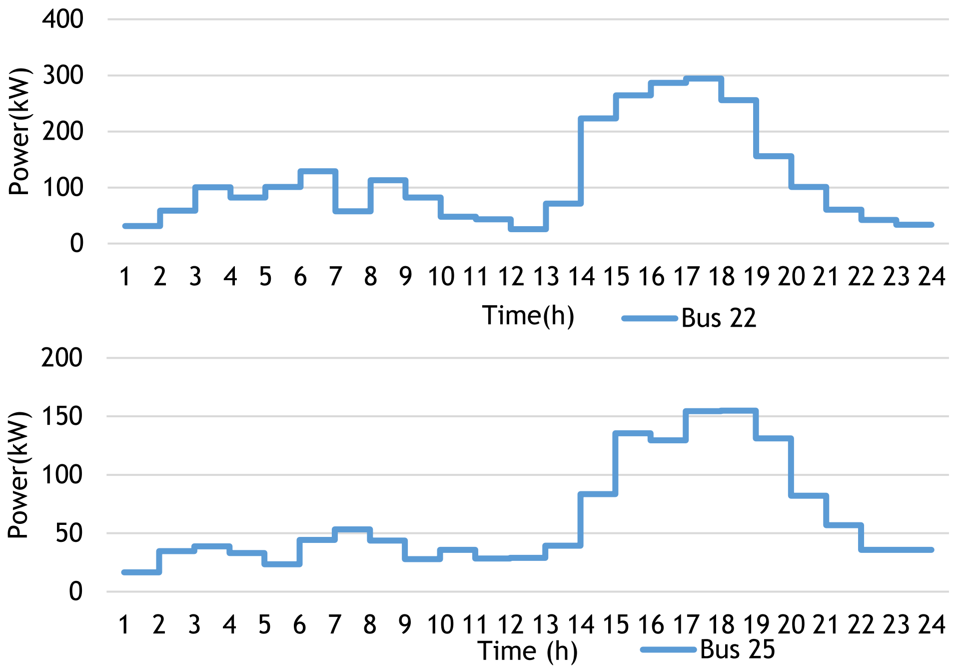

Figure 4.12 - The profile for the active power flow at neighborhood 1 (head) and neighborhood 2 (bottom).

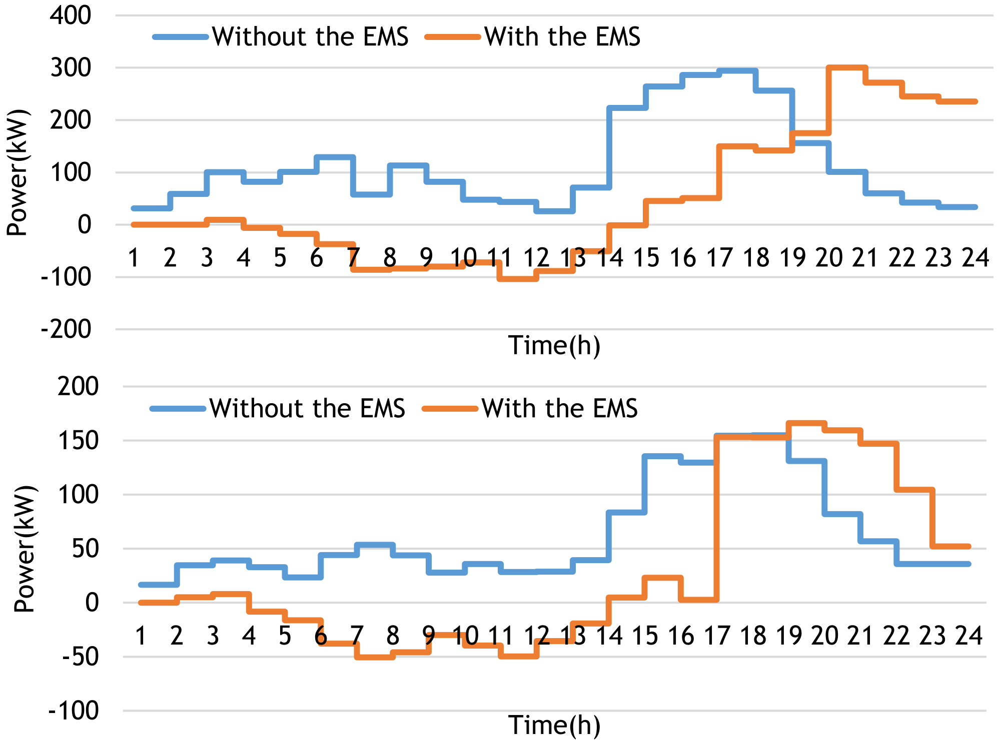

Figure 4.13 - The profile for the active power flow at bus 22 (head) and 25 (bottom).

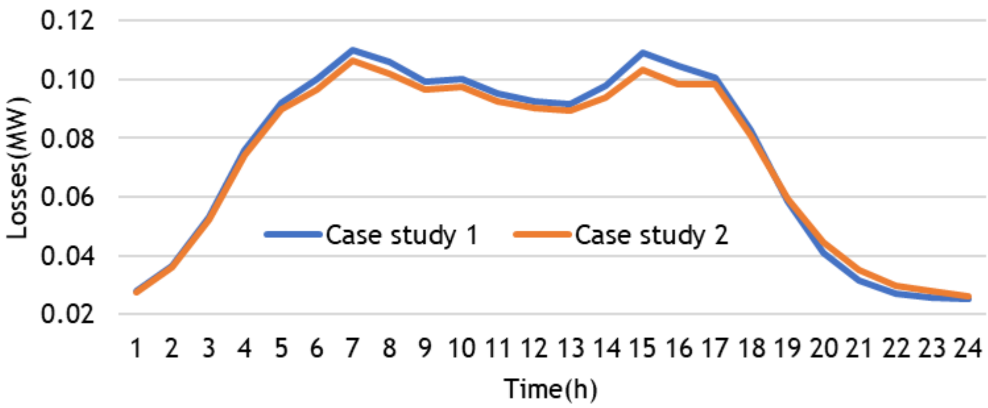

Figure 4.14 – Comparison between case study 2 and 1 - Total line losses in MW

The obtained voltage profiles for the buses 22 and 25, where the neighborhoods are located, after the implementation of the proposed EMS are presented in Figure 4.15 and Figure 4.16, respectively. It is clear that the upper and lower voltage limits have not been violated.

With regard to bus 22, between 08:00h and 19:00h (hours 3-13) the voltage levels have been improved, mainly, because of the excess of generation from the installed PV systems that was injected into the grid. On one hand, between 19:00h and 00:00h (hours 14-18) the voltage magnitude increases due to the low energy consumption, with the implementation of the EMS, in contrast with what it was verified in base case, in the same period.

On the other hand, between 00:00h and 06:00h (hours 19-24) the voltage levels are reduced as consequence of the high consumption of energy caused by the load shifting to the off-peak hours. Moreover, the upper and lower voltage limits in the different buses have not been violated after the proposed EMS was implemented.

With regard to bus 25, between 09:00h and 19:00h (hours 4-13) the voltage levels have increased, mainly, due to the excess of generation from the installed PV systems. However, it is worth noting that this increase was smaller than the verified in bus 22.

This was expected since the neighborhood 2, located in bus 25, has half of the houses than the other and consequently, the surplus of generation, from the installed PV systems, resulting from the proposed EMS optimization is much smaller when compared with the other neighborhood.

The total power injected into the network by neighborhoods 1 and 2 are 652 kW and 340 kW, respectively. Likewise, between 00:00 and 06:00 (hours 19-24) the voltage levels present a smaller reduction because the total demand shifted to off-peak hours is lesser than the other neighborhood.

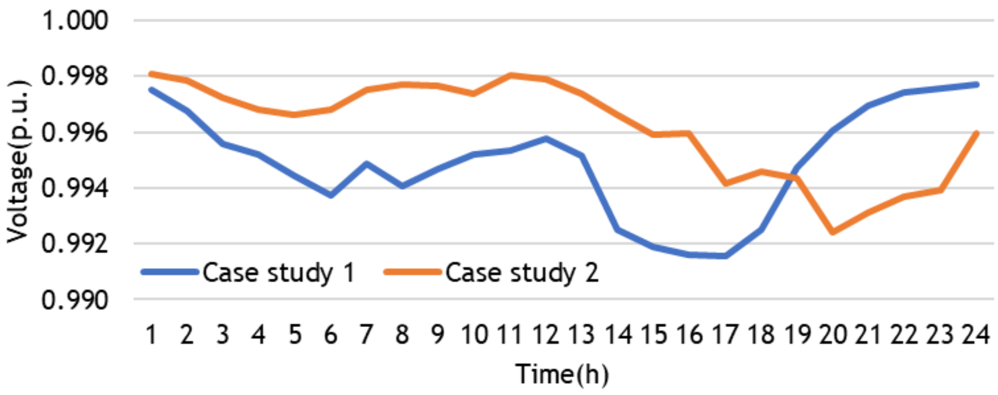

Figure 4.15 - Voltage levels corresponding to bus 22.

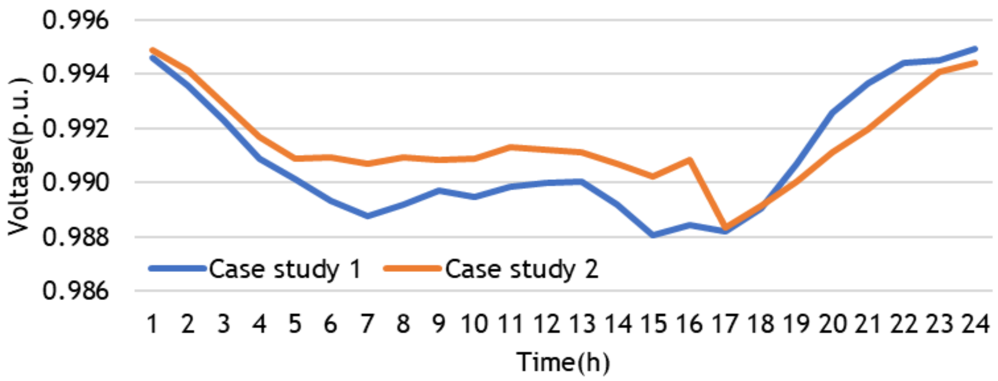

Figure 4.16 - Voltage levels corresponding to bus 25.

4.2.3 EVSPL with no HEMS

In this case study, it is considered the existence of an EVSPL with the proposed energy management system at bus 33. Moreover, the EVs and other loads, belonging to the houses at buses 22 and 25, are supplied without adopting any energy management methods, like what was done in the base case. With regard to active power losses, there was a much smaller reduction when compared to what was achieved in the second case, as the total line losses gone from 1.784MW, in the base case, to 1.780 MW. Figure 4.17 depicts the active power losses over a 24-hour period.

As illustrated in Figure 4.17, between 10:00h and 11:00h (hour 5) there is a reduction in the line active losses. Moreover, for an extended period, from 12:00h to 15:00h (hours 7-9), a considerably loss reduction is achieved. In these hours, the EVSPL injects a large amount of energy into the grid, about 1200 kW, which can help to supply part of the load in nearby buses.

Thus, with an introduction of the EVSPL, the power supplied by the grid and consequently current flows through lines are reduced significantly, which causes less losses. On the other hand, between 11:00 and 12:00 (hour 6) the opposite is verified, since the EVSPL has a demand of about 165kW which is satisfied by the electrical grid. This has a direct impact on the active power losses, which increase. The same explanation is valid for the extended period, including from 15:00h to 22:00h, when the EVSPL consumes around 750 kW.

The voltage profile for bus 33, before and after the presence of the EVSPL, is depicted in Figure 4.18. As it can be seen, the voltage levels have been improved in the hours that the EVSPL inject power into the grid, more specifically between 10:00h and 11:00h (hour 5) and from 12:00h to 15:00h (hours 7-9).

Hence, at times the EVSPL draws energy from the grid, the voltage levels have decreased. An example of this is observed between 16:00h and 17:00h (hour 11), when the EVSPL has a higher energy consumption of around 230 kW. Moreover, in the nearby buses it is noted a small increase on the voltage magnitude in the hours that the EVSPL has an excess of generation, as illustrated in Figure 4.19 for the bus 26. The upper and lower voltage limits in the different buses of the presented network haven't been violated after the implementation of the EVSPL.

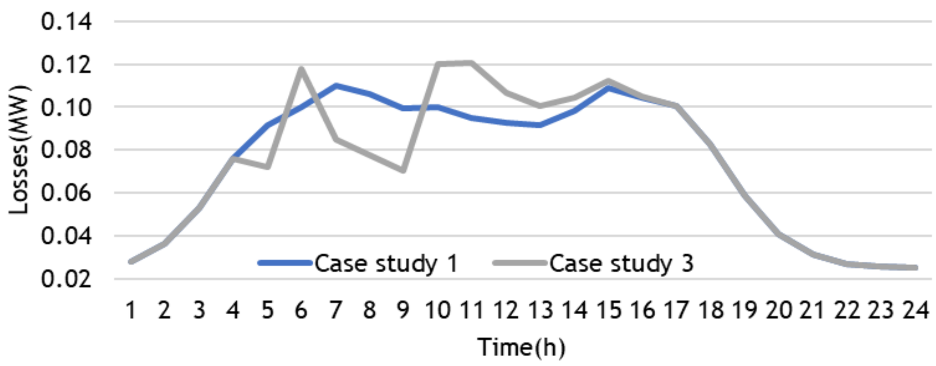

Figure 4.17 – Comparison between case study 3 and 1 - Total line losses in MW.

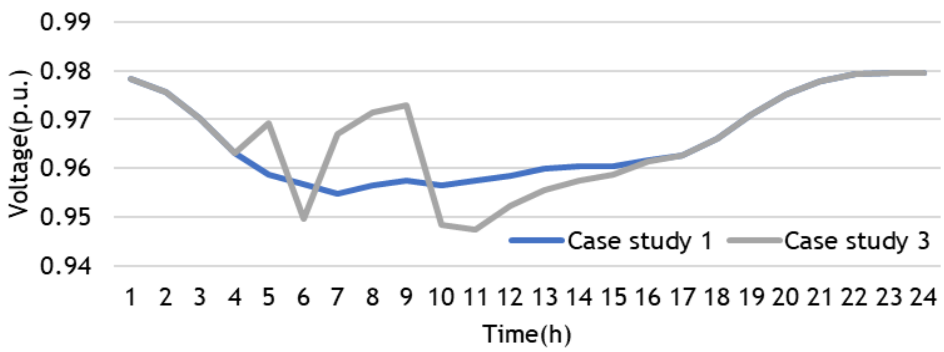

Figure 4.18 - Voltage levels corresponding to bus 33.

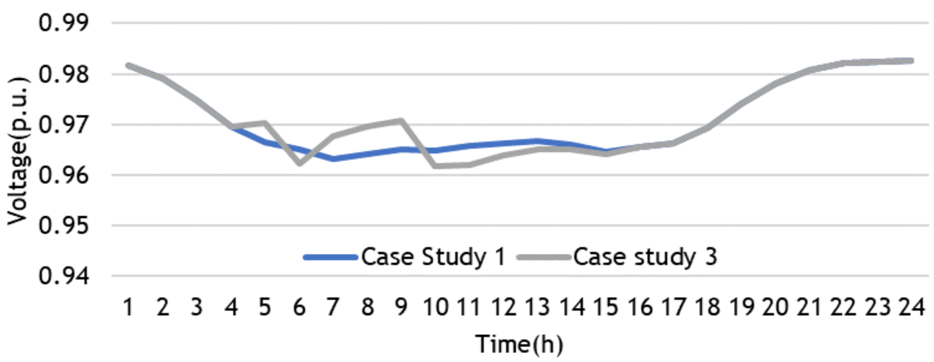

Figure 4.19 - Voltage levels corresponding to bus 26.

4.2.4 EVSPL and HEMS

In this case study, it is observed a higher reduction in the total active and reactive power losses, 1.745 MW and 1.195 Mvar, respectively. This reduction is, mainly, achieved with the contribution of the smart houses EMS. In Figure 4.20, a comparison between this case study and the base case, regarding the active power losses, over a 24-hour period, is illustrated.

As it can be seen, between 10:00h and 11:00h (hours 5) the line losses have decreased when compared with the base case. This is explained by the injected of energy into the grid by the EVSPL, which contributes with a larger amount, and the two neighborhoods. From 11:00h to 12:00h (hour 6) the opposite occurs, because although the two neighborhoods are injecting power into the grid, about 80 kW, the EVSPL draws a higher amount of power in this hour, about 163 kW.

Moreover, a significant reduction in the losses is observable between 12:00h to 15:00h (hours 7-9). In this period, the combined power injection into the grid of the neighborhoods and the EVSPL has the highest value, in a total of around 1340kW.

On one hand, between 15:00h and 20:00h (hours 10-14), the line losses show a notable increase. This growth is, almost exclusively, due to the EVSPL that draws a large amount of power from the grid to satisfy its operation requirements, in a total of around 710 kW, as it can be seen in Figure 4.5. The total numbers of houses have an insignificant consumption in this period, as shown in Figures 4.1 and 4.2 (the head).

On the other hand, between 20:00h and 00:00h (hours 15-18), and between 00:00h to 06:00h, the line losses have decreased/increased, respectively, since the implemented EMS optimally shifts the allowable appliances to low-demand periods. For the electrical networks' perspective this helps to balance the supply and demand in a more effectively, faster and above all, more locally way. For the prosumers' perspective this avoids the higher prices, in order to promote savings in their electricity bills.

Figure 4.21 intends to demonstrate the distinctly contribution that the EVSPL and the EMS, implemented in prosumers houses, have in the total line losses of this case study. The aggregation of the proposed EMS, installed in the houses, with the EVSPL have significant improvements in the losses, comparing with the case study 3, where only the EVSPL is considered.

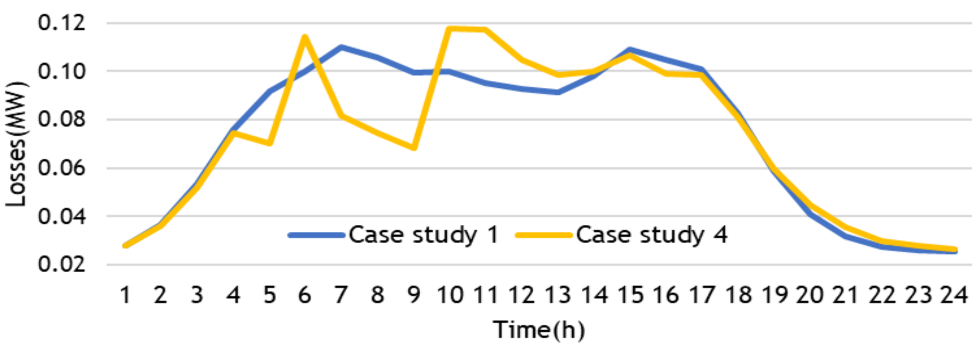

Figure 4.20 – Comparison between case study 4 and 1 - Total line losses in MW.

Only between 00:00h and 06:00h (hours 19-24), this aggregation translates into an increase of losses on the lines due to the shift of demand to the off-peak hours. Wind and solar PV generation are most widely used DG technologies around the world.

Light energy is directly converted into electrical energy using PV cell without using any rotational device. A PV cell produces Direct Current (DC) power which may be used directly for DC appliances. Conventionally Alternating Current (AC) appliances are widely used in power system. Therefore, Inverter circuits are required to convert DC produced by PV cell in AC.

It is clear that with the introduction of DG, from the optimal operation of the EVSPL and the smart houses, active and reactive power supplied by the grid is decreased, since part of load demand can be met by nearby DG unit.

The active power supplied by the grid is depicted in Figure 4.22 for the case study 1 and case study 4. As it can be observed, the power supplied by the grid is lower in the case study 4 almost for all the hours, with exception between 15:00h and 17:00h (hours 10-11), due to an increase of demand verified in the EVSPL, and between 00:00h to 06:00h (hours 19-24) due to an increase of demand verified in the smart houses. Even so, the total reduction achieved, with the aggregation of the EVSPL and the smart houses, is around 2670 kW.

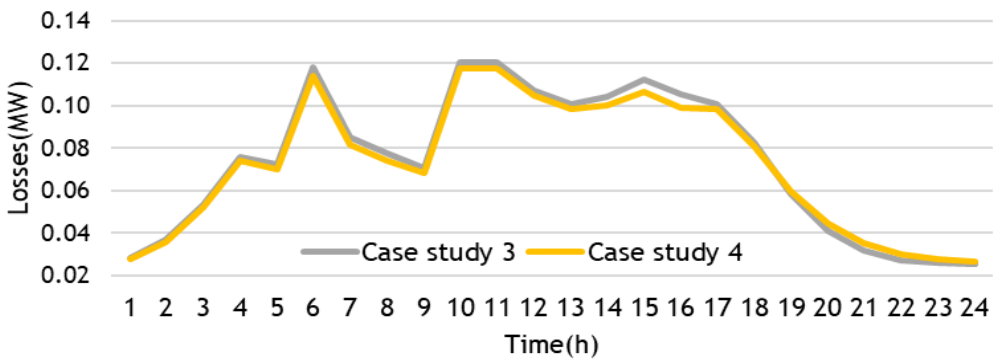

Figure 4.21 – Comparison between case study 4 and 3 - Total line losses in MW.

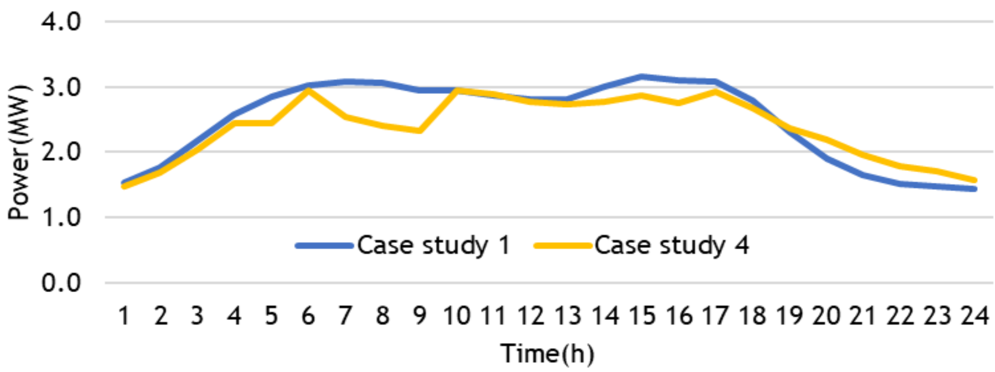

Figure 4.22 – Comparison between case study 4 and 1 - Active power supplied by the grid.

Although the reactive power supplied by the grid has decreased in case study 4, the total value achieved was much lower than the one verified for the active power. This fact is related with the nature of DG installed in the smart houses and in the EVSPL. PV cell only produces active power and therefore its reactive power generation is 0. Hence, utility network must be capable of meeting the reactive power demand.

For example, if the DG installed, in the EVSPL, was composed by wind units using synchronous generators with the ability to produce reactive power, a higher reduction is expected in the reactive power produced by the utility network. On the other hand, if the wind units use induction generators, it is expected an increase in the reactive power supplied by the utility network, as this type of generator absorbs reactive power.

This case study, where the aggregation of an EVSPL and a set of smart houses are promoted, is the one that achieves more loss reduction and improvements in the voltage levels, which remain within narrow grid constraints.

Chapter 5

Conclusions and Future work

The results of the current work and the developed methodologies reveal several aspects concerning the integration of distributed, renewable and mobile energy sources in VPP. The current section summarizes the work, drawing the main findings and providing an outlook on potential, associated research.

5.1 Main Conclusions

The current work has investigated the technical and economic feasibility of aggregating a group of prosumers with an EVSPL underneath the concept of VPP. In this regard, an EMS methodology was developed, for each of the VPP participants, that assigns the optimal planning of energy consumption/production for the VPP, and also addresses the electric requirements of the power system.

The energy management of prosumers was addressed through a DR strategy which contributes to significant economic benefits while simultaneously enhancing the security of the concerned power system. Shifting EVs charging process, that is responsible for a considerable percentage of the houses demand, and other loads away from peak periods, can play a huge part in eliminating the need to employ more expensive and less climate-friendly peaking power plants.

This work demonstrates that is possible to contain significantly the morning/evening peak periods with the proposed EMS, without jeopardizing the end-users comfort level, by taking advantage of the house-owned assets, like the installed PV and ESS systems. Moreover, the EVs managed by a VPP can mitigate the risks that arise from the expected proliferation of EVs in the coming years, since its high associated load will need to be accommodated correctly by the system to avoid problems like the overload of distribution transformers and cables or the change in the voltage profile of distribution feeders.

To accelerate their market integration, some infrastructure planning will be required. In this regard, a feasible solution emerges in terms of EV charging that are the EVSPLs.

The local VPP controller that supervises and coordinates the optimal operation of the EVSPL can provide ancillary services like regulation up/down through the discharging / charging of the EVs while maximizing its monetary profit. Based on the results obtained, the parking lot has a high potential to participate in regulation market, especially in the regulation-down market. Additionally, RESs can be used to supply a considerably fraction of the energy demand required to charge the EVs, reducing the injected power from the grid, and also increase the capability to benefit from selling energy to the grid at solar peak hours.

Such a configuration, of aggregating a group of prosumers and an EVSPL in a VPP, offers more flexibility to the system operator to mitigate the unpredictable and intermittent nature of RES, where EVs can become a valuable tool to balance the distribution grid locally and avoid costly infrastructure investments because this asset will be always underneath the VPP manage, except while they are moving. Therefore, the EVs can play a very active role in the future smart grids since they simultaneously can be transportation tools and priceless mobile energy storage units.

However, the results of this work show that the V2G technology is still very costly due to the battery depreciation as the cycles of charge/discharge significantly increases, even though this is expected to reduce in the near future as prices of batteries drop.

Regarding the expected profit obtained, for the considered day, it was calculated assuming that the VPP controller that manages the EVSPL participates in different electricity markets while the one that manages the group of prosumers only participates in the day-ahead market. The results show that not only the VPP profit was maximized through the implementation of the proposed EMS as well the prosumers achieved considerable savings in their electricity bills.

The proposed EMS was evaluated through a multi-period AC power flow analysis. The results show that the coordinated operation of the EVSPL and a set of prosumers is the case study in which the more loss reduction is achieved and also can maintain the voltage levels within prescribed constraints, even on far buses.

5.2 Future Work

Several prospects for future work are presented below:

- The possibility of the VPP controller, underneath the EMS' operation, control the rate of charging / discharging of the ESS and also the implementation of the V2G technology at home in order to provide ancillary services;
- Instead of the studies that have been done based on a standard modified distribution network, the current work could be adapted to the real distribution network where the parking lot and the houses are located;
- Explore and design new markets and regulatory mechanisms to get the most out of the aggregation of DERs. As the energy generation transitions to decentralized energy sources

that are connected at the distribution level, also the congestion on the distribution level must be addressed to guarantee a stable grid;

- The management of DERs in a VPP requires the monitoring of information from several DER installations and from sensors monitoring the environmental conditions. Such functionality requires a communication technology infrastructure that is able to support the aggregation of data and the virtualization of DERs. Thus, an energy information system that collects data from all the communication agents (system data, user's data, weather forecasts, DR requests, etc.) is open for future work. This work should focus on the EMS, one of the systems within the VPP architecture;
- VPPs could over time make a considerable contribution in the transition to a low carbon future, but they suffer from some weaknesses. Since VPPs rely heavily on software systems for data collection and communication, they are vulnerable to cyber-attacks that are a threat to the energy grid worldwide. Future research has to be developed on this subject to improve safety of the electrical systems.

5.3 Research Outputs

[C1] Tiago Almeida, et al., "Economic Analysis of Coordinating Electric Vehicle Parking Lots and Home Energy Management Systems," *in Proceedings of the 20th International Conference on Environment and Electrical Engineering*, EEEIC2020, Madrid, Spain, 09-12 June, 2020 **(submitted)**.

[C2] Tiago Almeida, et al., "Coordinated Operation of Electric Vehicle Parking Lots and Smart Homes as a Virtual Power Plant," *in Proceedings of the 20th International Conference on Environment and Electrical Engineering*, EEEIC2020, Madrid, Spain, 09-12 June, 2020 **(submitted)**.

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