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Commercial Demand Response in Virtual Power Plants

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Resumo

O crescimento global da economia, juntamente com o desenvolvimento contínuo e a utilização extensiva de tecnologias pelos consumidores, está a aumentar as exigências para um fornecimento de energia mais fiável e eficiente. Simultaneamente, o aumento no consumo a nível global, impulsionado por novas tecnologias, influenciará o modo como é produzida, distribuída e consumida a energia. A par de outros, espera-se que a produção distribuída de energia se torne uma tendência cada vez mais importante em muitos países. Juntamente com o crescimento da penetração de métodos de produção distribuída e a tendência evolutiva para um mercado energético mais competitivo, é fundamental políticas e meios de gerenciamento a nível técnico e económico. Com a finalidade de lidar com a produção distribuída e aumentar a sua participação nos mercados de energia, surge o conceito de Virtual Power Plant (VPP) que é considerado uma opção eficaz na agregação de produção distribuída e operação conjunta de todos os meios que permitirá a participação e venda, em grande quantidade, no mercado. A VPP acresce ao seu portefólio a capacidade de prestação de serviços auxiliares como o aumento de flexibilidade da rede a nível local. A maior incidência deste tipo de geração local verifica-se em centros urbanos, onde a exploração da flexibilidade de uma VPP e o desenvolvimento de um negócio robusto requer considerações avançadas sobre os seus constrangimentos técnicos e comerciais, bem como uma avaliação da relação custo-benefício na sua atividade e na participação no mercado energético. Considerando o potencial da participação dos consumidores comerciais em programas de resposta à procura, este trabalho propõe um novo enquadramento para fazer o agendamento dos recursos energéticos de uma rede de distribuição baseada no conceito de Technical Virtual Power Plant (TVPP). Este conceito visa aumentar a flexibilidade da rede, contribuindo para o aumento de qualidade do serviço, com maior fiabilidade e vantagens económicas para os consumidores e operadores. Um modelo estocástico de programação linear, é desenvolvido e otimizado com a finalidade de garantir uma solução global ideal, neste caso, a maximização do lucro total de uma TVPP. Considerando restrições operacionais, é permitida a presença de edifícios comerciais e de produção distribuída para participação no agendamento de recursos para o dia seguinte, no mercado energético, como comercializador (preço próprio). Assim, este documento apresenta uma abordagem tecno-económica abrangente integrada que avalia as restrições técnicas e as oportunidades de flexibilidade em consumidores comercial. O caso de estudo engloba a agregação e gestão do agendamento energético, da melhoria da fiabilidade do sistema através de um perfil de carga melhor, da participação em programas de resposta à procura através dos ativos de um consumidor comercial como veículos elétricos e sistemas de ar condicionado. O modelo é testado utilizando o sistema de teste do IEEE 119-Bus e os resultados demonstram que com a gestão ótima de produção distribuída, veículos elétricos e sistema de ar condicionado em edifícios comerciais que permite à TVPP aumentar o seu lucro em 49,23%.

Palavras chave: Central Elétrica Virtual Técnica, Recursos Energéticos Distribuídos, Recursos Energéticos Renováveis, Geração Distribuída, Mercado Energético, Veículos Elétricos, Sistemas de Ventilação e Ar Condicionado e Aquecimento, Clientes Comerciais, Resposta à Procura, Flexibilidade

Abstract

Global economy growth, continuous development, and the comprehensive endorsement of technology by consumers is increasing the demands of consumers for a reliable and efficient energy supply. Along with the growing energy consumption in the world, new technologies will have repercussions on the way we generate, distribute, and consume energy. Besides, distributed energy generation is expected to become a dominant tendency. The rapid penetration increase of Distributed Energy Resources (DER) and the current trend towards a more ambitious and competing electricity market craves new technologies and policies to face emerging technical and economic complications. To succeed handling distributed generation and to increase its participation in power markets, the concept of a Virtual Power Plant (VPP) has surfaced. The concept of a VPP is acknowledged as a competent solution and opportunity to aggregate and operate DER and allowing for wholesale energy market participation to provide the required flexibility services to the local grid. Also, many DERs are available in urban areas and manipulating the flexibility of a VPP and creating a prosperous business case requires state-of-the-art considerations on their technical and commercial constraints and trade-offs in developing the VPP's operations regarding flexibility while bidding in the market. Considering the potential of mobilizing commercial consumers in demand response programs, this thesis introduces a original work scheme for energy scheduling of a distribution grid based on the conception of a technical virtual power plant (TVPP). This concept aims to enhance the flexibility of the grid, while contributing to an increase in the quality and reliability of the system, which also brings economic benefits. In this thesis, a stochastic mixed-integer linear programming (MILP) optimization model was developed, which guarantees that the global optimum solution is obtained, in this case, maximizing the total profit of a TVPP. Regarding operational constraints, the TVPP allows the contribute of commercial buildings and other DERs in the day-ahead (DA) market, to make its own price as an independent agent. Considering this background, this thesis presents an extensive, integrated techno-economic approach that appraises the technical constraints and commercial flexibility opportunities. The case study includes the VPP's energy scheduling, improving system reliability by improving the voltage profile, and demand response and main commercial customers' assets (electric vehicles (EVs) parking lots and Heating Ventilation and Air Condition (HVAC) systems) aggregation and management. The model is tested using the IEEE 119-Bus test system, and results show that with the optimal management of DER, EVs parking lots and HVAC systems in commercial buildings allows the TVPP to increase its profit, by a percentage of 49,23%.

Keywords: *Technical Virtual Power Plant, Distributed Energy Resources, Renewable Energy Resources, Distributed Generation, Energy Market, Electric Vehicles, Heating Ventilation and Air Condition, Commercial Customers, Demand Response, Flexibility*

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Abreviaturas e Símbolos

List of Abbreviations

BRP	<i>Balance Responsible Parties</i>
CCGT	<i>Combined Cycle Gas Turbines</i>
CHP	<i>Combined Heat and Power</i>
CT	<i>Combustion Turbines</i>
CVPP	<i>Commercial Virtual Power Plant</i>
DA	<i>Day-ahead</i>
DER	<i>Distributed Energy Resources</i>
DG	<i>Distributed Generation</i>
DH	<i>District heating</i>
DR	<i>Demand Response</i>
DS	<i>Distributed Energy Storage</i>
DSO	<i>Distribution Network Operators</i>
EU	<i>European Union</i>
ESS	<i>Energy Storage System</i>
EV	<i>Electric Vehicle</i>
GHG	<i>Greenhouse Gases</i>
HVAC	<i>Heating Ventilation and Air Condition</i>
IBWT	<i>Italian Borders Working Table</i>
IL	<i>Interruptible Load</i>
ISO	<i>Independent System Operator</i>
MILP	<i>Mixed-integer Linear Programming</i>
MRC	<i>Multi-Regional Coupling</i>
NEMO	<i>Nominated Electricity Market Operator</i>
NWE	<i>North-Western Europe</i>
OMIE	<i>Iberian Market Operator</i>
PCR	<i>Price Coupling of Regions</i>
PV	<i>Photo Voltaic</i>
REE	<i>Red Eléctrica de España</i>
REN	<i>Rede Eléctrica Nacional</i>
RES	<i>Renewable Energy Sources</i>
RTE	<i>Réseau de Transport d'Électricité</i>
SWE	<i>South-Western Europe</i>
T&D	<i>Transmission and Distribution</i>

TL	<i>Transferable Load</i>
TOU	<i>Time of Usage</i>
TSO	<i>Transport System Operator</i>
TVPP	<i>Technical Virtual Power Plant</i>
VPP	<i>Virtual Power Plant</i>
V2G	<i>Vehicle-to-grid</i>

List of Symbols

Sets/Indices

s/Ω^s	Index/set of scenarios
h/Ω^h	Index/set of hours
g/Ω^g	Index/set of generators
ev/Ω^{ev}	Index/set of electric vehicles
$\varsigma/\Omega^\varsigma$	Index/set of market
l/Ω^l	Index/set of lines
$n/\Omega^n \{i, j \in n\}$	Index/set of nodes
k/Ω^k	Index/set of loads
$\{r, c, id \in n\}$	
HVAC/ Ω^{HVAC}	Index/set of HVAC system <i>Time of Usage</i>

Parameters

g_l, b_l, S_l^{max}	Conductance, susceptance and flow boundaries of each branch l (S, S, MVA)
R_l, X_l	Resistance, Reactance (Ω , Ω)
MP_l, MQ_l	Big-M parameters related with active and reactive power flows over each branch l
ρ_s	Probability of scenario s
OC_g	Cost of unit energy production
λ_h^{TOU}	TOU price associated with customers (€/MWh)
λ_h^ς	Day-ahead market price (€/MWh)
$PD_{s,h}^n$	Demand at node n (MW)
$QD_{s,h}^n$	Reactive demand at node n (MVar)

V_{nom}	Nominal voltage (kV)
η_{ev}^{ch}	Charging efficiency
η_{ev}^{dch}	Discharging efficiency
$E_{ev,n}^{min}, E_{ev,n}^{max}$	Energy Storage limit
μ_{ev}	Scaling factor
$p_{g,n,s,h}^{DG,min}, p_{g,n,s,h}^{DG,max}$	Power generation limits (MW)
pf_g	Power factor of DG's
pf_{ss}	Power factor of substation
$P_{solar,h}$	Hourly solar PV output (MW)
P_r	Rated power of RES unit (MW)
$P_{wind,h}$	Hourly wind power output (MW)
v_{ci}	Cut-in wind power (m/s)
v_{co}	Cut-out wind speed (m/s)
v_h	Sampled wind speed (m/s)
R_c	Certain radian point (usually 150W/m ²)
R_h	Hourly solar radiation (W/m ²)
R_{std}	Standard condition of solar radiation (usually 1000W/m ²)

Variables

$p_{\varsigma,n,s,h}^{market}, Q_{\varsigma,s,h}^{market}$	Power purchased from grid (MW, MVar)
$E_{ev,n,s,h}$	Reservoir level of EV (MWh)
$I_{ev,n,s,h}^{dch}, I_{ev,n,s,h}^{ch}$	Charging and discharging binary variables
$p_{g,n,s,h}^{DG}, Q_{g,n,s,h}^{DG}$	DG power (MW, MVar)
$p_{\varsigma,n,s,h}^{market}$	Power purchased from market (MW)
P_l, Q_l, θ_l	Active and reactive power flows respectively, and voltage angle difference of branch k (MW, MVar, radians)
PL_l, PL_l	Active and reactive power losses of each branch k (MW, MVar)
V_{n_i}, V_{n_j}	Voltage magnitudes at bus i and j (kV)
$u_{l,h}$	Switching (binary) variables of existing branches
$\theta_{n_i}, \theta_{n_j}$	Voltage angle at node i and j (radians)
$x_{l,h}$	Binary variable to indicate line status

$y_{l,h}^+, y_{l,h}^-$	Auxiliary variables to indicate the status of a line
$\Delta V_{n,s,h}$	Voltage deviation magnitude (kV)
$\chi_{l,h}$	Binary switching variable of line l
$f_{l,h}$	Fictitious current flows through line l
$g_{n,h}^{SS}$	Fictitious current injections at substation nodes
$d_{n,h}$	Fictitious nodal demand
n_{DG}	Number of candidate nodes for installation of distributed generation
$P_{HVAC,k,n,s,h}^{cool}$	Active and reactive power flows of HVACth system
$Q_{HVAC,k,n,s,h}^{cool}$	

Functions

PSC	Power Sold Cost to the load (€)
TVPP	TVPP imposed cost (€)
Penalty	Compensation for consumers extra cost duo EVs scheduling (€)
$Cost_{ev}^{operation}$	Customers EVs Optimal Cost (€)

Chapter 1

Introduction

This chapter serves as a topic introduction, the problem definition, motivation on a new perspective and research objectives. Followed by a presentation on the methodology used in the developed work as well as the structure of the dissertation.

1.1 Background

The electric power system structure has been evolving, especially in recent years away from a hierarchical structure to a more decentralized structure. Previously, the traditional power system was based on four distinct activities: production, transmission, distribution and the final use of energy by the end customers (who can have different types of loads) as shown in Figure 1.1 [1]. The energy flow in the traditional system was unidirectional from the top of the hierarchy all the way to the bottom, from large-scale production in large central generation units (based in the upper level of figure 1.1) which in turn feed a transmission system, interconnected which carries out the transport of energy to the substations located close to the consumption centres. Generation was constituted by big scale generation units based on three technologies: hydroelectric turbines, thermal relying on fossil fuels combustion and nuclear [2]. The power goes through the transmission level to the distribution level and the process occurs at distribution transformers. Energy is distributed in the high voltage network to big consumption centres where high voltage substations are installed. This is where the voltage step down takes place, to medium voltage and distribution in rural and urban zones is made to medium voltage consumers. At the distribution substations the voltage is stepped down once again, at low voltage and distributed to small consumers [3].

The described conventional paradigm presented advantages [1], such as:

- large scale power plants efficiency despite nowadays some equipment is dated and efficiency has decreased
- the interconnected network facilitated operation and management allowing the transport of considerable amounts of energy over long distances with contained losses. The reserve required was lower and the cheapest generator was the first to be dispatched, with large central contributing to a more stable system
- a unidirectional power flow means a simpler overall operation

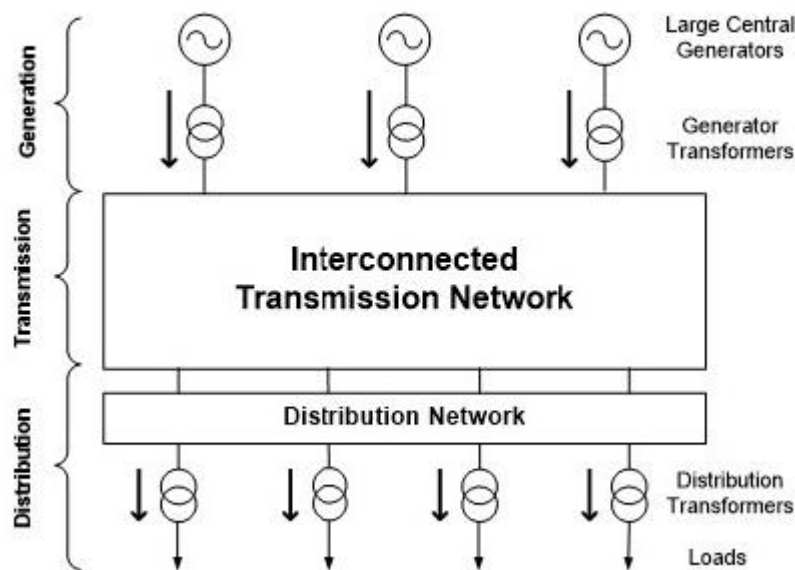


Figure 1.1 - Organization of Conventional Electrical Power Systems [1]

Still, there are disadvantages:

- production and consumption are very far away and big distance means big infrastructure investments translating to higher costs with an increase in losses over bigger distances
- environmental consequences, mainly from burning fossil fuels
- reliability concerns, since being an hierarchical system if a fault occurs at one level, the lower levels will consequently be affected

The ultimate goal of the conventional transmission and distribution grid can be described as territory coverage service reaching all consumers, being able to satisfy peak demand with reliability and stability voltage wise for electricity customers. The radial manner the conventional system was strictly built with several voltage levels able to transport bulk power over big distances from big production centres to all consumers across the territory [3], [4]. Therefore, the unidirectional power flow from production to consumption, through an interconnected infrastructure, resulted in simple, straightforward a planning and operation. Additionally, traditional assets develop their activity in defined geographical areas under monopolies subject to regulation entities which coordinate and control the supervision. These utilities are owners of all infrastructures from generation, through transmission, to distribution within their designated areas. They finance and build the required infrastructure after regulatory bodies approval [5].

From the 1990s, the traditional paradigm was subject to several challenges. The main one, derives from the significant growth of small-scale generation connected to the grid at the distribution level, named Distributed Energy. DG deserved the attention of system operators, planners, investors and policymakers. A important increase in DG installation is due to government incentives and promotion to achieve environmental goals and amplify the variety of energy sources[1]. The electric industry restructuring that took place globally, lead to the end

of the verticalized scheme integrated by generation, transmission, distribution and commercialization. New market opportunities and niches arises favoured by the direct access to the grid allowing end consumers to choose the energy plan and service best suited to their needs [5], [6]. A liberated market and the potential prosperity of DG might have pushed government interests even further.

The technological advancements, also contributed to interesting and favourable DG application of PV panels and Wind turbines. Technically speaking, with bigger DG penetration into the grid has several implications like variation in the voltage profile, bigger short-circuit power, harmonic distortion, operational stability and workers safety and security and islanding operation. Low DG penetration has small impacts and does not get much attention or supervision from grid operators, however, the proliferation seen in recent years made companies aware of the new paradigm, to study the resulting phenomena and develop technologies and applicable models that allow them to fully harness the potential in future situations [6], [7].

The paradigm change has allowed end consumers, especially residential consumers to install PV generation mainly on their roof or empty land to start generating their own electricity for self-consumption or to sell to the grid. Adding to this scenario, lar-scale renewable energy projects started to appear with PV and mainly wind generation proving to be highly efficient and generating electricity to sell to the grid [8], [9].

Commercial buildings and industrial consumers soon began to install their own rooftop PV panels in order to reduce their load during peak demand times (which often have higher unit costs of energy) or reducing their electricity bill. Overtime, residential, commercial and industrial consumers have embraced these novel forms of generation technology aided by government incentives and legislation, electricity companies' incentives as well as their own desire to become active and conscious consumers regarding climate change and reducing their emissions in the process. Recently, on the same line of thought electric vehicles have started becoming more and more common bringing a new change as load is concerned [10]. This proliferation of DER installations on the network as obliged distribution network operators to manage, control and take action to maintain the same levels of service quality with added uncertainties whether on network constraints, generation conditions and amount and load profiles [11].

Until now each DG has been managed individually, but in this scenario it is proposed the aggregation of these DGs to form a Virtual Power Plant (VPP) with several assets controlled by a single agent enabling it to bring better solutions to DG owners and end users. With all generation aggregated and controlled by the VPP it is possible to participate in the electricity market, chose demand response programs, sell or buy electricity from the grid and control loads in order to achieve the best possible results regarding the VPP and its assets [12]. VPPs formed by residential consumers, are increasing however, the issue of VPPs formed from larger consumers, especially commercial customers and some industrial customers with different working hours, load profiles with powerful equipment and machinery needing to be managed to reduce costs and increase energy efficiency on their activity [11]. In this framework it is therefore necessary to develop models and strategies to solve the identified issues considering the system operations, reliability, sustainability, economic and environmental objectives while meeting operator and customer demands.

1.2 Problem Definition

The economic development and the increased use of new technologies by consumers makes supplying energy which is reliable, cost-effective and within the power quality constraints a concern. One way to address the increase these concerns is to implement a VPP with the specific purpose of improving the flexibility and efficiency of the electrical grid. New features such as distributed generation from renewable energy sources, the integration of electric vehicles, the implementation of smart grid technologies, and others force the electrical grid to evolve and develop. At the same time as the consumers' demand is higher, there is also the integration problems associated with RESs, especially regarding the uncertainty and variability of these resources, that affect the operation of the system and the commercial consumers load profile and management of their assets.

In this scenario, the aggregation and management of these assets can be carried out by the VPP as it assesses consumers demand, load profile, DG production and commercial consumers EVs in the parking lots and HVAC systems operation in order to schedule and optimize the devices in order to bid into the day-ahead energy market. Therefore, two major issues are the forecast of generation for optimal efficiency and minimal power production costs and the scheduling of EVs charge/discharge cycles and HVAC system temperature range while maintaining favourable work conditions and providing flexibility to the grid. In summary, the VPP can manage these assets to satisfy demand, improve energy and environmental efficiency while maximizing profit.

In this framework it is therefore necessary to develop operational models to solve the problems raised considering the system's operational, economic and reliability constraints as well as to meet international environmental objectives.

1.3 Research Objective

The main objectives of this dissertation are to :

- Develop a mixed-integer linear programming (MILP) operation model considering distributed generation based on renewables, HVAC systems, electric vehicles (EVs) for the operation of a Virtual Power Plant in the electricity market and electric system infrastructure.
- Create a methodology to assess and control commercial customers appliances operating for the VPP to increase efficiency and therefore minimize costs.
- Identify whether the proposed solution is viable and the optimal parameters for the VPP operation.
- Study and optimize solutions taking into account all information and developed work.

1.4 Research Methodology

The proposed optimization model is a stochastic mixed integer linear programming (MILP) type, for which there are quite efficient off-the-shelf solvers. The model aims to optimally operate a Virtual Power Plant for Commercial Customers featuring all assets, network constraints and energy market. The problem is programmed in GAMS 24.0 and solved using the CPLEX 12.0 solver. All the simulations are conducted in an HP Z820 workstation with two E5-2687W processors, each clocking at 3.1GHz frequency, and 256 GB of RAM.

1.5 - Thesis Structure

This dissertation is divided in 5 chapters. Chapter 2 presents the state of the art and related concepts to the topic being studied. In Chapter 3 it is established the mathematical model developed from the objective function to the constraints used. Chapter 4 lists the electrical system data and assumptions used to create the problem-solving model. All the results of the simulations and respective conclusions are presented and discussed in Chapter 4. Chapter 5 highlights the main conclusions of this work, the future works that can be developed as well as the contributions of this dissertation.

Chapter 2

State of the Art

This Chapter presents the state of art and the existing concepts related to Virtual Power Plants as there has been an increase in the integration of Renewable Energy Sources (RESs) through Distributed Generation (DG), Energy Storage System (ESS) and the number of power sources on the consumer side which have all had a significant impact on energy supply and demand. Focusing on electricity assets in commercial buildings such as those used to produce and store electricity as well, as considering uncertainties from Heat Ventilation and Air Conditioning (HVAC) system, Electric Vehicles (EVs) and Lighting Control. Consumers aggregated into a Commercial Virtual Power Plant utilises Demand Response (DR) programs, loads, uncertainties and variability in its management to achieve an optimal solution which is usually to maximize their profit.

2.1 Demand Response Programs

2.1.1 Customers and Prosumers

A traditional consumer has been interacting with the grid in the same way for decades, which is a unidirectional receiving of electricity from the grid. Recently, a new concept emerged and is being highlighted, a prosumer, is someone who produces and consumes electricity. This is possible due to new connected technologies and the increase of renewable energy on the electric grid [9], [13]-[16]. The number of prosumers is growing as more and more users generate their own power from distributed energy resources (DER). Production is typically carried out through roof mounted photovoltaic panels for example, changing the paradigm of a one-way power flow to a paradigm based on a bidirectional flow of electricity [10], [17]-[19].

The new trend has several benefits, namely to preserve and protect the environment and bring more energy choices to households, commercial buildings and industries that are pushing the energy sector to develop itself and be more efficient than ever. The increasing number of prosumers implies new challenges, as there are uncertainties related to production, especially from renewable resources [11], [20].

Demand Response (DR) program uses electricity tariffs and techniques to reduce market price and increase system reliability with incentives to consumers. The participation of customers who produce electricity, allows for the reduction of energy costs, price volatility and the distribution grid can even postpone grid expansion [11]. In [4], [10] and [11] DR is defined as the users consumption behaviour within electricity grids and can be separated into two types: price based and incentive based. In the first type, consumers respond to market price and alters consumption based on the tariffs such as, Time of Usage (TOU). Tarrifs can change throughout the day according whether its peak, valley or flat periods and according to load characteristics. Incentive based DR relies on contracts signed by supply and demand parties, which can vary in power supply, reliability required by the user, and other factors. Renewable Energy Sources (RES) integration into the existing grid and Distributed Energy Storage (DS) are key factors to assure control (system reliability) in a smart grid, as new challenges arise from RES penetration on the demand side. According to [22] an optimal DR program needs to be defined, with [10] adding the need to have EVs into account, while in [23] DR is integrated with Combined Heat and Power (CHP) from industries. The defined DR for market participation of a Commercial Virtual Power Plant profiting through power trading by selling electricity to customers is the main objective in [24] therefore the TVPP needs optimal coordination between its key assets and their relations as shown in **Figure 2.1**. Reference [25] develops a VPP model including wind power, photovoltaic, EVs, ESS, loads (Interruptible load, adjustable load and transferable load) in the form of a DR program. Interruptible load (IL) refers to peak load, mainly as commercial load, so the power reduction is generally low but the compensation cost for load reduction is high (to be avoided by industries) [26]-[28]. Transferable load (TL) is related to energy storage capacity, such as air conditioning, water heating, lighting, and others. This load can be moved without drastically changing the user's comfort, so its compensation price is generally lower. Regarding Prosumers [2], [7] and [16] a VPP includes the aggregation of owners of small plant and prosumers for electricity market access.

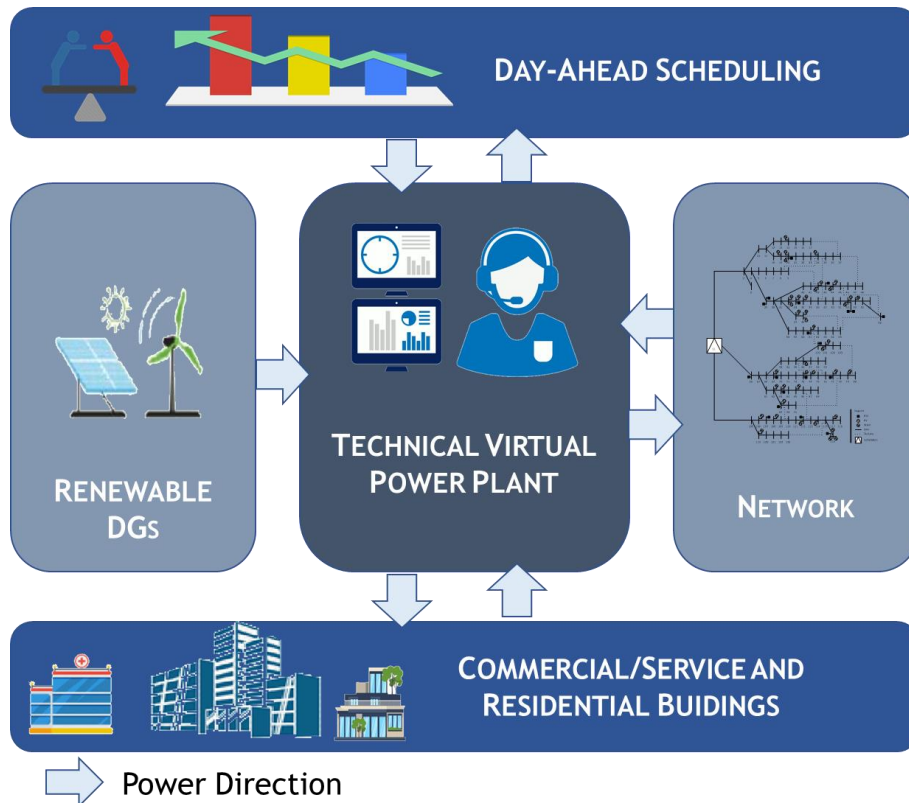


Figure 2.1 - TVPP operation relations with its DERs and energy market participation

A prosumer's assets include may EVs, DGs, Smart Homes, and their DR. In papers [29], [30] there is an extensive description of prosumers. They can be classified as Standalone Prosumer (minimum energy production required, can not buy or sell electricity), Energy Buying Prosumer (does not meet minimum production required so requests to buy energy from another prosumer) and Energy Selling Prosumer (has surplus energy and if requirements are fulfilled, they can sell energy) to consider each type and their information for DR purposes.

2.1.2 Commercial Consumers appliances and utilities

The commercial sector formed by government facilities, service-providing facilities and equipment to develop their activity, and other public or private organizations. Commercial customers' electricity consumption is responsible for a significant part of power consumption with lighting, heating, ventilation and air being the biggest uses of electricity[11]. Commercial demand is higher during business hours and decreases substantially during the night, weekends and holidays [28], [31].

Commercial consumers search and choose for electricity rates and plans in the current energy market and the cost may vary greatly [32]. They can vary from customer to customer, even if they are in the same region, because of their individual energy requirements. The time of the year is also a factor as electricity prices can change depending on the rime of day or season of the year [33]. In a competitive market if there is a higher number of suppliers to choose from, more variation will be likely. Location, minimum consumption, unpredictability (some consumers), consumption during peak hours and penalties are all factors that dictate the electricity cost [34], [35]. **Table 2.1** demonstrates some different types of commercial customers, which have different electricity consumption and tariffs incline with its specifications and conditions[11], therefore, reflected on the total electricity cost.

Recently research has been developed around residential customers, and a few of these papers can be selected and applied to commercial customers. Commercial buildings usually have a higher tariff, since they are seen as large, concentrated loads in the distribution network. Control techniques for DR are presented in [11] with HVAC strategies for peak shaving load, managing and controlling EVs in parking lots and lighting for this type of customers. The proposed work in [22]-[24], [5], [36], [37] differentiates CVPP from TVPP with the difference being that CVPP does not consider the impacts on the distribution network, just profit (business aggregation). According to [12] all EVs parameters must be included in the uncertainty modelling. Different consumers (residential, commercial and industrial) with loads and characteristics are studied highlighting major differences between commercial and industrial consumers [10], [17] and [27].

Table 2.1 - Electricity consumption in commercial sector for four types of commercial consumers [11]

Type of Commercial Customer	Consumption (kWh)	Total Cost (thousand euros)
Hotel	979.89	421.35
Restaurant	472.44	228.95
Store/Office	504.91	217.11
Workshop	649.59	279.32

Heating, cooling and Air-Conditioning (HVAC) systems are an important part of any commercial building (hotels, schools, universities, office buildings, etc). They help to control the temperature, air characteristics such as humidity and air pollution to provide pleasant indoor environment for both users and equipment in the building. Heating the air in the building with radiators or air vents. Ventilation consists in extracting polluted air, keeping internal air circulating and removing excessive moisture to maintain clean air in the designated space. Mechanical systems with filters and powered by fans allow the whole process. Air-Conditioning works as a cooling solution and maintains desired humidity levels using air or water cooling systems [39]. An HVAC system aims to provide an environment with these factors maintained within a desired range[11], [22]. Due to the fact HVAC systems consumption accounts for a high energy stake usage in buildings, they must be designed, installed, scheduled and maintained properly in order to reduce energy consumption and costs and greenhouse gas emissions.

Lighting constitutes a smaller portion of energy consumption, yet still significant. Automatic lighting control systems allow the decrease of operating time and, therefore, a decrease on energy consumption based on various factors like occupancy/usage, time of the day and abundance or lack of daylight. The control scheme has a unique set of factors that dictate their performance in terms of energy saving as well as user acceptance [11]. User acceptance is especially important as commercial building occupants must have a safe, healthy and productive environment to work.

The standout feature for commercial customers is that by optimally controlling these systems buildings can minimize their imposed costs as can be seen in **Figure 2.2** by controlling systems and power flow. HVAC represents around 47% of building load making it attractive to control for DR through welfare constraints, maintaining an adequate temperature range for users. Also EVs parked in parking lots are managed using an efficient charging/discharging schedule algorithm [11], [12], [40], and can participate in DR. Lighting is improved by using energy saving techniques and technologies.

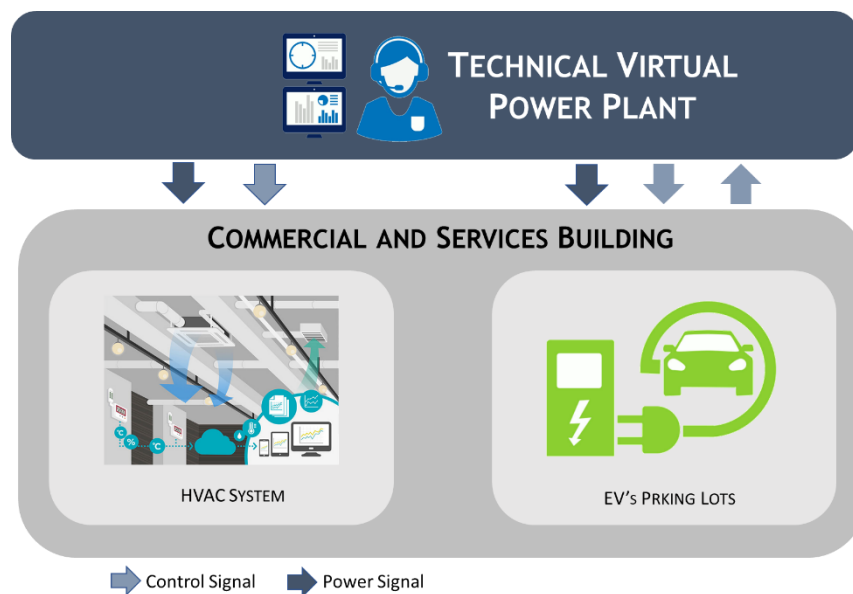


Figure 2.2 - Responsive loads of a commercial building controlled by TVPP

The adoption of EVs could heavily impact on electricity markets [31]. First, electricity demand will increase based on a shift from fossil fuels to electricity. If many users charge their vehicles a can be expected. On the other hand, smart electric vehicles may be used for storage services and work in favour of the electricity grid by charging when electricity demand is low and feeding electricity back into the grid during peak times, where it is scarce and expensive [22]. TVPP operates mainly in the distribution network and provides its services, while considering technical constraints, bringing advantages not only in terms of maximizing network efficiency but also expansion flexibility and postponing unnecessary infrastructure construction.

2.2 Aggregated Loads

2.2.1 Energy Market

2.2.1.1 Wholesale Electricity Market

Europe's electricity system will continue to experience large changes in the near future. The transition regarding a conscious, low carbon economy means RESs will have a growing role, becoming more efficient and with greater efficiency being demanded there is also, the electrification of the transport sector is accelerated, and other sectors all powered by technological advancements and need to change. The paradigm change means increasing consumer engagement and giving them a meaningful role in managing their demand, production of electricity for auto consumption and feed the excess to the grid. In this situation, electricity market, law and regulations, and existing infrastructure must adapt to this new paradigm in which big service providing companies no longer detain the market monopoly [26], [31]. Additionally, markets need to redesign themselves in way that investments in low carbon technologies are encouraged, while being able to assure security and continuous supply with minimum possible costs for households, commercial buildings and industries[1], [19]and [34].

Aiming to minimize greenhouse gases (GHG), electricity is a fundamental aspect to consider. Starting by a better electricity usage and the increase share of electricity production from RESs and secondly, the contribution of electricity in total energy usage is predicted to rise, mainly in the transport sector (EVs) and in heating and cooling, with electric systems. All combined, electricity is seen as a major factor to phase out fossil fuels' emission and usage by 2050.

In order to make this possible, significant investments are required to generate electricity, transmission, distribution, and consumption. The claim is to find a balance between investing and keeping electricity affordable for consumers from residential to energy intensive industries. The same investments need to ensure stability of the electricity supply facing a higher demand and variability in generation from RESs that may vary according to the weather and other factors [41], [42].

Electricity markets need to adjust to ensure their support of and adherence to EU's policy objectives, which are [18]:

- incentivating investments in low emissions electricity production
- promote the use of equipment with high energy efficiency and sustainable consumer goods
- incentivating investments in a reliable and, ideally, faultless grid that is purposeful for growing penetration of RESs and variety of electrical applications
- keeping cost low and providing affordable energy for all consumers

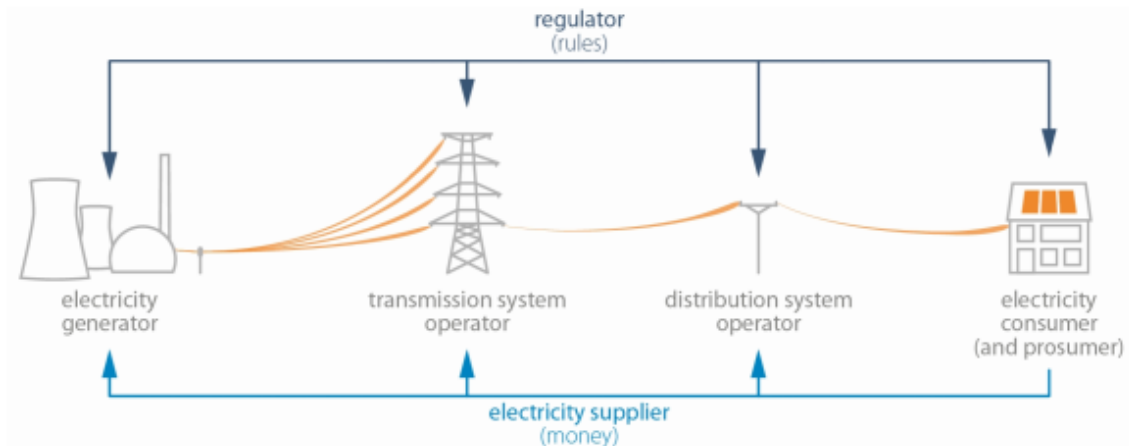


Figure 2.3 - Overview of the electric system [7]

The electricity system is shown in **Figure 2.3** and represents the physical infrastructure for generation, transmission and distribution complimented by an organised electricity market (regulation). The physical grid (energy flow) is based on electricity generators and transport systems, either long-distance transmission or distribution to residential, industrial and commercial consumers [9], [22] and [27].

The electricity market, based on financial flows, consists of:

- suppliers, who sell electricity to consumers after buying it from generators
- consumers, who use it and pay their supplier via their electricity bills
- transmission system operators, who get paid for the territory coverage and transport of electricity over long distances, and for guaranteeing stability
- distribution network operators (DSO), who get paid for making electricity reach clients
- regulators, who set rules and supervision the the market

Balancing supply and demand is crucial since production must satisfy the consumption in every moment [29]. If not, there is a risk of a system breakdown. Base load is served by non-flexible generators (normal consumption level), while flexible generators serve demand peaks [39]. Variable capacity has increased with the introduction of RESs, this means increased flexible generation is required to meet demand when variable generators' production is not enough [16]. To ensure the security and service quality of electricity supply, there is a minimum generation capacity required to be always available to meet demand. A brief balance in supply and demand is achieved using primary reserves (activated within seconds), secondary reserves (activated within a few minutes) and tertiary reserves (activated within 15 minutes) [8], [43]. Moreover, renewable energy generators, with priority on the European market and grid, usually generate enough energy to satisfy a big part or all demand, even during peak hours, making it hard for conventional generators to be profitable with low time operational plants [28], so energy companies do not find compelling to keep power plants that are only used when the demand is too high (peak) in reserve.

Due to the adopted legislation in EU over the years, electricity markets have changed drastically, stepping away from a regulated environment dominated by a few companies (monopolies) to an increasingly competitive one. The legislation is based on development checkpoints where the major goal is achieving the same prices across EU with an increasingly interconnected electricity market [44]. The Renewable Energy Directive obliges Member States to give direct access to RESs to the power grids and priority. Other legislation regarding electricity related themes that have to do with regulation within energy markets, security and supply quality, overseas network and emissions trade from EU [45]. EU competition policy and tax are other important policy areas.

European electricity markets operate on various levels and vary based on geography, timescale and type of consumer. The wholesale market is organized differently than retail market, which are able to mold according to consumers [38]. Markets can differ in geographical terms, from retail market with regional propositions to export in wholesale. Time scale dictates wholesale market range from real-time balancing markets to long term contracts. Open markets allow other entities responsible for producing electrical energy, and with compromises regarding the transmission and distribution system operation. They have the duty to give access to their networks by third parties [35]. The involved ones in the wholesale market are responsible for generation, supply and consumption [40]. As mentioned above, electricity must be produced and supplied at the exact moment when required, therefore, the compromise of delivering electricity is implicit in most transactions at some point in the future [46]. Subject to the arrangement or market, these negotiations may vary according to time periods:

- long-term contracts: 20 years or more
- forward and future markets: weeks to years agreed initially
- day-ahead market: the following day
- intra-day market: required delivery within a specified time period
- balancing market: real-time balancing of supply and demand

Electricity negotiation can occur in private terms (over-the-counter market) or through energy exchanges, which bring a transparent price from buyers, sellers and offers [34]. Prices on the market fluctuate according to supply and demand: regarding market wholesale, the 80€/MWh barrier can be beaten or even dip to zero or below in cases of surplus production. The first generator to be dispatched is the one with the lower price, and consecutively based on price (merit order). The generator demands a price to satisfy marginal demand is known by all. Putting this concept into practice has created “merit order effect”. European wholesale prices drop due to this effect, since variable generators based on RESs have no primary resource cost and can submit lower prices which regulate the price level for other conventional generators [47]. This lower price can be beneficial to all regions even where there is no significant renewable energy production because of the integration of the wholesale markets at a national and international point, also known as market coupling. Price is dictated by the interconnection capacity, in case of sufficient interconnection capacity, prices do not suffer variation, and the market will converge. When the demand for exportation/importation exceeds the capacity (known as congestion), electricity can progress from a lower to a higher priced region, resulting in regions with different prices [48].

To achieve EU and national targets, Member States promotion is based on various techniques. The standard support mechanisms for renewable electricity production are based on feed-in tariffs and feed-in premiums, with a recent rise on competitive auction. Member states aim to design support schemes to introduce more and more technologies, while phasing out support for conventional, cost competitive technologies [37]. Currently, due to the market design and grid development face new challenges because of these major trends' impact on European energy markets [4]:

- further electrification of the economy (electrification of the transport sector and heating) increases electricity demand
- growing share of distributed renewables (solar, wind) and must maintain the momentum to reduce emissions. Therefore, increased interconnection capacity is required to transport to end used RESs based generation
- creation of innovative business models from energy service companies and aggregators
- incentive for residential installations of RESs has contributed to an increase in price, but simultaneously generation from variable sources can contribute for lower market prices
- the number of prosumers is growing. More self-consumption translates to less electricity demanded from the grid, leading to a decrease revenue for grid operators, making it unviable for investing and might charge a higher price to consumers who not generate electricity, in order to be able to finance them
- flexible generation capacity is, sometimes, hard to obtain profits from, but national capacity remuneration mechanism is a compelling procedure
- innovations in technology, such as smart meters, smart grids and appliances, energy storage systems, EVs can be ingenious in electricity markets
- time-variant pricing, based on scarcity, could incentive moderate consumption and storage when demand is at its peak, and to consume or store when supply is high
- infrastructure built for transmission between nations and interconnection capacity to avoid congestion, but the agreement, compromise and finance for the infrastructure can feature difficulties

All the above challenges are mitigated with the introduction of a Virtual Power Plant, since its structure allows their operators to participate in the whole sale electricity market. A new agent manages DERs and DR programs and can participate in different energy markets. As previously mentioned VPPs can be classified as Commercial VPP or Technical VPP, for a Commercial VPP the DERs and ESSs are used as central resources [49], [50] and the restrictions regarding the location of each resource is not taken into account, on the other hand a model for the TVPP regarding the network constraints and its energy management strategy is needed. The main goal of a VPP is to maximize profit, therefore its agents should choose an optimal bidding strategy and bid on the day-ahead (DA) market making the TVPP a price maker agent [9], [12] and [13]. One drawback with renewable production is their uncertainty and variability, which constitutes a downside for electricity market participation. This barrier can be mitigated by making all conventional and renewable technologies work together as a solution to generate electricity during periods of low renewable production or reserve energy in batteries if the renewable production is abundant. Such aggregation and diversity of DERs allows to operate as a single entity [41]. If it is beneficial, a VPP can purchase electricity and then sell it, locally, so as to maximize profit [23], [37], [48].

2.2.1.2 Day-Ahead Market

As a structural part of the market, the day-ahead market looks to, representing the several agents in the market for the next twenty-four hours, submit selling and buying bids to satisfy electrical energy transactions [21]. This market operation, in Europe since 2014 is a essential piece to achieve the European Internal Energy Market [28].

Every day at 12:00 CET the day-ahead market session starts. Prices and electrical energy negotiations are taking place for the twenty-four hours of the following day throughout Europe[42]. The price and amount of energy to be traded at a specific hour are set by the intersection between supply and demand, according to the European markets' model agreed and approved and must it be obliged [33].

The Pool/Market Operator is the entity who establishes relationships between generators, buyers and the independent system operator (ISO). It oversees dispatchment based on buy/sell propositions and can be symmetric or asymmetric and free or mandatory. The relationship between production is load is assured by it. It works, typically, in the day-ahead market and for smaller time intervals, in which the electricity generators announce, at some point, the minimum they are willing to receive for a certain amount of production and distribution companies, commercials and eligible clients do the opposite by stating the maximum that they are willing to pay for that amount [51], this is shown in **Figure 2.4**. The Pool organizes propositions and does a central dispatch based on prices, generators get paid and loads pay market price, the so-called the Market Clearing Price [13], [31], [52].

Demand influences the market as production and load both present propositions, despite the load being highly inelastic. It works better with more agents and if none dominates an high stake of supply or demand [40]. This is better understood through examination of Table 2.2 selling proposals and buying bids, which is then turned into Figure 2.5 to see their intersection.

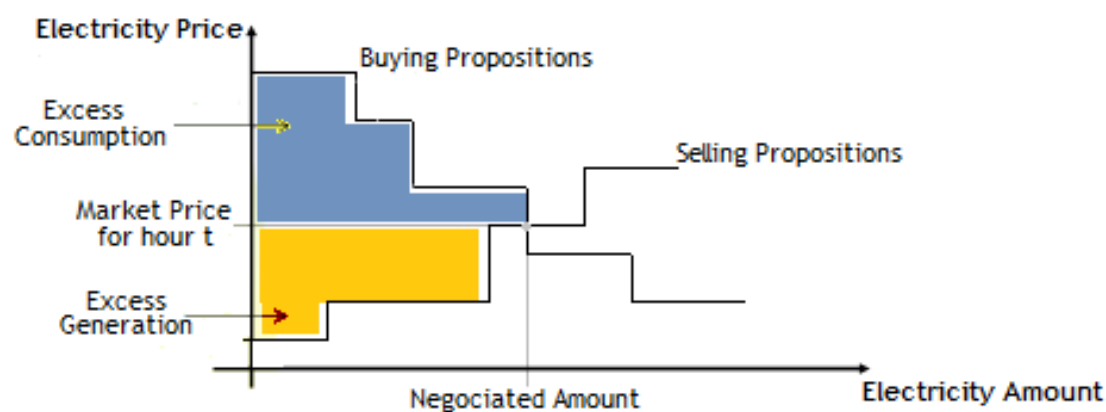


Figure 2.4 - General representation of a symmetric Pool

Table 2.2 - Simple proposition example

Sell		Buy	
Amount (MW)	Price (€/MWh)	Amount (MW)	Price (€/MWh)
500	10	500	60
500	20	1000	70
500	0	500	30
1000	30	1000	35
500	40	500	70
1000	40	1000	50
500	50	500	45
500	10	-	-

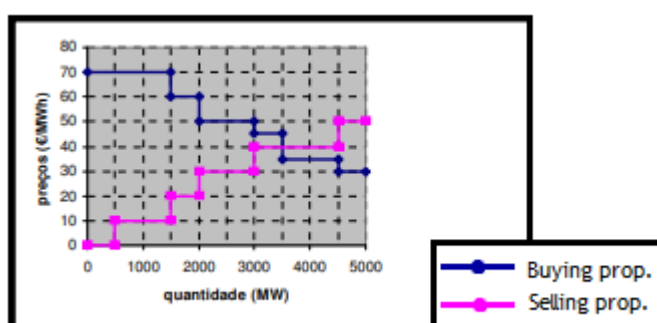


Figure 2.5 - Pool example with Table 3 (3500 MWh at 40€/MWh)

The buying and selling agents based in Portugal or Spain will hand over their buying bids to the day-ahead market through Iberian Market Operator (OMIE) (Spanish centre), being the only Nominated Electricity Market Operator (NEMO) in these countries. The submitted bids by both parts are accepted established on their economic merit and considering congestion between price zones. If, at specific daily period, the interconnection capacity between areas is superior to the required electricity flow resulting from negotiation, the price of electricity will be the equal in both zones. Otherwise, if interconnection at a specific time is at its limit, the prices result in a different one for each zone, being higher in the zone demanding more electricity than the established interconnection capacity. The mechanism for electricity price setting is known as market coupling [34], [53].

The DA market results, based on contracts made between buyer and seller, from an economic perspective is the simplest and most efficient method, but given electricity's properties, it is also compulsory for it to comply with the network physical characteristics. The resulting schemes are sent to the System Operator for validation and approval with a focus on their technical viability [54]. The process of managing the system's technical constraints and limits, guarantees a proper dispatch of the market results. This way, the resulting day-ahead market may be forced to small changes due to the technical analysis done by the System Operator, providing a viable program [41], [55], [56]. Electricity can be traded bilaterally in the day-ahead market via contracts negotiated bilaterally [32], [57].

The intraday markets work as an important tool that enables agents to do adjustments to the resulting market schedule of the day-ahead market's, by set forth selling and buying bids, dictated by real time needs [39], [58].

Nowadays intraday markets are organized according to bidding session's conditions and extended international European Market, and they too are consummate once the system operator has dealt with needed readjustments to make it viable, after the day-ahead market previous schedule. Like the DA market, when these markets are processed, the results are directed to system operators for the dispatch balancing process to take place [59].

2.2.2 Managing DER

Renewable energy plays a crucial part in achieving EU's energy and climate goals. Not only it is abundantly amply accessible in the EU, but also cost-competitive with fossil fuels, as mentioned before. It can support and reducing the energy systems costs and dependency on imported fossil fuels, whilst creating business opportunities and employment contributing to economical prosperity [23]. The EU took initiative on renewable energy, as recent data shown in **Figure 2.6** [48] represents the amount produced by each country, and has putted in serious efforts, through legislation, to consolidate renewable sources in EU's energy systems. The Renewable Energy Directive (2009/28/EC) established purposes for member countries, at the time seen as a way to ambitious goal, proved to be the targets to follow by several countries around the globe. This directive was revised in December 2018 and adopted as part of the CLEAN energy for all Europeans Package. A new binding renewable energy target for 2030 of at least 32% is included, with a clause for the possibility of revision by 2023.

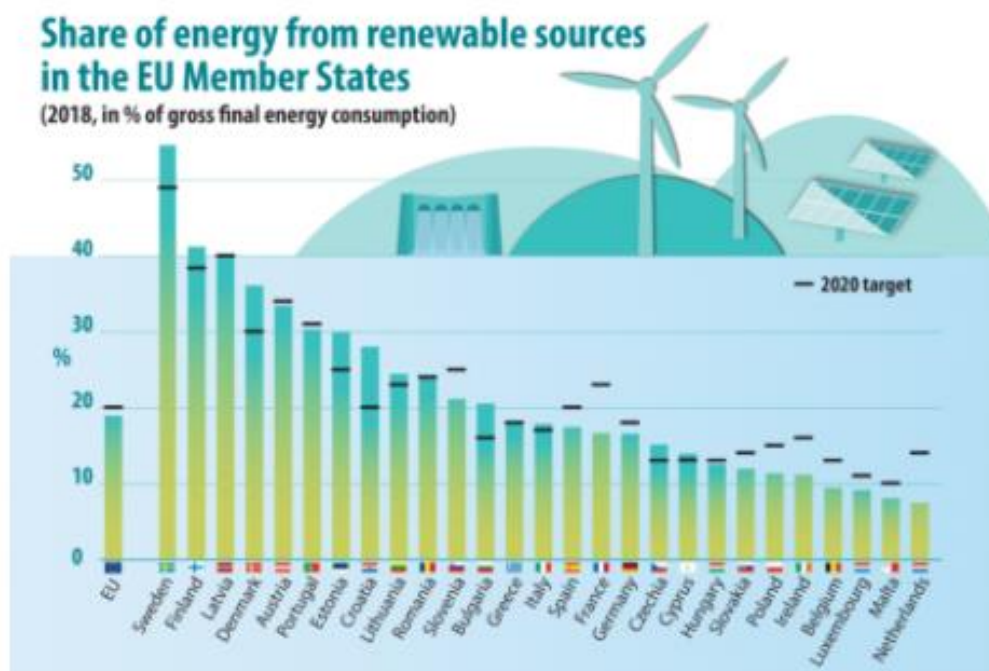


Figure 2.6 -Share of energy from renewable sources in 2018 [27]

Willing to go beyond, the European Green Deal showcases several initiatives across all sectors, in order to fulfil the goal of making EU climate neutral by 2050. Renewable energy, along with energy efficiency, is an essential milestone that will help achieve such goals. The European Commission will propose directives for involving technological advance in all sectors. The future of the European energy system is going to be built based on today's initiatives. The European Commission also has a new game plan aimed at offshore wind power growth, this strategy will be impacted by energy grids, markets, management of maritime space and industrial policy dimensions regarding offshore wind farms. The process has to assess opportunities and challenges and is accomplished with EU renewable energy legislation being reviewed and revised when necessary [42].

The way EU managed DER means it is a showcase on renewable energy and has undergone through serious changes to increment market capitalization. Determined measures combined with research and development of projects and strong investments, helped reach a stable base. All these instruments facilitated the access to renewable technologies, by making them affordable to install/use for member countries population. Solar panels and wind turbines have become a familiar sight, which a major contribute is the boosted market activity. The cost of photovoltaic production has, in particular, decreased approximately by 75% from 2009 to 2018. In 2014 a never seen before situation happened: onshore wind became cheaper than traditional generation by fossil fuels. In 2019, EU electricity production from renewable sources surpassed coal for the first time, introducing a new idea that they are the future, and are now as compelling or even cheaper than fossil fuels in many situations [32], [36]. Following technological advancements, citizens have also become more empowered with the ability to produce, store and sell their own energy produced from renewable resources. It is foreseeable the growth of renewables, with the increase in PV being mostly driven by a rise in installations for self-consumption in rooftop panel installation, and vacant lots [36].

The renewable energy policy goals could prove successful using a large variety of instruments shown in **Table 2.3**. Based on the premises that the primary resource and conditions for RESs production are available, the associated costs and objective for market penetration will impact the country's option for one solution or a set of instruments; there is at least an instrument for each one of the renewable energy sources; as experience is acquired it is shared with other countries and schemes for support are created [60]; the market penetration of renewables is subject to policies and other factors which have a correlation achieving goals.

DER are energy resources connected to the grid at the distribution network, throughout different points with several purposes from production (mainly from RES) to control and supply network services. Some DERs such as energy storage, natural gas turbines or demand response, can be dispatchable and have a major role in stabilizing variable resources on the grid [51]. DER can constitute planning and challenges for grid operators since there is now a two-way flow of power [21], and the resources maybe owned and controlled by the customer or a third party [19], [22].

Solar photovoltaics' resources are characterised by low power and intermittent power output [61]. These are generally distributed on the grid and operators have almost no control over these installations, making them "blind". Besides PV, solar projects are increasing in size and speed of development, with more powerful plants being made due to consumer demand and grid design innovation [33]. In addition to PV other types of distributed generation resources can be considered: combined heat and power (CHP), natural gas turbines, micro-turbines, biomass plants, wind turbines, and fuel cells [8], [40], [41].

Table 2.3 - Policy instruments used to promote renewable energy sources

No. Policy Instruments	
1. Direct Instruments	1.1. Financial Measures
	1.1.1. Subsidies and loans
	1.1.2. Tax exemptions or advantage
	1.1.3. Feed-in tariffs
	1.1.4. Green certificates
	1.1.5. Bidding
	1.1.6. Funding research and development
	1.1.7. Interconnection regulations
	1.1.8. Independent power producer framework
	1.1.9. Biofuels mandate
2. Indirect Instruments	1.2. Non-financial Measures
	1.2.1. Negotiated agreements between producers and government
	1.2.2. Quota obligation on production
	1.2.3. Quota obligation on consumption
	2.1. Information campaigns
	2.2. Education and training
	2.3. Labelling
	2.4. Technology standards and certification
	2.5. Grid connection standards

Energy storage system involves a variety of technologies, such as pumped hydro, thermal storage, and batteries, with the latter two being more likely to be deployed as DER. Storage can help provide flexibility to the grid, since the excess can be used for later use or send power to the grid and aid balancing and avoid energy waste[10], [31].

Demand response includes all resources and applications that can alter load, mainly shedding and provide services to the electricity grid, such as voltage and frequency control. Installations can be automated or manually controlled to either residential, commercial or industrial load and provide flexibility and help maintain reliability and flexibility while allowing to postpone investments in the infrastructure [34], [55], [62]. Electrical vehicles use batteries so they can also operate by drawing electricity from the grid or providing stored electricity for balancing [11].

DER proliferation as seen in the last years is justified by the need to reduce carbon emissions, increases in government incentives and tax benefits, avoidance or delay of investment in network or generation infrastructure, consumers acceptance and preference for renewable energy, access to revenue streams, increased reliability and efficiency, improved control, and others [9], [53], [63], [64]. Operational challenges force system operators to use other sources to satisfy the load when there is no sunlight or wind and to protect the grid against power quality issues. At the distribution level, where most PV installations are, integration can be even more demanding since distribution level is blind to grid operator and less likely to be controlled[44]. The distribution grid was not projected to take in variable output fluctuations and two-way power flows, affecting quality [29]. Voltage and frequency can be impacted by these conditions that cause peaks and voids in supply, and potentially unsettle stability, cause extra stress and wear of the distribution infrastructure [38], [58].

In addition, peak production from photovoltaic installations and peak demand occurs at different times. Peak demand starts rising just as the sun sets (minimum production) causing the need for other generation units to ramp up quickly [65]. Generation facilities that serve base load, such as nuclear and coal, were not designed to accommodate or even give response to such quick ramp up required. However, a recent combined cycle gas turbines (CCGT) can ramp up rapidly, and equipment kits are applicable to recondition older plants [12], [66].

Dispatchable DER resources can assist in mitigating variability effects from RES production. However, some issues of variable DER may remain when considering dispatchable DER, such as being blind to the network and difficult to have control over the resources [39]. Improving forecasting and the ability to accurately predict time and place of maximum sunlight or wind is essential to manage the consequences of variable resources, in all regions with this penetration invests in improvements for better overall results [14], [67]. For example, in Germany forecasting errors in PV occurred due to unexpected impact. This situation acted as a big warning for grid operators as they were enforced to activate all operating reserves under contract for a few hours in 2010. Nowadays they use PV forecasting tools at distribution and transmission, and are developing a forecasting system with equipment in wind and solar facilities to provide real time data, so system operators adjust production accurately [15], [20].

The access to centralized generation resources constitutes a solution in managing intermittent energy resources, especially those that can be put in service, out of service and ramp rapidly to adapt to fluctuations [68]. The cutting edge flexible CCGT plants satisfies this need, and dated plants can be modified to be suited for quick starts and ramping. Additionally, hydropower plants benefit from having reservoirs, once these can ramp right away to provide the required power to the system [66].

2.2.3. Dispersed RES as a whole agent

Dispersed generation consists in a decentralized power plant, feeding directly into the distribution grid. The electric grid infrastructure has been based on a system of large power plants feeding consumers through transmission and distribution system. The concept of dispersed generation is based on smaller, high efficient power plants built close to customers, side by side on the existing grid [21], [31], [40]. This generation offers several benefits for consumers, power providers, and other stakeholders meaning everyone has a reason to adopt more DG installation [17]. Distributed power generators are small compared with big production centres and are able to bring benefits contrarily to centralized electricity generation. The benefits derive from the fact that the generating units are modular, meaning distributed power can be highly flexible [34]. It can provide power where it is needed when it is needed. Generators can be quieter and there is no pollution, making it suitable for on-site installation and storage at some consumers' locations.

DER can provide flexibility and with growing shares of variable renewable energy sources in the generation portfolio increases flexibility required [11]. Changes in load from one hour to the next one grows. DERs are mainly connected to distribution grid, increasing the complexity of the grid management. Producing electricity and supplying replaces, in part, traditional generation, causing existing generators to have lower operational times and not being able to counterbalance the changes in base demand and therefore are not able to satisfy the flexibility disparity on the distribution network [40]. Flexibility from DERs can be provided with technological advancements reducing its cost and increasing price volatility, improving flexibility [14]. For example, local demand and supply is balanced with flexible generation from DG and storage.

Many distributed generation, storage facilities, consumers, and prosumers are able to provide flexibility. Each one can offer a small amount of flexibility, so aggregators are fundamental to compile the flexibility from the smaller sources. This aspect can be executed by several entities, for example, electricity and telecommunication companies or appearing companies originated from a market niche and specialized in doing so. Competition for the better service and profit can stimulate development of innovative solutions [53].

Although the aggregator is decisive for DER integration, it might cause a clash between interests. The role of an aggregator can have nefarious implications on those involved in the market [15]. Imbalances can be caused, so there is the need for coordination when operating in the day-ahead market and intraday market. If an aggregator is a market participant it is imperative to have its own balance responsibility, or an agreement [51], also be able to provide auxiliary services (balancing and congestion management) in real time. The aggregator services are facilitated by having DER [45]. The major topic lays in the settlement between parties and stipulated adjustments to not financially penalize third parties on the market, as long as the appropriate adjustments are respected, coordination between aggregator and Balance Responsible Parties (BRP) is minimum.

Adding to coordination between aggregators and BRPs, it is also required between Distribution System Operators and Transmission System Operators. DSO grid operation must evolve with further sophistication, going from the conventional passive to a active operation like the transmission network. DSO and TSO activities may collide, this can be avoided by coordinating, potentially with an interface for information exchange regarding bids and resources state of operation. Conflict between both parties might arise, so when they relate to physical constraints, it is crucial to bear in mind that the conflicts that require a solution are subject to constraints of the physical network. DER participation in the market can be limited, in some cases, by physical constraints. As local problems can only be solved at the local level, the physical needs of the DSO will have priority. In case of an economic clash for a resource desired by both, the precedence is given to whom makes the best offer, therefore getting access to the resource. Aggregators and DER have barriers [46] as market restrictions and services solutions where historically projected for fit and purpose to the needs of big central generation units. The process of adjustment for new generators is undergoing, but to be able to participate there is more to be done. For instance, minimum bids and bid increments have been reduced significantly, to accommodate smaller generation, in day-ahead markets. Currently the verge in day-head market is significantly lower, which implies favourable conditions for aggregators and DER. While a lower price has been implemented in a few balancing markets, minimum bid and increments persist high [69], creating a barrier for market participation with DERs. Moreover, activation rules could dictate the possibilities for participation from the demand perspective, and this impact needs to be analysed for defining future rules. Activation periods or high frequency of activation can dictate the exclusion of many demand assets. The demand response participation in the PJM market (United States) including several demand response services, that can be supplied based on the duration and frequency variation [5]. Joint operations are made through a VPP which interconnects all parties in order to comply with rules and specifications to satisfy demand, as **Figure 2.7** shows that in order to enter the market, as a price maker agent, the VPP is the aggregation of dispersed energy resources, renewable ones, that otherwise would not be able to produce enough energy to be able to sell. This new agent focuses on the management of the different RES for the distribution system operator, coordinate loads and can also participate in the DA market, bringing advantages to distribution system control, postpone investments and bidding equilibrium by reducing electricity cost [11], [60], [70].

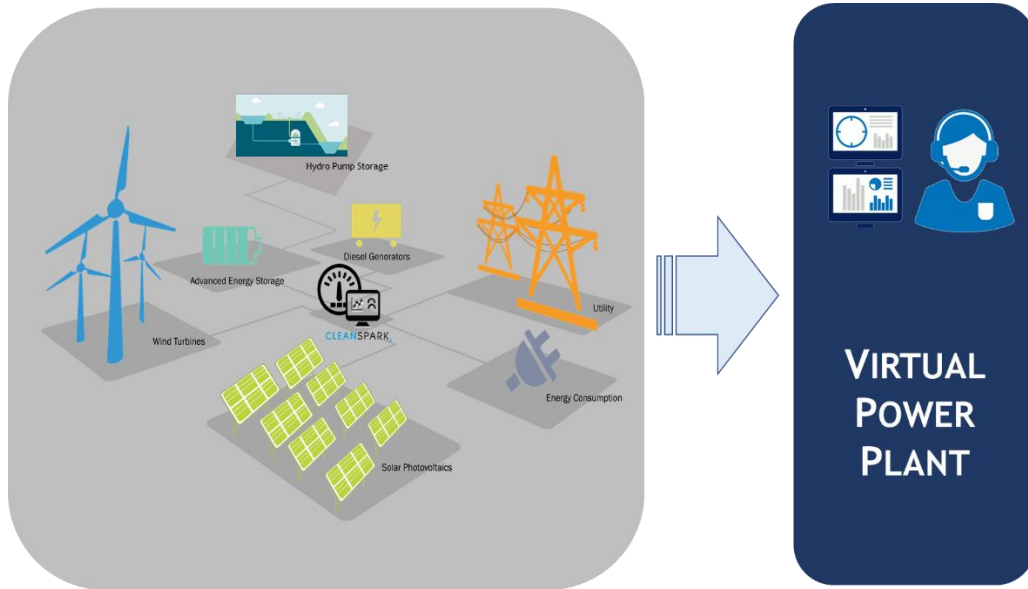


Figure 2.7- Concept of a VPP as a whole agent [69]

2.2.4 Load flexibility (HVAC an EVs)

In order to provide load flexibility and other services to the electric grid, in commercial customers, the VPP has a significant source of flexibility from the HVAC systems and EVs plugged in the parking lots by controlling and managing them. The TVPP considers load consumption and RESs production and uncertainties, with the HVAC system containing about 47% of the building load. The work presented in [11] shows the HVAC is controlled considering users and staff comfort constraints, such as ideal temperature range in each room. Regarding the parked EVs which are managed through an efficient charging/discharging scheduling algorithm and load can be decreased by discharging and injecting electricity (selling) to the grid [12]. **Figure 2.8** shows that is achieved by analysing data associated with the predicted consumption load as a noticeable amount of load from commercial buildings is flexible and load shedding can be done [22] giving the VPP the ability to adjust itself and provide auxiliary services to the grid.

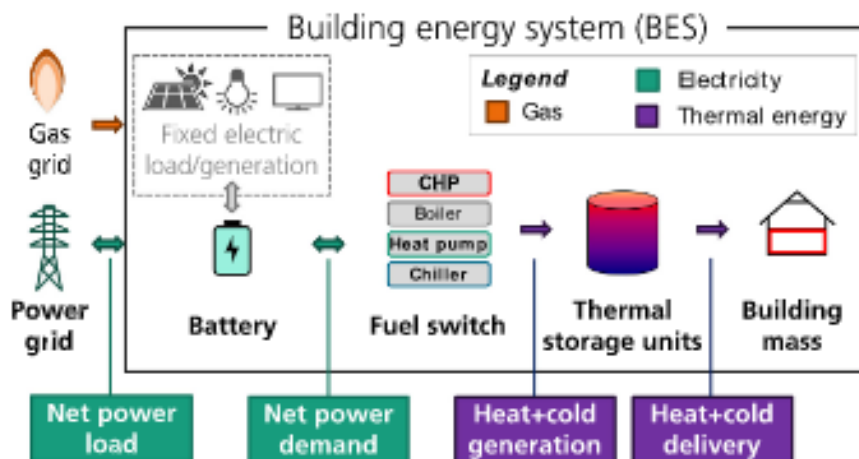


Figure 2.8 - Illustration of different flexibility and storage options within a building [39]

2.3 Maximizing profit with bidding strategy

In general, electricity is by nature difficult to store in large scales in an economically feasible way. Given the objectives of matching production and consumption of electricity by maximizing social economic welfare, the European power markets provide a regulated, non-discriminatory, and transparent environment that is accessible for every market participant. In these markets, electricity can be traded either at power exchanges offering standardized products or through bilateral over-the-counter trades between counter parties. Regarding power exchanges, market participants have different central marketplaces for different timeframes, for example markets for future contracts and options (long-term derivatives markets) provide a platform for traders to financially edge against the volatility of wholesale prices up to several years in advance, reducing price and quantity risks. On the other hand, short-term spot markets allow traders to optimize their generation portfolio for the next day or the same day (intraday). Because of the great significance of the day-ahead market for the allocation of existing resources and the dispatch of power stations, the following analysis targets the day-ahead market. In a perfect competition no power supplier would be able to affect the market price by bidding prices other than its marginal costs, and in this circumstance makes the supplier a price taker. In reality, there is, however, a limited number of market participants with different technologies, each with a different cost structure. Furthermore, a vendor can be the owner of several power plants and, thereby bidding for an entire portfolio of plants and technologies (a VPP, for example) offers a wider scope of action, than offering prices for energy at a single plant. Incorporating those market conditions and structures, with motivation to exploit imperfections and inefficiencies in the market, is a form of strategic bidding. A successful use of this technique to increase a suppliers' profit without lowering its production costs demonstrates the operators' market power, in other words, it is the ability of a supplier to influence and, simultaneously, benefit from market prices.

A procedure has to be decided as a bidding strategy in both markets. The bidding strategy of a TVPP must focus on market uncertainties, prices and DG units' generation and, ideally, have a structure to include commercial DR in the VPPs' strategy [71]. As a result, the optimal bidding strategy is obtained considering a bilevel optimization model to maximize profit (upper level) in market and calculates the ideal schedule for the resources. The lower level consists in modelling the independent system operator market clearing problem, maximizing market social welfare and define the power exchanged of the TVPP and other market rivals [11], [23]-[25]. In this case the TVPP does the scheduling for optimal bidding strategy. To make this possible, firstly dispatches the controllable resources and decides if it sells or purchases energy from the market, considering the best option. The TVPP can also predict the bidding of other participants using information (historical) and takes into account uncertainties associated. Research in [21], [22] considers households and their management minimizing infrastructure cost and maximizing market profit with associated generation uncertainties (VPP as a price-maker).

A VPP integrating CHP-DH and RESs based generations and its optimal strategy is taken into account in [25]. In [2] with three bidding strategies being studied: "static", "flexible DA" and "flexible RT" differing one from another in the dispatch decisions. Trading in the energy market is subject to external factors which introduce uncertainties, mainly if errors occur in the forecast of RESs electricity generation, demand and prices fluctuations cause by uncertain evolution of the day-ahead. The coordinated participation of CHP-DH and RES in the day-ahead market (DA) and the need to access several bidding strategies requires a methodology, taking advantage of the flexibility introduced by CHP-DH to recompensate the uncertainty on day-ahead market from generation to prices and imbalances penalties.

The VPP can simultaneously contract with energy or spinning reserve markets for concluding which bidding strategy is best for both. The VPP in [36] has several areas, each one connected to the conventional network, fed through a substation with radial operation as shown in **Figure 2.9**. Thermal suppliers fed local thermal loads and the global network is split into distinct areas, being composed by two main parts: electrical and thermal. Electrical part assets consist of photovoltaic and wind generators, fuel cells, electrical connection of CHP, micro turbines, energy storage, and demand response programs. On the other hand, the thermal part to satisfy demand consist of boiler, thermal connection of CHP and thermal storage. Considering a large scale VPP, DERs location in the network is spread and may vary from zone to zone.

In a CVPP, the aggregator starts to negotiate a fair price for its power production with the electricity market regulators. A CVPP is mainly based on the economic specification so that the aggregator can choose the most beneficial deal among the many aggregators present in the market. A CVPP implements the commercial aggregation irrespective of any network operation. It offers the visibility and contribution of numerous DER entities in the energy markets. Its function is to submit bids and offers into the wholesale energy market while maintaining the balance of trading portfolios. It lowers the imbalance of capacity, unlike stand-alone DER units, by integrating many small-scale units. CVPPs are not restricted to geographical locations and can include areas far away from transmission grids and distributed networks. CVPPs also contain outage demand management. To summarize Figure 2.10 represents that a CVPP. It deals with the demand and generation forecasts, DER characteristics analysis, bidding submission to the market and generation scheduling to maximize the profit.

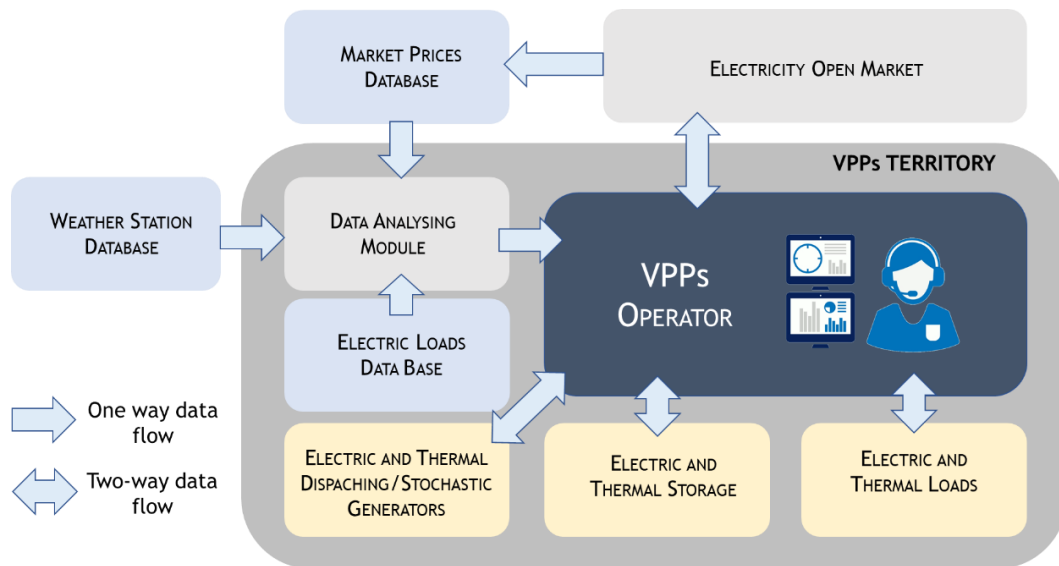


Figure 2.9 - The typical structure of the electric-thermal interconnected VPP [5]

2.4 Literature review

Existing works on Virtual Power Plants focus on reducing energy losses through assets' management mainly by residential consumers and their behaviour to maximize profit. That is, aiming to obtain an unified asset to manage through consideration of the interaction and coordination between the VPP aggregator and energy consumers/prosumers, their demand response and load profile [21], [22]. Many VPP in literature are composed of DERs, RESs and ESSs and consider the uncertainties of RES, mostly to participate in the day-ahead market.

In [22] a three-stage stochastic bi-level optimization model is formulated, and the uncertainties are modelled in the day-ahead market, with real-time balancing prices, DR, DERs production and load. In many papers the upper level exploits the VPP profit maximization and the lower level considers the ISO DA market-clearing problem [11], [20], [22], [24]. In [9], [41] the VPP is seen as the aggregator of both conventional power plants and renewable resources, which proposes a novel model for the day-ahead market trading in energy and reserve markets as a single entity in order to optimize resources and electricity consumption. All management is made by the same entity considering uncertainties and deploying reserves ([9] considers EVs grouped to provide spinning reserve) by order of the system operator. Continuing the same line of thought with a bi-level problem for TVPP [23] proposes a new framework with district heat networks and distributed electricity network, in this new multi-carrier energy network, the CHP is the link between heat and electricity networks. New constraints and technical performance for distribution networks are proposed. CHP and District Heating (DH) can be used by the VPP to compensate for uncertainties regarding RES electricity generation providing a better bidding strategy for the day-ahead market [2] with three bidding strategies studied that differ on dispatch decisions. The static strategy does not consider the scheduled output of the CHP, whereas "flexible DA" and "flexible RT" differ in the information available to perform a reschedule, with the first scheduling for the entire day and the latter adjusting each time based on renewable generation and price scenarios. A Virtual Power Plant aggregates large amount of distributed energy, including DG and ESS and controllable loads [10], [65]. The bidding strategy in [65] only considers the integration in an auxiliary service, with the same VPP structure as seen in other papers and uses GAMS solver to give the optimal solution based in the consideration of carbon-electricity integration. Paper [10] considers the operation of two indispensable assets: EVs and PV equipped parking lots to achieve an optimal energy management to study their possible integration on a VPP framework. Said work is developed using optimization and simulation tools like GAMS and Matlab to coordinate the entire operation regarding a VPP.

Regarding, specifically, commercial buildings, a TVPP aggregates DR potential of said buildings and other DERs in the distribution network and participates in a competitive DA market. The VPP operator schedules its resources and designs the optimal bidding strategy to maximize profit. This strategy is a mix of dispatching controllable resources and decisions on whether to buy or sell electrical energy while accounting for consumption, load variation and RESs production (uncertainties). The TVPP is both a buyer and seller on the energy market so it needs to take the consumers' requirements into consideration as the HVAC system represents almost half of the total load in buildings which makes it attractive for DR purposes. EVs in the parking lots are managed through a algorithm's based on charge/discharge cycles [10]. These two combined and efficiently managed (by the building or by the TVPP at an extra cost) can have a notable impact on minimizing costs).

Regarding DERs, with RESs, DGs, ESSs, loads all participating in DR programs in addition to HVAC systems and EVs. Having all assets and liabilities considered, the operator participates in the wholesale market by submitting optimal bids in order to maximize profit [11]. This paper considers the TVPP as a price maker agent in a competitive market where several agents aim to maximize their profit or minimize relevant costs, each agent predicts their bidding strategy of others based on previous data and associated uncertainties using a scenario based simulation. Related with this scope several works can be found in the literature to maximize results in the upper level [11] takes into account, network constraints, Microturbines, PV units, EVs, HVAC system, commercial building optimal cost and all limitations. In the lower-level problem adding to several agents and rival scenarios, the goal is to minimize imposed system costs and maximize social welfare[23], [69]. Technologies are growing rapidly and in [12], besides considering a VPP, electricity market prices and power generation capacity uncertainties like in [11], [21], [22], presents a novel EV uncertainty model with all vehicle characteristics being introduced into the whole stochastic optimization model along with other uncertainties. This allows the VPP with parking lots to schedule this asset with more accuracy prior to participating in the electricity market. Adding to EVs [37], uses the concept of microgrid in the scheduling model to prevent unrealistic power exchanges, showing that coordinated operation can improve load restoration and reduce load supply costs at the microgrid. Paper [5] proposes the application of certain standards to microgrids and VPPs, including control techniques, ESS and market participation in both island and grid connected operation. Industrial microgrids are addressed in [28] with their heavy loads and behaviour, energy management can be challenging with VPPs' DG and DR being determined by the system. This concept of industrial VPP is managed through the scheduling of each industrial unit by introducing DR programs and load control for market participation and better performance. The same is studied in [36] but on a more general level, applied to domestic and small commercial consumers. With a new paradigm, the possible lack of sufficient quantity of fossil fuel, global warming and associated concerns the need for RESs has become a priority [69] and it urges the need to reduce the uncertain influence of renewable energy resources (wind and PV) on a VPP operation [20] with price-based demand response and incentive-based demand response, ESS and a convention gas turbine. A day-ahead framework in a joint energy and regulation reserve markets is presented in [67] where it assumes that VPP provides required regulation reserve through its DG (synchronous) based on delivery request probability on DA market. This model aggregates EVs through bilateral, incentive-based contracts with vehicle owners and contemplates a penalty cost for impact of carbon dioxide emissions. In a joint venture for electric-thermal market [25] proposes a two stage model, the first stage a multi-bid day-ahead market bidding model considering both economic and social benefits and VPP dispatch optimization, and the second stage for the intra-day market with penalties and it is tested in China with an electric-thermal coupled virtual power plant. The undergoing shift in traditional energy systems with bidirectional peer-to-peer energy flows pushed consumers to be prosumers, smart grids and VPPs have to facilitate prosumers coordination, contributing to this integration, paper [29] presents valuable control methods, management and optimization for prosumers and DERs including various DR approaches and infrastructure in order to point out factors which affect a proper integration of DERs, prosumers and VPP operation.

2.5 Chapter Summary

This chapter presented the concept of a VPP, its assets, requirements, conditions, advantages and disadvantages and objectives. The need to better integrate and furthermore, aggregate renewable distributed generation resources and optimize it overcoming challenges considering electricity market, users, renewable resources uncertainties, grid constraints, load consumption, demand response, power reserve, etc to maximize energy efficiency and social welfare as the current state of play was discussed.

Different technologies proposed and at disposal to operate and control grid, resources and users were presented to solve the problem and give another perspective on how a bigger and better management can bring a future insight to electricity generation, transportation, consumption and markets with users actively participating in generation and maintenance through a VPP controlled by an entity. Finally, the last section gathered an overview of existing works present in the literature that relate to the present work and the one to be developed.

Chapter 3

Mathematical Formulation

In this chapter, the algebraic formulation of this problem is described and demonstrated. The objective of the model was to identify the optimal operating point of the VPP considering the trade-off between the comfort of commercial consumers and cost savings in the presence of RESs based DG, EVs, and HVAC systems. The problem is formulated as a stochastic mixed-integer linear programming and it aims to maximize profit while taking various constraints into account.

3.1- Objective Function

The objective of the current work is to maximize the VPP's profit based on the revenue of power sold to customers (PSC) and imposed cost to the technical virtual power (TVPPC) plant while considering technical and economic constraints. The objective function was formulated as the difference between the TVPP cost (including DGs operational cost, energy bought to the market, EVs, and HVAC system power supply) and the revenue generated from the PSC.

$$\text{Max Profit} = \text{PSC} - \text{TVPPC} \quad (3.1)$$

The PSC cost term is presented in (3.2). This equation represents the power consumption of each consumer with regular load, EVs charging and HVAC system on for cooling while considering TOU tariffs. The function is divided into three as each consumer may or may not have such additional assets.

$$\begin{aligned} \text{PSC} = & \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \lambda_h^{\text{TOU}} P_{k,l,s,h} \\ & + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} \lambda_h^{\text{TOU}} P_{ev,k,n,s,h}^{\text{ch}} \\ & + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{HVAC \in \Omega^{HVAC}} \lambda_h^{\text{TOU}} P_{HVAC,k,n,s,h}^{\text{cool}} \end{aligned} \quad (3.2)$$

The total operation cost of the TVPP (3.3) is given by the DG production of energy and maintenance cost minus the power sold in the day-ahead market, the power sold by discharging EVs, and a Penalty. The Penalty (3.4) is the price required to pay to charge EVs or by activating the HVAC system to keep ambient air conditions as requested minus the cost of operating the EVs and HVAC systems.

$$\begin{aligned}
TVPP = & \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{g \in \Omega^g} OC_g P_{g,k,n,s,h}^{DG} \\
& - \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{\zeta \in \Omega^\zeta} \lambda_h^\zeta P_{\zeta,k,n,s,h}^{market} \\
& - \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} \lambda_h^{ev} P_{ev,k,n,s,h}^{dch} \\
& - Penalty
\end{aligned} \tag{3.3}$$

$$\begin{aligned}
Penalty = & \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} \lambda_h^{TOU} P_{ev,k,n,s,h}^{ch} \\
& + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{HVAC \in \Omega^{HVAC}} \lambda_h^{TOU} P_{HVAC,k,n,s,h}^{cool} \\
& - Cost_{ev,HVAC}^{operation}
\end{aligned} \tag{3.4}$$

$$\begin{aligned}
Cost_{ev,HVAC}^{operation} = & \left(\sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} P_{ev,k,n,s,h}^{ch} \lambda_h^{TOU} \right. \\
& - \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} \lambda_h^{ev} P_{ev,k,n,s,h}^{dch} \left. \right) \\
& + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} \sum_{HVAC \in \Omega^{HVAC}} \lambda_h^{TOU} P_{HVAC,k,n,s,h}^{cool}
\end{aligned} \tag{3.5}$$

3.2-Constraints

3.2.1 Kirchhoff's Current Law

The sum of all incoming current into a node should be equal to the sum of all outgoing current, which is given by Kirchhoff's Law. This is applied to both active (3.6) and reactive (3.7) power flows, and must be always respected:

$$\begin{aligned}
& \sum_{g \in \Omega^g} P_{g,n,s,h}^{DG} + \sum_{k \in \Omega^k} \sum_{ev \in \Omega^{ev}} (P_{ev,k,n,s,h}^{dch} - P_{ev,k,n,s,h}^{ch}) + P_{\zeta,s,h}^{market} \\
& + \sum_{in,l \in \Omega^l} P_{l,s,h} - \sum_{out,l \in \Omega^l} P_{l,s,h} = (PD_{s,h}^n + P_{HVAC,k,n,s,h}^{cool}) \\
& + \sum_{in,l \in \Omega^l} \frac{1}{2} PL_{l,s,h} + \sum_{out,l \in \Omega^l} \frac{1}{2} PL_{l,s,h}; \forall \zeta \in i
\end{aligned} \tag{3.6}$$

$$\begin{aligned}
& \sum_{g \in \Omega^g} Q_{g,n,s,h}^{DG} + Q_{c,n,s,h}^c + Q_{\zeta,s,h}^{market} \\
& + \sum_{in,l \in \Omega^l} Q_{l,s,h} - \sum_{out,l \in \Omega^l} Q_{l,s,h} = (QD_{s,h}^n + Q_{HVAC,k,n,s,h}^{cool}) \\
& + \sum_{in,l \in \Omega^l} \frac{1}{2} QL_{l,s,h} + \sum_{out,l \in \Omega^l} \frac{1}{2} QL_{l,s,h} \forall \zeta \in i
\end{aligned} \tag{3.7}$$

In these equations $P_{l,s,h}$ and $Q_{l,s,h}$ represent the active and reactive power flow in the line respectively, $PD_{s,h}^n$ and $QD_{s,h}^n$ and represent the active and reactive demand at the nodes and $PL_{l,s,h}$ and $QL_{l,s,h}$ represent the active and reactive energy losses in the lines.

3.2.2 Kirchhoff's Voltage Law

Inequalities (3.8) and (3.9) present the linearized AC power flows through each feeder, which are governed by Kirchhoff's Voltage Law. Note that $\theta_{l,s,h}$ refer to the angle difference $\theta_{n,s,h} - \theta_{m,s,h}$ where n and m are bus indices corresponding to the same line l , based on a previously developed work [72].

$$|P_{l,s,h} - (V_{nom}(\Delta V_{n,s,h} - \Delta V_{m,s,h})g_k - V_{nom}^2 b_k \theta_{l,s,h})| \leq MP_l(1 - \chi_{l,h}) \tag{3.8}$$

$$|Q_{l,s,h} - (-V_{nom}(\Delta V_{n,s,h} - \Delta V_{m,s,h})b_k - V_{nom}^2 g_k \theta_{l,s,h})| \leq MQ_l(1 - \chi_{l,h}) \tag{3.9}$$

It is important to note that, due to the reconfiguration problem, equations (3.8) and (3.9), have binary variables to make sure the flow through a given line is zero when its switching variable is zero (the line is disconnected). Moreover, the introduction of those variables results in bilinear products which can result in undesirable non-linearity. For that reason, the big-M formulation was used, set to the maximum transfer capacity, to avoid the non-linearity.

3.2.3 Power Limits

The maximum amount of flow that can pass through a line is given by inequality (3.10). Equations (3.11) and (3.12) represent active and reactive power losses in a given line l.

$$P_{l,s,h}^2 + Q_{l,s,h}^2 \leq \chi_{l,h}(S_l^{max})^2 \quad (3.10)$$

$$PL_{l,s,h} = R_l(P_{l,s,h}^2 + Q_{l,s,h}^2)/V_{nom}^2 \quad (3.11)$$

$$QL_{l,s,h} = X_l(P_{l,s,h}^2 + Q_{l,s,h}^2)/V_{nom}^2 \quad (3.12)$$

3.2.4 Electric Vehicles model

EVs are modeled by the expressions (3.13)-(3.18).

$$0 \leq P_{ev,k,n,s,h}^{ch} \leq I_{ev,k,n,s,h}^{ch} P_{ev,k,n,h}^{ch,max} \quad (3.13)$$

$$0 \leq P_{ev,k,n,s,h}^{dch} \leq I_{ev,k,n,s,h}^{dch} P_{ev,k,n,h}^{ch,max} \quad (3.14)$$

$$I_{ev,k,n,s,h}^{ch} + I_{ev,k,n,s,h}^{dch} \leq 1 \quad (3.15)$$

$$E_{ev,k,n,s,h} = E_{ev,k,n,s,h-1} + \eta_{ev}^{ch} P_{ev,k,n,s,h}^{cg} - \frac{P_{ev,k,n,s,h}^{dch}}{\eta_{ev}^{dch}} \quad (3.16)$$

$$E_{ev,k,n}^{min} \leq E_{ev,k,n,s,h} \leq E_{ev,k,n}^{max} \quad (3.17)$$

$$E_{ev,k,n,s,h0} = \mu_{ev} E_{ev,n}^{max}; E_{ev,k,n,s,h24} = \mu_{ev} E_{ev,n}^{max} \quad (3.18)$$

The limits on the amount of power charged and discharged are given by (3.13) and (3.14), respectively, while (3.15) guarantees that charging and discharging processes do not happen simultaneously at any given time. The state of charge is modelled as shown in (3.16). Inequality (3.17) ensures that the storage level is always within a permissible range. Finally, (3.18) sets the initial storage level and ensures the storage is left with the same amount of charge at the end of the operational period. For sake of simplicity, both η_{ev}^{ch} and η_{ev}^{dch} are often set to be equal and their efficiencies are expressed in the percentage of energy at the nodes where EVs are connected to.

3.2.5 HVAC model

HVAC systems are modelled by expressions (3.14)-(3.25)

$$T_{HVAC,k}^{min} \leq T_{k,n,s,h}^{ideal} \leq T_{HVAC,k}^{max} \quad (3.19)$$

$$0 \leq P_{HVAC,k,n,s,h}^{cool} \leq P_{HVAC,k,n,s,h}^{cool,max} \quad (3.20)$$

$$\begin{aligned} T_{kt,n,s,h}^{in} = & \left(1 - \frac{\Delta T}{1000 \cdot M_k \cdot c_{air} \cdot R_k}\right) \cdot T_{k(t-1),n,s,h}^{in} \\ & + \frac{\Delta T}{1000 \cdot M_k \cdot c_{air} \cdot R_k} \cdot T_{(t-1)}^{amb} \\ & - \frac{COP_{HVAC}}{0,000277 \cdot M_k \cdot c_{air}} \cdot P_{HVAC,k,n,s,h}^{cool} \quad , \quad \forall k, t > 1 \end{aligned} \quad (3.21)$$

$$T_{kt0,n,s,h}^{in} = T_{k,n,s,h}^{inicial} \quad , \quad \forall k \quad (3.22)$$

$$P_{HVAC,k,n,s,h}^{cool} = u_{kt,n,s,h} \cdot P_{HVAC,k,n,s,h}^{cool} \quad , \quad \forall k, t \quad (u = 0 \text{ OFF}, u = 1 \text{ ON}) \quad (3.23)$$

$$T_{kt,n,s,h}^{in} \quad \forall k, t \in \underset{T_{kt,n,s,h}^{dec}}{\operatorname{argmin}} \{ T_{kt,n,s,h}^{inc}, T_{kt,n,s,h}^{dec}, T_{kt,n,s,h}^{therm}, T_{kt,n,s,h}^{in} \cdot \left\{ \frac{1}{N_k} \cdot \sum_{s \in \Omega^s} \sum_{h \in \Omega^h} \sum_{k \in \Omega^k} (T_{kt,n,s,h}^{inc} + T_{kt,n,s,h}^{dec}) \right\} \} \quad (3.24)$$

$$T_{kt,n,s,h}^{therm} \leq T_{kt,n,s,h}^{ideal} + T_{kt,n,s,h}^{inc} \quad , \quad \forall k, t \quad (3.20)$$

$$-T_{kt,n,s,h}^{therm} \leq T_{kt,n,s,h}^{dec} - T_{kt,n,s,h}^{ideal} \quad , \quad \forall k, t \quad (3.21)$$

$$T_{kt,n,s,h}^{in} \leq T_{kt,n,s,h}^{therm} + T_{k,n,s,h}^{Dead-band} \quad , \quad \forall k, t \quad (3.22)$$

$$-T_{kt,n,s,h}^{in} \leq T_{k,n,s,h}^{Dead-band} - T_{kt,n,s,h}^{therm} \quad , \quad \forall k, t \quad (3.23)$$

$$-T_{kt,n,s,h}^{dec} \leq 0 \quad , \quad \forall k, t \quad (3.24)$$

$$-T_{kt,n,s,h}^{inc} \leq 0, \forall k, t \quad (3.25)$$

3.2.6 Renewable Generation Power Limits

The active and reactive power limits of the DGs are given by (3.26) and (3.27), respectively. Inequality (3.28) limits the DGs ability to inject or consume reactive power.

$$P_{g,n,s,h}^{DG,min} \leq P_{g,n,s,h}^{DG} \leq P_{g,n,s,h}^{DG,max} \quad (3.26)$$

$$Q_{g,n,s,h}^{DG,min} \leq Q_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG,max} \quad (3.27)$$

$$-\tan\left(\cos^{-1}(pf_g)\right)P_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG} \leq \tan\left(\cos^{-1}(pf_g)\right)P_{g,n,s,h}^{DG} \quad (3.28)$$

3.2.7 Conventional Generation Power Limits

The active and reactive power limits at the substations are given by (3.29) and (3.30), due to stability reasons.

$$P_{\zeta,s,h}^{market,min} \leq P_{\zeta,s,h}^{market} \leq P_{\zeta,s,h}^{market,max} \quad (3.29)$$

$$Q_{\zeta,s,h}^{market,min} \leq Q_{\zeta,s,h}^{market} \leq Q_{\zeta,s,h}^{market,max} \quad (3.30)$$

The reactive power that is withdrawn from the substation is subject to the bounds presented in inequality (3.31).

$$-\tan\left(\cos^{-1}(pf_{\zeta})\right)P_{\zeta,s,h}^{market} \leq Q_{\zeta,s,h}^{market} \leq \tan\left(\cos^{-1}(pf_{\zeta})\right)P_{\zeta,s,h}^{market} \quad (3.31)$$

3.2.8 Radiality Constraints

The radial operation of the considered system is guaranteed by including the constraints in (3.32) through (3.38). Constraints (3.34)-(3.38) ensure radiality in the presence of DGs and simultaneously avoid islanding.

$$\sum_{l \in \Omega^l} \chi_{l,h} = 1, \forall m \in \Omega^D; l \in n \quad (3.32)$$

$$\sum_{in, l \in \Omega^l} \chi_{l,h} - \sum_{out, l \in \Omega^l} \chi_{l,h} \leq 1, \forall m \notin \Omega^D; l \in n \quad (3.33)$$

$$\sum_{in, l \in \Omega^l} f_{l,h} - \sum_{out, l \in \Omega^l} f_{l,h} = g_{n,h}^{SS} - d_{n,h}, \forall n \in \Omega^S; l \in n \quad (3.34)$$

$$\sum_{in, l \in \Omega^l} f_{l,h} - \sum_{out, l \in \Omega^l} f_{l,h} = -1, \forall n \in \Omega^g; \forall n \in \Omega^D \quad (3.35)$$

$$\sum_{in,l \in \Omega^l} f_{l,h} - \sum_{out,l \in \Omega^l} f_{l,h} = 0, \forall n \notin \Omega^g; \forall n \notin \Omega^D \forall n \notin \Omega^S \quad (3.36)$$

$$0 \leq \sum_{in,l \in \Omega^l} f_{l,h} + \sum_{out,l \in \Omega^l} f_{l,h} \leq n_{DG}; l \in n \quad (3.37)$$

$$0 \leq g_{n,h}^{SS} \leq n_{DG}, \forall n \in \Omega^S; l \in n \quad (3.38)$$

3.3 - Chapter Summary

This chapter has presented the mathematical formulation used in this dissertation. The objective function and the constraints have been fully described. The objective is to maximize the total profit of the VPP. In this model, DGs from RESs are considered to be present and the problem is developed as a stochastic mixed-integer linear programming (MILP) optimization. Additional formulation to study and optimize the network considering commercial consumers with EVs and HVAC systems management is also presented. In the following chapter, the IEEE 119-bus distribution network system data and assumptions are demonstrated as well as the scenarios considered in the optimization process.

Chapter 4

Case Study, Results and Discussion

In this chapter, the case study is presented. This chapter, describes the system data and the assumptions that will be used to test the mathematical formulation presented in Chapter 3. It also contains a scenario description section, with the results from the analysis of each scenario considered during the optimization process. In Chapter 4, the numerical results obtained from the simulated operational model are also presented and discussed. The objective is to analyse the total costs and operational variables and their contributions towards a profit maximization of a TVPP, while having the most efficient system possible considering the integration of DERs, RESs, EVs, DR, different loads, and market operation.

4.1- Case Study, Results and Discussion

The standard IEEE 119 bus test system is used to simulate and validate the mathematical model defined and explained in the previous chapter. The data concerning this system can be found in Annexure A.1 its schematic representation is presented in Figure 4.1. The data concerning the loads are presented in Annexure A.2. The type of DG unit and the buses to which it is connected, as well as the points of interconnection between the EVs parking lots and HVAC systems and the network, are also shown in Figure 4.1. Two types of DG units are considered as illustrated: wind power and solar power. The installed capacity of these units is 1MW in both cases. Annexure A.3 refers to the nodes where DG units are connected and its type, while Annexure A.4 contains the data concerning the location and quantity of the interconnection points between the EVs and HVAC systems, and the network. In addition to the above, the following assumptions and system data are also considered in the analysis of the problem:

- A time horizon of 24 hours is considered;
- The value assumed for the nominal voltage is 12,66 kV;
- In each node a voltage deviation of $\pm 5\%$ is considered;
- The reference node is the substation, with a voltage magnitude being set to its nominal value and the angle to 0° ;
- 0.95 is the value of the power factor at the DG units;

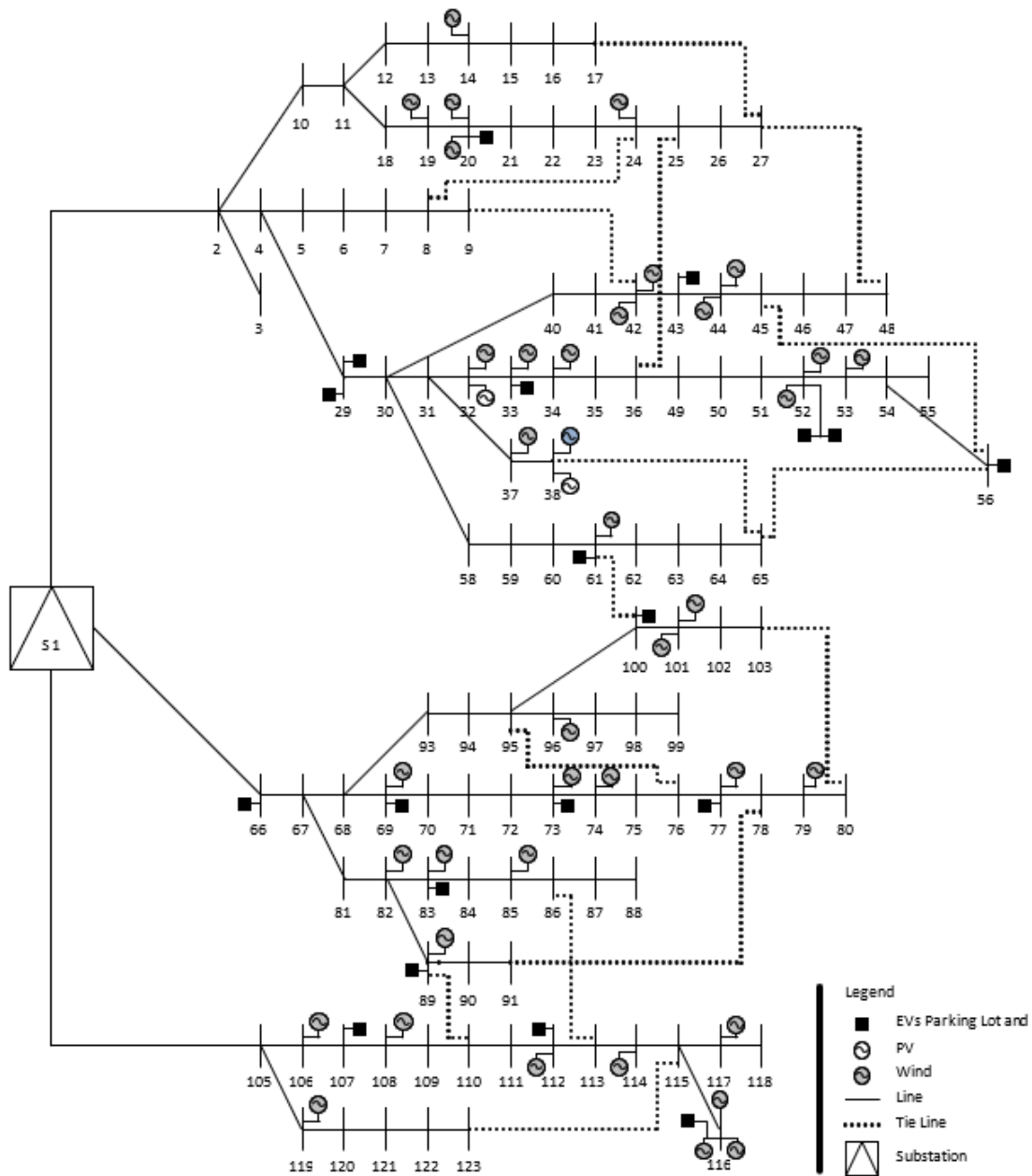


Figure 4.1- Adapted IEEE 119 bus test system.

- 0.8 is the value of the power factor at the substation;
- EVs rates of charge and discharge of energy are considered the same and equal to 90%;
- The operation cost of EVs during charge and discharge is 5 €/MWh;
- The EVs discharge cannot go below 40% of their total load capacity;
- The operation cost of solar DG units is 40 €/MWh;
- The operation cost of wind DG units is 20 €/MWh
- Commercial buildings can also charge EVs at night;
- Optimization for usage during a summer period.

Commercial customers are distributed throughout the network and are fed through nodes 14, 29, 34, 43, 52, 56, 61, 66, 69, 73, 77, 83, 100, 107, 112 and 116. Each one of these customers have HVAC and EVs units, with each EV park having 10 cars. The distribution of these parking lots can be seen in the following table:

The developed work was based on three study cases, the first considering that all of the power needed to meet the loads will be supplied directly and exclusively by the market. The second case responds not only to the power supplied by the market, but also to the aggregation of DGs of solar and wind power, which are renewable resources that are presented in the distribution grid. The third case study considers the power purchased from the market, the aggregation of power from the DGs, and the aggregation of power provided by a variety of sources such as EVs through Vehicle-to-grid (V2G) interface technologies, HVAC use in commercial buildings, and DR flexibility. In this final case, the variation of the temperature range in commercial buildings is assessed.

4.2-Scenarios Description

The variability and uncertainty associated with RESs are one of the main challenges for the electric power system as discussed in Chapter 2. One of the issues in the planning and operation of a distribution system is the intermittency of renewable energy sources, which is related to the variations in time and the unpredictability of operational situations. Additionally, there are also other uncertainties, mainly associated with the long-term electricity, carbon and fuel price, laws, legislation and policies, etc. To account for these factors, a reasonably large range of possibilities must be assumed, providing a strong variety of potential scenarios. A scenario can be defined as the evolution or the progression of an uncertain parameter over a given period.

In the case of the power demand scenarios, long-term demand profiles based on historical data are considered. Regarding the wind power production scenarios, the resulting power output from Equation (4.1) is used. For the solar power production scenarios, the power output is given by Equation (4.2). This approach is stated and described in [72] and applied in the present context. Each one of the resulting scenarios has 8760 snapshots, where a snapshot refers to a demand or generation pattern at a given time. To verify the tractability of the problem, this multi-dimensional input data is grouped into smaller groups using a clustering technique known as k-means clustering. This technique, aggregates the snapshots that are more similar so reducing the total number in each scenario.

$$P_{wnd,h} = \begin{cases} 0, & 0 \leq V_h \leq V_{ci} \\ P_r(A + Bv_h^3), & v_{ci} \leq v_h \leq v_r \\ P_r, & v_r \leq v_h \leq v_{co} \\ 0, & v_h \leq v_{co} \end{cases} \quad (4.1)$$

$$P_{sol,h} = \begin{cases} \frac{P_r R_h^2}{R_{std} R_c}, & 0 \leq R_h \leq R_c \\ \frac{P_r R_h}{R_{std}}, & \leq R_h \leq R_{std} \\ R_c, & R_h \geq R_{std} \end{cases} \quad (4.2)$$

For this study, three different scenarios are considered for the power demand, as well as three different scenarios for solar power production and three different scenarios for wind power generation. These scenarios are combined to form a set of 27 distinct scenarios with the same probability of realization. Note that it was found that considering a larger number of scenarios and all their possible combinations contribute to a more complex matrix. This leads to a higher computational effort, without achieving significant advantages in the accuracy of the outcome. For this reason, the set of 27 possible scenarios is considered ideal and the most appropriate for the efficiency of the model.

4.2.1 Power Demand Scenarios

The uncertainty of power demand is analyzed in three separate scenarios as shown in Figure 4.2.

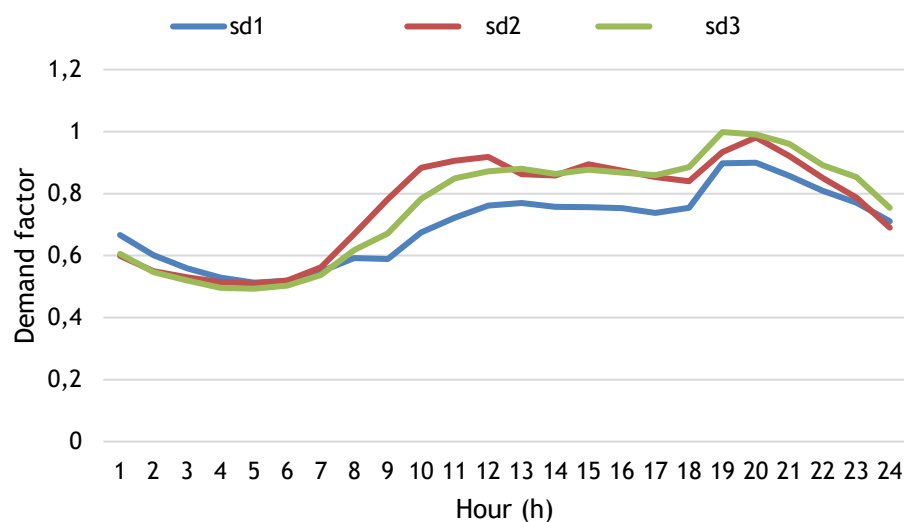


Figure 4.2- Demand scenarios

4.2.2 Wind Power Production scenario

Likewise, for the analysis of uncertainty in wind power production three different scenarios (sw1, sw2 and sw3) are assumed and are shown in Figure 4.3.

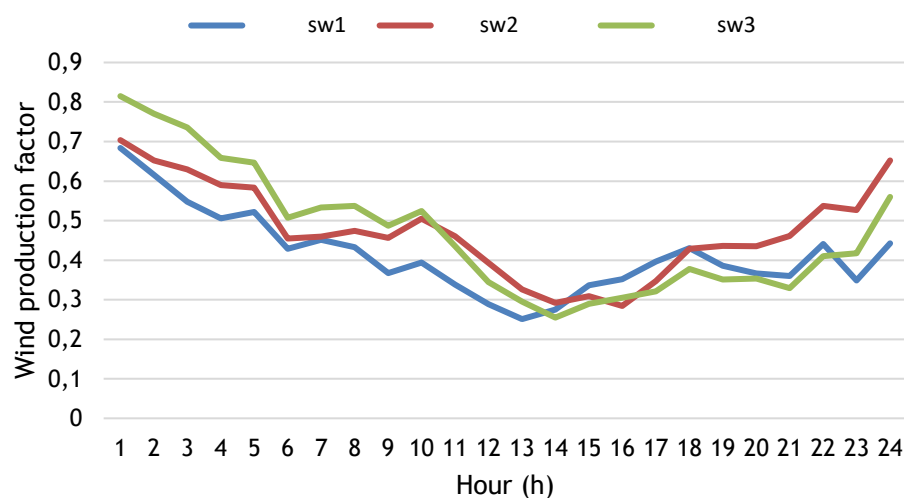


Figure 4.3- Wind power scenarios

4.2.3 Solar Power Production scenario

Finally, for the analysis of uncertainty in the production of solar power three different scenarios are considered as shown in Figure 4.4.

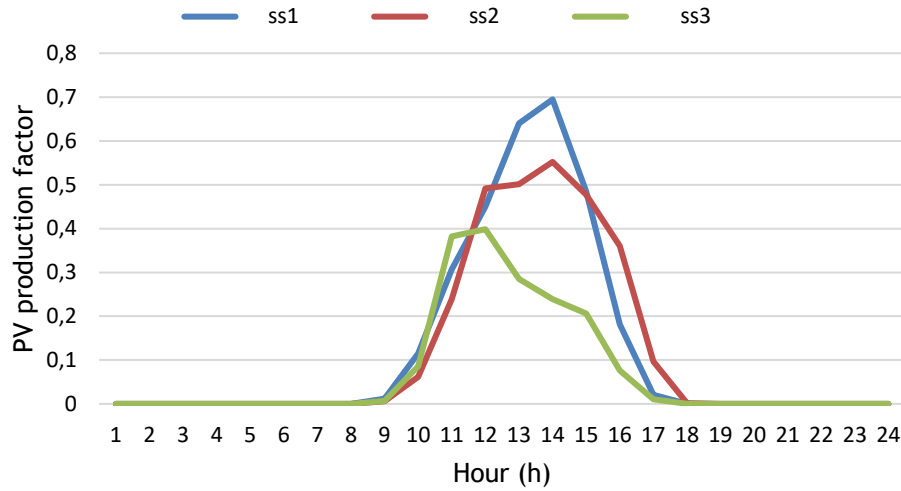


Figure 4.4 - Solar power scenarios

4.3 Case Study 1

In case study 1 all demand is met through purchasing power from the market. This is done by the TVPP to meet the loads. The profit is obtained after all operational needs are assessed and is calculated by subtracting the power sold to the loads (PSC) and the cost imposed by the TVPP (TVPPC). In this case the profit is 16285,81€.

Figure 4.5 presents the day-ahead schedule showing that all power is bought from the market to satisfy the system's demand. Notice that the demand profile has its peak at 20:00 and valley (minimum value) at 04:00. In terms of voltage control and system reliability, case study 1 can be seen as the more traditional operating method. The average voltage deviation at each node can be seen in Figure 4.6.

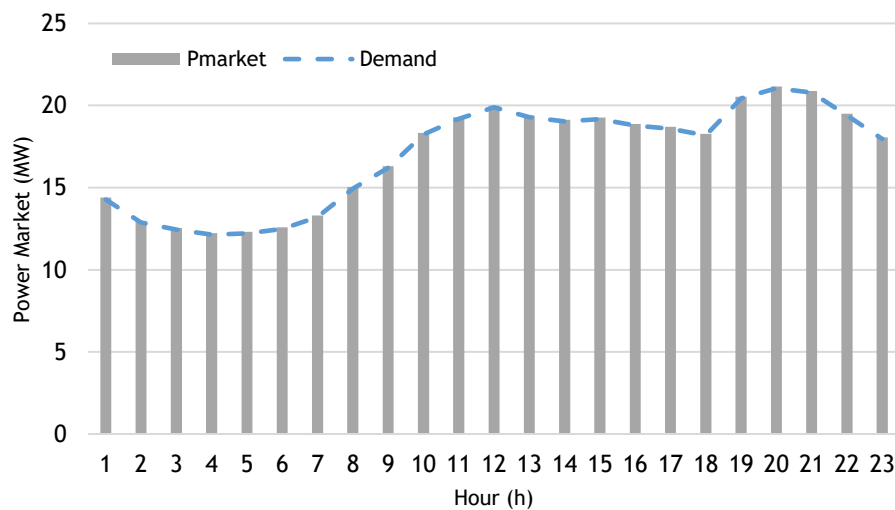


Figure 4.5 - Day-ahead schedule (case study 1)

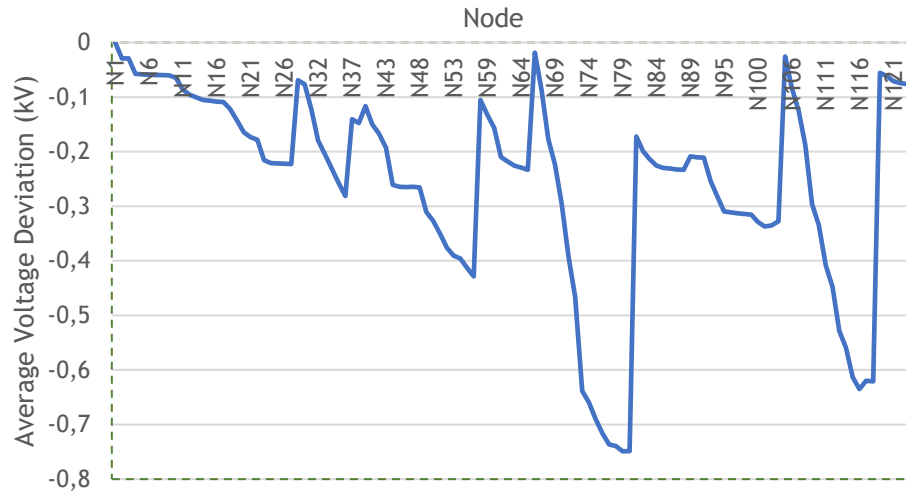


Figure 4.6- Voltage deviation (case study 1)

This figure shows that with a greater distance between the node and the substation, the voltage deviation increases when compared to the nominal value. Nodes 2, 66, and 105 are the closest to the substation and, therefore, have the least deviation from the nominal value. The opposite occurs in nodes 56, 80, and 116 which have the largest voltage deviation. When reliability is concerned, in this case, it means that the nodes with more voltage deviation represent areas where reliability is lower and may need improvement to prevent anomalous situations.

4.4 Case Study 2

Case study 2 differs from the previous one by the existence of renewable energy sources DGs in the electrical grid, mainly solar and wind, meaning there are external power sources (generation) besides the pre-existing power bought at the market. The objective function remains the same but now more variables will have an effect not only on costs but also on operational points. This means that the nature of these RES plants, namely their associated uncertainty and variability will affect profit optimization of the VPP. His uncertainty was considered and modeled through a set of scenarios.

In Table 4.1 the TVPP costs are presented for case study 1 and 2. Comparing both cases an increase in profit of 45,33% is seen. This is due to a 1,55% higher PSC and a remarkable TVPP cost reduction of 47,39% achieved through the integration of DG, making the amount of energy purchased to the market significantly lower which in turn reduces the operational costs of the TVPP. This can be seen in Figure 4.7 where the day-ahead schedule is presented with wind generation supplying almost half the demand. Therefore, in comparison with the previous case the TVPP management is more efficient with the existing market having a smaller impact as the use of the available DG production is a priority and this helps to lower the final price to end consumers.

Table 4.1 - Profit and costs (case study 2)

	Profit (€)	PSC (€)	TVPP (€)
Case Study 1	16285,80	44091,62	28498,09
Case Study 2	29791,10	44783,89	14992,79

Note that at certain times of the day, mainly from 03:00 to 06:00 production exceeds demand and this may lead to energy being wasted as energy storage has not been considered in this case study. Energy storage allows operators to take advantage of that excess for later usage. Also, the existence of the DG in the system allows generation to be closer to the end consumer and this reduces energy losses which will be reflected in lower costs. In this regard, DG integration in the grid enhances the system's flexibility and allows for a better management of its assets.

Comparing both cases side by side, case study 2 has a maximum voltage deviation which is 53.08% lower than the maximum value in case study 1, the power from the market is only 27,92% of the amount bought in case study 1. This shows the beneficial effect on network usage, social welfare, and advantages to the end-users of DGs. A comparison of the voltage deviations in both case study 1 and case study 2 is shown in Figure 4.8.

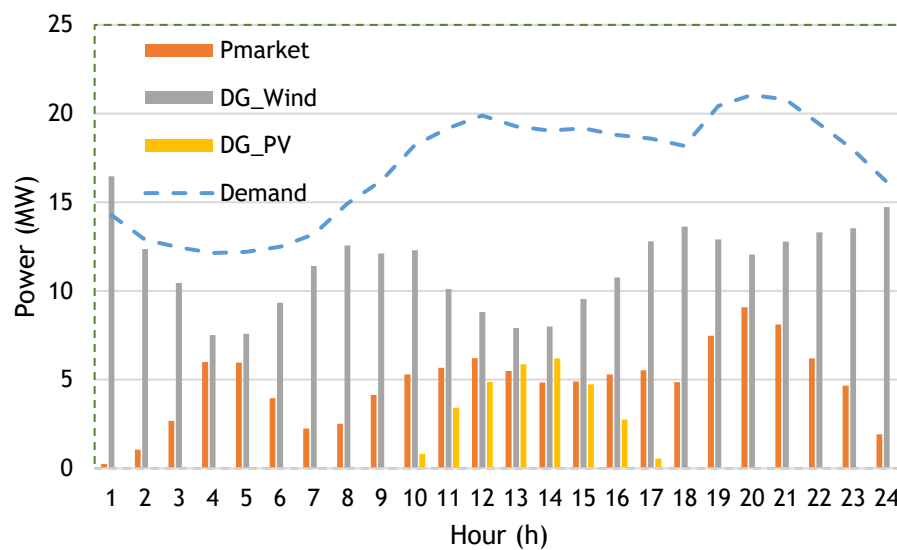


Figure 4.7 - Day-ahead sch

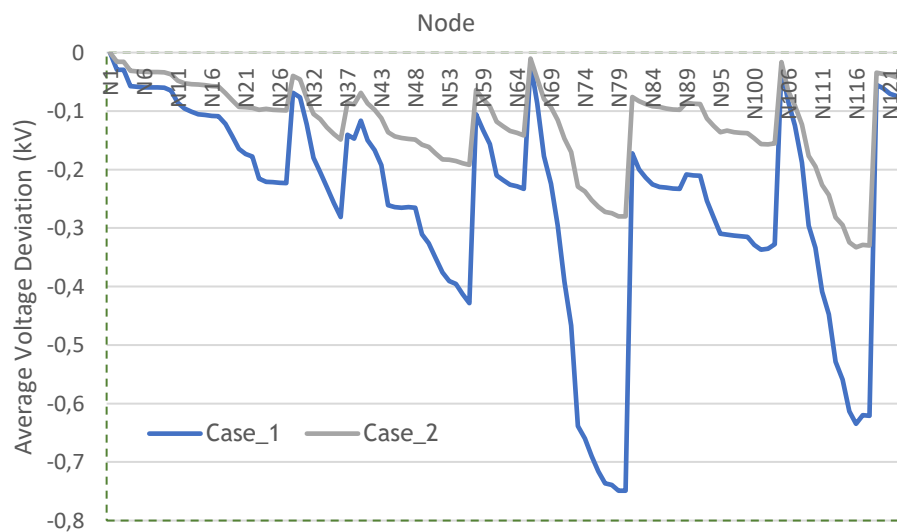


Figure 4.8 - Voltage deviation (case study 2)

The average voltage deviation in this case with DG is significantly lower, as there is local production and is directly fed into the grid. This means that the effect of increasing distance between the node and the substation is mitigated compared to case study 1 as DGs units help to keep the system more stable as the voltages have improved magnitude and phase values. This analysis shows that the TVPP operation with DG positively impacts the system's reliability through a better voltage profile.

4.5 Case Study 3

Case study 3 combines power purchased from the market, the aggregation of power from the DG units, the aggregation of power provided from EVs through V2G interface technologies in parking lots, HVAC systems in commercial buildings, and DR flexibility. The functioning of the HVAC system with different temperature ranges and variations (in summer) is evaluated to assess the best operation mode considering the trade-offs between efficiency and maintaining the user's comfort. This case study is divided into two parts: one for the comparison between case study 3 and the previous case studies; and the part analyzing the effect of different operating conditions for the HVAC system, considering different temperature ranges, relative to each other and to Case Study 2.

Table 4.2 shows the profit, the power sold to consumers and the TVPP operational cost for case study 1 to 3. From the table, it is possible to see that overall profit is higher in case study 3 with the profit increasing by 49,23% relative to case study 1 and a 7,13% improvement from case study 2. Regarding the PSC value, in case study 3 it is 1,55% lower than case study 1 and equal to Case Study 2.

Therefore, the main difference is due to the operation costs of the TVPP. In case study 3, the total cost is only 44,58% of the value from the first case study. The value in Case 3 is lower than the same value in case 2 by a value of 15,26%. This improvements of the cost in Case Study 3 relative case study 2 might seem minor it is significant as the number of commercial customers is limited. Increasing the type and size of the commercial customer's assets, would lead to better results and more profit.

The day-ahead schedule represented in Figure 4.9 demonstrates the most important parameters and variables considered and their contributions to the system. In this case, the presence of DR is considered. The effects of considering DR can be seen also in terms of the load profile, especially between the peak hours from 19:00 to 21:00 where the demand is slightly higher and the market price reaches its maximum value during that time. This occurs due to the joint effect of DR in commercial and residential consumers, which creates sufficient flexibility during this period, allowing the TVPP to perform better management of the assets. In terms of scheduling, it can be seen that there is a large contribution from renewable energy sources, reaching 72,79% of the total scheduled energy. The largest contribution is made by wind in 65,61%, however, the contribution of PV is also significant, especially during its peak production times. These results are in line with the results presented in Case Study 2. The introduction of EVs and HVAC systems can also be seen in Figure operational modes. In reality, their effect would be enhanced if more parking lots and HVAC in commercial buildings are considered since in the current study they are a minority.

Table 4.2 - Profit and costs (case study 3)

	Profit (€)	PSC (€)	TVPP (€)
Case Study 1	16285,80	44091,62	28498,09
Case Study 2	29791,10	44783.89	14992,79
Case Study 3	32078,58	44783.89	12705,30

The EVs management and scheduling are based on charging and discharging cycles during the day based on demand, market price, and charging and discharging limits through the coordination between the TVPP and these vehicles to charge or discharge. The objective is to maximize the profit while still allowing the EVs to be used by their owners. This optimization results from the pre-optimization of the optimal cost of commercial buildings, using DR programs, together with the operation of the commercial buildings, through the control of the EV's in the parking lots and the management of the HVAC. In Figure 4.10, the aggregation and TOU price output of the EV's is presented. The blue bars in Figure 4.10 illustrate the charging period of the EVs which occurs while the TOU price is at its minimum which occurs at night as the cars are less likely to be used during this period. This ensures that the maximum battery charge is available for the next day either for driving or to be used in the V2G mode. The discharge cycles occur mainly during working hours and when the TOU price (grey line) is at its highest during the day as it is ideal to supply energy because there is high demand with a higher price, allowing for better results and maximize profit. Note that the orange bars continue from 20:00 to 22:00 despite TOU price being lower but it is during this period that the demand and market price are at their daily peak making it ideal to continue discharging for even greater efficiency, compensation, and cost reduction.

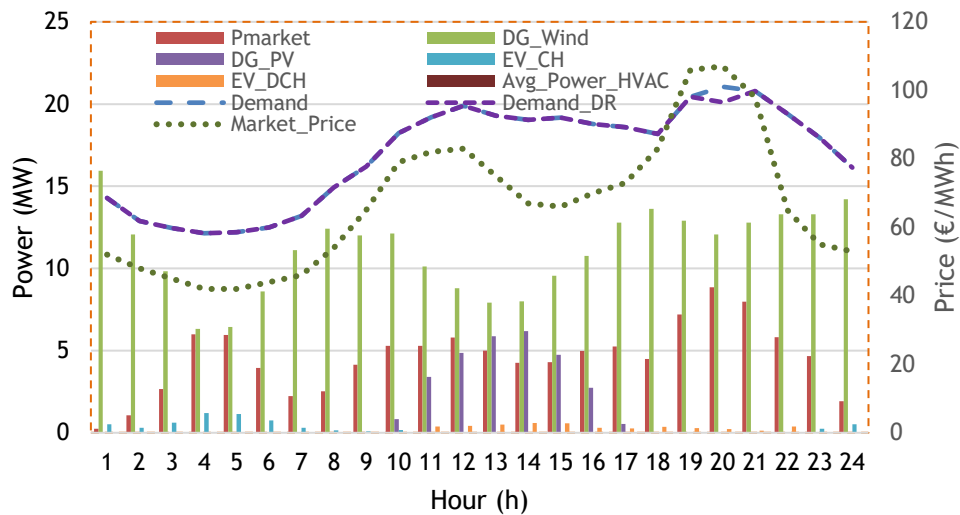


Figure 4.9 - Day-ahead schedule (case study 3)

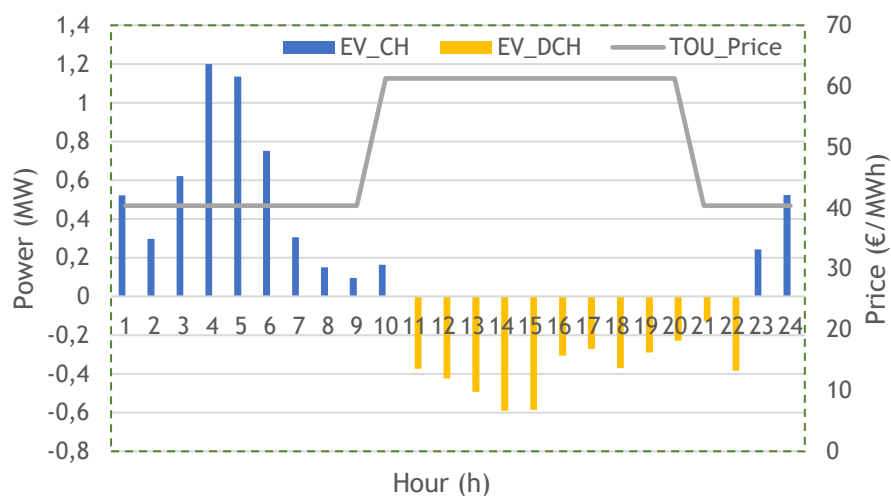


Figure 4.10 - EVs charge/discharge cycles

In Case Study 3, the HVAC system works as a cooling solution to provide a pleasant work environment for workers. As Figure 4.11 suggests, during the night time the system is turned off and is activated early in the morning, 07:00, where it starts its function of improving the air conditions. The blue bars show how much power the system is using to keep the temperature at 19°C, the absence of consumption at some points is justified by the air thermal capacity which can be translated as the ability to maintain the ideal conditions. During office hours, the temperature is always kept at its minimum except for variations caused by savings (made by reducing power consumption) that create slight increases in the temperature or by operating at maximum consumption followed by turning off the system for some hours due to peak demand and therefore peak price and is expensive to have them on as they represent a large amount of commercial buildings load and consumption (approximately 47%). When the system is off due to peak load/price concerns, the temperature rises to its maximum allowed and then the system comes back on to ensure higher savings without disregarding workers' comfort. These fluctuations are represented by the orange line oscillating between the minimum and maximum temperature.

Regarding the voltage profile deviation, Case Study 3 is on pair with Case Study 2, as Figure 4.12 shows that their profiles are very closely matched achieving a maximum voltage deviation 52,50% lower than case study 1. This is due to the beneficial effect on network usage, demand DR, EVs, and HVAC systems management from the various DGs. Local generation applied to commercial customers' appliances results in benefits for the grid while TVPP operator reduces costs even further with all loads being supplied with greater efficiency which creates even more appealing financial results.

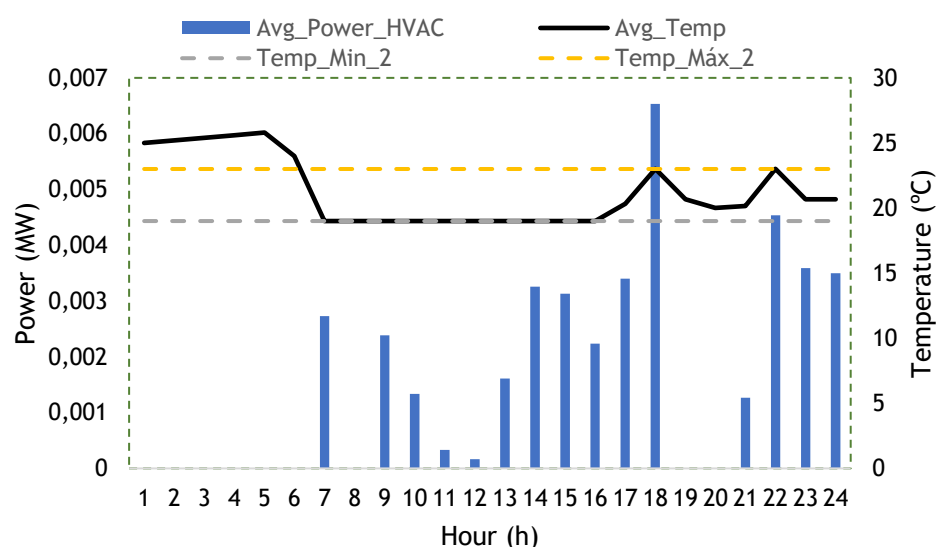


Figure 4.11 - HVAC system activity (standard range)

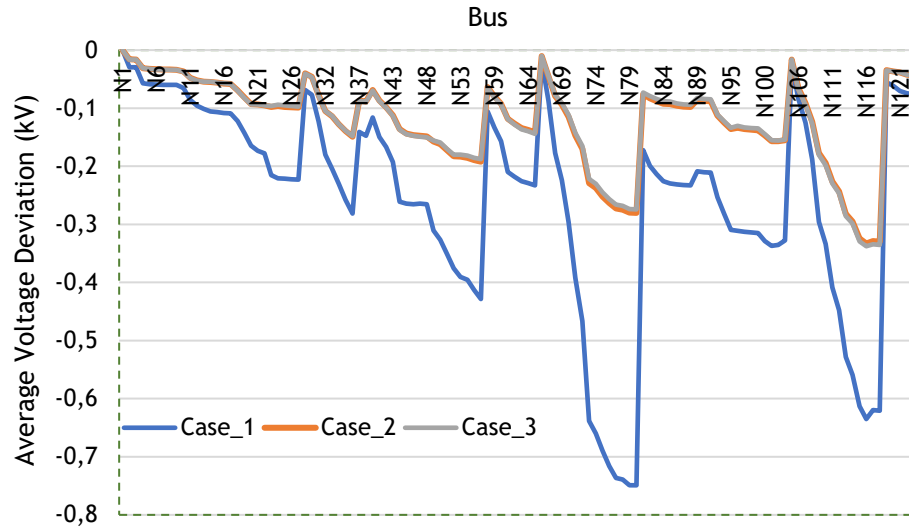


Figure 4.12 - Voltage deviation of all case studies

4.3.1 Case Study 3: Narrower Temperature Range

In this section, the impact of reducing the operating range of HVAC temperatures will be assessed. The temperature range previously seen can be adapted according to specifications of comfort rather than savings and in this case, the allowable temperatures range from 20°C to 22°C. This causes the profit to be slightly lower with the same power sold to the load and an increase of 1,50% in the VPP costs. The increase in costs is due to the need to have the system on for longer to deliver the ambient conditions required meaning the power consumed will also increase making it expensive to run especially during the hourly periods when the price is high as seen in Figure 4.13. In comparison with the case where the temperatures are allowed to range between 19°C to 23°C the power used is 13.11% lower than this case. This is because extra running hours and more power consumption translate to higher costs. This new temperature range does not affect the electric system's operational parameters, so it is considered the same conditions as case study 3 for voltage deviation.

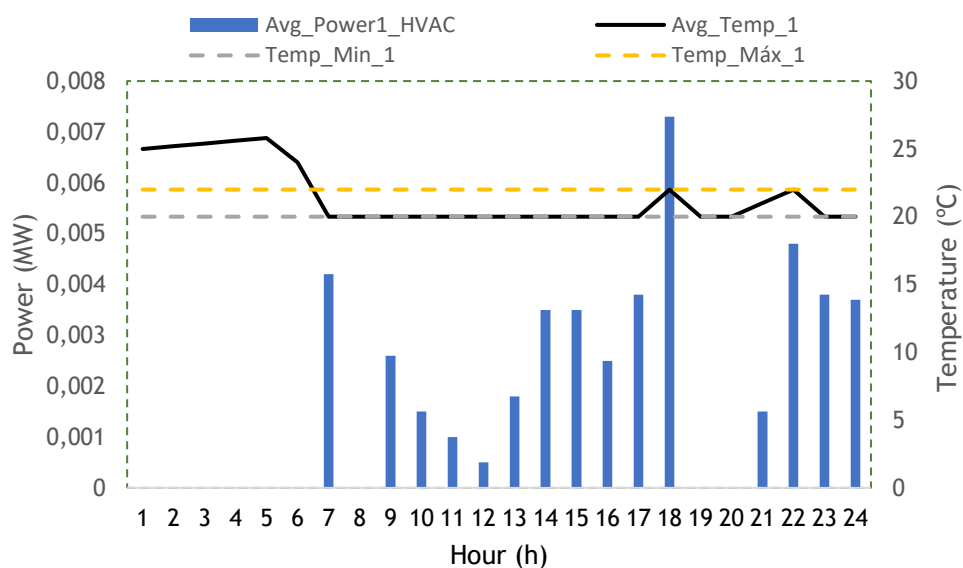


Figure 4.13 - HVAC system activity (narrow range)

4.3.2 Case Study 3: Wider Temperature Range

In this section, the impact of increasing the allowable operating range of the HVAC temperatures will be assessed. The temperature range previously seen was adapted according to specifications of savings over comfort and in this case, the allowable range is now from 18°C to 24°C, allowing for more flexible management to increase savings and reduce cost. This means profit will be higher than both of the previous configurations, being 2,70% better than the original case study 3 and 3,28% better than the stricter temperature gap case. All three have the same power sold to the load and the main difference is from the TVPP imposed cost, where having the temperature between 18°C and 24°C accounts for a 7% reduction compared to the main in Case Study 3 and 8,37% compared to the previous case in the VPP costs. The increase in costs is caused by the flexibility of having the system temperature variation wider, which allows the system to consume less power and being switched off for longer to deliver the ambient conditions required. Less HVAC system power usage and off for longer periods means a lower price to pay when operational and the ability to avoid running it during peak demand and peak price, resulting in lower costs. The temperature evolution throughout the day and on/off periods can be seen in Figure 4.14. The comparison of the three cases can be seen in Figure 4.15. In comparison with temperature ranging from 19°C to 23°C power used in this range is 15,80% higher. Extra running hours to keep the temperature between 20°C and 22°C means more power consumption and that translates to higher costs with this case saving 25,96% of the power used.

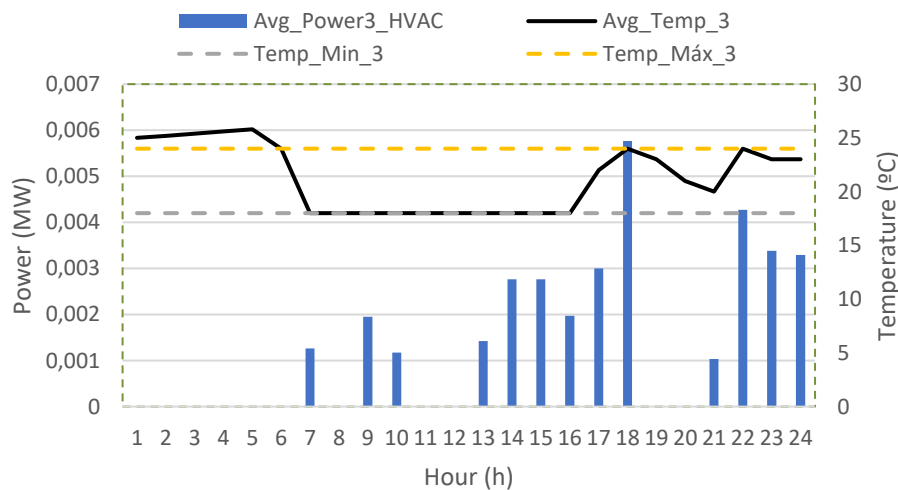


Figure 4.14 - HVAC system activity (wide range)

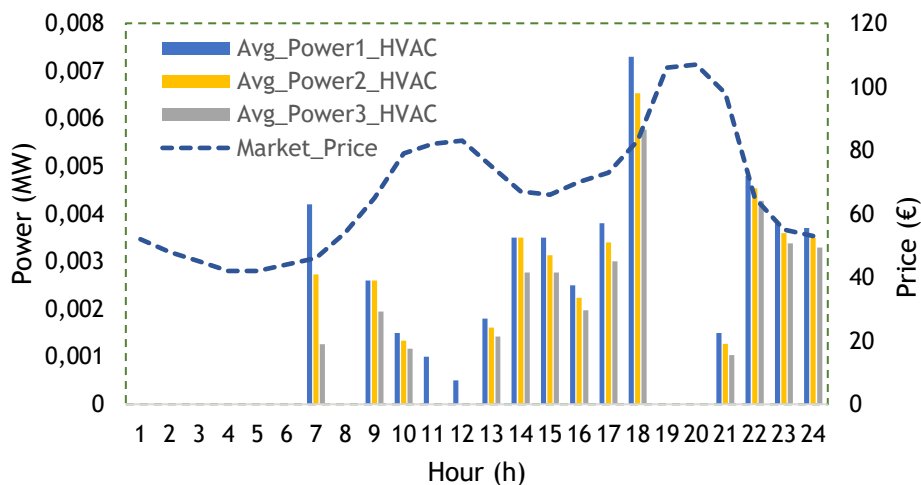


Figure 4.15 - HVAC system comparison

Having analysed all case 3 variations according to temperature range it is possible to conclude that it is a matter of agreement between the consumer and the VPP operator to achieve great efficiency and minimum costs to improve VPP profit and to lower the commercial consumer bill without compromising safe and healthy air conditions at the working place.

4.6-Chapter Summary

Firstly, Chapter 4 has described the data of the system under consideration, the assumptions made and the different scenarios that allow an analysis of the TVPP operational modes. Then, the model was tested using an analysis of the operations considering various technical characteristics, decision variables, and different issues. A MILP operation model was presented that aims to identify ideal management, operation conditions, and the correlation between assets and the overall result to be implemented to benefit the consumers, the aggregator, and the electric system while improving environmental outcomes. The results show the economic benefits of the TVPP's operation for all concerned agents considering the technical constraints and user demand profiles. Various trade-offs between comfort and cost savings were discussed. The TVPP showcases a model that can bring several benefits not only to the system operation but also to all other levels regarding energy consumption.

The developed work also studied the optimization of different TVPP assets, mainly EVs and HVAC systems, considering usability, comfort, and cost. The decision of selecting the best strategy (based on profit maximization) was made after all different perspectives were consulted. From the results, it was possible to define objectives and trends to obtain the ideal result while considering all variables.

Chapter 5

Conclusions and Future Works

This chapter describes the main conclusions of this dissertation, as well as some potential future research areas that could be done in order to extend the study on commercial demand-response in VPP and its exploitation. Finally, the contributions of this work are highlighted by presenting the publication, a result of this dissertation work

5.1 Conclusions

Considering the potential of activating commercial consumers in demand response programs, this work proposes a new framework for energy scheduling of a distribution grid based on the concept of a technical virtual power plant (TVPP). This concept aims to enhance the flexibility of the grid, while contributing to an increase in the quality and reliability of the system, which also brings economic benefits. In this work, a stochastic mixed-integer linear programming (MILP) optimization model was presented, which guarantees that the global optimum solution is obtained, in this case, maximizing the total profit of a TVPP. Regarding operational constraints, the TVPP allows the presence of commercial buildings and other distributed energy resources a day-ahead (DA) electricity market, as a price maker agent.

In this work, several studies were made. The first one carried out an analysis on the standard operational grid to establish a benchmark to act as a comparison for the other case studies. Then the concept and contributions of a VPP are introduced in the second case study, which included the integration of DG from RES. The third study case used higher levels of DG, and the management of commercial customers' EVs and HVAC systems while participating in DR programs for better market performance. To perform this analysis an improved stochastic MILP was used to obtain numerical results and tested on a 119 bus test system to assess the impact of the VPP. The work showed that:

- The positive contribution from the VPP in terms of DG integration was seen from the analysis of the voltage deviations as the VPP increases flexibility in the connected grid and therefore increases reliability and lowers costs. This can be seen in the comparison between Case 2 and Case 1 where the system had a cost reduction of 47,39% achieved by the integration of DG;

- DR participation from commercial customers allows for an improved consumption profile. Additionally, it allows for the possibility of load shedding from peak hours due to the control of EVs and HVAC systems and this helped to reduce the operation costs and avoid penalties. Also, this joint management of resources, as seen in case 3, allows the TVPP to increase the profit by 49.23% in relation to case study 1 and by 7,13% in relation to case study 2;
- The study of the operational regime of the HVAC systems showed the possibility of further cost reductions based on flexible operating temperature ranges. The results show that the use of a larger temperature range can translate to savings of approximately 25,96% of the power used by this type of consumer;
- The results of the analysis show the overall benefits of a TVPP connected between the grid and the end consumer while allowing the TVPP to maximize profit as well as improving energy efficiency and better environmental outcomes.

In summary, the electrical system is subject to great change through the integration of various DER assets. A TVPP can operate and control these assets in a manner that brings significant benefits to the system, the consumers as well as the TVPP operator.

5.2 Future works

Possible future research can investigate:

- To use a more complex system considering several end consumers and DG units at each node;
- To increase the number of commercial customers, HVAC systems, parking lots (with even more capacity), and other controllable assets (lighting, for example);
- To add sensibility analysis or other variables that influence the compromise between cost and usability.

5.3 Works Resulting from this Dissertation

This thesis abstract was submitted as “Commercial Demand Response in Virtual Power Plants” in: Proceedings of the 2021: *International Conference on Smart Energy Systems and Technologies – SEST 2021* (technically co-sponsored by IEEE), Vaasa, Finland, 6-8 September, 2021

Appendix A

A.1 IEEE 119 Bus Distribution Test System Data - Lines

Line	From	To	R [Ω]	X [Ω]	Line Capacity [MVA]
Line 1	1	2	0,036	0,01296	13,2
Line 2	2	3	0,033	0,01188	4,4
Line 3	2	4	0,045	0,0162	13,2
Line 4	4	5	0,015	0,054	8,8
Line 5	5	6	0,015	0,054	8,8
Line 6	6	7	0,015	0,0125	8,8
Line 7	7	8	0,018	0,014	4,4
Line 8	8	9	0,021	0,063	4,4
Line 9	2	10	0,166	0,1344	4,4
Line 10	10	11	0,112	0,0789	4,4
Line 11	11	12	0,187	0,313	4,4
Line 12	12	13	0,142	0,1512	4,4
Line 13	13	14	0,18	0,118	4,4
Line 14	14	15	0,15	0,045	4,4
Line 15	15	16	0,16	0,18	4,4
Line 16	16	17	0,157	0,171	4,4
Line 17	11	18	0,218	0,285	4,4
Line 18	18	19	0,118	0,185	4,4
Line 19	19	20	0,16	0,196	4,4
Line 20	20	21	0,12	0,189	4,4
Line 21	21	22	0,12	0,0789	4,4
Line 22	22	23	1,41	0,723	4,4
Line 23	23	24	0,293	0,1348	4,4
Line 24	24	25	0,133	0,104	4,4
Line 25	25	26	0,178	0,134	4,4
Line 26	26	27	0,178	0,134	4,4

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Line	From	To	R [Ω]	X [Ω]	Line Capacity [MVA]
Line 27	4	29	0,015	0,0296	8,8
Line 28	29	30	0,012	0,0276	8,8
Line 29	30	31	0,12	0,2766	8,8
Line 30	31	32	0,21	0,243	4,4
Line 31	32	33	0,12	0,054	4,4
Line 32	33	34	0,178	0,234	4,4
Line 33	34	35	0,178	0,234	4,4
Line 34	35	36	0,154	0,162	4,4
Line 35	31	37	0,187	0,261	4,4
Line 36	37	38	0,133	0,099	4,4
Line 37	30	40	0,33	0,194	4,4
Line 38	40	41	0,31	0,194	4,4
Line 39	41	42	0,13	0,194	4,4
Line 40	42	43	0,28	0,15	4,4
Line 41	43	44	1,18	0,85	4,4
Line 42	44	45	0,42	0,2436	4,4
Line 43	45	46	0,27	0,0972	4,4
Line 44	46	47	0,339	0,1221	4,4
Line 45	47	48	0,27	0,1779	4,4
Line 46	36	49	0,21	0,1383	4,4
Line 47	49	50	0,12	0,0789	4,4
Line 48	50	51	0,15	0,0987	4,4
Line 49	51	52	0,15	0,0987	4,4
Line 50	52	53	0,24	0,1581	4,4
Line 51	53	54	0,12	0,0789	4,4
Line 52	54	55	0,405	0,1458	4,4
Line 53	54	56	0,405	0,1458	4,4
Line 54	30	58	0,391	0,141	4,4
Line 55	58	59	0,406	0,1461	4,4
Line 46	59	60	0,406	0,1461	4,4
Line 57	60	61	0,706	0,5461	4,4
Line 58	61	62	0,338	0,1218	4,4
Line 59	62	63	0,338	0,1218	4,4
Line 60	63	64	0,207	0,0747	4,4
Line 61	64	65	0,247	0,8922	4,4
Line 62	1	66	0,028	0,0418	13,2
Line 63	66	67	0,117	0,2016	13,2

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Line	From	To	R [Ω]	X [Ω]	Line Capacity [MVA]
Line 64	67	68	0,255	0,0918	8,8
Line 65	68	69	0,21	0,0759	4,4
Line 66	69	70	0,383	0,138	4,4
Line 67	70	71	0,504	0,3303	4,4
Line 68	71	72	0,406	0,1461	4,4
Line 69	72	73	0,962	0,761	4,4
Line 70	73	74	0,165	0,06	4,4
Line 71	74	75	0,303	0,1092	4,4
Line 72	75	76	0,303	0,1092	4,4
Line 73	76	77	0,206	0,144	4,4
Line 74	77	78	0,233	0,084	4,4
Line 75	78	79	0,591	0,1773	4,4
Line 76	79	80	0,126	0,0453	4,4
Line 77	67	81	0,559	0,3687	8,8
Line 78	81	82	0,186	0,1227	8,8
Line 79	82	83	0,186	0,1227	4,4
Line 80	83	84	0,26	0,139	4,4
Line 81	84	85	0,154	0,148	4,4
Line 82	85	86	0,23	0,128	4,4
Line 83	86	87	0,252	0,106	4,4
Line 84	87	88	0,18	0,148	4,4
Line 85	82	89	0,16	0,182	4,4
Line 86	89	90	0,2	0,23	4,4
Line 87	90	91	0,16	0,393	4,4
Line 88	68	93	0,669	0,2412	4,4
Line 89	93	94	0,266	0,1227	4,4
Line 90	94	95	0,266	0,1227	4,4
Line 91	95	96	0,266	0,1227	4,4
Line 92	96	97	0,266	0,1227	4,4
Line 93	97	98	0,233	0,115	4,4
Line 94	98	99	0,496	0,138	4,4
Line 95	95	100	0,196	0,18	4,4
Line 96	100	101	0,196	0,18	4,4
Line 97	101	102	0,1866	0,122	4,4
Line 98	102	103	0,0746	0,318	4,4
Line 99	1	105	0,0625	0,0265	8,8
Line 100	105	106	0,1501	0,234	8,8

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Line	From	To	R [Ω]	X [Ω]	Line Capacity [MVA]
Line 101	106	107	0,1347	0,0888	8,8
Line 102	107	108	0,2307	0,1203	4,4
Line 103	108	109	0,447	0,1608	4,4
Line 104	109	110	0,1632	0,0588	4,4
Line 105	110	111	0,33	0,099	4,4
Line 106	111	112	0,156	0,0561	4,4
Line 107	112	113	0,3819	0,1374	4,4
Line 108	113	114	0,1626	0,0585	4,4
Line 109	114	115	0,3819	0,1374	4,4
Line 110	115	116	0,2445	0,0879	4,4
Line 111	115	117	0,2088	0,0753	4,4
Line 112	117	118	0,2301	0,0828	4,4
Line 113	105	119	0,6102	0,2196	4,4
Line 114	119	120	0,1866	0,127	4,4
Line 115	120	121	0,3732	0,246	4,4
Line 116	121	122	0,405	0,367	4,4
Line 117	122	123	0,489	0,438	4,4
Line 118	48	27	0,5258	0,2925	4,4
Line 119	17	27	0,5258	0,2916	4,4
Line 120	8	24	0,4272	0,1539	4,4
Line 121	56	45	0,48	0,1728	4,4
Line 122	65	56	0,36	0,1296	4,4
Line 123	38	65	0,57	0,572	4,4
Line 124	9	42	0,53	0,3348	4,4
Line 125	61	100	0,3957	0,1425	4,4
Line 126	76	95	0,68	0,648	4,4
Line 127	91	78	0,4062	0,1464	4,4
Line 128	103	80	0,4626	0,1674	4,4
Line 129	113	86	0,651	0,234	4,4
Line 130	110	89	0,8125	0,2925	4,4
Line 131	115	123	0,7089	0,2553	4,4
Line 132	25	36	0,5	0,5	4,4

A.2 IEEE 119 Bus Distribution Test System Data - Nodes

Node	PI [MW]	QI [MVar]	Node	PI [MW]	QI [MVar]
1	-	-	33	0,4753	0,4561
2	0,1338	0,1011	34	0,1514	0,1368
3	0,0162	0,0113	35	0,2054	0,0833
4	0,0343	0,0218	36	0,1316	0,0931
5	0,0730	0,0636	37	0,4484	0,3698
6	0,1442	0,0686	38	0,4405	0,3216
7	0,1045	0,0617	39	0,0000	0,0000
8	0,0285	0,0115	40	0,1125	0,0551
9	0,0875	0,0511	41	0,0540	0,0390
10	0,1982	0,1068	42	0,3931	0,3426
11	0,1468	0,0760	43	0,3267	0,2786
12	0,0260	0,0187	44	0,5363	0,2402
13	0,0521	0,0232	45	0,0762	0,0666
14	0,1419	0,1175	46	0,0535	0,0398
15	0,0219	0,0288	47	0,0403	0,0320
16	0,0334	0,0265	48	0,0397	0,0208
17	0,0324	0,0252	49	0,0662	0,0424
18	0,0202	0,0119	50	0,0739	0,0517
19	0,1569	0,0785	51	0,1148	0,0580
20	0,5463	0,3514	52	0,9184	1,2051
21	0,1803	0,1642	53	0,2103	0,1467
22	0,0932	0,0546	54	0,0667	0,0566
23	0,0852	0,0397	55	0,0422	0,0402
24	0,1681	0,0952	56	0,4337	0,2834
25	0,1251	0,1502	57	0,0000	0,0000
26	0,0160	0,0246	58	0,0621	0,0269
27	0,0260	0,0246	59	0,0925	0,0884
28	0,0000	0,0000	60	0,0852	0,0554
29	0,5946	0,5226	61	0,3453	0,3324
30	0,1206	0,0591	62	0,0225	0,0168
31	0,1024	0,0996	63	0,0806	0,0492
32	0,5134	0,3185	64	0,0959	0,0908

Node	PI [MW]	QI [MVar]	Node	PI [MW]	QI [MVar]
65	0,0629	0,0477	93	0,0629	0,0430
66	0,4788	0,4637	94	0,0307	0,0349
67	0,1209	0,0520	95	0,0625	0,0668
68	0,1391	0,1001	96	0,1146	0,0817
69	0,3918	0,1935	97	0,0813	0,0665
70	0,0277	0,0267	98	0,0317	0,0160
71	0,0528	0,0253	99	0,0333	0,0605
72	0,0669	0,0387	100	0,5313	0,2249
73	0,4675	0,3951	101	0,5070	0,3674
74	0,5949	0,2397	102	0,0264	0,0117
75	0,1325	0,0844	103	0,0460	0,0304
76	0,0527	0,0225	104	0,0000	0,0000
77	0,8698	0,6148	105	0,1007	0,0476
78	0,0313	0,0298	106	0,4565	0,3503
79	0,1924	0,1224	107	0,5226	0,4493
80	0,0658	0,0454	108	0,4084	0,1685
81	0,2382	0,2232	109	0,1415	0,1343
82	0,2946	0,1625	110	0,1044	0,0660
83	0,4856	0,4379	111	0,0968	0,0836
84	0,2435	0,1830	112	0,4939	0,4193
85	0,2435	0,1830	113	0,2254	0,1359
86	0,1343	0,1193	114	0,5092	0,3872
87	0,0227	0,0280	115	0,1885	0,1735
88	0,0495	0,0265	116	0,9180	0,8986
89	0,3838	0,2572	117	0,3051	0,2154
90	0,0496	0,0206	118	0,0544	0,0410
91	0,0225	0,0118	119	0,2111	0,1929
92	0,0000	0,0000	-	-	-

A.3 IEEE 119 Bus Distribution Test System Data - DG quantity

Node	Photovoltaic	Wind
14	-	1
19	-	1
20	-	2
24	-	1
32	1	1
33	-	1
34	-	1
37	-	1
38	1	1
42	-	2
52	-	2
53	-	1
61	-	1
69	-	1
73	-	1
74	-	1
77	-	1
79	-	1
82	-	1
83	-	1
85	-	1
89	-	1
96	-	1
101	-	2
106	-	1
108	-	1
112	-	1
114	-	1
116	-	3
117	-	1
119	-	1

A.4 IEEE 119 Bus Distribution Test System Data - EVs Parking Lots and HVAC Systems

Node	Wind
20	1
29	2
33	1
43	1
52	2
56	1
61	1
66	1
69	1
73	1
77	1
83	1
89	1
100	1
107	1
112	1
116	1

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