FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

P2P Market Transactions Congestion Impact on the Distribution Network Considering Physical Constraints

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Resumo

Nos últimos anos, o aumento de consumidores ativos na rede de distribuição, transformaram a estrutura de mercado numa estrutura mais moderna, independente, flexível e distribuída. A nova tendência de transações peer-to-peer (P2P) nos sistemas de energia, onde consumidores tradicionais se transformam em prosumers que podem maximizar a utilização de energia, partilhando-a com os seus vizinhos. A presença de mecanismos P2P desempenha também um papel fundamental na difusão de fontes de energia renováveis na rede. Assim, emerge o mercado P2P onde prosumers e consumidores podem fazer transações de energia sem nenhuma arbitragem convencional no processo de transação. Porém, embora as transações de energia locais permitam a existência de redes mais descentralizadas e abertas, estes modelos têm um impacto significativo no controlo, operação e planeamento da rede de distribuição.

Neste trabalho é apresentado um modelo melhorado com o objetivo de avaliar o impacto das transações P2P no congestionamento da rede de distribuição, onde as restrições da rede de distribuição são consideradas bem como a incerteza associada aos recursos renováveis e à carga. A função objetivo foi modelada para minimizar os custos com as transações de cada consumidor/prosumer. Assim, foi desenvolvida uma ferramenta computacional para alcançar o objetivo estabelecido. Esta ferramenta foi validada utilizando um ramo adaptado do sistema de teste IEEE 119 bus, na qual foram considerados diferentes situações operacionais em três casos de estudo, considerando diferentes tecnologias renováveis e sistemas de armazenamento de energia instaladas em cada consumidor e/ou prosumer.

Nesse sentido, a dissertação apresenta uma análise alargada relativa ao impacto dos mercados energéticos P2P no sistema de distribuição, em particular em termos de custos, congestionamentos e perfis de tensão. Os resultados da simulação indicam que a introdução de tecnologias facilitadoras das smart grids levou a benefícios técnicos e económicos tanto para a rede de distribuição como para os seus utilizadores. Nomeadamente com: uma redução nos custos para cada utilizador, uma melhoria na qualidade dos perfis de tensão, redução no congestionamento bem como um alisamento do perfil de carga da comunidade, da perspetiva da rede.

Palavras-chave: Comunidades de Energia, Congestionamento na Rede de Distribuição, Fontes de Energia Renovável, Geração distribuída, Limites da Rede, Qualidade dos perfis de tensão, Rede de Distribuição, Tecnologias Facilitadoras das Smart Grids, Transações Peer to Peer

Abstract

In recent years the increasing number of consumers participating in the distribution grid has motivated the transformation of the energy market's structure into a more modern, independent, flexible and decentralised system. The novel trend of peer to peer (P2P) transactions has allowed traditional consumers to become prosumers, capable of maximising the usage of their energy production by sharing it with their neighbours. The P2P mechanisms also play a fundamental role in promoting the deployment of renewable energy sources (RES) throughout the grid. Thus, the P2P market has emerged to allow both prosumers and consumers to trade energy independently from the conventional market. However, while local energy transactions will allow for a more open and decentralised grid, it will nevertheless have a significant impact on the planning, control and operation of distribution grids.

In this work an improved model is presented to evaluating the impact of P2P transactions on distribution grid congestion, considering its restrictions and the uncertainty associated with RES generation and load are thoroughly considered. The objective function has been modelled to minimise the transaction costs of each prosumer/consumer. Accordingly, a computational tool has been developed. The validity of this tool was tested on a branch adapted from a 119-bus IEEE test grid, in which different operational scenarios have been considered through 3 case studies, taking into account the different RES technologies and energy storage systems installed by each prosumer/consumer.

Summary, this dissertation presents a broad analysis of the impact of P2P energy markets on the distribution grid, particularly in terms of costs, congestion and voltage profiles. Simulation results indicate that the introduction of smart grid enabling technologies and P2P transactions has led to both technical and economic benefits for the distribution grid and its users, with: reduced costs for all users, improved voltage quality, reduced congestion, and the overall flattening of the community's load profile.

Keywords: Distributed Generation, Distribution Network, Distribution Network Congestion, Energy Community, Grid Constraints, Renewable Energy Sources, Smart Grid Enabling Technologies, Voltage Quality, Peer-to Peer Transactions

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The making of this body of work would not have been possible without the aid and collaboration of several people, to whom I express my most sincere gratitude.

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José Branco

“The mind commands the body and it obeys.
The mind orders itself and meets resistance”

Frank Herbert

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Abbreviations and symbols

List of abbreviations

ADMM	Alternating Direction Method of Multipliers Algorithm
BSS	Battery Storage Systems
BESS	Battery Energy Storage Systems
CES	Customer-owned Energy Storage Systems
DER	Distributed Energy Resources
DG	Distribution Grid
DG	Distributied Generation
DSSE	Distribution System State Estimation
DW	Dish Washer
EENS	Energy not Supplied
EMS	Energy Management System
ESS	Energy Storage Systems
EV	Electric Vehicle
DSSE	Distribution System State Estimation
GSFTO	Golden Section Fibonacci Tree Optimisation
HEM/HEMS	Home Energy Management System
HILP	High-Impact Low-Probability
HVAC	Heating, Ventilation and Air-Conditioning system
ISO	Independent System Operator
LP	Linear Programming
MDP	Makarov Dicision Process
MIP	Mixed-Integer Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MIQCP	Miexed Integer Quadratically Constrained Program
MV	Medium Voltage
NN	Neural Network
P2P	Peer-to-Peer
PV	Photovoltaic
RES	Renewable Energy Sources
SFLA	Shuffled frog leaping algorithm
SMILP	Stochastic Mixed Integer Linear Programming
SOC	State of Charge
SoH	State of Health
TE	Transactive Energy
UML	Unified Modelling Language

V2G	Vehicle to Grid
VSI	Voltage Stability Index
VED	Virtual Energy District
VPP	Virtual Power Plant
WM	Washing Machine

List of symbols

Sets/ Indices

$t \in \Omega^T$	Time period
$s \in \Omega^S$	Scenarios
$w \in \Omega^W$	Prosumer w
$c \in \Omega^C$	Controllable loads c= {HVAC, dish washer, washing machine}
$f \in \Omega^F$	Variable operating fazes of the controllable loads
$k \in \Omega^k$	Branch set/index
$es \in \Omega^{es}$	Energy storage systems (ESSs) set/index
$i \in \Omega^i$	Bus set/index

Parameters

$CE^{ESS}_{w,s}$	Prosumer *w*'s ESS's charging efficiency
$CE^{EV}_{w,s}$	Prosumer *w*'s EV's charging efficiency
$\eta^{ESS,des}_{w,s}$	Prosumer *w*'s ESS's discharging efficiency
$\eta^{EV,des}_{w,s}$	Prosumer *w*'s EV's discharging efficiency
$P^{inflexibleload}_{w,t,s}$	Prosumer *w*'s inflexible load for time period t [kW]
N	Parameter which imposes restrictions on grid purchase as a complementary strategy to demand responce
$N_{w,c,s}$	Operational periods of prosumer *w*'s controllable load c
$P^{fase}_{w,f,c,s}$	Power consumed by prosumer *w*'s controllable load c during phase f [kW]
$P^{PV,gem}_{w,t,s}$	Power produced by prosumer *w*'s PV system during period t [kW]
$R^{ESS,charging}_{w,s}$	Prosumer *w*'s ESS's rate of charge [kW]
$R^{ESS,discharging}_{w,s}$	Prosumer *w*'s ESS's rate of discharge [kW]
$R^{EV,charging}_{w,s}$	Prosumer *w*'s EV's rate of charge [kW]
$R^{EV,discharging}_{w,s}$	Prosumer *w*'s EV's rate of discharge [kW]
g_k, b_k, S^{max}_k	Branch k: conductance, susceptance and flow limit [S,S,MVA]
R_k, X_k	Branch k: Resistance and Reactance [Ω,Ω]
MP_k, MQ_k	M parameters related to active and reactive power flows on branch k
$SOC^{ESS}_{t,w,s}$	Prosumer *w*'s ESS's initial state of charge [kWh]
$SOC^{ESS,max}_{t,w,s}$	Prosumer *w*'s ESS's maximum state of charge [kWh]
$SOC^{ESS,min}_{t,w,s}$	Prosumer *w*'s ESS's minimum state of charge [kWh]
$SOC^{EV,ini}_{t,w,s}$	Prosumer *w*'s EV's initial state of charge [kWh]
$SOC^{EV,max}_{t,w,s}$	Prosumer *w*'s EV's maximum state of charge [kWh]
$SOC^{EV,min}_{t,w,s}$	Prosumer *w*'s EV's minimum state of charge [kWh]

$T^{a}_{w,s}$	Prosumer *w*'s EV's time of arrival
$T^{d}_{w,s}$	Prosumer *w*'s EV's time of departure
$T^{dur}_{w,f,c,s}$	Duration of phase *f* of prosumer *w*'s controllable load *c* [Δt - hours]
$\lambda^{bought}_{t,s}$	Energy purchasing price [€/ MWh]
$\lambda^{sold}_{t,s}$	Energy selling price [€/ MWh]
ΔT	Duration of time period *t*

Variables

$P^{bought,grid}_{w,t,s}$	Power bought from the grid by prosumer *w* during time period *t* [kW]
$P^{bought,local}_{w,t,s}$	Power bought from the neighbourhood by prosumer *w* during time period *t* [kW]
$P^{bought,T}_{w,t,s}$	Total by prosumer *w* during time period *t* [kW]
$P^{ESS,charging}_{w,t,s}$	Charging power of prosumer *w*'s ESS during time period *t* [kW]
$P^{ESS,discharging}_{w,t,s}$	Discharging power of prosumer *w*'s ESS during time period *t* [kW]
$P^{EV,charging}_{w,t,s}$	Charging power of prosumer *w*'s EV during time period *t* [kW]
$P^{EV,discharging}_{w,t,s}$	Discharging power of prosumer *w*'s EV during time period *t* [kW]
$P^{ESS,used}_{w,t,s}$	Power used for self-consumption from prosumer *w*'s ESS during time period *t* [kW]
$P^{EV,used}_{w,t,s}$	Power used for self-consumption from prosumer *w*'s EV during time period *t* [kW]
$P^{appliance}_{w,t',c,s}$	Power used by prosumer *w*'s controllable load *c* during time period *t* [kW]
$P^{PV,used}_{w,h,s}$	Power used for self-consumption from prosumer *w*'s PV system during time period *t* [kW]
$P^{sold,ESS}_{w,t,s}$	Power discharged by prosumer *w*'s ESS, sold to the grid or neighbourhood, during time period *t* [kW]
$P^{sold,grid}_{w,t,s}$	Power injected into the grid by prosumer, and which flows back into the grid *w* during time period *t* [kW]
$P^{sold,EV}_{w,t,s}$	Power discharged by prosumer *w*'s EV, sold to the grid or neighbourhood, during time period *t* [kW]
$P^{sold,local}_{w,t,s}$	Power injected into the grid by prosumer *w* which is sold in the neighbourhood during time period *t* [kW]
$P^{sold,PV}_{w,t,s}$	Power from prosumer *w*'s PV system, sold to the grid or neighbourhood, during time period *t* [kW]
$P^{sold,T}_{w,t,s}$	Total power injected into the grid by prosumer *w* during time period *t* [kW]
$P^{NS}_{t,s,i}$	Active power not supplied on bus *i* [kW]
$P_{k,s,t}$	Active power flow on branch *k* [kW]
$PL_{k,s,t}$	Active power losses on branch *k* [kW]
$V_{i,s,t}, V_{j,s,t}$	Voltage magnitude on busses *i* and *j* [V]
V_{nom}	Nominal system voltage [V]
$u_{k,t}$	Change of (binary) variables on existing branches
$SOC^{ESS}_{t,w,s}$	State of charge of prosumer *w*'s ESS during time period *t* [kWh]
$SOC^{EV}_{t,w,s}$	State of charge of prosumer *w*'s EV during time period *t* [kWh]

$x^2_{w,s,t'}$	Binary variable: 1 if: power flows from the grid to prosumer *w*/ its EV is charging; if else: 0
$x^3_{w,s,t'}$	Binary variable: 1 if: power flows from the grid to prosumer *w*/ its ESS is charging; if else: 0
$x^{fase}_{w,t,f,c,s}$	Binary variables: 1 if the operation faze of prosumer *w*'s controllable load *c* is startup/ongoing/finishing ($x = \{y, u, z\}$) for period *t*; if else: 0

Chapter 1

Introduction

This chapter presents a brief introduction to the topic, covering the background, problem definition and the research objectives. Furthermore, the methodology used as well as the structure of this dissertation are also presented.

1.1 Background

The past decade has seen increased public' awareness of the damage that will be caused by climate change, which has pressured governments and businesses to decarbonize the economy [1]. The electricity sector is key to shift. Traditionally, electricity distribution systems have been viewed through a hierarchical, unidirectional framework, where power is centrally generated in large, fossil-powered plants before being transmitted and distributed to low-level consumers.

However, recently, advances in renewable generation and telecommunications have allowed a new market participant to emerge, an active consumer or 'prosumer', that can generate its own power supply and address some of its energy demand [2]. Consequently, peer-to-peer (P2P) markets have been developed to allow prosumers to trade energy independently from the conventional market [3]. Moreover, the presence of many prosumers can not only facilitate the deployment of renewable energy sources (RESs), at a small scale by increasing the economic viability of small RES installations, but also at a larger scale by allowing energy demand to fluctuate more and better match the variable and uncertain nature of renewable energy generation [4]. In addition, P2P transactions can affect distribution grid operation; however, whether this impact is positive or negative remains unclear. Ultimately, this new kind of energy system has shown great potential, as it is more decentralised, independent and flexible while promoting the deployment of more RESs.

1.2 Problem definition

With the ever-increasing adoption of distributed energy resources (DER), coupled with advances in energy storage and telecommunications, consumers are being enabled to trade energy directly with independent producers. The motivation to participate comes from the low marginal costs associated with DERs and storage systems when compared with retail prices offered by private service providers. This novel type of transaction is framed within the peer-to-peer (P2P) markets, wherein small-scale market participants can freely buy and sell energy with their peers, and are thus called prosumers, since they are both consumers and producers. This type of market can allow a prosumer to take advantage of his DER by selling surplus power, for example, which would otherwise be wasted or require a storage system to be used later.

Moreover, in conventional approaches to P2P transactions, grid restrictions are not considered in practice, but power flowing through the grid must follow the energy balance equations and grid restrictions. However, implementing a P2P market that accounts for these restrictions in a satisfactory manner is a complex and difficult challenge. Therefore, this dissertation will investigate the following research question:

What will be the impact of P2P markets on distribution grid operation?

Furthermore, it is necessary to develop an optimisation model that is capable of operating under these restrictions and realistically simulates demand and generation, to study the technical and economic impacts of P2P markets.

1.3 Research objectives

The main objectives of this work are:

- To develop a bibliographic review of the impact of P2P markets on the distribution grid, with a focus on congestion.
- To create a mathematical formulation to understand the impact of P2P transactions on the distribution grid, taking into account its physical restrictions.
- To understand P2P energy markets in detail and evaluate their pros and cons.
- To perform several case studies that simulate different load and generation scenarios.
- To evaluate the impact of P2P markets on the operation of the distribution grid in terms of costs, transaction behaviours, voltage profiles and grid congestion.

1.4 Methodology

This work proposes a model based on stochastic mixed-integer linear programming (SMILP). The model aims at minimising the total costs of the prosumers, over a 24-hour period, while accounting for grid restrictions and the operation of smart grid enabling technologies and P2P transactions. Fig. 1.1 illustrates the approach taken in this work. The distribution network and the interactions among the consumers/prosumers can be seen, where several actors utilise smart grids enabling technologies. These technologies allow the existence of P2P transactions and the possibility of selling energy to the grid. These transactions are analysed in terms of costs, energy mix, P2P transactions, congestion and voltage, while considering network constraints to assess the impact of these transactions on network operation.

The problem is programmed in GAMS 24.1.2 and solved using CPLEX. Moreover, all simulations are conducted in a workstation with two 6-core processors with a frequency of 3.46 GHz and 96 GB of RAM, running a 64-bit version of Windows.

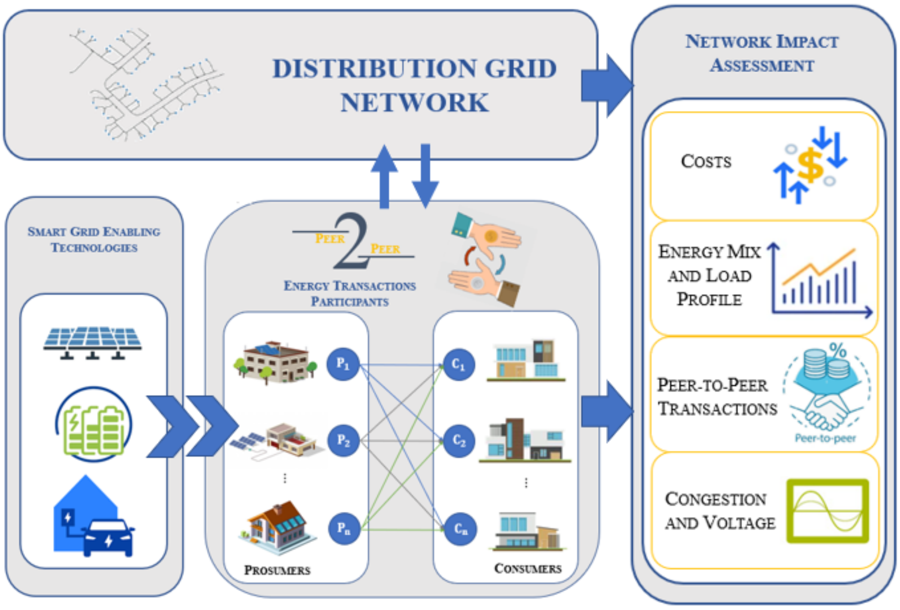

Figure 1.1: P2P grid and market framework

1.5 Thesis structure

This dissertation is organised into 5 chapters. Aside from the present chapter, Chapter 1, Chapter 2 presents a state of the art, introducing the concepts related on the topic being studied as well as a bibliographic review of relevant works. Chapter 3 details the mathematical formulation developed in this work comprised of an objective function and a set of restrictions. In Chapter 4, the numerical results of the simulations are presented and discussed. Finally, Chapter 5 highlights the main conclusions of this dissertation as well as its contribution, furthermore some future works are pointed out.

Chapter 2

Overview on peer-to-peer markets

The present chapter presents the concepts and state of the art concerning the impacts of peer to peer electricity trading on the distribution network, with regards to Electricity markets, Peer to Peer (P2P) markets and the Impact of Peer to Peer markets on the distribution network. Ultimately, a bibliographic review is presented, focusing on literature relevant to this work which are summarised and categorised by themes and approached topics.

2.1 Electricity markets

2.1.1 Concept

Current electricity markets follow a pool structure wherein a market operator is responsible for providing a centralised dispatch, for the next day, based on day-ahead electricity sale and purchase bids. Put simply, bids, consisting of an amount of power and a price, for a given time interval, are organised in terms of cost. Purchase bids are put in a decreasing order while sale bids are put in an ascending order, and thus, for each time slot, the market clearing price is set where both bid curves meet, as depicted in Fig. 2.1 (adapted from [5]).

Besides the spot market mentioned above, electricity producers and buyers are free to negotiate among themselves. As a consequence electricity can also be traded through bilateral contracts. Moreover, the independent system operator (ISO) must verify that the dispatch arrived at by market clearing and bilateral contracts is technically feasible and if it isn't propose changes to it. Figure 2.2 (adapted from [5]) outlines the interactions and functions of the different market participants.

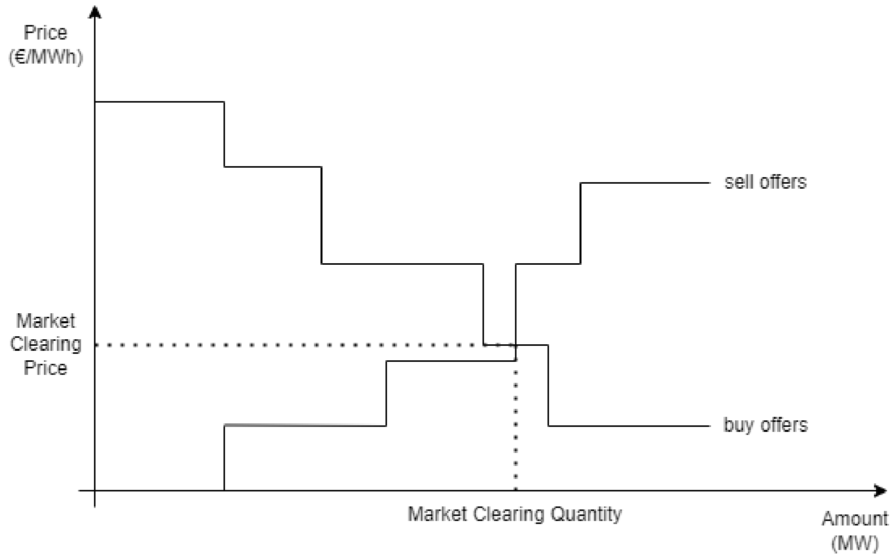

Figure 2.1: Symmetric Pool market operation

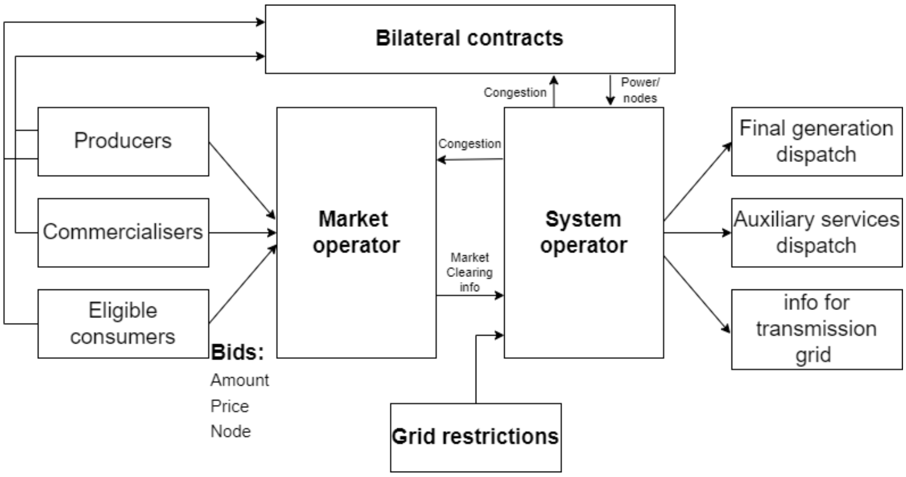

Figure 2.2: Electricity system: mixed operational model

In addition to the day-ahead energy market, there is also an intraday real-time market used to account for, and balance, real-time uncertainty in load and supply (namely variable RES). Moreover there also exist other non-energy markets, such as, the reserve market meant to assign reserve capacity throughout a day, as well as the Ancillary Services Market, typically used to reward services like helping maintain grid frequency [6].

2.1.2 Advantages and challenges

The main future challenges of electricity markets will arise due to the increasingly greater share of variable renewable generation. In this context, six key challenges have been identified in the work of [7]:

1. Much higher price volatility from hour to hour and day to day;

2. Increased relevance of intraday markets;
3. Higher costs for fossil plants due to higher shares of investment depreciation costs;
4. Increased relevance of energy storage and “smart” grids;
5. Higher shares for balancing markets;
6. Increased complexity in balancing supply and demand over time.

Additionally, while in a conventionally structured power system, electricity markets usually consist of day-ahead and balancing markets, which are cleared sequentially and independently, with the introduction of stochastic and non-dispatchable renewable energy resources power injection is uncertain. Consequently, new services such as ancillary services will be required in order to equilibrate balancing markets [8].

However, there is a plentiful body of literature proposing solutions to these problems, called "barriers" in [9], and while each barrier is addressed by at least one proposed solution, no single proposal is able to address all the barriers simultaneously. Consequently, a future-proof market design must combine different elements of proposed solutions to comprehensively mitigate market barriers [9]. Furthermore, the introduction of RESs brings with it the capacity to generate low carbon electricity, which is arguably its single greatest advantage, at a lower levelised cost of electricity (LCOE) than conventional sources [10].

2.1.3 Energy storage

The volatility in power output of RESs has created a necessity for methods to mitigate it, one of which being energy storage. There are several types of Energy Storage Systems (ESSs), the most common being Pumped Hydro-power and Battery Storage Systems (BSSs), however several novel systems have been presented in the literature, such as using Electric Vehicles (EVs) as ESSs [11], [12] and hydrogen fuel cells, explored in [13].

Furthermore, besides being use-fool tools to harvest and take advantage of energy that would otherwise be wasted, as explored in [12] and [14], ESSs will also play a role in increasing the grid’s resiliency against high-impact low-probability (HILP) events, ie, earthquakes, tsunamis, etc [15], [16], as well as in smoothing the output of RESs at a power-plant level [13]. Depicted in Fig. 2.3 is the change in the integration of RESs into the power distribution system [17].

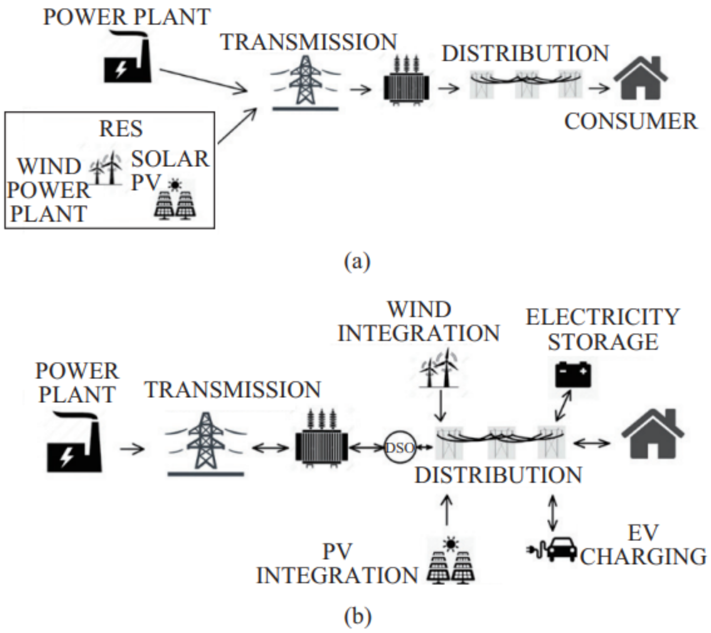

Figure 2.3: (a) Conventional Power Distribution System. (b) Future Power Distribution System

2.2 Peer to peer markets

2.2.1 Concept

The P2P market structure is intrinsically linked with the emergence of a new market entity: the prosumer, that can be defined as a consumer with some form of small-scale electricity generation [18]. Consequently, P2P trading can be described as a next generation energy management technique for smart grids where prosumers can actively participate in their energy management either by selling their excess production or by reducing their load through demand response [19]. Shown in Fig 2.4 is a high level overview of the different interactions and interests that each participating entity has in the operation of grid-integrated local P2P markets as well as some of the challenges that arise [19].

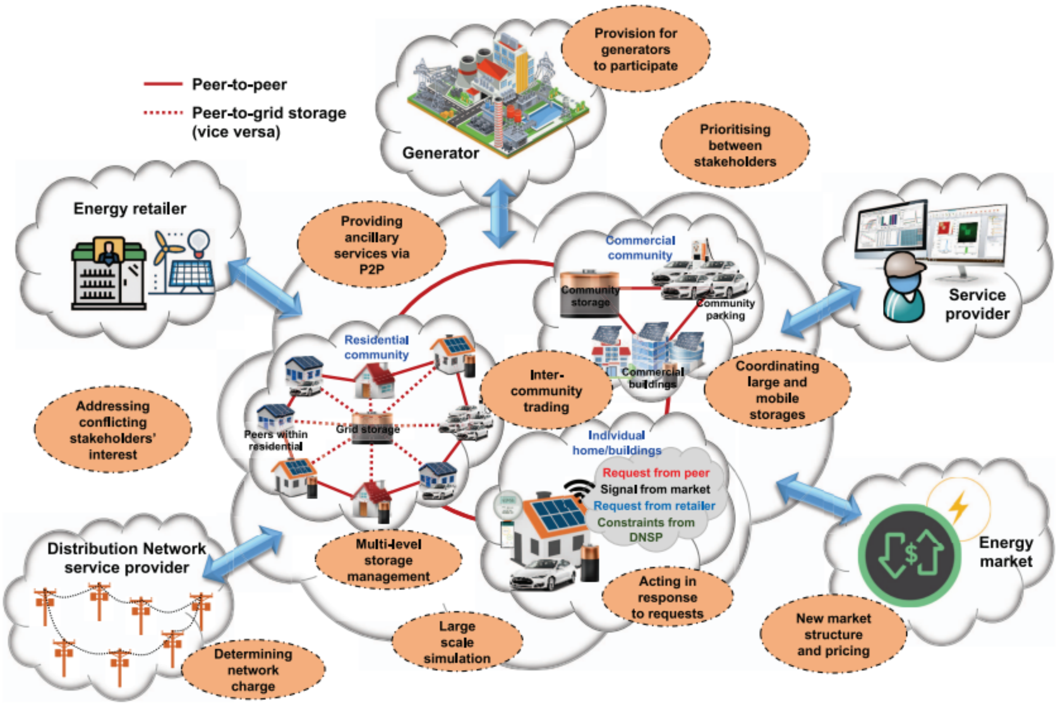

Figure 2.4: Overview of future P2P challenges

2.2.2 Existing Architecture

According to [18] and [19] current P2P market structures proposed in the literature can be divided into tree broad types: 1) decentralised markets, 2) centralised markets and 3) composite or distributed markets, Fig. 2.5, based on [18].

1. Decentralised markets: in this type participating prosumers are free to negotiate directly with one another without the presence of any centralised supervision [19]. However [18] has found that precisely due to the lack of central control this type of market structure does not maximise social welfare.

2. Centralised markets: where an central entity, such as a community manager, has the responsibility of providing a dispatch such that it maximises social welfare [18]. The community manager also has the function associated with energy trading to the outside of the community [19].

3. Composite/ Distributed market: basically a mix of the other two types, prosumers are free to directly negotiate with each-other or can engage in the market through a community manager [19]. Moreover, unlike in a decentralised market, prosumer information is shared with the community manager [18].

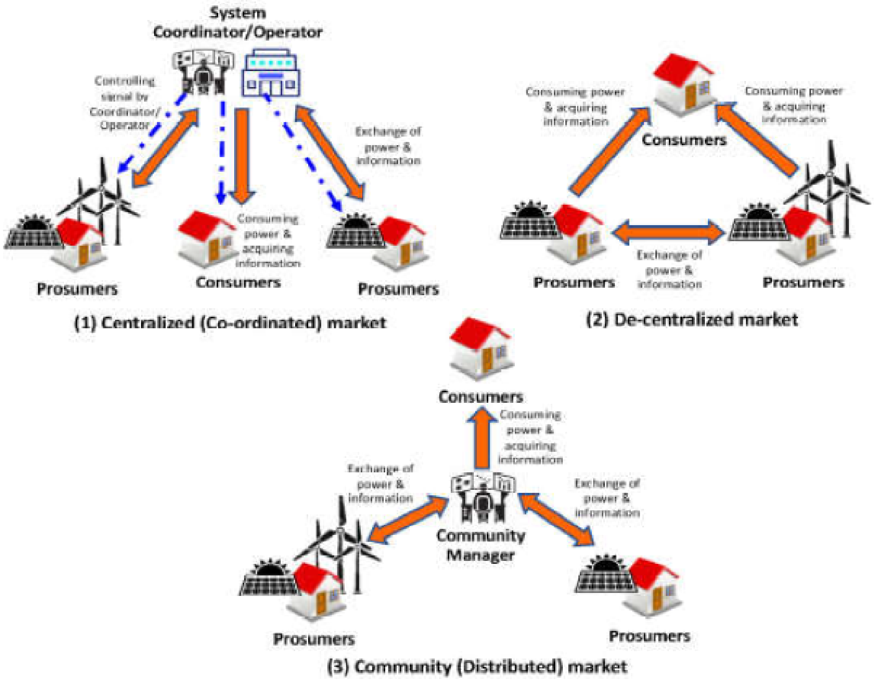

Figure 2.5: Categories of P2P trading structures

Finally [19] has identified two layers to a P2P energy trading network, namely, a virtual layer and a physical layer. The virtual layer is comprised of: an information system, to enable communication between market participants, monitoring market activity and must be capable of setting restrictions on participants decisions to ensure network security and stability; market operation, to provide dispatching, payment rules and bidding format; pricing mechanism, to match supply and demand; energy management system (EMS), that has real-time access to supply and demand data, using it to develop a prossumer's generation and consumption profile and subsequently produce an appropriate bidding strategy. At last, the physical layer consists of the hardware which provides grid access, metering and communication [19].

2.2.3 Advantages and Challenges

The development of P2P markets has gone hand in hand with the increasing deployment of small-scale RESs generation at a distribution grid level and as such aims at mitigating some of the resulting challenges.

The main benefits of implementing a P2P scheme arrived at by the literature include:

- Increased renewable deployment [20]
- Reduced peak demand [19];
- Balancing and congestion management through better operation of distributed energy resources [20];

- Reduced reserve requirements [19];

- Provision of ancillary services to the main power grid [21];

However there are, at present, some limitations. For example, current literature assumes that wholesale markets can be used as "price takers" yet with the wide deployment of P2P markets this can no longer be the case. As such further research needs to be undertaken in order to determine what impact large scale usage of P2P markets will have on wholesale markets . Another problem lies in the physical flow of electricity. Whereas power may be traded on a P2P basis, the actual grid acts as a pool with peers not actually exchanging electricity physically [21].

2.3 Impact of the P2P market on the distribution network

As the current distribution grid infrastructure has not been designed with distributed generation (DG) in mind there is a necessity for investigating what impact DG and P2P markets will have on it, Fig. 2.6 [22].

Consequently, several pieces of work have analysed the consequences of P2P and DG on the distribution grid in terms of its lines load factor and its buses voltage profiles. Typically by comparing a base case without DG and several cases with increasing levels of DG.

In terms of voltage profiles, [23] has analysed the case of an unbalanced distribution network with and without wind generation plus ESS while [24] compared several cases with increasing levels of DG and EV load, also in a distribution grid. In both papers' base cases bus voltage decreased as the bus in question was further from the feeder bus, which is typical in a radial grid. However with DG the opposite was true with voltage profiles increasing with the level of DG.

Regarding congestion, both [25] and [26] noted that peak load could be reduced with the implementation of a P2P system, wtih [24] remarking that there could be a reversal of power flow at a "fairly low penetration" of DG.

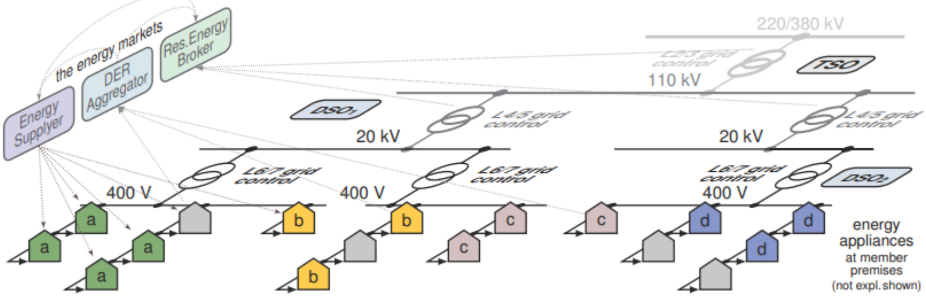

Figure 2.6: Distribution network with DG and P2P

2.4 Literature review

In this section a systematic literature review as been performed in order to classify each paper in terms of problem type and approach given its category with the goal of stressing the contribution of this piece of work, distinguishing it form precious works.

2.4.1 Energy communities

Most literature has focused on providing market models for the operation of renewable energy communities, indeed, [27–32] have put forwards models for operating an energy community based on a market with the later two incorporating P2P energy trading. Moreover, [33] besides providing a market model has also performed an investigation on the legal framework for energy communities at an Italian and European level and has identified several key barriers for the proliferation of this kind of legal entity.

The authors in [34] has put forwards a novel decision making methodology for energy communities with the goal of optimising the production portfolio. The work in [22] has identified identifies which functions a community energy management system must be capable of performing to achieve the given objectives and has also constructed Unified Modelling Language (UML) case diagrams for such functions. The work of [35] has analysed the techno-economic benefits of community-owned versus individually-owned energy assets considering the network/grid constraints. The authors in [36] have presented an agent-based transactive energy (TE) trading platform while deploying a simulated-annealing-based Q-learning algorithm to develop bidding strategies for ESSs to participate in the TE markets. Also, [37] has proposed an optimal scheduling method for a zero net energy community micro-grid with customer-owned energy storage systems (CES). The authors in [38] have reviewed recent advances in the application of game-theoretic methods to local energy trading scenarios.

Finally, [39] has proposed a review framework which as partly been used to analyse the researched literature concerning energy communities. Thusly, in Table 2.1 a few thematic categories are defined, based on the work of [39]:

Table 2.1: Some types of energy community framework

	Terminology	**Defenition**
VPP	Virtual power plant	A cluster of dispersed generator units, controlable loads and storage systems, agregated in order to operate as a unique power plant.
VED	Virtual energy district	A localised area where different residential and/or industrial users coexist , requireing or producing energy.
HEM	Home energy management system	A system to control energy management in domestic propreties.

Moreover three different kind of grid layouts for energy communities have been considered, namely:

- Micro-grid
- Downstream of a supply point
- Distributed around the network

Finally the same source also defines three levels of control:

- Type A: Management of multiple buildings, assets or appliances (aggregated) where assets and buildings are connected and affect the management of each other.
- Type B: Separate management/ control of individual appliances, assets or buildings with no connection between each other/ no overall management system.
- Type C: Basic provision of information with no direct management/ control of buildings, assets or appliances and reliance on user behaviour to take action/ manual control of assets.

With this in mind, Table 2.2 summarises the topics approached by the investigated literature for the category of energy communities:

As can be seen in Table 2.2 most of the literature as focused on a Virtual Energy district energy community integrated either downstream of a supply point, for-instance, a substation or as a micro-grid. Moreover most do not include load prediction methods on their models using a deterministic model for their work. Energy storage as been taken into account in all papers except in [31] and [33], furthermore [32], [28–30] have considered some kind of demand response technique. Finally none have included vehicle to grid (V2G).

Table 2.2: Categorisation of reviewed papers

Ref	**Type**	**Layout**	**Control hierarchy**	**Prediction technique**	**Optimisation algorithm**	**Management type**	**ESS?**	**Demand response?**	**V2G?**
[27]	Virtual energy district	Downstream of a supply point	Decentralised	(deterministic)	ADMM		yes	no	no
[31]	Micro-grid	Downstream of a supply point	hierarchical (nano to micro to grid)			C	no	no	no
[32]	Virtual power plant/ energy district	Downstream of a supply point	Decentralised		MDP- Markov decision process/ Fuzzy Q-learning	A	yes	Only for ESS	no
[29]	Virtual power plant	Distributed around the network	centralised	(deterministic)	Coalitional game model	A	yes	yes	no
[28]	Virtual power plant/ energy district	Downstream of a supply point	Decentralised		Nash bargaining/ ADMM		yes, at community level	yes	no
[35]	Virtual power plant	Distributed around the network		(deterministic model)	cooperative game theory model	A	yes	no	no
[36]	Virtual power plant	Micro-grid	Decentralised		simulated-annealing-based Q-learning		yes	no	no
[37]	Virtual power plant	Micro-grid	centralised	(deterministic)	MIP		yes	no	no
[33]	Building energy management system	Micro-grid	centralised				no	no	no
[30]	Virtual power plant/ energy district	Downstream of a supply point	centralised	Stochastic Model Predictive Control (MPC)		A	yes	yes	no

2.4.2 Peer to peer markets

The literature on this topic has overwhelmingly focused on developing P2P market frameworks, indeed [27, 28], [40–42] have developed some form of peer to peer market wherein consumers can buy electricity on the P2P market or from the wider grid and prossumers may also sell their surplus power. Notably, the authors of [40] have also included uncertainty trading. Moreover, [41] and [42] have employed block-chain technology in their work. Taking into account a utility's point of view, [43] and [44] have put forwards utility focused P2P market designs wherein energy transactions must be approved by the utility.

Literature reviews have been presented in [45] and [18]. The former as analysed the methods and technologies used to simulate each aspect in a grid-connected peer-to-peer energy trading network and attempted to draw some comparisons between the methods used in the reviewed literature, while the latter has researched recent development trends, challenges and opportunities of P2P markets based on pilot projects and regulatory and policy changes in Thailand. Also, [46] has looked at the implementation of a P2P trading mechanism to jointly wind power as well as reserve generation to compensate the former's uncertainty.

In this regard, Table 2.3 is a summarises the reviewed works on this topic. Indeed, most noticeably the literature on this topic was overwhelming focused on market design for PV prosumers, with most papers also contemplating some form of ESSs.

Table 2.3: Summary of analysed literature on P2P markets

Ref	**Problem category**	**Which RES?**	**Demand response?**	**Storage?**	**EV/ V2G?**	**System under study**	**Algorithm**
[27]	market design	PV		yes, but not specified		grid connected energy community	ADDM
[28]	market design	PV		yes, but not specified		building energy community	ADDM
[40]	market design	PV	yes, EV/ ESS charging	yes, but not specified		grid connected energy community	MILP
[43]	market design					simulation: 33-bus test network	linear programming
[41]	market design	PV		yes, but not specified		multi micro-grid system	Blockchain based
[?]	market design	PV	yes, EV charging +space heating	BSS	Evs, but no V2G	grid connected energy community	Blockchain based
[44]	day-ahead trading strategy	PV		yes, but not specified		industrial, regional integrated energy system	Lagrange multiplier method

2.4.3 Energy storage

The reviewed works, as concerns energy storage, have delved into a broad set of problem categories. However, the literature has largely focused on battery storage systems (BSSs) paired with a PV system. As a matter of fact, aside from the literature reviews presented in [17] and [11], only the work of [15] has not considered PV generation.

Literature reviews have been presented in [17] and [11] with the latter investigating which grid services could be provided by EVs and the former focusing on Optimal Planning of Energy Storage Units in Distribution Network and Their Impacts on System Resiliency.

Azizivahed *et al.*, [47], have investigated the the energy not supplied (EENS) and voltage stability index (VSI) of distribution networks in dynamic balanced and unbalanced distribution network reconfiguration, including RESs and ESS systems, while [48] has developed a technique for finding the most suitable voltage source (VS) which can act as a voltage and frequency reference for a micro-grid with BESS during an outage.

Concerning the use of ESSs as a method for improving grid resiliency, [15] and [16] have developed frameworks for increasing grid resiliency against low-probability, high-impact events (HILP), such as earthquakes or severe storms. Both have put forwards novel metrics to quantify system resiliency and models for optimising the deployment of ESSs to increase resiliency, the latter used a non-sequential Monte Carlo Simulation framework, while the former employed linear programming based algorithm.

On the operational front of ESSs, [49] and [12] have proposed operational models for an end-user with energy storage, RESs generation and with some loads capable of demand response to participate in TE markets with the goal of optimising cost. While [14] has developed a methodology to optimise the size of RESs generation and ESSs systems in order to minimise curtailments.

Finally, [50] has presented novel neural network (NN) based state of health (SoH) estimator for a lithium-ion (Li-ion) battery based ESS and [13] has surveyed the economic feasibility of different types of energy storage.

As can be seen in Table 2.4, literature on ESS has overwhelmingly focused on battery storage systems (BSSs) paired with a PV system. Whereas in terms of usage research is quite varied, ranging from energy waste reduction to voltage stability, intermittency reduction and resiliency.

Table 2.4: Summary of reviewed literature on energy storage

Ref	**Problem category**	**Test system**	**Which RES?**	**Which ESS?**	**Demand response?**	**Algorithm**
[17]	(lit review) + resiliency					
[11]	(lit review)			EV		
[49]	Cost optimisation	-	PV	BSS	yes, EV charging + hot water load	obi solver
[47]	Voltage stability/ energy not supplyed	119-bus test network	PV	BSS	-	shuffled frog leaping algorithm (SFLA)
[15]	Resiliency	medium-voltage distribution feeder in Tehran	-	BSS		linear programming (LP) optimization
[50]	SoC estimation	33-bus test grid	PV	BSS	yes, home management system	novel neural network
[48]	Voltage/ frequency stability		PV	BSS	yes, energy management system	
[13]	Intermittency		PV+ wind	BSS + fuel cell	-	
[12]	Cost/ waste optimisation	(model is made for an individual end user)	PV+ wind	BSS + EV	yes, EV charging	mixed-integer linear programming (MILP) + genetic algorithm
[16]	Resiliency	IEEE 69-bus test system	PV+ wind	yes, but not specified	-	MILP
[14]	capacity/ waste optimisation		PV+ wind	BSS		golden section Fibonacci tree optimisation (GSFTO) algorithm

2.4.4 Distribution network congestion

The body of literature surveyed on distribution network congestion has no singular point of focus unlike previous categories like research on P2P markets. Indeed, works on this topic have studied problems such as voltage quality, costs optimisation, intermittency, congestion and the impact of data quality on system state estimation. Furthermore, besides [51] and [24], the presence of RES has been considered (either PV or Wind), with [51] and [52] also contemplating flexible loads.

Fassina *et al.* [24] and Munikoti *et al.* [53] have studied the impact on voltage profiles on a distribution grid of distribution generation sources, with the former also including EV charging load and analysing the steady state impact while the latter assessed the impact of photo-voltaic generation on the voltage quality of the distribution network with a novel method impact of photo-voltaic generation on the voltage quality of the distribution network.

Parizy *et al.* [26] has proposed a novel optimisation algorithm with two levels. The first aims at finding the minimum incentive that will result in a desired level of RESs penetration based on 3 penalties for emitting air pollution and power losses. The second is a mixed integer non-linear programming (MINLP) based algorithm that finds the optimal sizing and location of RES such that it minimises energy costs.

Nayak *et al.* [23] has studied the power-flow of a wind farm equipped with a battery energy storage system (BESs). While [51] has developed a two-level sensitivity analysis framework with the goal of such an analysis is to allow system operators to quantify the sensitivity of their distribution system state estimation (DSSE), at a medium voltage (MV) level, to changes in low voltage (LV) data from home energy management system (HEMS) such as a demand response signal or appliance parameters. Finally, [52] and [25] have put forwards models for coordinating electricity and heat/cooling demand with varying renewable generation.

As can be ascertained by analysing Table 2.5 research on distributed network congestion isn't overwhelmingly focused on a single problem category. Moreover, most authors have included some form o RES generation.

Table 2.5: Summary of literature concerning Distribution Network Congestion

Ref	Problem category	Test system	Which RES?	Which ESS?	Demand response?	Algorithms
[26]	Cost optimisation	IEEE 24-node system	PV+ wind	yes, but not specified		mixed integer non-linear programming
[23]	Intermittency	37-bus unbalanced radial distribution network	Wind	BSS		backward forward sweep algorithm
[51]	Impact of HEMS data quality on DSS estimation	IEEE 13-bus MV distribution system			yes	Karush–Kuhn–Tucker conditions from the HEMS and DSSE optimization formulations
[24]	Voltage quality	radial distribution network				
[52]	RES curtailment optimisation	6-bus/ 30-bus distribution grid	PV+ wind	(heat storage)	yes	MILP
[25]	Reduce grid congestion	modified IEEE 33-node distribution network	PV+ wind			Mixed Integer Quadratically Constrained Program (MIQCP) problem
[53]	Voltage quality	modified version of IEEE 37 bus and IEEE 123 bus test systems	PV			

2.5 Chapter Summary

In this chapter, a state of the art was presented throughout four sections. The first delved into the concept, advantages and challenges of electricity markets, as well as the role played by energy storage in these. The second explained the concept, existing architecture, advantages and challenges of P2P markets. The third presented an overview on the consequences of the deployment of P2P markets in the distribution network. Finally, a fourth section was made in which an extensive bibliographic review of relevant literature is presented with an added categorisation of reviewed works by topic and aspects approached. Based on the reviewed works, it is possible to verify the absence of works which simultaneously take into account the effect of smart grid enabling technologies with P2P transactions by way of analysing their impact on the grid.

Chapter 3

Mathematical formulation

This chapter presents the mathematical formulation used to model user behaviour in a peer-to-peer envi ronment with the presence of distributed energy resources. It is based on the work of [54] , built upon a new set of restrictions to account for network constraints. The model is formulated as a stochastic mixed-integer linear programming (MILP) optimisation problem to minimise the total cost of each prosumer. Furthermore, key assumptions and the utilised solar generation prediction model are described.

3.1 Objective function

In the present work the objective function aims to minimise the total cost of each prosumer, as shown in equation (3.1). Essentially, the formula is the difference between the cost of total acquired power by each prosumer w, during a period Δt, and the cost of total injected power by each prosumer w, during a period Δt.

$$\sum_{s} \rho_s \sum_{w} \sum_{t} (\lambda_{t,s}^{bought} . P_{w,t,s}^{bought,T} . \Delta t - \lambda_{t,s}^{sold} . P_{w,t,s}^{sold,T} . \Delta t) \tag{3.1}$$

3.2 Restrictions

3.2.1 Energy transactions

The following equations present restrictions regarding energy transactions on the energy market between prosumers and with the wider grid. Equation (3.2) states that for a given prosumer, w, bought energy must come either from the grid or another prosumer. The following restriction (3.3) asserts that for each prosumer, w, energy sold must go to the grid or to another prosumer. Finally, equation (3.4) states that, for the community as a whole, total energy bought must equal total energy sold.

$$P_{w,t,s}^{bought,T} = P_{w,t,s}^{bought,grid} + P_{w,t,s}^{bought,local} \tag{3.2}$$

$$P^{sold,T}_{w,t,s} = P^{sold,grid}_{w,t,s} + P^{sold,local}_{w,t,s} \tag{3.3}$$

$$\sum_{w} P^{bought,local}_{w,t,s} = \sum_{w} P^{sold,local}_{w,t,s} \tag{3.4}$$

Equations (3.5 to 3.7) represent the energy transactions among prosumers and the grid. Equation (3.5) states that the total power sold by each of the community's prosumers equals to all the power sold by PV systems and discharge of EVs and ESS systems. Equations (3.6 and 3.7) establish a possible limit on the total power acquired by the community, where N can impose a maximum on energy obtained from the grid as a complementary strategy to demand response.

$$P^{sold,T}_{w,t,s} = P^{sold,PV}_{w,t,s} + P^{sold,EV}_{w,t,s} + P^{sold,ESS}_{w,t,s} \tag{3.5}$$

$$P^{bought,T}_{w,t,s} \leq N.x^{2}_{w,t',s} \tag{3.6}$$

$$P^{bought,T}_{w,t,s} \leq N.(1 - x^{2}_{w,t',s}) \tag{3.7}$$

Equation (3.8) shows the balance of power. It states that each prosumer must have a balance between its acquired energy from various sources, and its load. In other words, the sum of total power acquired, either from the grid or the local market, plus power from its PV panels, ESSs systems and EVs must equal the sum of inflexible loads, flexible loads, such as controllable appliances, and the charging demands of its EV and ESSs systems.

$$P^{bought,T}_{w,l,s} + P^{PV,used}_{w,l,s} + P^{EV,used}_{w,l,s} + P^{ESS,used}_{w,l,s} = P^{inflexibleload}_{w,t,s} + P^{EV,load}_{w,t,s} + P^{ESS,load}_{w,t,s} + \sum_{c} P^{apliances}_{w,t',c,s} \tag{3.8}$$

Finally a prosumer's photovoltaic production is defined in (3.9) must be either used or sold in its entirety at all times.

$$P^{PV,used}_{w,h,s} + P^{PV,sold}_{w,h,s} = P^{PV,gen}_{w,h,s} \quad \forall w,t \tag{3.9}$$

3.2.2 Controllable appliances

Controllable appliances include devices such as a dish washer or washing machine. These typically operate in pre-defined cycles which means that the durations and load profiles of their work-cycles are known. Thus, considering the presence of demand response their work periods can be shifted to a time of lower prices. This type of load is modelled using equations (3.10 to 3.16).

Equation (3.10) defines the power consumed by a controllable appliance as the sum of the power consumed by the appliance during each phase. The device can operate at distinct phases such as startup, running, finishing and stopping.

$$P^{appliance}_{w,t',c,s} = \sum_{f} (x^{fase}_{w,t,c,s} . P^{fase}_{w,f,c,s}) \tag{3.10}$$

Restriction (3.11) states that each piece of controllable equipment cannot be simultaneously operating at more than one phase of its work-cycle.

$$\sum_{f} x^{fase}_{w,t,c,s} \leq 1 \tag{3.11}$$

Expressions (3.12 to 3.15) enforce the logical sequence among the operating phases.

$$y^{fase}_{w,t,f,c,s} \leq 1 \tag{3.12}$$

$$y^{fase}_{w,t,f,c,s} = y^{fase}_{w,f,c,s,(t+T^{duration}_{w,f,c,s})'} \tag{3.13}$$

$$y^{fase}_{w,t,f,c,s} - z^{fase}_{w,t,f,c,s} = x^{fase}_{w,t,f,c,s} - x^{fase}_{w,f,c,s,(t-1)'} \tag{3.14}$$

$$z^{fase}_{w,t,f,c,s} = y^{fase}_{w,t',f+1,c,s} \tag{3.15}$$

Finally, equation (3.16) sets the number of times a specific appliance should operate during the optimisation period.

$$\sum_{t} y^{fase}_{w,t,f,c,s} = N_{w,c,s} \tag{3.16}$$

3.2.3 Electric vehicles

Equations (3.17 to 3.23) describe the behaviour of Electric vehicles (EVs). In equation (3.17) a balance is defined among the power provided by an EVs for its prosumer's self-use together with the sold by the EVs and the power discharged by the Evs affected by its discharge efficiency.

Charging and discharging limits are presented in equations (3.18) and (3.19), respectively. During the period between EV's arrivals and departures, its charging or discharging power is bounded by 0 and a maximum value used to represent a previously defined charging or discharging rate.

Finally, state-of-charge (SOC) conditions are set in equations (3.20) to (3.23). In addition, EVs must be fully charged by its time of departure.

$$P^{EV,used}_{w,t,s} + P^{sold,EV}_{w,t,s} = \eta^{EV,discharging}_{w,s} . P^{EV,discharging}_{w,t,s} \tag{3.17}$$

$$0 \leq P^{EV,charging}_{w,t,s} \leq R^{EV,charging}_{w,s} . x^{3}_{w,t'} \quad w \in [T^{a}_{w,s}, T^{d}_{w,s}] \tag{3.18}$$

$$0 \leq P_{w,t,s}^{EV,discharging} \leq R_{w,s}^{EV,discharging}.(1-x_{w,t'}^{3}) \quad w \in [T_{w,s}^{a}, T_{w,s}^{d}] \tag{3.19}$$

$$SOC_{t,w,s}^{EV} = SOC_{t,w,s}^{EV,ini} + CE_{w,s}^{EV}.P_{w,t,s}^{EV,charging}.\Delta t - P_{w,t,s}^{EV,discharging}.\Delta t \quad \forall w \; if \; t = T_{w,s}^{a} \tag{3.20}$$

$$SOC_{t,w,s}^{EV} = SOC_{t-1,w,s}^{EV,ini} + CE_{t,s}^{EV}.P_{w,t,s}^{EV,charging}.\Delta t - P_{w,t,s}^{EV,discharging}.\Delta t \quad \forall w,t \; \in t = [T_{w,s}^{a} - T_{w,s}^{b}] \tag{3.21}$$

$$SOC_{w,s}^{EV,min} \leq SOC_{t,w,s}^{EV} \leq SOC_{w,s}^{EV,max} \tag{3.22}$$

$$SOC_{t,w,s}^{EV} = SOC_{w,s}^{EV,max} \quad \forall w, \; if \; t = T_{w,s}^{d} \tag{3.23}$$

3.2.4 Energy storage systems

Each prosumer's ESS system is modelled using equations (3.24) to (3.29). These equations work in a similar manner to the previously described EVs. Charging and discharging limits are defined in equations (3.25) and (3.26). SOC is defined in equations (3.27) to (3.29).

$$P_{w,t,s}^{ESS,used} + P_{w,t,s}^{sold,ESS} = \eta_{w,s}^{ESS,discharging}.P_{w,t,s}^{ESS,discharging} \tag{3.24}$$

$$0 \leq P_{w,t,s}^{ESS,charging} \leq R_{w,s}^{ESS,charging}.x_{w,t'}^{4} \quad \forall w,t \tag{3.25}$$

$$0 \leq P_{w,t,s}^{ESS,discharging} \leq R_{w,s}^{ESS,discharging}.(1-x_{w,t'}^{4}) \quad \forall w,t \tag{3.26}$$

$$SOC_{t,w,s}^{ESS} = SOC_{t-1,w,s}^{ESS,ini} + CE_{t,s}^{ESS}.P_{w,t,s}^{ESS,charging}.\Delta t - P_{w,t,s}^{ESS,discharging}.\Delta t \quad \forall w,t \geq 1 \tag{3.27}$$

$$SOC_{t,w,s}^{ESS} = SOC_{w,s}^{EV,ini} \quad \forall w \; if \; t = 1 \tag{3.28}$$

$$SOC_{t,w,s}^{ESS,min} \leq SOC_{t,w,s}^{ESS} \leq SOC_{w,s}^{ESS,max} \quad \forall w,t \tag{3.29}$$

3.2.5 HVAC systems

Equations (3.30) to (3.32) define a simplified model for the heating, ventilation and air conditioning systems (HVAC) which aims primarily at maintaining temperature within defined parameters.

Temperature variation is calculated based on (3.30) which is in turn based on an equivalent thermal system. Furthermore, the temperature may change in-between a minimum and maximum values according to the defined scenarios and its power.

$$\theta_{w,t+1} = \beta_{w,s} * \theta_{w,t} + (1+\beta_{w,s})(\theta^{0}_{w,t,s} + COP_{w,s} * R_{w,s} * P^{HVAC}_{w,t,s} \tag{3.30}$$

$$\theta^{min}_{w} \leq \theta_{w,t+1} \leq \theta^{max}_{w} \quad \forall w,t \tag{3.31}$$

$$0 \leq P^{HVAC}_{w,t} \leq P^{HVAC,max}_{w,t} \quad \forall w,t \tag{3.32}$$

3.2.6 Kirchhoff's laws

3.2.6.1 Kirchhoff's current law

A major main technical impediments to distribution grid operation is Kirchhoff's current law, wherein the sum of all currents entering a bus must be equal to the sum of all outward flows. This applies to both active and reactive powers in equations (3.33 and 3.34), respectively.

$$\begin{aligned}
&\sum_{w} P^{bought,T}_{w,t,s,k} - P^{sold,T}_{w,t,s,k} \\
&\qquad + \sum_{w} P^{PV,used}_{w,t,s} + \sum_{w} P^{EV,used}_{w,t,s} + \sum_{w} P^{ESS,used}_{w,t,s} \\
&\qquad + \sum_{in,k} P_{w,t,s} - \sum_{out,k} P_{w,t,s} \\
&\qquad = \sum_{out,w} P^{inflexibleload}_{w,t,s} + \sum_{w} P^{appliance}_{w,t',c,s,i} \\
&\qquad + \sum_{w} P^{EV,charging}_{w,t,s} + \sum_{w} P^{ESS,charging}_{w,t,s} + \sum_{in,k} \frac{1}{2} PL_{k,s,t,w} \\
&\qquad \sum_{out,k} \frac{1}{2} PL_{k,s,t,w}
\end{aligned} \tag{3.33}$$

$$\begin{aligned}
&\sum_{w} Q^{bought,T}_{w,t,s,k} - Q \\
&\qquad + \sum_{w} Q^{PV,used}_{w,t,s} + \sum_{w} Q^{EV,used}_{w,t,s} + \sum_{w} Q^{ESS,used}_{w,t,s} \\
&\qquad + \sum_{in,k} Q_{w,t,s} - \sum_{out,k} P_{w,t,s} \\
&\qquad = \sum_{out,w} Q^{inflexibleload}_{w,t,s} + \sum_{w} Q^{appliance}_{w,t',c,s,i} \\
&\qquad + \sum_{w} Q^{EV,charging}_{w,t,s} + \sum_{w} Q^{ESS,charging}_{w,t,s} + \sum_{in,k} \frac{1}{2} QL_{k,s,t,w} \\
&\qquad \sum_{out,k} \frac{1}{2} QL_{k,s,t,w}
\end{aligned} \tag{3.34}$$

In equation (3.33), inward active power flows include PV generation, power from EV and ESS discharge, total energy acquired (both from the grid and local market) and active power not supplied. In terms of outward power flows, inflexible load, load from controllable appliances, EVs and ESSs charging load, power sold to the grid and losses were considered. In equation (3.34) similar formulation is present concerning reactive power.

3.2.6.2 Kirchhoff's voltage law

All feeders must also comply with Kirchhoff's voltage law. Notably these equations are not linear nor convex making it difficult to integrate them into more complex problems. As such, the variables MP_k and MQ_k have been created to represent maximum transfer capacity and thus avoid non-linearity. Moreover, two assumptions have also been considered. Firstly, when accounting for distribution grids, the difference between voltage angles (θ_k) is relatively small, this results in a geometrical simplification where $\sin\theta_k = \theta_k$ and $\cos\theta_k = 1$. Secondly, the magnitude of the voltage in each bus are assumed to be close to its nominal value. As such, expression (3.35) and (3.36) represent the linear active and reactive power flow equations, respectively, where V_i corresponds to the voltage drop at node i (3.37) and θ_k defines the line connecting buses i and j (3.38), wherein, $i, j \in w/\{0\}$.

$$|P_{k,t,s} - (V_{nom}(\Delta V_{i,s,t} - \Delta V_{j,s,t})g_k - V_{nom}^2 b_k \theta_{k,t,s})| \leq MP_k(1 - \mu_{k,t}) \tag{3.35}$$

$$|Q_{k,t,s} - (V_{nom}(\Delta V_{i,s,t} - \Delta V_{j,s,t})b_k - V_{nom}^2 g_k \theta_{k,t,s})| \leq MQ_k(1 - \mu_{k,t}) \tag{3.36}$$

$$\Delta V^{min} \leq \Delta V_{i,s,t} \leq \Delta V^{max} \tag{3.37}$$

$$\theta_{k,s,t} = \theta_{i,s,t} - \theta_{j,s,t} \tag{3.38}$$

3.2.7 Power flow limits

Apparent power flow, which cannot be greater than or equal to the nominal value on any given line, is further represented as $S = \sqrt{P^2 + Q^2}$. In addition, the maximum flow capacity of each line must respect the power flow limits (3.39).

$$P_{k,s,t}^2 + Q_{k,s,t}^2 \leq (S_k^{max})^2 \tag{3.39}$$

Finally, active and reactive power losses are represented in (3.40) and (3.41), respectively.

$$PL_{k,s,t} = \frac{R_k(P_{k,s,t}^2 + Q_{k,s,t}^2)}{V_{nom}^2} \tag{3.40}$$

$$QL_{k,s,t} = \frac{x_k(P_{k,s,t}^2 + Q_{k,s,t}^2)}{V_{nom}^2} \tag{3.41}$$

3.3 Assumptions

The following assumptions have been made in this work. First, concerning HVAC operation, many specific operating periods have been set considering users´ needs and comfort levels. Consequently, with these periods in mind, the temperature was assumed to vary within 24ºC and 28 ºC. Second, electricity prices follow the same trends as demand. Third, voltage deviations should be less than ±5% of the nominal value. Finally that for node 1 voltage is the nominal value with a corresponding 0º angle. Moreover, ESSs and EVs are assumed to have charging/discharging efficiencies of 90% and 95%, respectively.

3.4 Uncertainty and Variability

PV generation is characterised by variability and uncertainty. Therefore, to realistically model its behaviour a stochastic algorithm presented in [55] is used. In this paper 20 synthetic hourly solar radiation series are generated. Then, from this data an average profile is created. Given this average solar radiation profile, an average power output profile is calculated by plugging it into the power curve. Then, using Cholesky factorisation to attribute its initial generation conditions, a new profile is generated, as well as two more assuming a ± 5% uncertainty in solar radiation. Figure, 3.1. In addition, to the PV, the uncertainties associated with the load profile are considered to be ±1%. Furthermore, the price is assumed to follow the demand trend.

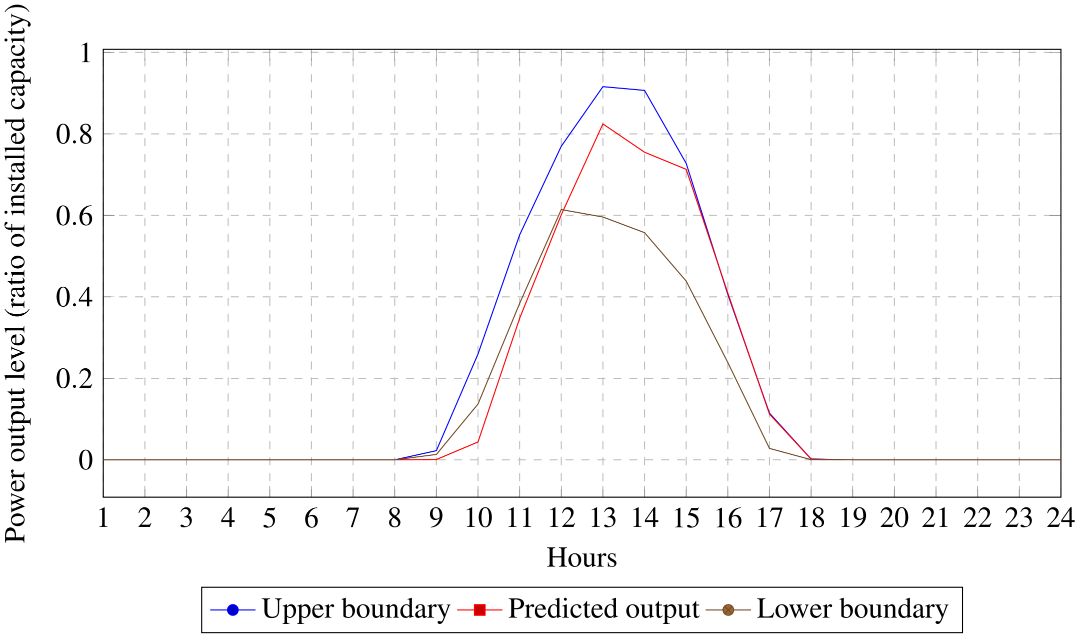

Figure 3.1: Solar PV power output uncertainty characterisation, example

3.5 Chapter summary

In this chapter, the mathematical formulation of the objective function and associated restrictions are presented and explained. The aim is to minimise each user's total costs of acquiring electricity. The model considers the presence of P2P energy transactions, two forms of energy storage (fixed ESS systems and EVs capable of discharging energy - V2G), distributed generation through PV installations and the grid's physical constraints. Moreover, the model is developed as a MILP optimisation problem. Additionally, the model simulating PV output is briefly presented along with the key assumptions.

Chapter 4

Case study, results and analysis

In this chapter , three case studies are presented and used to test the validity of the mathematical model described in Chapter 3. A detailed description of each case is given, and the numerical results of every case study are presented and discussed. The goal is to analyse the impact of P2P transactions on the distribution grid while considering its physical restrictions. Hence, we conducted a study of the different characteristics of each prosumer/consumer and their respective technologies. Finally, the key conclusions regarding the energy transaction costs, grid congestion and voltage profiles are summarised.

4.1 System description

The system used to validate the methodology proposed in the previous chapter is based on a branch of a 119-bus IEEE test grid, depicted in Fig. 4.1, chosen to represent a typically structured distribution grid, with two branches downstream of a feeder bus. Line data is shown in Appendix A.1, Table A.1 . Lastly, Table 4.1 indicates each prosumer/consumer's location in the grid.

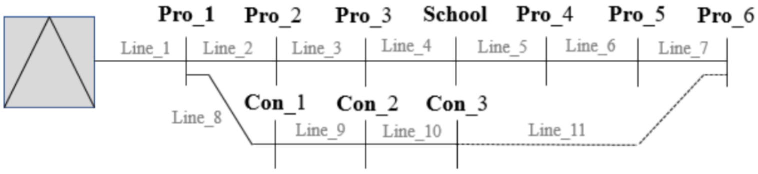

Figure 4.1: Used Test grid

Table 4.1: Client's corresponding bus

Bus	**Client**
Pro_1	w1
Pro_2	w2
Pro_3	w3
School	w10
Pro_4	w4
Pro_5	w5
Pro_6	w6
Con_1	w7
Con_2	w8
Con_3	w9

4.2 Case description

The methodology proposed in Chapter 3 has been tested in two different case studies and compared with a default case, meant to represent the current status of grid operation. Importantly, before performing any kind of meaningful analysis, one must first understand the differences among the cases. Therefore, before describing each case in detail let us first enumerate the common aspects.

- Unless specified, client (consumer/prosumer) type is residential by default;
- In cases 1 and 2, both prosumers and consumers have controllable loads and HVAC;
- In the P2P market, prosumers can buy and sell energy (from their PV generation and/or EV/ESS storage);
- Consumers may only buy energy from the P2P market or the grid, ie, can't sell to the P2P market;

With these considerations in mind, as well as the assumptions previously presented in Chapter 3, each case can be described as follows.

4.2.1 Case 0

Case 0 is the benchmark, meant to represent the current status of the distribution grid. There is no P2P, all clients are consumers and there is no distributed generation or storage. Moreover, the total demand is lower since flexible loads and HVAC aren't considered, along with the inefficiencies associated with the use of energy storage. Table 4.2 summarises this case, individually highlighting which technologies are present as well as the type of P2P transactions available.

Table 4.2: Case 0: available technologies and P2P transaction per client

Client	Type	EV	ESS	PV	P2P
w1	Consumer	no	no	no	no
w2	Consumer	no	no	no	no
w3	Consumer	no	no	no	no
w4	Consumer	no	no	no	no
w5	Consumer	no	no	no	no
w6	Consumer	no	no	no	no
w7	Consumer	no	no	no	no
w8	Consumer	no	no	no	no
w9	Consumer	no	no	no	no
w10	Consumer (school)	no	no	no	no

4.2.2 Case 1

This case introduces the P2P market structure. There is a mix of residential consumers and prosumers, along with a service prosumer (school). Except for the latter, these users will have similar load profiles, the consequences of which shall be discussed later. Moreover, residential prosumers will have similarly sized PV generation and ESS/EV storage capacity, whereas w10 won't have EV but will own larger ESS and PV systems. Case 1 is summarised in Table 4.3, but more detailed data is presented in Table A.2, Appendix A.2.

Table 4.3: Case 1: available technologies and P2P transaction per client

Client	Type	EV	ESS	PV	P2P
w1	Prosumer	yes	no	yes	both
w2	Prosumer	no	no	yes	both
w3	Prosumer	yes	yes	yes	both
w4	Prosumer	yes	yes	yes	both
w5	Prosumer	yes	yes	yes	both
w6	Prosumer	no	yes	yes	both
w7	Consumer	yes	no	yes	buy
w8	Consumer	yes	no	yes	buy
w9	Consumer	no	no	yes	buy
w10	Prosumer (school)	no	yes	yes	both

4.2.3 Case 2

In this case, two residential users (w2 and w9) are now industrial prosumers. This is meant to introduce a greater variety of load profiles, and thus more varied transactional behaviour, and evaluate their impact on the developed model. Furthermore, it can be inferred that having a monotonous set load profiles, among all users, due to a lack of user diversification, will discourage P2P transactions since all users would want to buy and sell power at the same time. Consequently, introducing two new low-voltage industrial users adds more heterogeneous demand, thus increasing the opportunities for P2P transactions. A description of this case is shown in Table 4.4, and more comprehensive data can be found in Table A.3, Appendix A.2.

Table 4.4: Case 2: available technologies and P2P transaction per client

Client	**Type**	**EV**	**ESS**	**PV**	**P2P**
w1	Prosumer	yes	no	yes	both
w2	Prosumer (industrial)	no	no	yes	both
w3	Prosumer	yes	yes	yes	both
w4	Prosumer	yes	yes	yes	both
w5	Prosumer	yes	yes	yes	both
w6	Prosumer	no	yes	yes	both
w7	Consumer	yes	no	yes	buy
w8	Consumer	yes	no	yes	buy
w9	Consumer (industrial)	no	no	yes	buy
w10	Prosumer (school)	no	yes	yes	both

4.3 Results and discussion

In this section, the numerical results for all three case studies are presented, compared and discussed. The goal is to evaluate the impacts that the implementation of a P2P market, distributed energy resources (DER) and smart grid enabling technologies will have on the system presented in Section 4.1.

4.3.1 Costs

To review the change in energy costs among the cases, they were compared with each other in terms of the total costs per user, average cost per unit of energy (case vs. case and consumer vs. prosumer) and total cost for the community. As seen in Fig. 4.2, the costs decreased for all actors from Case 0 to Case 1, with a 16.1% reduction in total costs, on average. Regarding Case 2, due to w2 and w9 becoming an industrial prosumer and consumer, respectively, their total costs have increased while all other participants experienced no change. This can be justified by the increased energy demand of the industrial actors.

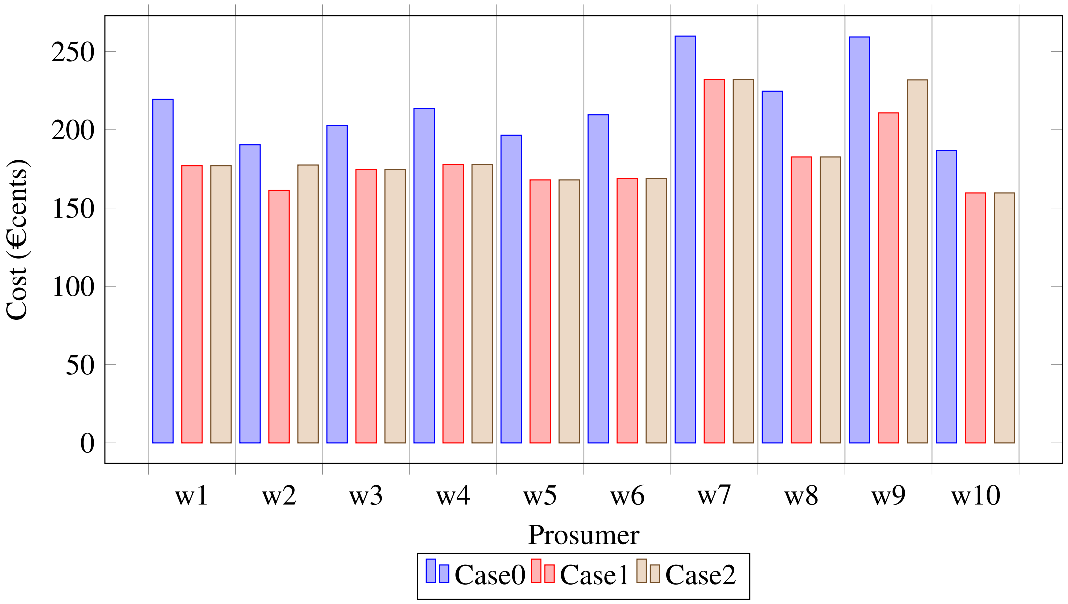

Figure 4.2: Cost comparison between scenarios

In Table 4.5, an increase in the load is visible with every case, which is due to the introduction of new flexible loads (washing machines, dishwashers, HVAC) that were not previously present, ie, Case 0's total load corresponds only to Case 1's inflexible loads. Furthermore, in Case 2, users w2 and w9 are changed into industrial prosumers which have a higher inflexible demand. However, the most notable change among the cases is the 22% decrease in the unit cost of energy, which can be attributed to the presence of PV generation, decreasing the amount of energy that needs to be acquired, and the deployment of ESS and EV V2G systems, which allow energy to be bought during periods of lower prices to be consumed throughout periods of higher prices. Additionally, there was a 16.1% reduction in total costs from Case 0 to Case 1 despite the overall increase in load.

Finally, as shown in Table 4.6, prosumers have lower overall unit costs of energy than consumers, in Cases 1 and 2 (-2.8%, Case 1; -8.2%, Case 2); however, all users have decreased costs when compared with the control case. This can be justified by the presence of P2P transactions despite their relatively small scale because they are fixed and most energy is bought from the grid,

Table 4.5: Total costs per case

Case	Total costs (€cents)	Total load (kWh)	Average Unit cost (€cents/kWh)
0	2162.330	763.433	2.832
1	1812.744	822.453	2.204
2	1849.948	838.215	2.207

which allows prosumers to generate income and partially offset their costs, whereas consumers are only benefited from a reduction in costs.

Table 4.6: Consumer v prosumer, average unit cost of energy

Average unit cost (€cents/kWh)			
Type	**Case0**	**Case1**	**Case2**
Prosumer	-	2.198	2.158
Consumer	2.832	2.245	2.334

4.3.2 Energy mix

Here, an analysis of each user's source of energy is made. The purpose was to discover which mechanism (storage, PVgen or P2P market) had the greatest contribution and on what grounds. As previously stated, in Case 0, all energy is purchased from the grid, whereas in Cases 1 and 2, power may also be procured from PV generation, storage (EV and ESS) or the P2P market.

Figure 4.3 shows each prosumer's energy mix by source. Most of the consumed energy is directly provided by the grid (as opposed to indirectly, i.e., through storage), supplying an average of 72.5% of each prosumer's energy, followed by PV generation, with about 17%, and storage (8.5%), and the P2P is responsible for the smallest proportion, only 2%. Moreover, all the energy discharged by the storage systems (EV+ESS) has been charged from grid power, with most power traded on the P2P market coming from the community's storage systems.

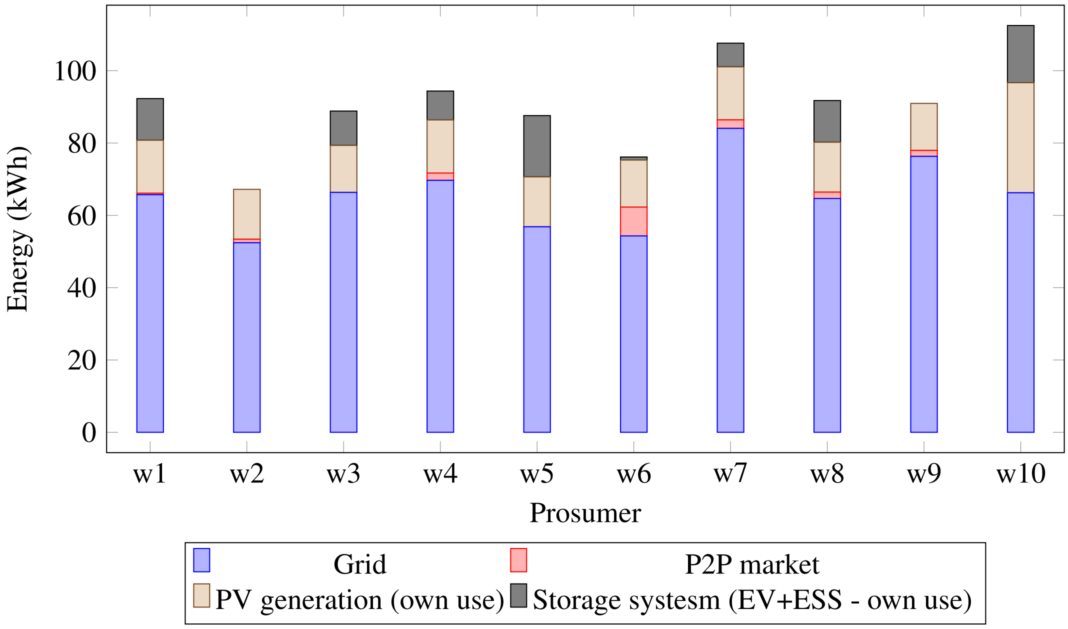

Figure 4.3: Case 1: energy mix by prosumer

Looking globally at the community, Fig. 4.4, shows that it is only responsible for roughly 19% of its own energy supply. This is due to the relatively small size of the PV installations, which are not capable of generating a surplus large enough to be able to charge the storage systems during the day. Moreover, most of the storage capacity lies in the prosumers' EVs, which are not connected to the house, and thus, being unavailable throughout significant parts of the day since they are also used for transit, which limits their use as storage systems. However, as studied later, the biggest impact of P2P and DER is not on the overall energy mix, but on the way that demand is distributed throughout the day.

Aside from analysing the energy mix as a whole, an individual hourly energy mix profile can also be studied. Figure 4.5 shows prosumer w4's energy mix profile as well as its total load, on an hourly basis. Looking at this figure, two periods call for attention: one from 1:00 to 4:00 and a second from 17:00 to 22:00, where the sum of the input energy, from all sources, is greater than the total load (minus charging demand). Indeed, only the first event can be explained by the presence of EV and ESS charging demand. The second period, however, is because of the surplus power being sold on the P2P market, even though the prosumer is simultaneously purchasing energy from the grid. Another observation is that the prosumer's PV generation is complemented by its ESS system and purchases on the P2P market during the morning to midday demand peak, while in the evening, demand is mostly covered by the prosumer's EV discharge. Finally, about 74% of w4's energy comes from the grid, and the remaining 26% of power, resultant of smart grid enabling technologies and largely concentrated during the second half of the day, helps to create a concentrated period of increased self-sufficiency.

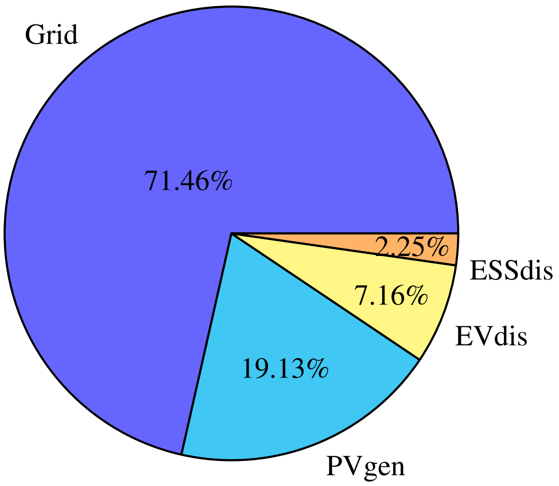

Figure 4.4: Case 1: community's energy mix

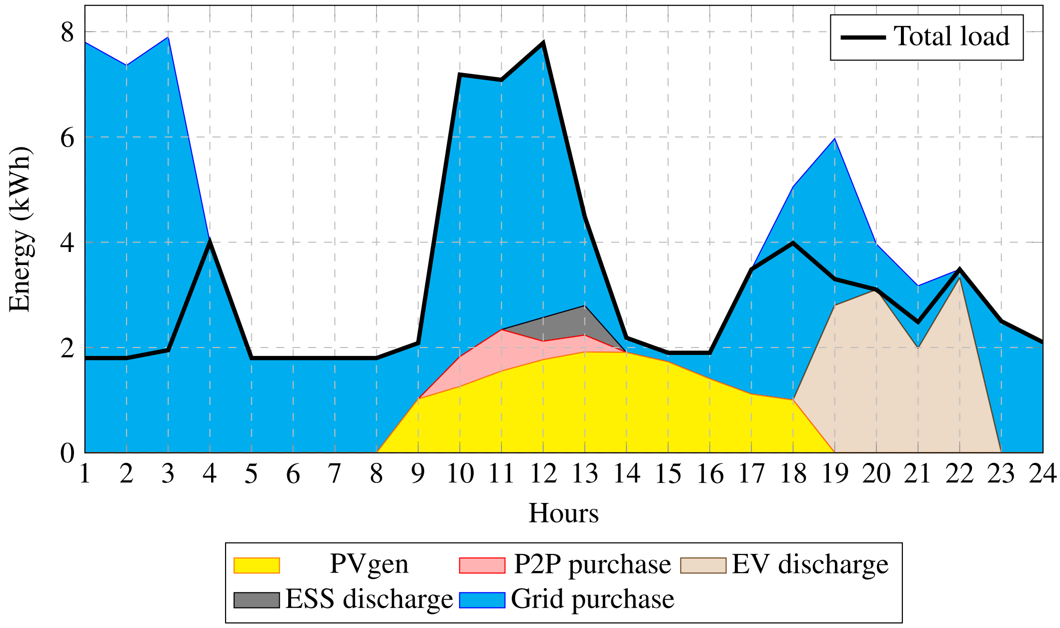

Figure 4.5: Case 1: w4 hourly energy mix and total load (excluding EV+ESS charging loads)

4.3.3 Load profiles

In this section, a detailed analysis is made of the load and generation profiles of all users, both individually and as a whole. The impact of price-sensitive, flexible loads together with PV generation and the net load of EV and ESS storage is investigated. Furthermore, the consequences of having different types of users (residential, services, industrial) will also be studied.

The consequences of the introduction of P2P technologies are clearly visible in Fig. 4.6, which shows the community's total grid demand profile, per case. Comparing Case 1 with Case 0, the daytime demand peak at 13:00 has been reduced by 45.5% while the evening peak at 19:00 has been reduced by 42.9% . Moreover, grid demand on both Cases 1 and 2 is smaller from roughly 7:00 to 23:00 when compared with the base case.

However, a new peak has been created for Case 2 at 1:00, about 200% larger than the previous demand (Case 0 to Case 1), which is entirely due to ESS and EV charging demand, where the latter can only be charged or discharged when the vehicle is at home. This time constraint leads to high charging loads during the night-time since it's the only opportunity where the EV can replenish the energy discharged during transit and V2G operation, where prices are low and it doesn't have to output power to the house or the P2P market. This is also a great example of the avalanche effect, where new load valleys and peaks are created because of the large-scale presence of price-sensitive loads.

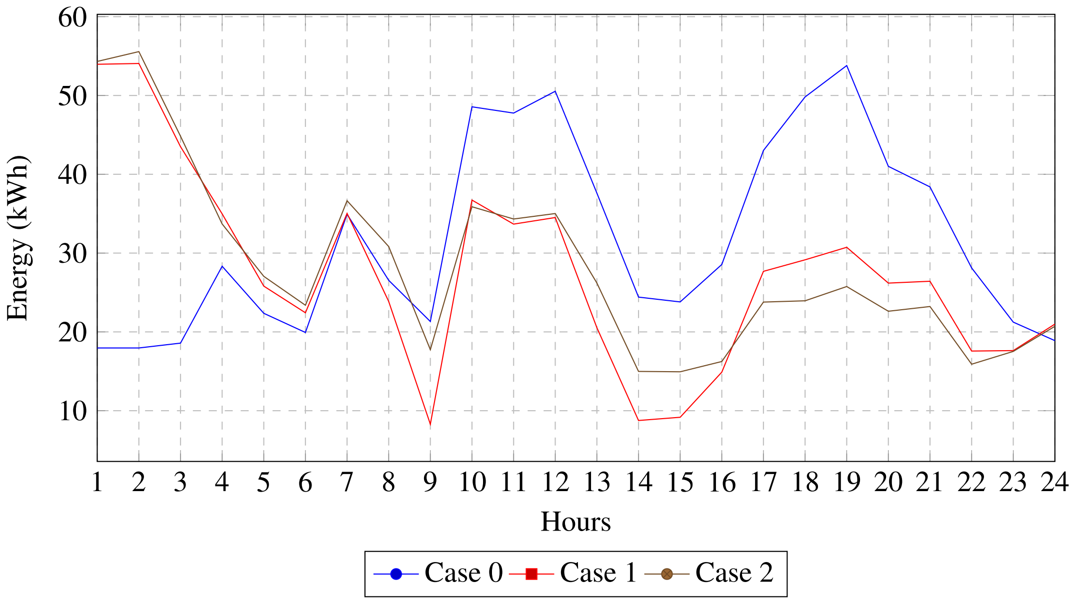

Figure 4.6: Total community grid demand per case

Fig. 4.7 displays the net load of the community's DER. It explains the differences in grid demand from Case 0 (with no DER) to Case 1. The charging of energy storage systems creates a large load during the early morning hours while, together with PV generation, providing a base-load power supply during day and evening times. As discussed later, the evening supply of stored power will be largely traded in the P2P market.

Moreover, one can see that charging of storage systems only happens during the early morning hours. This can be explained by the fact that prices at this time are the lowest while PV generation isn't large enough to provide a storable surplus during the day. Indeed, due to the overall small size of PV installations, the only prosumer to produce excess power is w10, whose surplus is entirely absorbed by other prosumers and consumers through the P2P market, without necessitating energy storage. Concerning photovoltaic generation, shown in Fig. 4.8, peak output is achieved at 13:00. Each prosumer has an installed capacity of 2 kWp, excluding w10, who has 6kWp.

In this work, the community's total demand was also analysed, including the community's total load without EV and ESS charging demand, i.e., only the sum of inflexible loads, controllable loads and HVAC, which are shown by user (Fig. 4.9) and by load type (Fig. 4.10). The community's load profile is largely set by inflexible loads which comprise 92.9% of total demand, and is characterised by two major load peaks, one at around midday and another during the evening.

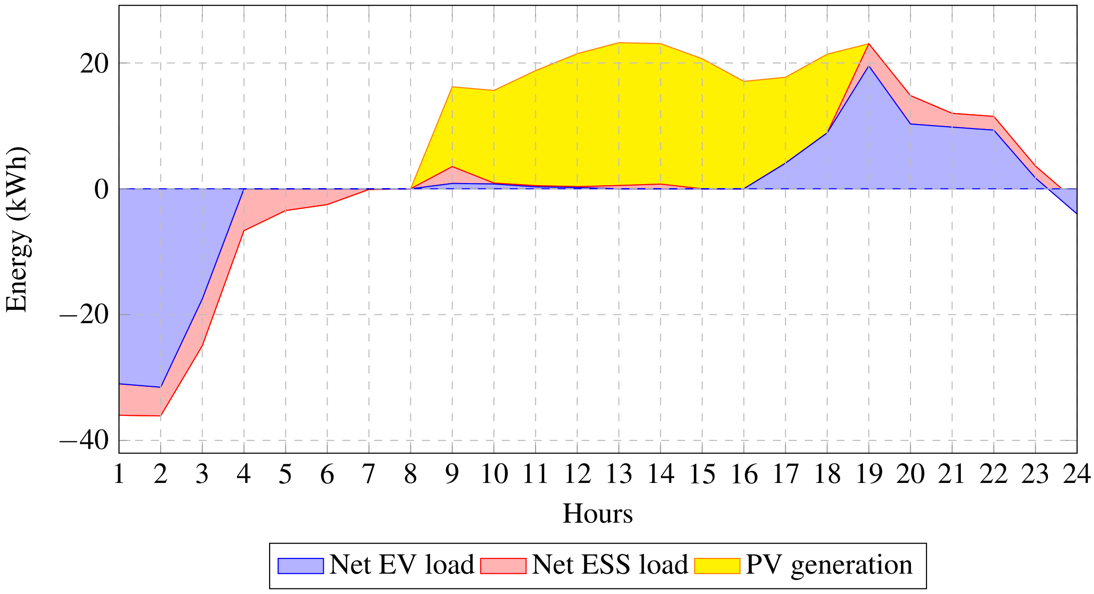

Figure 4.7: Case 1: community's usage of the distributed energy resources

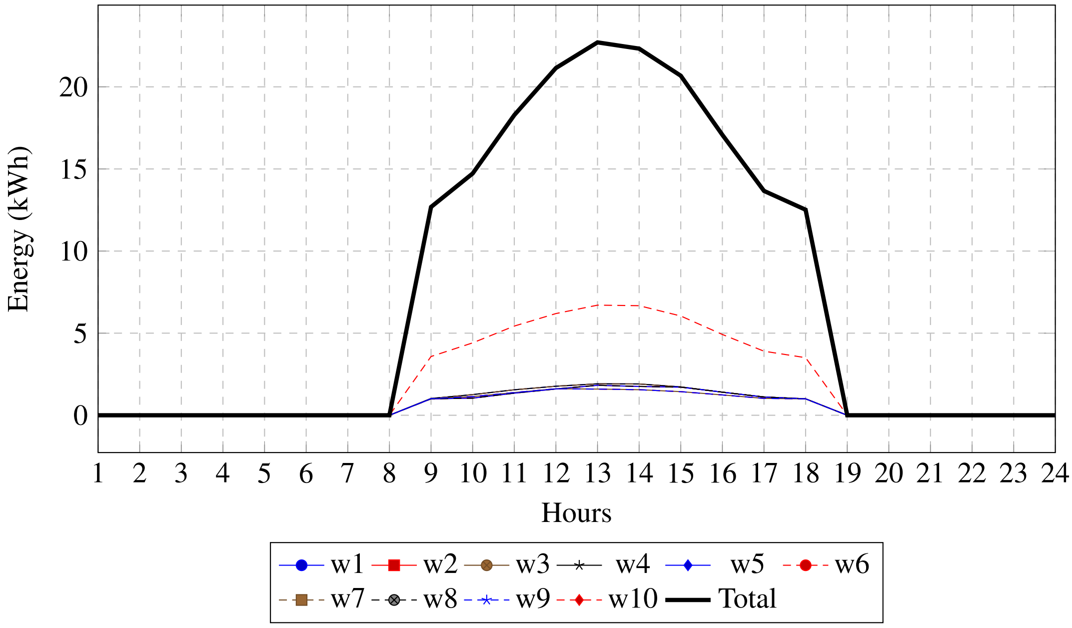

Figure 4.8: Case 1: PV generation

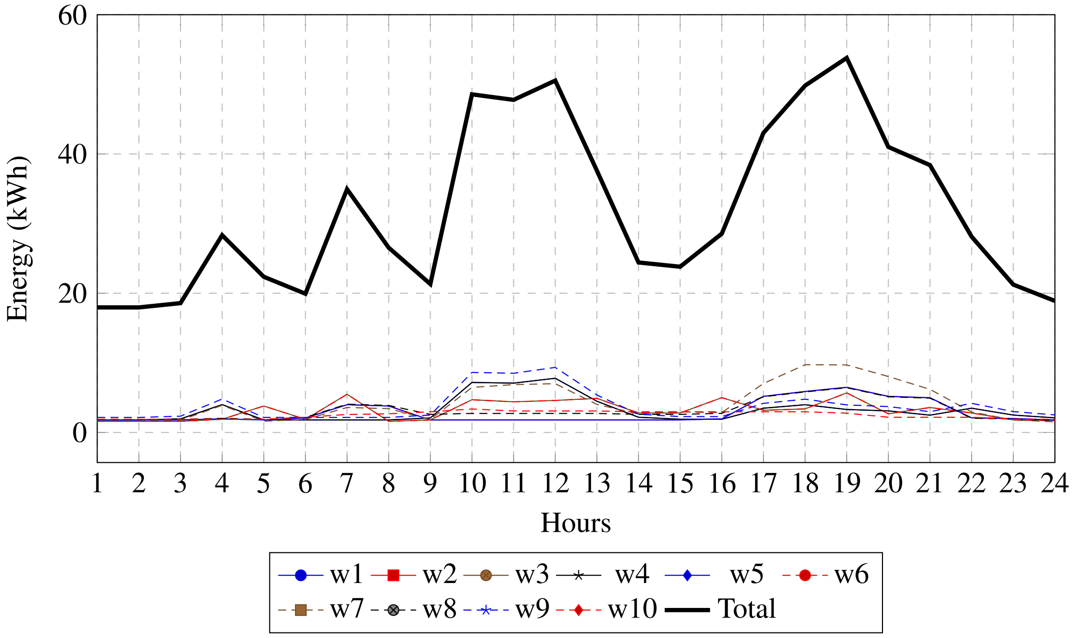

Figure 4.9: Case 1: community's total and individual load profiles, excluding EV and ESS changing loads

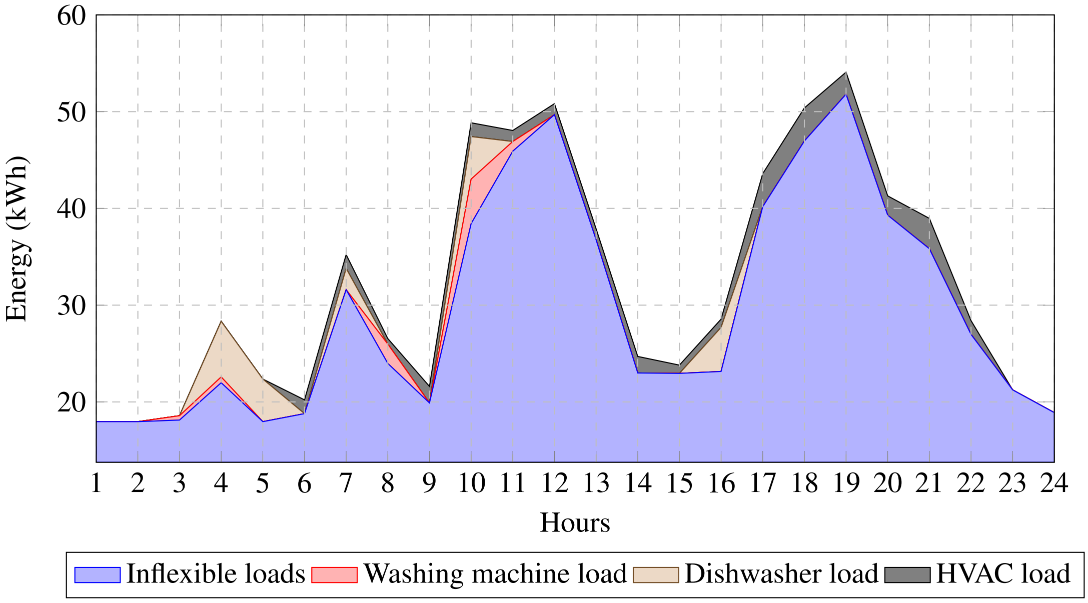

Figure 4.10: Case 1: community's demand profile by load type, excluding EV and ESS changing loads

Finally, we can compare the load profiles of different types of users, namely residential prosumers, industrial prosumers and schools, as shown in Fig. 4.11.Case 1's w2 prosumer is characterised by two load peaks, 6:00 to 9:00 and 17:00 to 21:00, which correspond to the time when a full-time worker is at home and awake.

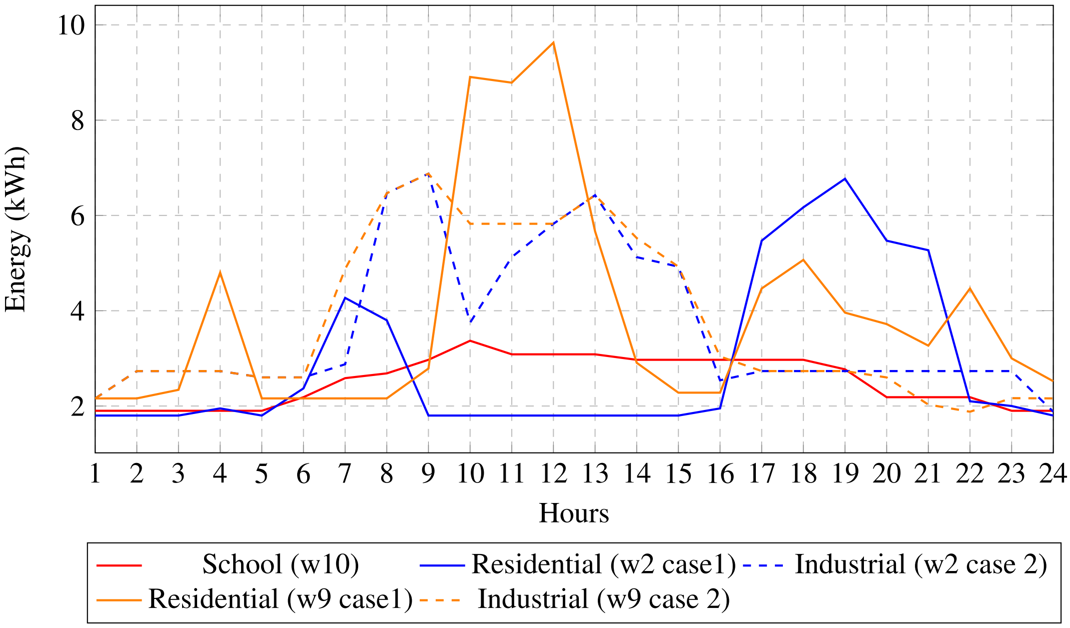

Figure 4.11: Different types of load profiles

However, Case 1's w9 has its peak load from 11:00 to 13:00. For the remaining users, their periods of peak load largely coincide with working hours because they are industrial/ services prosumers. Lastly, having different types of users and consequently different load profiles in a P2P market environment is useful in the sense that not everyone will have peak power demand or surplus at the same time, which allows for better energy sharing through trade.

4.3.4 P2P market transactions

In this section the transactional activity in the P2P market is studied, the major trading periods are identified as well as the source and destination of traded energy, namely which users and systems (PV, ESS, EV) provide power.

Figure 4.12 shows the hourly P2P market activity. Market transactions are concentrated around two periods of the day: one smaller midday period from 8:00 to 14:00, with a peak at 13:00 hours, and a larger evening period from 15:00 to 24:00, peaking at 18:00. These largely correspond to the two load peaks seen in Fig. 4.9. However, the first period sees a significantly smaller trading volume because PV generation is the highest, and thus, a consumer/prosumer's need for "imported" energy is lower. The opposite is true for the second, evening period, which involves almost no solar generation. Consequently, since prosumers can't produce their own energy, they must buy it, which results in a greater trading volume. Notably, the energy being sold during the evening is almost entirely supplied by the storage systems, either ESS or EV.

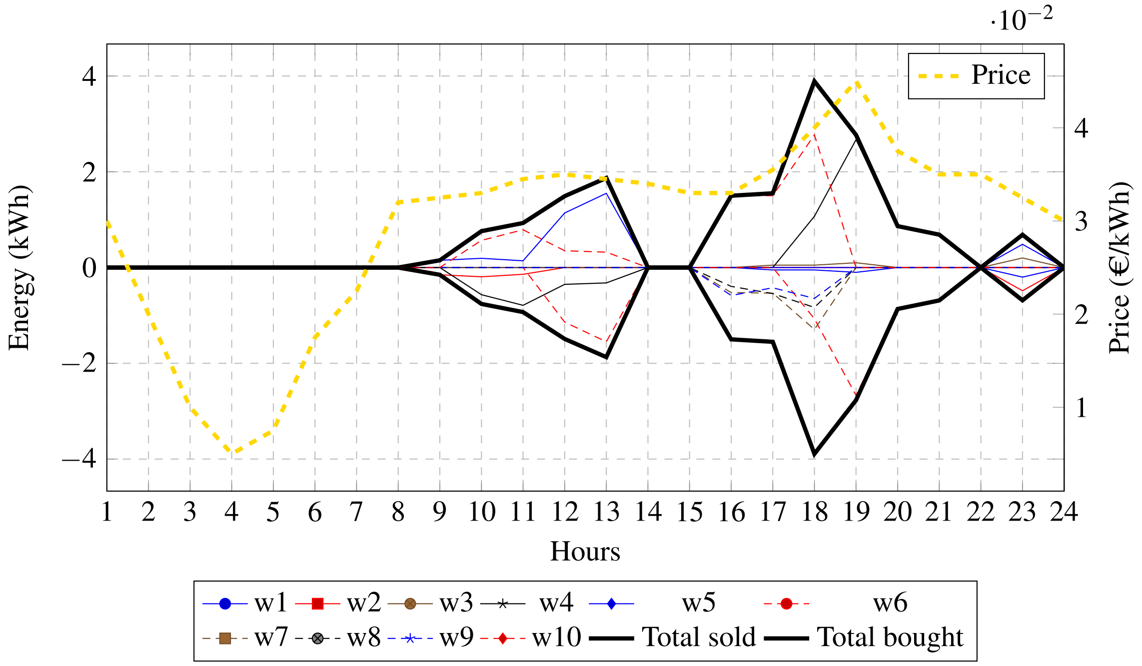

Figure 4.12: Case 1: Summary of P2P transactions (sold - positive axis; bought - negative axis)

Finally, the price tends to follow demand, with peaks at 12:00 and 19:00, with the midday period having lower prices. This is, once more, due to the presence of PV generation at this time, which reduces the demand for "imported" energy, and thus price.

Figure 4.13 and Table 4.7 indicate P2P market transactions depending on the source and destination user. Prosumers w1, w2 and w6 together with consumers w7, w8 and w9 only bought energy, whereas prosumer w4 was the only market participant to buy and sell power, with the rest only selling. Prosumer w10, the school, was responsible for 45% of the total energy sold, largely due to the larger capacity of its PV and ESS systems.

Table 4.7: Case 1: P2P market transactions (in kWh) by source/destination

From/to	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10	**Total sold**
w1	\										0
w2		\									0
w3	0.4		\								0.40
w4				\		5.29					5.29
w5		0.97			\	2.69					3.66
w6						\					0.00
w7							\				0.00
w8								\			0.00
w9									\		0.00
w10				2.03			2.35	1.77	1.65	\	7.80
Total bought	0.4	0.97	0	2.03	0	7.98	2.35	1.77	1.65	0	17.15

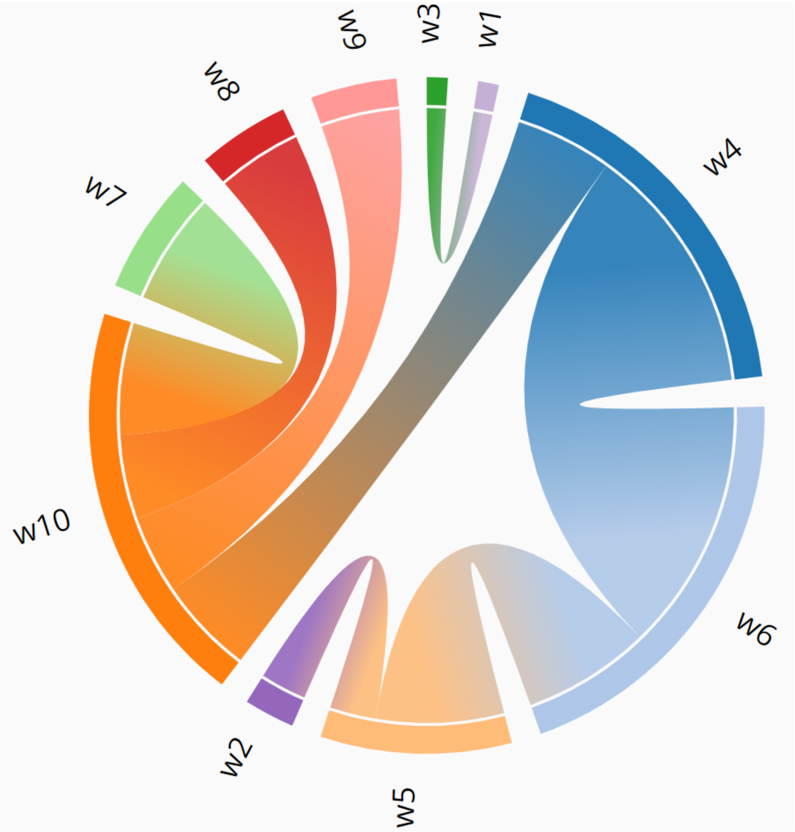

Figure 4.13: Case 1: P2P market transactions

Concerning Case 2, simulations have resulted in a very similar outcome and, as such, the same principles apply as in Case 1.

4.3.5 Congestion and voltage quality

Finally, the last analysis was conducted on the congestion of each line and the voltage deviation in each bus where the different cases were compared.

Figure 4.14 displays the load through each line for all three cases, while Table 4.8 does the same but for the capacity factor as well, showing the variation among the cases. In Case 0, 6 of the 10 lines were overloaded with an average capacity factor of 1.13 across all lines, whereas there were only 1 and 2 lines overloaded in Cases 1 and 2, respectively. There was a 15.37% decrease in line capacity factor from Case 0 to Case 1, with the most notable improvements being on lines 4 and 7. This is due to the presence of distributed generation, which decreased the amount of energy that has to be imported, coupled with smart grid facilitating technologies (like p2p, demand response and storage), which allow the community to waste less of their distributed generation that would otherwise be lost to the mismatch between demand and supply.

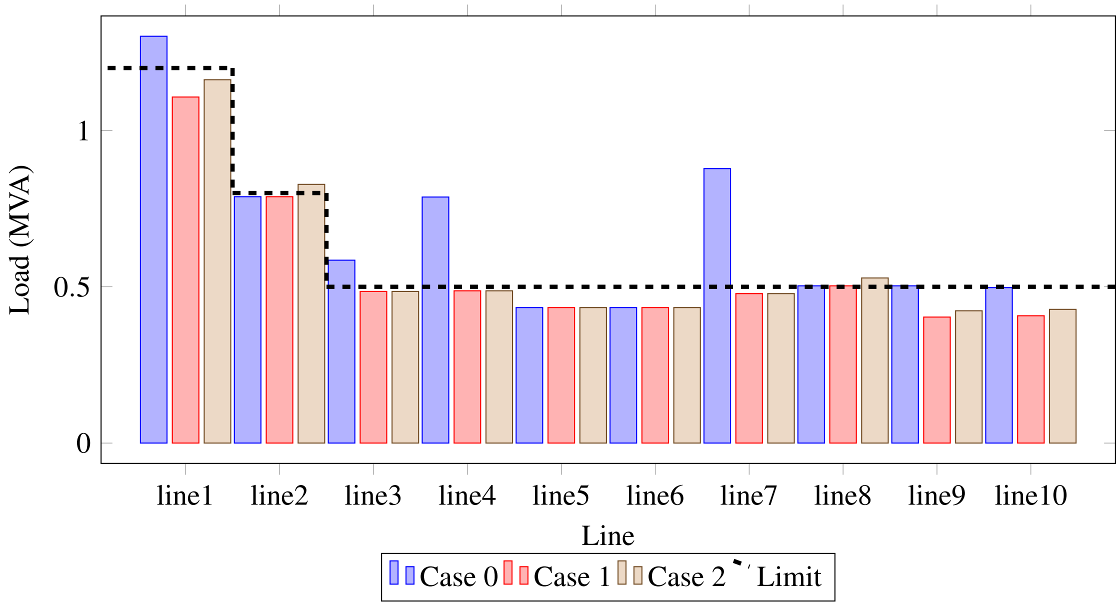

Figure 4.14: Line congestion

As previously stated, the difference between Cases 1 and 2 is the presence of industrial players, w2 and w9, which are characterised by higher energy demand. This results in a slight increase in the capacity factor of those lines that are directly upstream from them.

Fig. 4.15 shows the voltage profiles across the different cases. Predictably, in all cases, voltage drops more when nodes are farther away from the feeder bus. Consequently, the most downstream bus, w6, presents the greatest voltage drop. However, with the introduction of Case 1 to the grid, there was a remarkable improvement in voltage quality across all buses, with the biggest benefits, in absolute terms, occurring in buses w4 to w6. Moreover, there was an average improvement of 37.19% in voltage quality from Case 0 to Case 1.

Table 4.8: Line capacity factor across all cases

Line	**Capacity factor (%)**			**% change from previous case**	
	Case 0	**Case 1**	**Case 2**	**Case 0 to 1**	**Case 1 to 2**
line1	**108.47**	92.27	96.88	-14.93	5
line2	98.54	98.54	**103.46**	0	5
line3	**117.02**	97.02	97.02	-17.09	0
line4	**157.45**	97.45	97.45	-38.11	0
line5	86.71	86.71	86.71	0	0
line6	86.71	86.71	86.71	0	0
line7	**175.64**	95.64	95.64	-45.55	0
line8	**100.63**	**100.63**	**105.66**	0	5
line9	**100.63**	80.63	84.66	-19.88	5
line10	99.48	81.48	85.55	-18.10	5
Average	113.13	91.71	93.97	-15.37	2.5

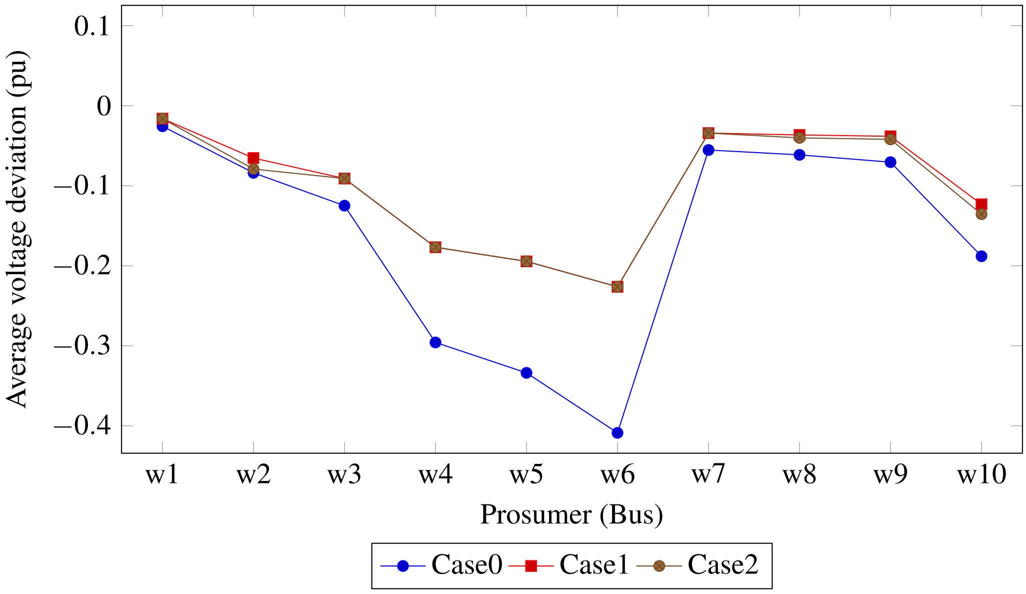

Figure 4.15: Voltage profiles

Table 4.9: Percentage change in voltage profiles across all cases

% change from previous case		
Prosumer (bus)	**Case 0 to 1**	**Case 1 to 2**
w1	37.06	0
w2	22.01	-21
w3	27.15	0
w4	40.20	0
w5	41.74	0
w6	44.65	0
w7	38.22	0
w8	40.53	-10
w9	45.82	-10
w10	34.51	-10
Average	37.19	-5.10

In Case 2, once more there was a worsening of performance on the buses directly upstream of w9 and w2, again due to their increased load. Despite the greater load, voltage deviations in Case 2 were still smaller than in Case 0. Thus, based on the results, it can be concluded that the deployment of smart grid technologies, including P2P transactions, has generally led to improvements in the congestion and voltage profiles.

Finally, while it wasn't the case in the case studies analysed in this work, an argument could be made that excess PV output might lead to greater congestion. For example, in a radial network where one branch is mainly exporting energy to another mostly importing branch, through

P2P transactions, the lines connecting these two branches might become congested. However, the presence of energy storage can mitigate this effect by absorbing excess PV generation and distributing throughout the day, thus limiting congestion while avoiding wasting PV power.

4.4 Chapter summary

In this chapter, the system used to simulate the mathematical formulation presented in Chapter 3 is described, together with the three case studies used to validate the model. The first case was meant to be a benchmark that represents current distribution grid operation, i.e., without a P2P market and distributed energy resources, while the other two cases introduced these technologies to the grid, along with a different combination of user types.

Then, the numerical results were presented, analysed and compared among the cases in terms of costs (community total, user total, user average cost per unit of energy and average cost per unit of energy of consumers vs prosumers), energy mix (for individual users and for the community as a whole), demand and supply profiles, and grid congestion and voltage quality. Briefly, the main conclusions were that: costs were lower for all users after introducing Case 1 conditions, with prosumers having lower energy costs per kWh than consumers on average; the main two load peaks (as seen from the grid) were significantly reduced thanks to the deployment of PV generation and storage systems; however, the charging demand of the storage systems created an entirely new demand peak; P2P market transactions were concentrated around the previously mentioned pair of demand peaks, contributing to their decrease; and congestion and voltage quality were improved with the presence of P2P transactions.

Chapter 5

Conclusion and future work

In this chapter, the main conclusions of this dissertation are presented, as well as a summary of the work. Furthermore, several ideas for future works are proposed to advance the study of the impact of P2P markets on the distribution grid.

5.1 Conclusion

In this dissertation, a stochastic MILP model was developed that is capable of simulating the operation of a distribution grid with smart grid technologies and P2P transactions, which takes into account the grid's physical restrictions and aims to minimise the users' total costs. This model was used to simulate three case studies that represented different load and generation scenarios based on several mixes of prosumer and consumer types. The numerical results were obtained by applying the developed mathematical formulation on an adapted branch of a 119-bus IEEE test grid with 10 users. Consequently, the analysis of the three case studies resulted in the following conclusions:

- In terms of costs, the total cost was reduced on a collective basis since the energy cost of every user was lowered. Moreover, it was noted that, while the unit cost of energy was lower for everyone after the introduction of smart grid enabling technologies and P2P transactions, prosumers paid less per kWh on average than consumers.
- Regarding the community's overall load profile, the two major demand peaks that were initially present were significantly reduced after the introduction of smart grid enabling technologies and P2P transactions. However, a new load peak was created after introducing the charging demand of the ESSs and EVs.
- Transactions on the P2P market were concentrated during the demand peaks, contributing to their reduction.
- Finally, after introducing the smart grid enabling technologies and P2P transactions, the voltage profiles and grid congestion were both improved.

In conclusion, this work has highlighted the benefits of introducing smart grid enabling technologies, such as distributed generation and storage, together with P2P transactions, which provide both technical and economic benefits to the distribution grid and its users.

5.2 Future works

Possible future works on this topic involve:

- Extending the analysis beyond a one-year period.
- Including more case studies, such as not allowing storage systems to charge from the grid, and considering larger PV systems and using P2P transactions as an alternative to energy storage.
- Increasing the scale of the controllable loads as a percentage of total load and investigating their effects on congestion and voltage profiles.

Appendix A

System data and results

A.1 System data

Table A.1: Line data

Line	**From bus**	**To bus**	**R(Ω)**	**X(Ω)**	**Line capacity (MVA)**
1	Substation	Pro_1	0,0625	0,0265	1,2
2	Pro_1	Pro_2	0,1501	0,234	0,8
3	Pro_2	Pro_3	0,1347	0,0888	0,5
4	Pro_3	School	0,2307	0,1203	0,5
5	School	Pro_4	0,447	0,1608	0,5
6	Pro_4	Pro_5	0,1632	0,0588	0,5
7	Pro_5	Pro_6	0,33	0,099	0,5
8	Pro_1	Con_1	0,1501	0,234	0,5
9	Con_1	Con_2	0,1347	0,0888	0,5
10	Con_2	Con_3	0,2307	0,1203	0,5

A.2 Case data

Table A.2: Case 1: detailed user data

Client	**Bus**	**Type**	**EV**		**ESS**		**PV capacity (kWp)**	**P2P?**
			Capacity (kWh)	**Max charging/ discharging rate (kW)**	**Capacity (kWh)**	**Max charging/ discharging rate (kW)**		
w1	Pro_1	Prosumer	16	3.3			2	both
w2	Pro_2	Prosumer					2	both
w3	Pro_3	Prosumer	24	7.2	4	0.6	2	both
w4	Pro_4	Prosumer	22	6.6	3	0.6	2	both
w5	Pro_5	Prosumer	16	3.3	3	0.6	2	both
w6	Pro_6	Prosumer			3	0.6	2	both
w7	Con_1	Consumer	24	7.2			2	buy
w8	Con_2	Consumer	24	7.2			2	buy
w9	Con_3	Consumer					2	buy
w10	School	Prosumer (school)			9	1.8	6	both

Table A.3: Case 2: detailed user data

Client	**Bus**	**Type**	**EV**		**ESS**		**PV capacity (kWp)**	**P2P?**
			Capacity (kWh)	**Max charging/ discharging rate (kW)**	**Capacity (kWh)**	**Max charging/ discharging rate (kW)**		
w1	Pro_1	Prosumer	16	3.3			2	both
w2	Pro_2	Prosumer (industrial)					4	both
w3	Pro_3	Prosumer	24	7.2	4	0.6	2	both
w4	Pro_4	Prosumer	22	6.6	3	0.6	2	both
w5	Pro_5	Prosumer	16	3.3	3	0.6	2	both
w6	Pro_6	Prosumer			3	0.6	2	both
w7	Con_1	Consumer	24	7.2			2	buy
w8	Con_2	Consumer	24	7.2			2	buy
w9	Con_3	Consumer (industrial)					4	buy
w10	School	Prosumer (school)			9	1.8	6	both

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