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A peer-to-peer exchange framework for microgrids to improve economic and resilient operation

A thesis presented for the degree of Doctor of Philosophy

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Abstract

Peer-to-peer (P2P) exchange is an emerging approach in smart grids which enables users to share their energy production or storage surplus or the flexibility of their demand with other end-users. This provides benefits to both energy producers and consumers. In this work, a P2P exchange framework methodology is developed. It relies on a Time-of-Use (ToU) tariff scheme to value the benefit in time-shifting demand to low cost / low carbon periods. Two groups of stakeholders are considered, the local distribution network operator (DNO) and the microgrid (MG) users. Energy trading follows three principles: First, energy sharing occurs by using the storage and renewable assets of the microgrid. Second, P2P exchange is enabled during the high-tariff period and third, it is based on cooperation to achieve mutual benefits for the DNO and the MG users. The stakeholders share the cost and benefits of P2P energy trading. The main steps of the developed methodology include a battery sizing process, user categorization and priority order, zoning and optimum battery discharging. The electrical limits of transformer and storage inverter power are considered in the process. The developed methodology investigates the benefits gained by the DNO and MG users. Benefits are examined in terms of economic benefits for the stakeholders (profits), system resilience in case of faults, carbon emissions reduction and energy storage lifetime increase. Case studies are used to illustrate the capabilities of the methodology in determining the expected performance of a P2P scheme under a range of conditions and geographical locations. The results show that this method of P2P exchange will have significantly different impacts depending upon the local conditions for demand, generation, resilience standards and tariff structure.

Declaration

I hereby declare that this thesis is a record of work undertaken by myself, that it has not been the subject of any previous application for a degree, and that all sources of information have been duly acknowledged.

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List of Publications

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N. Spiliopoulos, P. Taylor, D. Giaouris, and N. Wade, "A novel approach for peer-to-peer exchange in microgrids with respect to carbon emissions," in *CIRED workshop*, 2018, [Online]. Available: https://www.cired-repository.org/handle/20.500.12455/1131.

N. Spiliopoulos, D. Giaouris, P. Taylor, and N. Wade, "Resilience Improvement From Peer-To-Peer Energy Management Strategy in Microgrids , Considering Faults , Carbon Emissions and Economic Benefits ," in *CIRED Conference*, 2019, [Online]. Available: https://www.cired-repository.org/handle/20.500.12455/597.

Acronyms

Acronym	Definition
AMI	Advances Metering Infrastructure
BAU	Business As Usual
BO	Battery Owners
CDM	Clean Development Mechanism
CIRED	International Conference on Electricity Distribution
CPR	Critical Peak Rebates
CPP	Critical Peak Pricing
CREST	Centre for Renewable Energy Systems Technology
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generators
DLC	Direct Load Control
DLT	Distributed Ledger Technology
DNO	Distributed Network Operator
DoS	Denial of Service
DP	Dynamic Pricing
DR	Demand Response
DRP	Demand Response Provider
DSM	Demand Side Management
DSO	Distribution System Operator
EE	Energy - Efficiency
EENS	Expected-Energy-Not-Served
EMS	Energy Management Strategy
ET	Emissions - Trading
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FIT	Feed -In - Tariff
FLT_{Batt}	Battery Fault scenario
FLT_{COM}	Communication Fault scenario
FLT_{Feed}	Feeder Fault scenario
FLT_{TF}	Transformer Fault scenario

FP&L	Florida Power and Light
GC	Grid - Connected
GHG	Green-House-Gases
HEMS	Home Energy Management
HT	High-Tariff
ICT	Information and Communications Technology
ID	Identity
IDS	Intrusion Detection System
IEA	International Energy Agency
IoT	Internet-of-Things
JI	Joint implementation
LC	Local controller
LCA	Life-Cycle Analysis
LIB	Lithium-Ion Battery
Li-ion	Lithium-ion
LOLP	Loss Of Load Probability
LT	Low-Tariff
MCC	Microgrid Central Control
MG	Microgird
MILP	Mixed Integer Linear Programming
MO	Market Operator
MPC	Model-Predictive Control
NPV	Net Present Value
PC	Personal Computer
PCC	Point of Common Coupling
PHEV	Plug-in Hybrid Electric Vehicle
PL	Power Limits
P2P	Peer-to-Peer
PV	Photovoltaic
RES	Renewable Energy Sources
RTP	Real-Time Pricing
SAIDI	System-Average-Interruption-Duration Index
SAIFI	System-Average-Interruption-Frequency Index
SO	System Operator
SSEZ	Small-Scale Energy Zone

TCL	Thermostatically Controlled Loads
TF	Transformer
ToU	Time-of-Use
TV	Television
UC	Unit Commitment
UK	United Kingdom
UPEC	Universities Power Engineering Conference
V2G	Vehicle-to-Grid

Nomenclature

a	Battery degradation coefficient	[$Ah^{-1}K^{-2}$]
a_1-a_4	Curve fitting coefficients	Dimensionless
A_h	Battery A_h-throughput	[Ah]
b	Battery degradation coefficient	[$Ah^{-1}K^{-1}$]
b_1-b_4	Curve fitting coefficients	Dimensionless
B_1	Pre-exponential factor of battery degradation	[Ah^{-1}]
B_2	Exponential factor of degradation	[$C\text{-rate}^{-1}$]
$Batt_{rated}$	Battery rated capacity	[kWh]
B_{P2P}	Benefits gained form P2P exchange for each user k	[£]
$B_{P2P\text{-}CO2}$	Benefits gained from carbon savings	[£]
$B_{P2P\text{-}PV}$	Benefits gained from PV surplus fed in the grid	[£]
$B_{P2P\text{-}tot}$	Total benefits gained from P2P exchange	[£]
B_{tot}	Total benefits gained	[£]
c	Battery degradation coefficient	[Ah^{-1}]
c_1-c_4	Curve fitting coefficients	Dimensionless
C_{batt}	Battery cost per kWh	[£/kWh]
C_{BAU}	Total cost of BAU scenario	[£]
$C_{CO2\text{-}saved}$	Tariff paid for each tonne of carbon emissions saved	[£/tn CO_2]
$C_{deg\text{-}est}$	The estimated degradation cost	[£]
$C_{grid\text{-}BAU}$	Cost paid for the energy used from the grid, in BAU scenario	[£]
$C_{grid\text{-}P2P}$	Cost paid for the energy used from the grid, in P2P scenario	[£]
C_{HT}	High tariff based on the existing ToU tariff scheme	[p/kWh]
C_{inv}	Cost of each inverter device	[£]
C_{invest}	Investment cost	[£]
C_{loss}	Battery cycle loss during one-by-one discharging	[%]
$C_{loss\text{-}factor}$	Cycle loss factor	Dimensionless
$C_{loss\text{-}opt}$	Battery cycle loss during optimum discharging	[%]
C_{LT}	Low tariff based on the existing ToU tariff scheme	[p/kWh]
Compensation	Money paid by DNO for compensation due to fault	[£]

C_{P2P}	Total cost of P2P scenario	[£]
$C_{P2P\text{-}tariff}$	The tariff paid for each kWh delivered from batteries during the P2P exchange	[£]
$C_{PV\text{-}surplus}$	Tariff paid for each kWh fed in the grid by PV surplus for P2P exchange scenario	[£/kWh]
$C_{PV\text{-}surplus(BAU)}$	Tariff paid for each kWh fed in the grid by PV surplus for BAU scenario	[£/kWh]
d	Battery degradation coefficient	[K^{-1}(C-rate)$^{-1}$]
d_1-d_4	Curve fitting coefficients	Dimensionless
DoD	Depth-of-Discharge during one-by-one discharging	Dimensionless
DoD_{opt}	Depth-of-Discharge during optimum discharging	Dimensionless
DoD_{autumn}	Depth-of-Discharge during one-by-one discharging for Autumn representative day	Dimensionless
$DoD_{autumn\text{-}opt}$	Depth-of-Discharge during optimum discharging for Autumn representative day	Dimensionless
DoD_{spring}	Depth-of-Discharge during one-by-one discharging for Spring representative day	Dimensionless
$DoD_{spring\text{-}opt}$	Depth-of-Discharge during optimum discharging for Spring representative day	Dimensionless
DoD_{summer}	Depth-of-Discharge during one-by-one discharging for Summer representative day	Dimensionless
$DoD_{summer\text{-}opt}$	Depth-of-Discharge during optimum discharging for Summer representative day	Dimensionless
DoD_{winter}	Depth-of-Discharge during one-by-one discharging for Winter representative day	Dimensionless
$DoD_{winter\text{-}opt}$	Depth-of-Discharge during optimum discharging for Winter representative day	Dimensionless
E_1	Total energy loss due to fault	[kWh]
$E_{batt\text{-}sc}$	Energy needed from each battery for self-consumption	[kWh]
E_{max}	Maximum energy discharged by inverter	[kWh]
$E_{max\text{-}batt}$	Maximum energy discharged by battery	[kWh]
E_{PV}	Energy produced by PV panel	[kWh]
$E_{PV\text{-}surplus}$	Total energy surplus produced by PV panel	[kWh]
$E_{PVtot\text{-}P2P}$	Total energy produced by each PV panel during P2P exchange	[kWh]
$E_{tot\text{-}P2P}$	Total energy required for P2P exchange process	[kWh]
I	Discharging current	[Amps]
I_{max}	Maximum discharging current	[Amps]
I_{opt}	Optimum discharging current	[Amps]

I_{rate}	Battery discharging C-rate	[C-rate]
I_{tot}	Total discharging current	[Amps]
k	Number of users and batteries	Dimensionless
$loss_{batt}$	Percentage of estimated battery losses	[%]
n	Number of representative days	[day]
NPV	Net present value	[£]
p	Percentage of participation in cost and benefits	[%]
P_b	Price of the whole battery pack	[£]
P_{inv}	Maximum power limit of each inverter device	[kW]
P_L	Load demand of user k in time t	[kW]
P_{net}	Net power of user k in time t	[kW]
P_{PV}	Power generated by a PV panel k at time t	[kW]
$Q_{calendar\ loss}$	Battery calendar cycle loss	[%]
$Q_{cycle\ loss}$	Battery cycle loss due to operation	[%]
$Q_{total\ loss}$	Total battery cycle loss	[%]
q	Discount rate	[%]
r	Reduction tariff offered to GC users	[p/kWh]
SoC	Battery State-of-Charge	[Ah]
SoC_{max}	Maximum State-of-Charge	[Ah]
SoC_{min}	Minimum State-of-Charge	[Ah]
T	Absolute temperature	[K]
t	time	[min]
t_{dist}	Time of disturbance due to fault	[min]
$T_{P2P\text{-}end}$	Time P2P exchange ends	[min]
$T_{P2P\text{-}start}$	Time P2P exchange starts	[min]
$W_{CO2\text{-}saved}$	Carbon emissions saved	[tn]
y	years	[yrs]
ΔT_{P2P}	Duration of P2P exchange process	[min]
η	Maximum threshold of battery capacity loss	[%]

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Chapter 1. Introduction

In this chapter a brief introduction of the thesis will be presented, describing the research objectives and the novelty of the research. A brief description of smart grid concept will be presented. The context of the research is given by higlighting the main functionalities of smart grids will be highlighted compared to traditional power systems. The role of smart grids in grid decarbonization will be explained, focusing on their main assets such as renewables and energy storage. An outline of the thesis will be also presented.

1.1. Introduction

1.1.1. Introduction to thesis

In this work, a novel peer-to-peer (P2P) exchange framework is presented for microgrids (MGs) to improve their economic and resilient operation. The presented method was developed gradually by investigating certain areas of the current literature. To fulfil this goal particular research objectives were defined and achieved.

1.1.2. Research objectives

The primary aim of this thesis is to develop a novel peer-to-peer (P2P) exchange framework for microgrids (MGs) to improve economic and resilient operation. MGs are small-scale power systems consisting of self-controllable interconnecting Distributed Energy Sources (DERs) and load customers within clearly defined electrical boundaries [1]. Microgrids can operate in two different modes: grid-connected and islanded. In the grid-connected mode the microgrid exchanges power with the main grid, while in islanded mode it operates independently from the main grid, relying on its own assets for power and energy needs [1].

The presented methodology was developed after identifying research gaps in the current literature. To achieve this the research objectives are:

1) Identify energy management techniques that are applied in MGs in the context of smart grids that contribute to economic and resilient operation.
2) Investigate the role of energy storage in MG operation, identify a suitable storage technology for P2P exchange, and determine the modelling requirements to represent the storage features throughout its operational lifetime.
3) Examination of how P2P exchange can enhance resilient operation of MGs alongside providing economic benefits to stakeholders.
4) Develop a P2P exchange method that builds on the above objectives to provide transparent rules for cooperative sharing of energy resources in a MG for economic and resilient operation.

1.1.3. NOVELTY

Technical aspects such as optimum battery size, battery degradation, system resilience in case of faults have not yet been examined in the context of P2P trading. In this work, the research is focused on technical aspects of P2P exchange, with particular interest in storage assets. The synergistic benefits accrued by local DNO and MG users if participating in a P2P exchange scheme are examined. The benefits gained are examined in terms of economic benefits for the participants (profits), system resilience in case of faults, carbon emissions reduction and increased battery lifetime.

1.2. CONTEXT OF RESEARCH

1.2.1. THE CONCEPT OF SMART GRIDS

A grid by definition is a network of electrical conductors that deliver electricity to particular points [2]. For smart grids there is not a definition which is accepted universally, as there are different ways to describe it. A simple definition is that a smart grid is an intelligent grid [2]. While conventional grids just transmit and distribute electrical power, smart grids are capable of actively storing and communicating information and making decisions according to certain criteria [2].

Traditional Power Grids	Smart Grids
Mechanization	Digitization
One-way communication	Two-way communication
Centralized power generation	Distributed power generation
Radial topology	Network Topology
A small number of sensors	Sufficient sensors and monitors
No automatic monitoring	Automatic monitoring
Manual recovery	Semi-automatic and automatic recovery
Pay attention to failures and disruptions	Adaptive protection measures
Manual checking equipment	Remote supervisory controlling equipment
Handling emergencies through staff and telephone	Decision support system and reliable prediction
Finite control	Pervasive and intensive control system
Limited pricing information	Complete pricing information
Fewer user options	More user options

Table 1.1: Traditional Power Grids versus Smart Grids [3]**.**

A main feature of smart grids is the fact that they can deliver electricity in a reliable, sustainable and secure way [4]. A smart grid is also described as a modern grid which optimizes the energy efficiency between suppliers and consumers in real time [5]. The main differences between the traditional power grids and the smart grids are summarized in Table 1.1.

1.2.2. SMART GRID FUNCTIONALITIES

The functionalities of smart grids are summarized below [2]:

- Reliability, security, and efficiency of the electric grid.
- Deployment and integration of distributed resources and generation.
- Demand response and demand-side resources
- Deployment of “smart” technologies such as for metering and distribution automation
- Integration of “smart” appliances and consumer devices
- Advanced electricity storage and peak-shaving technologies, including plug-in electric hybrid electric vehicles (PHEVs), and thermal-storage air conditioning
- Timely information and control option
- Interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.

Reliability, security, and efficiency of the electric grid

Reliability in a system represents its ability to successfully cover the needs of the ends users in each timestep [2]. Smart grids improve fault detection and permit self-healing [6], [7]. The increasing complexity of modern power grids require suitable data mining algorithms to support system reliability such as Bayesian networks [8]. Smart grid are capable to increase system efficiency by using remote monitoring of hybrid generation and automatic smart grid management applications [9]. As smart grids require a high amount of information exchange, they are vulnerable to cyber-attacks that might compromise their operation. For this reason, different approaches have been proposed to ensure system security such as intrusion detection system (IDS) and models that help to analyze, understand and prevent cyber-attacks [2].

Deployment and integration of distributed resources and generation

Smart grids encourage the integration distributed energy resources (DER) such as renewables and storage applications, mitigating the dependency on fossil fuels and promoting sustainability [2]. Wind generators, photovoltaic panels, batteries and thermal storage applications are some of the most common DER used. As the integration of DER requires the control of a large amount of data, decentralized approaches are also developed to alleviate data burden [10].

Demand response and demand-side resources

Demand response and demand-side resources are promising approaches in smart grids that permit to the end users to actively participate in the reduction of peak demand or in the time shifting of it, receiving financial benefits [2]. The end users are no longer passive consumers as it happens in conventional power systems, but they are actively involved to the demand management. Demand response approaches aim to control consumption according to generation, increasing system reliability [11].

Deployment of "smart" technologies such as for metering and distribution automation

Smart metering is a fundamental feature of smart grids, which establishes a two-way communication between the consumers and the utility grid [2]. In this way the consumers receive more accurate bills and can control better their energy use [2]. Advanced metering infrastructure (AMI) is used, collecting information and taking actions through communication channels, making transformer monitoring, power outage management and electric-vehicle integration feasible options [12].

Integration of "smart" appliances and consumer devices

Smart appliances and devices can communicate with utility grid to reduce peak demand and time-shift demand intelligently on their own [2]. These devices are established in households and control their operation automatically based on particular rules, such as smart washing machines that are switched off during high demand periods and operate during low demand periods [13]. Under this concept, Internet of Things (IoT) is a modern technology which enables the communication of a number of devices, people, data, and processes, seamlessly [14]. Different wireless platforms have been developed, such as ZigBee, which are used to enable coordination of the device operation [15].

Advanced electricity storage and peak-shaving technologies, including plug-in electric hybrid electric vehicles (PHEVs), and thermal-storage air conditioning

Storage applications are indispensable part of smart grids, in order to mitigate the intermittent nature of renewables [2]. EVs could be used also as mobile batteries capable of providing energy to the grid, during peak demand periods, using the Vehicle-to-Grid (V2G) technology [2]. V2G technology improves the ancillary services of the smart grids such as peak power shaving, spinning reserve, voltage and frequency regulations [16]. Different architectures have been investigated in order to control a large number of EVs with V2G ability. The most popular is the architecture of aggregator [17]. The aggregator is considered to be a central in-charge who coordinates all the required operational activities and maintains the link between energy market players and the EV owners [17]. Thermal storage air conditioning technology combines a thermal storage device and a conventional air-conditioning system [18]. It produces and stores the heat needed for air conditioning during nighttime when the demand for air conditioning is small and utilizes the stored heat at a peak during daytime [19]. Thermal storage air conditioning is considered as an efficient energy management solution for smart grids [18].

Timely information and control option

As the grid becomes smarter timely information is achieved in order to make suitable decisions at the correct time. Smart end-user devices and time synchronization provide necessary data for power quality verification and detection of illegal users [20]. Intelligent control in smart grid offers significant advantages such as optimum power generation by real time load demand, fault detection and reconfiguration, optimal reactive power control for distributed generation [2].

Interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid

An efficient operation of smart grids requires a coordination of different domains such as customers, generation, service providers, markets, transmission, distribution [2]. The complexity and the large amount of devices make interoperability a necessary part of smart grids [2].

1.2.3. GRID DECARBONIZATION

Climate change is defined as the long-term alteration of climate in a particular location, region or the entire planet [21]. One of the major causes of climate change are the green-house-gases (GHGs), where the most important is the carbon dioxide (CO_2) [22]. Different actions have been made to cope with the climate change threat. One of the most important was the Kyoto Protocol signed in 1997 [21]. The main mechanisms developed to reduce carbon emissions are clean development mechanism (CDM), joint implementation (JI), and emissions trading (ET) [21]. Following these mechanisms, EU energy policy aims to reduce carbon emissions by 20%-30% compared to 1990 until 2020, and a further reduction of 80% until 2050 [23].

Smart grids are expected to play a major role to decarbonization of modern power systems by increasing the integration of renewables, reducing significantly their dependence on fossil fuels [24]. The development of smart grid technologies coupled with other sectors of the economy could promote a sustainable development [25]. At present around one fifth of the World's total energy is been used in the electricity sector, while three quarters of it is covered by fossil fuels [25]. Thus, a grid decarbonization

1.2.4. Smart grid assets – renewables and storage

The most important assets of smart grids are renewable energy sources (RES) and storage devices. According to IEA definition, "renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, the wind or from heat generated deep within the earth" [26].Wind and solar power are the most popular RES that are increasingly integrated in modern power systems. Other RES are thermal, biopower and marine energy [27].

Wind turbines transform wind kinetic energy to mechanical to generate electricity [27]. Conventional wind turbines have an horizontal-axis design where two or three blades are rotated following the laws of aerodynamics [27]. Over the last decades, their size have been increased significantly, leading to a 200-fold increase of power output [27]. PV panels is the most common device to capture solar energy, by using photoelectric effect in order to produce electricity through a semiconductor. The most widely used semi-conductor is silicon [27]. RES integration, promotes grid decarbonization in the context of a sustainable development, and it can be installed closer to the end users [28]. RES can offer significant benefits to modern power grids [29]:

- Energy cost savings
- Savings in power losses in the transmission and distribution networks
- Put over new large power plants
- Put over transmission line extension
- Increased reliability
- Enhances power quality
- Reduced land use
- Reduction in peak power requirements
- Potential use as emergency supply

Wind power and PV panels are fast growing technologies and their costs have reduced significantly. Wind power is one of the cheapest available RES that become even cheaper [24]. Solar panels are also a cost-effective solution, as their cost has been decreased tremendously by 99% in the last 40 years, due to the progress in the materials research [24]. A further decrease of RES is expected in the future, making them the main power source in the share of generation globally by the early 2040 [25]. The benefits of wind and solar power along with the constant cost reduction has led to significant increase of global wind and PV installations. Wind power installations have been increased from 24GW in 2001 to 651GW in 2019 (Figure 1.1) [30]. Similarly, global PV installations have been increased from 50GWp in 2010 to 680GWp (Figure 1.2) [31].

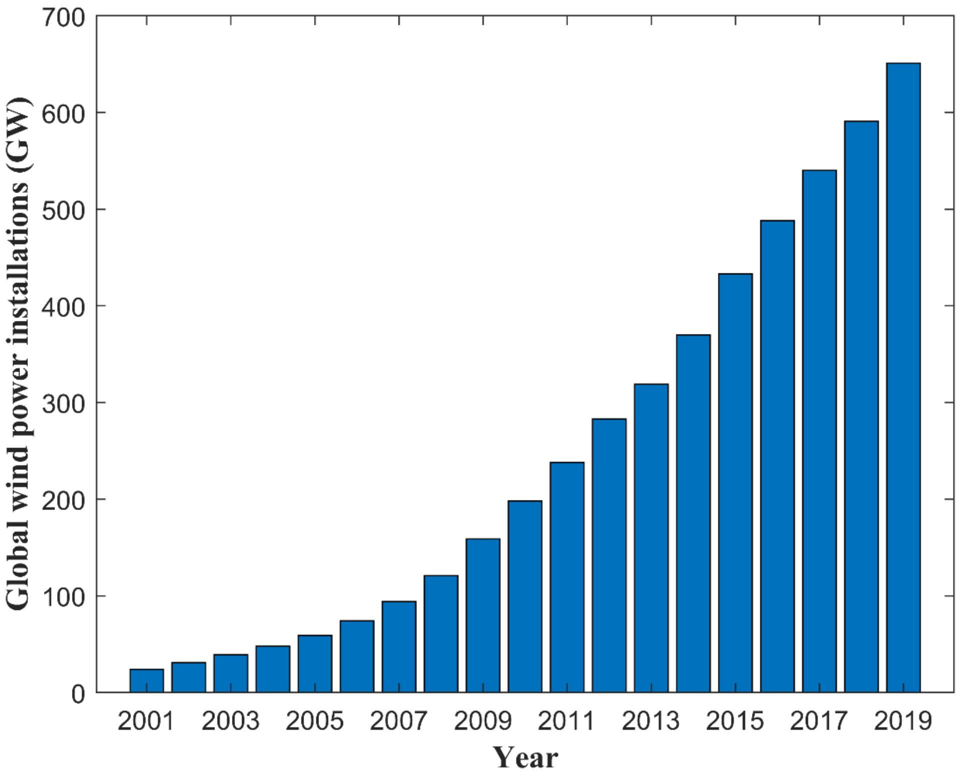

Figure 1.1: Historic development of total wind installations [30]**.**

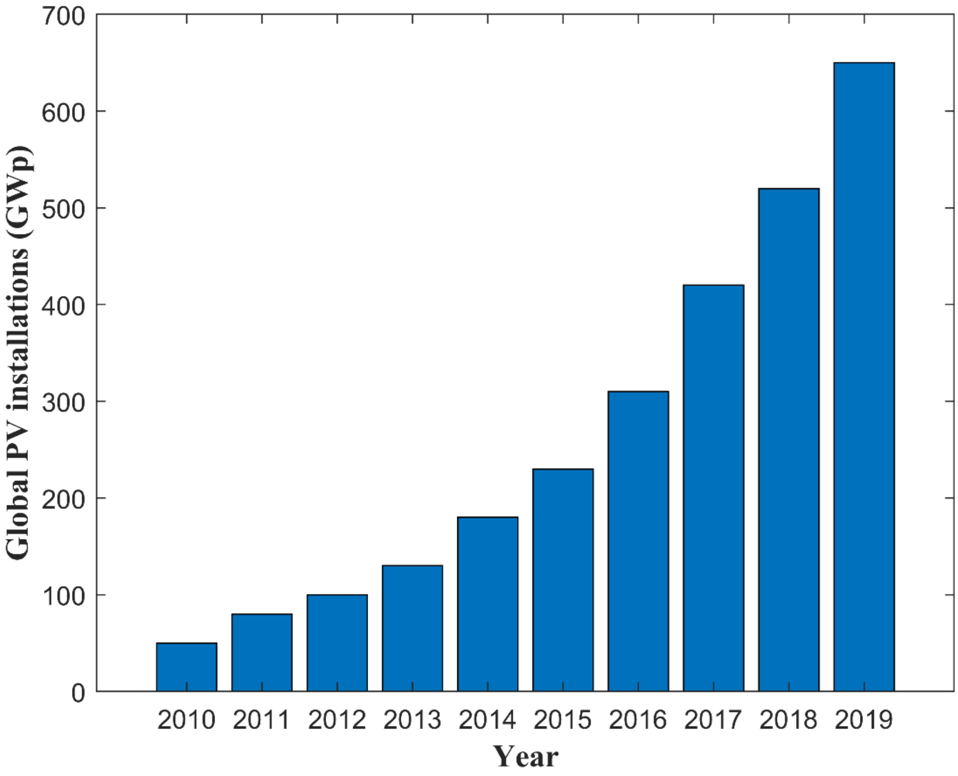

Figure 1.2: Cumulative installed PV power by country [31]**.**

Despite the significant advantages the RES offer to modern grids, they pose new challenges that need to be addressed. These challenges are related to their intermittent nature and their special characteristics that differentiates them from the conventional power generators. The main characteristics of renewables are [32]–[34].

- Variability in their power output due to the variability of their primary source (e.g. wind, sun).
- Their generation has uncertainties due to the unpredictable nature of their primary source.
- They are constrained by the location of their installation.
- Most of their generators are non-synchronous.
- They have low short-run costs.
- They usually have insufficient generation adequacy.

To address these challenges different technology solutions are developed, such as transmission expansions, voltage management and integration of energy storage technologies, energy management techniques [32], [35], [36].

Energy storage technologies play a vital role in smart grids, as they mitigate the intermittent nature of renewables, permitting their high utilization [37]. Moreover, energy storage technologies increase grid flexibility and ancillary services in order to address the supply/demand challenges of modern power grids [37]. Ancillary services are defined as the services that maintain integrity and stability of transmission or distribution system, including power quality [38]. Examples of ancillary services are: Voltage/frequency regulation, demand response and resource adequacy [39]. A summary of the ancillary services provided by energy storage technologies are presented in the table below (Table 1.2):

	Grid Quality	Cost Saving
A	-Voltage Regulation -Frequency Regulation -Congestion Relief	-Demand Response -Self-Consumption -Energy Arbitrage
B	-Black Start/Backup Power -Power Quality	-Resource Adequacy -Distribution & Transmission Deferral

Table 1.2: Summary of ancillary services provided by energy storage technologies [39]**.**

Different energy storage technologies have been developed providing a wide range of options according to the problems and challenges they need to address. Each technology has its own advantages and disadvantages [37]. Some of the most important energy storage technologies are hydro, compressed-air, battery, flywheel, capacitor, supercapacitor, superconducting magnetic and thermal systems [37]. Despite the advantages they offer, new challenges emerge regarding their operation and control [37].

1.3. THESIS OUTLINE

The rest of the thesis is organized as follows: In Chapter 2, energy management techniques in MGs are investigated. The role of MGs in smart grids and the most important energy management techniques in this context, are described. The active role of consumers is highlighted, and MG planning and operation issues are presented.

In Chapter 3, a brief review of available storage technologies is presented focusing on battery devices and especially on lithium-ion batteries. Their advantages and disadvantages are presented in detail compared to the other available technologies. The degradation effect is identified as a crucial factor for lithium-ion battery lifetime. The role of storage in distribution networks is also described and a piece of our publish work is presented regarding the benefits of lithium-ion batteries for domestic users.

The concepts of resilience and P2P exchange are described in detail in Chapter 4. Particular type of faults are presented and the concept of resilience in MGs is investigated. Significant issues regarding P2P exchange are analyzed and explained in detail, such as market designs and trading platforms. A detailed literature review for P2P exchange is also presented and the existing research gaps are highlighted.

In Chapter 5, a novel framework for P2P exchange in MGs is presented. The goals of the developed methodology are explicitly stated, and the main steps of the developed methodology are explained in detail. Different scenarios are examined to thoroughly investigate the impact of the method to system resilience. The work presented in this chapter is the main contribution of this thesis, based on the knowledge acquired and the research gaps that were identified in the current literature.

A case study is presented in Chapter 6, based on the develop methodology of the previous chapter. The results obtained are presented in detail for each step providing relevant graphs. This chapter shows the practicality of the developed framework and how it could be implemented and provide benefits to the stakeholders.

In Chapter 7, more case studies are presented including different ToU tariff schemes and locations. From the obtained results four different graphs are created for different objectives. This chapters show that the method developed in Chapter 5 is generalized and could be applied to any locations. In this way, it is a useful tool that provide insights about the potential benefits the stakeholders can gain by applying the certain method.

In the last chapter, the optimum discharging is compared with an one-by-one battery discharging. The aim is to investigate which discharging scheme causes less battery capacity loss. Curve fitting process is used to correlate the dept of discharge with the discharging currents. The obtained results are presented.

Finally, the key issues of the thesis are summarized and discussed. Different limitations and barriers identified during the research process are presented. The conclusions conducted from this work are also presented along with some ideas for future expansion.

1.4. CHAPTER SUMMARY

In this chapter, a short introduction of the thesis was presented. The research objectives and the novelty of this work were highlighted. A brief description of the smart grid concept was made. Main functionalities of smart grids were described compared to the traditional power systems. The role of smart grids was investigated in the context of grid decarbonization. Renewables and energy storage technologies were identified as main assets of smart grids. An outline of the present thesis was also presented.

Chapter 2. Energy management in microgrids

In this chapter, the role of MGs in modern smart grids and the advantages they provide are highlighted and energy management techniques related to them are identified. Research is focused on centralized and decentralized techniques with special interest on a new type of users, which are producers and consumers at the same time (prosumers). Planning and operation techniques of MGs are also investigated, in terms of optimum sizing of the available assets (PVs, Storage devices) and implementation of control techniques.

2.1. Role of microgrids in smart grids

A MG, is characterized as a small-scale power system which is self-controllable interconnecting DERs and loads within clearly defined electrical boundaries [1], [40]. A main feature of MGs is the fact that they are connected with the main grid through points of common coupling (PCCs) at their boundaries [41]. MGs can be operated in two different modes: grid-connected and islanded. In the grid-connected mode the M is connected with the main grid, while in the islanded mode it can be operate independently from the main grid, relying only on its own assets [41]. This feature makes them of particular interest for researchers. One of the main advantages of MGs is that they can integrate RES that could be used locally in a decentralized way, reducing power losses and mitigating environmental impacts of climate change. Moreover, MGs connect also local users to the main grid in such a way that they can be treated as a flexible aggregated and controllable load [42]. MGs have become the main field of research from academic community as their deployment could significantly enhance resilience of modern power systems [41]. As one of their main features is the islanded operation, they could run independently under extreme events by optimum use of their DER and reconnect to the main grid when they have been eliminated [43]. This significant feature protects also the main grid from major outages, arising though significant challenges to their operation and control [41].

2.2. ENERGY MANAGEMENT TECHNIQUES IN MICROGRIDS

Energy management techniques are used in order to allocate efficiently the available energy resources, by scheduling the dispatch of distributed generators (DGs), energy storage systems (ESS), controllable loads and energy imports/exports to fulfill certain objectives [44]. Energy management in MGs is an important issue which becomes more popular as MGs become indispensable part of modern power system and more challenging as the integration of RES is increased [45]. There are two main energy management approaches, one from the generators side (unit commitment) and one from the demand side (Demand-side management approaches).

Unit commitment (UC) is one of the most common energy management techniques, in order to allocate the available resources in an economic and secure way [46]. The Unit commitment is formulated as an optimization problem, which varies depending on the mix of the available units and particular operating constraints [46]–[48]. Different optimization techniques have been used to address UC problem including, stochastic programming, MILP and robust optimization [49]–[52]. The increasing integration of renewables pose new challenges to the UC problem due to the intermittent nature of renewables, as it is dominated by uncertainties [53]. Robust optimization is one of the most promising techniques to tackle their uncertainty [53]. Rolling-horizon strategy is another energy management technique in order to perform the UC scheduling [52].

In this work, UC is related to the optimum dispatch of the available storage assets of the MG. The developed methodology establishes a P2P exchange where it is based on the optimum discharging of the available storage assets under particular constraints. More details will be presented in the next chapters.

Demand side management (DSM) is defined as the modification of demand consumption patterns in order to increase efficiency and flexibility of power systems operation [36]. DSM can be used to achieve different load shaping objectives, such as peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape (Figure 2.1) [54].

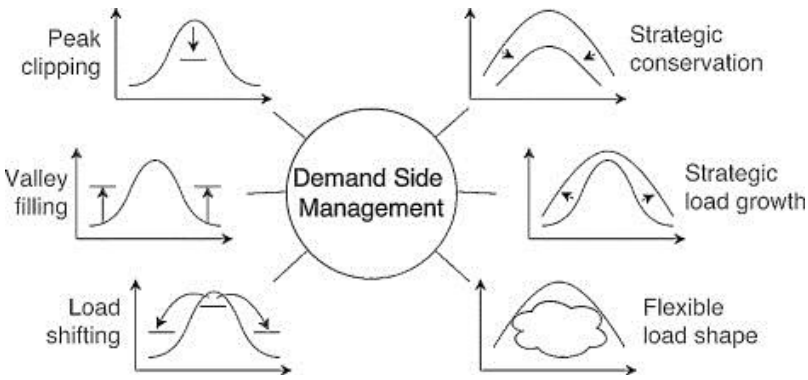

Figure 2.1: Basic load techniques of DSM [54].

DSM becomes popular in modern power systems and it is classified in "Energy Efficiency" (EE) and "Demand Response" (DR) strategies [36]. Energy Efficiency aims to reduce the required energy for the provision of services or products, while Demand Response provides incentives to end-use customers to modify their energy consumption when the wholesale prices are high, or the system reliability is compromised [55].

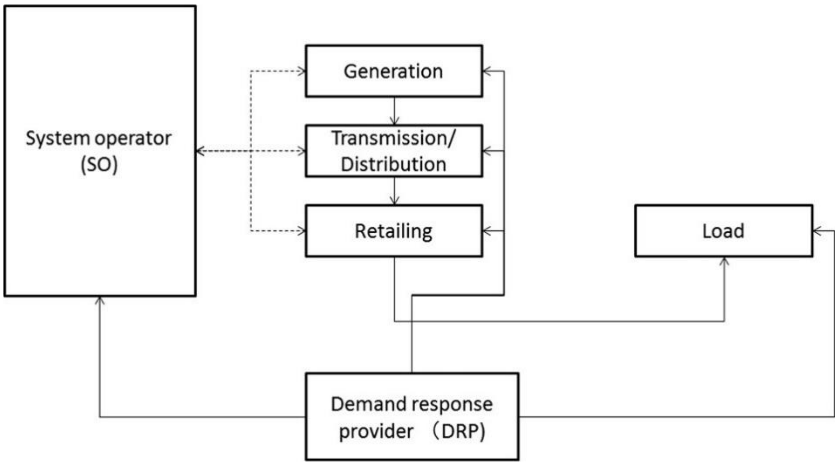

Figure 2.2: Demand response in a typical electricity market [36]**.**

While DSM implementation used to be quite challenging in the past, due to technological barriers, which have been overcome in the era of smart grids, making DSM a quite popular approach [56], [57]. Different business models have been developed to integrate DR, in relation to typical electricity markets (Figure 2.2) [36]. The system operator (SO) is the stakeholder, which is responsible to maintain system reliability, by applying economic efficient measures. The generation stakeholder is responsible for energy generation. The energy mix can include fossil fuels or renewable energy sources such as PV, wind etc. [36].The transmission/distribution stakeholder is responsible for allocating the energy in a reliable and secure way. Retailing stakeholder performs the retailing of electricity to loads [36]. The load stakeholder is the entity which consumes energy, and it is exposed to particular tariffs/prices posed by other stakeholders such as retailer and transmission/distribution. A new concept is introduced in [36], called Demand response provider (DRP), which represents an entity which transforms DSM activity into business offering certain prices to other stakeholders. One common DR strategy is the direct-load control (DLC) of particular devices, for certain periods of time. DRP offers bilateral contracts to the end users offering particular benefits for shutting down particular devices. The contract usually includes contract duration and maximum number of interruption hours. Activation signals and monitoring data are also determined in the contracts [36]. Essentially the load owner permits to the system operator to control particular loads. The DLC is applied automatically by the SO without the involvement of the load owner [36]. These approaches are suitable for small loads that are flexible and can be aggregated at large numbers, such as the thermostatically controlled loads (TCLs), such as air-conditions and refrigerators [58], [59]. Two examples of successful DLCs strategies are offered by Florida Power and Light (FP&L) named "On Call" [60], and another offered by ETSA utilities [61].

Some of the advantages that DSM offers are frequency regulation, capacity provision, market efficiency enhancement [36]. Frequency regulation (FR) requires very fast response in order to maintain generation-load balance, keeping its levels close to a desired reference value [62]. In conventional power systems FR was performed from generation stakeholders. However, in modern smart grids storage assets and DSM techniques are also used [63], [64]. Moreover, DSM offers extra capacity to the system, and can efficiently reduce peak load demand by performing suitable DR actions [x-69]. The increased flexibility offered by DSM enhances significantly, market efficiency since it permits a more efficient scheduling of the available resources [65]. Load shaping is another significant advantage that DSM provides, as significant amount of energy consumption could be shifted to periods where the total demand is low (load shifting) [66]. DSM techniques finally can reduce significantly grid cost, as during high retailing prices consumption can be modified accordingly. DR aggregation is an important cost saving element [36].

Despite the significant benefits that DSM offers to modern power systems, new challenges emerge. One significant challenge is the lack of ICT infrastructure, as advance metering, communication and control techniques are absent in most existing power systems [57]. Moreover, there is not a full understanding of the benefits offered by the DSM strategies, leading to lack of business cases [57]. In addition, the successful implementation of DSM techniques, require a complete technical, economic and environmental assessment of the existing power systems, which is insufficient in most cases [57]. The DSM techniques also increase the complexity of modern power systems compared to the conventional ones [57]. Finally, the lack of DSM business cases leads to the lack of appropriate markets and incentives for the users [57].

In this work DSM techniques will be used in case of faults. If the available energy in batteries during fault, is insufficient to cover the energy/power needs of the MG users, a direct load curtailment of particular devices will be performed. In this way, the MG will still operate independently but will cover partially the load of its end-users. In case, the available energy is sufficient, no DSM actions will be performed. More details will be presented in the next chapters.

Time-of-Use (ToU) tariffs is a modern way to incentivize users to actively manage their consumption and participate in DSM techniques [67]. In a ToU tariff scheme the electricity prices varies through time, depending on different factors such as network constraints and wholesale price of electricity [68]. In this way end-users have incentives to reduce their energy consumption during the high-tariff periods and shift their consumption to lower tariff periods [68]. Current research demonstrates a considerable reduction in peak energy consumption, depending on the ToU tariff design [69]. Different ToU tariff schemes have been used in several countries involving industrial and commercial customers, including gradually domestic users [68]. According to [68] five different ToU tariff designs are recognized in current literature:

- <u>Static ToU:</u> Tariffs are fixed in a regular way, having certain peak-time periods and off-peak time periods.
- <u>Dynamic ToU(DP):</u> Tariffs are fixed, but vary from day-to-day. In this case, customers are notified in advance about the tariffs of each day.
- <u>Real-time pricing (RTP):</u> Prices vary in real-time, depending on the wholesale electricity market.

- Critical peak pricing (CPP): Pricing is fixed for most of the day, but there are some high price events, where the users are informed in advance about the price increase.
- Critical peak rebates (CPR): Pricing is flat, but at certain times (notifiable in advance) customers are rewarded for reducing their electricity demand compared to an agreed amount.

Current research findings show that static ToU tariff are more preferred than dynamic and dynamic pricing [68], [70], [71].

2.3. Active role of consumers (prosumers)

The transition of modern power systems to an increasingly decentralized structure with local energy production and consumption, has led to the phenomenon of users that both producer and consume renewable energy, modifying actively their consumption This type of users is known as prosumers [72]. In other words, a prosumer can be energy producer, energy seller and energy consumer at the same time (Figure 2.3). There is an increasing implementation of projects in local communities, where the energy management is allocated in such a way that integrates local users and distribute gained benefits among them [73]–[75]. In this way, new markets emerging engaging the active participation of prosumers, in contrast to a passive energy consumption that occurs in conventional power systems [72]. Prosumers as considered as novel way of facing the emerging challenges in modern power systems, increasing the integration of distributed energy sources and mitigating GHG emissions [76], [77]. Moreover, they contribute to the mitigation of RES intermittency through changes in demand behavior, integration of storage assets and usage of particular market designs such as time-of-use (ToU) tariffs schemes [78], [79]. For this purpose, different business models have been developed to facilitate the role of prosumers by encouraging local energy production/consumption and local trading [72], [80]. Different value logics have been introduced such as market, municipal and community value logics [72].

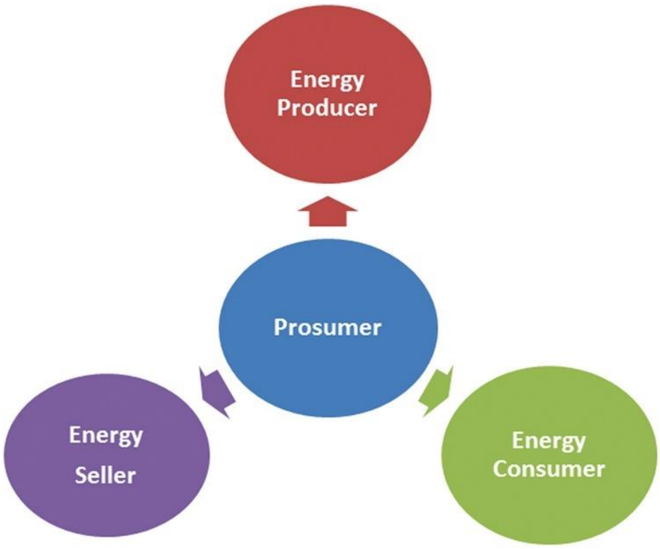

Figure 2.3: Concept of prosumer [81].

Different approaches have been used in order to develop models that simulate the trading among prosumers. Decentralized approaches, such as agent-based models, are selected by researchers as they permit the energy distribution among prosumers without the need of a central controller [82]. The integration of prosumers in modern systems require suitable infrastructure of advance metering (AMI) and systems of home energy management (HEMS), providing the necessary information of energy demand and consumption among users [83]. Moreover, the users receive information about energy availability and prices for each timestep [83]. One common way of energy sharing among prosumers, is the connection of them in a local control center connected to the grid. Two key elements have been recognized for energy sharing: communication infrastructure and optimization techniques [82]. Smart metering and internet of things (IoT) applications are used to enable interaction among prosumers [84]. Various challenges have been recognized in existing literature regarding energy management among prosumers. Some of the most important are: Development of energy sharing vision, data security, equipment installation, funding and investment, equipment installation and management/maintenance issues [83].

2.4. MICROGRID PLANNING AND OPERATION

Planning of MGs is a significant issue that attracts special interest from researchers, as MGs become more popular in modern power systems. The main tool is a cost-benefit analysis in order to justify if a particular amount of money should be invested or not [85]. However, an accurate economic approach is quite challenging as there are factors of uncertainty. Thus, different modelling approaches have been proposed in current literature, to facilitate successful MG planning [85]. Researchers use suitable optimization techniques in order to find the optimum size of particular MG assets, such as PV panels and storage devices [86]–[90]. The aim is to minimize investment cost, operation and maintenance cost, and carbon emissions [85]–[87]. Genetic algorithms, neural networks, swarm particle optimization and mixed-integer-optimization are some of the optimization techniques used [86], [90]. Another important stage of MG planning is the power flow analysis, which is similar to ones used for the conventional power systems [85]. In case of MGs droop characteristics of DGs are used [90], [91], which essentially show the relation between active and reactive power to frequency and voltage respectively [85]. Different, power flows methods have been used, such as Newton trust region method [91], and modified versions of conventional Gauss-Seidel [x-54] Newton -Ramson methods [92].

The increasing integration of RES in MGs, making their control and operation quite challenging due to their intermittent nature [85]. The reliability of their operation is a key factor, which requires particular control techniques in different layers. Three main layers are recognized: distribution, MG and unit layer [85]. Each layer has different characteristics and its operation is dominated by different entities. In the distribution level there is a market operator (MO), and a distributed network operator (DNO). MG level includes microgrid central control (MCC) and unit level local controllers (LC) [85]. The supervisory control could be either centralized or decentralized [93]. Different methods have been used in order to ensure stability of MG operation, including small signal models dynamic techniques using droop characteristics of DGs or more generalized approaches [94]–[96].

In this work, a cost-benefit analysis is used to estimate the benefits gained and find the optimum battery size for each user. DSM techniques will also be used, with direct load curtailment of particular devices when the MG transformer or supply are lost, and the available energy stored in the batteries is not sufficient to cover the total demand of all users. These concepts will be explained thoroughly in Chapter 5.

2.5. Chapter summary

The advantages of MGs in modern power systems were examined in this chapter. Energy management techniques are key factors for allocating the energy optimally, reducing system costs, increasing system reliability and resilience and ensuring safety. Demand side management techniques and demand response are common approaches to control the load within the desired limits (peak shaving, load shifting etc.). Energy management techniques are either centralized or decentralized, influencing the efficient allocation of available energy resources. ToU tariffs incentivize users to actively modify their energy consumption based on the prevailing energy and system costs. The active role of consumers is considered as a crucial factor compared to the passive behavior of the users in traditional power systems.

Chapter 3. Energy storage technologies in smart grids

In this chapter, available storage technologies will be identified, highlighting their advantages and disadvantages. The aim is to select practical and affordable storage solutions, suitable for distribution networks. Energy/power density, response time, cost and Energy/power density are some of the identified key parameters.

3.1. Energy storage technologies

Concerns about climate change, has led the research interest to alternative solutions such as Renewable Energy Sources (RES). The intermittent nature of RES makes energy storage an indispensable part of their integration to modern power systems. Moreover, energy storage technologies are identified as key players for providing ancillary services and cope with demand/supply challenges [37]. Their great potential in future application has increased the interest of academic community in order to find flexible efficient and affordable ways to store energy.

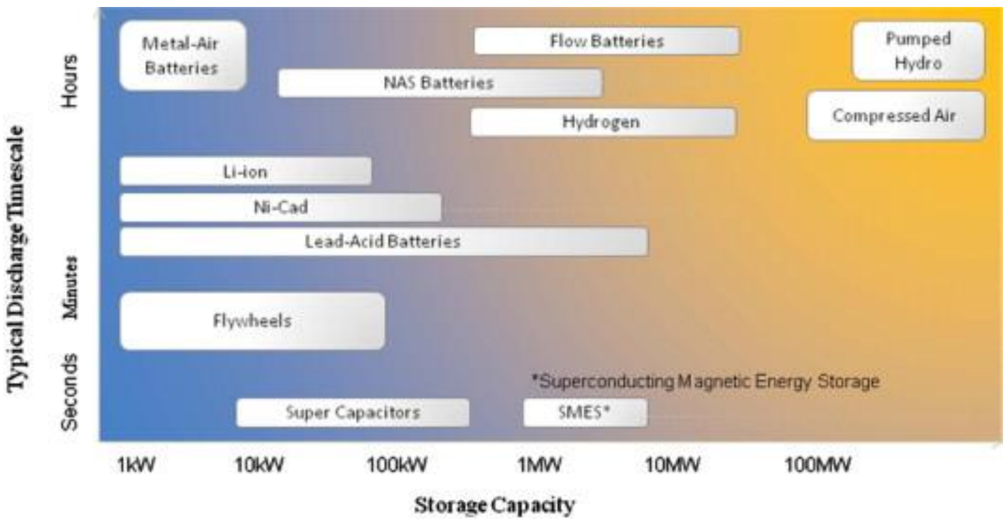

Figure 3.1: Discharging time and storage capacity of different storage applications [37].

Some of the most important energy storage technologies so far are pumped hydro, compressed-air, battery, flywheel, capacitor, supercapacitor, superconducting magnetic and thermal systems [37]. Each technology has its own advantages and disadvantages offering a wide range of options for energy experts, based on their location, application scale, and provided services (e.g. frequency regulation [97], voltage control, Time-of-Use (ToU) tariff energy management) [98], [99]. Differences in discharging time and storage capacity are shown in Figure 3.1. One of the most promising storage technologies that becomes popular are lithium-ion batteries, due to their high-power intensity, efficiency and decreasing cost. However, there are concerns that restricted focus on the development of lithium-ion batteries, may put at risk the development of other alternatives [100]. Moreover, the mainstream storage technologies may be insufficient to meet the challenges for further decentralization and decarbonization of existing power systems [100].

3.2. Electrochemical energy storage -Batteries

Electrochemical energy storage operates under three major principles: a) separation of charge, b) transport of charged species and c) recombination of charge [101]. The fundamental concept behind electrochemical energy is the conversion of chemical energy into electrical energy. The major electrochemical storage applications include batteries, fuel cells and electrolytic capacitors [101]. Electrochemical storage devices require two specialized parts of electrodes separated by conductor known as “electrolyte” [101]. In batteries, specific energy and power are dictated by the chemistry and the battery materials [101]. Batteries and fuel cells provide several advantages for mobile applications making them good candidates for transport sector. There is an ongoing debate in research community about which technology will eventually dominate it [102].

Batteries are a mature electrochemical storage technology which provides high power and energy densities [103]. Various battery types have been developed such as lithium-ion(Li-ion), sodium-sulphur (NaS), nickel-cadmium (NiCd), lead acid (Pb-acid), lead-carbon batteries, as well as zebra batteries (Na-NiCl2) and flow batteries [104]. Various electrode and electrolyte materials are investigated by researchers to reduce cost and improve energy/power density, battery lifetime and safety [104].

3.2.1. LITHIUM-ION BATTERIES

Research on Lithium-ion batteries has made significant progress during the last decades, making them a reliable and mature storage technology with high potential of further improvement in the near future [105].The significant advantages of lithium-ion batteries (LIBs) has attracted the interest of researchers globally, increasing the publications over 260% between 2010 and 2017. This increase is around 4.5 times higher than increase rate of general academic literature [106]. The light weight and the compact nature of LIBs has made them very attractive for electric vehicles, facilitating the decarbonization of transportations towards a low-carbon future [107], [108]. LIBs are expected to play a vital role in the integration of RES, mitigating their intermittent nature and providing services to modern power systems [108]. The increasing demand for LIBs has created a fast-growing industry, where large industry players are involved looking for opportunities and important shares of the new market [108]. The chemistry of LIBs provides higher power and energy density and lower self-discharging rates compared to other chemistries [37], [109]. Moreover, they have higher cycle life (~10,000) and higher efficiency (~100%) [37]. The aforementioned advantages make LIBs suitable for a wide range of applications either stationary or portable (EVS, laptops, smart phones)(Figure 3.2) [109], [110].

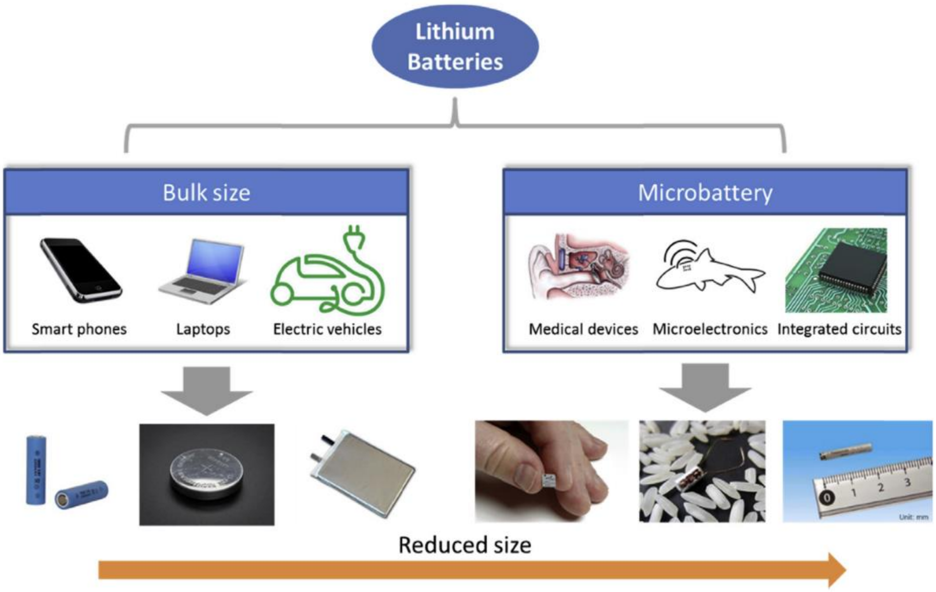

Figure 3.2:Examples of Lithium-ion applications [109].

One of the main concerns of LIBs is the capacity loss occurring during their "storage" and operation know as degradation effect. There are two different types of degradation that leads to capacity loss. One is the calendar cycle loss, while the other is the cycle loss during operation [111]. Calendar cycle loss is a phenomenon that cannot be avoided as it happens naturally, while the battery remains idle. However, operation cycle loss can be mitigated by controlling particular parameters of battery operation. Generally speaking, degradation effect is a quite complex phenomenon that occurs in some battery technologies (such as lithium-ion, lead acid) due to irreversible chemical reactions that take place inside the battery. Degradation effect increases the internal resistance of the battery, causing a permanent capacity loss. Different key factors that affect degradation effect has been recognized. The most important ones are: charging/discharging current, temperature, SoC window during operation. Different approaches have been used in order to degradation models that quantify by approximation the degradation effect under particular conditions. A common approach is to use impedance models, where battery resistance is represented as an impedance in an equivalent circuit model, and then it is associated with the capacity loss [112]–[114]. Another commonly used method is the use of dV/dQ curves, as they can represent the unique characteristics of anodes and cathodes of each battery [115]–[119]. Both methods provide the ability to estimate capacity loss without opening the battery cells [120]. According to recent studies, the discharging current is a crucial factor as it affects also the internal temperature of the battery [111], [121]. Higher currents lead to higher degradation effect and vice versa, while their correlation is not linear. Moreover, narrower SoC window leads to lower cycle loss and vice versa [119].

As LIBs are expected to be used widely towards a low carbon future, environmental concerns arise related to their industrial production, looking for potential negative effects on a cycle life basis [105], [122], [123]. Life-cycle analysis (LCA) has identified as suitable method to quantify the environmental impacts of LIBs through their lifetime, by international standards [124], [125]. From the existing literature the average energy demand and GHG emissions for battery production is 328kWh and 110 kg CO2eq per kWh respectively for all chemistries [105].However, the review concludes that the existing studies provide insufficient data regarding the environmental impact of LIBs, or making simplified assumptions leading to no reliable results, and thus more investigation is required [105].

3.3. ROLE OF STORAGE IN DISTRIBUTION NETWORKS

Energy storage systems (ESSs) become increasingly popular in modern distribution networks, offering technical, economic and environmental advantages [126]. Power quality enhancement, frequency regulation, load peak shaving/shifting, voltage control, facilitation of RES integration, reduction of system costs, increase of system reliability and resilience and mitigation of GHG effect are some of the most important ones [127]–[130]. The aforementioned benefits can be facilitated by optimal ESSs placement sizing and operation [126]. As the penetration of RES is increased significantly during the last decades, ESSs play a vital role to balance generation and demand improving the performance of whole power grid [128]. Moreover, ESS can be used to provide a range of ancillary services, providing extra benefits to their owners [128]. For distribution networks, an ESS converts an electrical energy form to another form that can be stored and used when it is needed [131], [132]. One of the most important challenges for their implementation is the sizing process of ESSs and the energy management techniques that set the rules according to which the energy is stored and distributed to the system [126]. For this purpose, simulation models are developed to confront economic and security aspects of ESSs.

3.4. BENEFITS OF LI-ION BATTERIES FOR DOMESTIC USERS

The investigation of energy management techniques in MGs and the review of the available energy storage technologies, led to the development of a simulation model which we presented in the international UPEC conference [133]. The aim was to investigate the benefits provided by li-ion batteries for domestic users, under a certain time-of-use (ToU) tariff scheme. A particular household in UK was selected, with a PV panel and a lithium-ion battery. A cost-benefit analysis method was used in order to quantify the gained benefits, taking into consideration the degradation effect of the battery [133]. The simulation model was developed in MATLAB software by examining and comparing different scenarios. The results showed that li-ion battery could be a cost-effective solution for domestic users. Moreover, the obtained results showed a high dependence between the degradation effect, TOU tariffs, FITs, domestic energy consumption and the benefits gained [133]. The implemented EMS is based on the net consumption of the user. A negative net consumption practically means that there is PV surplus, which could be used in two different ways: a) charge the battery or b) sell it to a neighbor. This work examines under where circumstances the energy transfer to a neighbor is possible [133]. Three different tariffs are considered (low, medium and high) and two scenarios are examined: In the first one the battery is discharged only during the high tariff period, while in the second one during the high and medium tariff period [133]. The annual capacity loss due to degradation was estimated by using curve fitting method and equations presented in [134]. The results were compared to a baseline scenario where the user has no battery in order to calculate the benefits gained.

3.5. CHAPTER SUMMARY

Exploring the current literature for energy storage technologies, it was clarified that storage assets could play a vital role in RES integration, increase system resilience and reduce carbon emissions. Therefore, storage is an indispensable part of modern power systems towards the transition to smart grids. Lithium-ion batteries are one of the most promising storage technologies, as their cost becomes affordable, providing high efficiency and power density. Battery cycle loss is an important factor of its operation, causing capacity loss due to complex internal phenomena and it should be taken into consideration when they are used in the field. There are two types of cycle loss: Calendar cycle loss, operation cycle loss. Different discharging techniques should be sought in order to minimize total cycle loss and prolong battery lifetime. A relative work published in UPEC conference was also briefly presented.

Chapter 4. Resilience and P2P exchange

In this chapter the concept of Resilience and P2P exchange will be investigated. The difference between resilience and reliability is clarified, and different type of faults are defined from the literature. The role of resilience in MGs will be examined, and the main aspects of P2P exchange concept will be covered As the main issue examined in this thesis will be P2P exchange for microgrids, to improve economic and resilience operation a detailed literature review will take place seeking for the research gaps in the existing research. The aim is to cover the existing literature to identify to what extend the concept of resilience is investigated in the context of P2P exchange process. The main aspects covered by literature on P2P exchange are investigated, looking for uncovered areas that this work will contribute to. The concept of zoning in distribution networks will be also examined. Parts of published work will be presented to this chapter, relevant to P2P exchange and resilience.

4.1. Resilience

Resilience can be defined as the ability of a power system to respond comprehensively and recover rapidly from faults due to extreme events [41]. Distribution systems seems to be the most vulnerable to faults, as the vast majority of blackouts have started from them [41]. For this reason, the concept of resilience in a power system usually coincides with the resilience of its distribution system [41]. The power outages usually occur due to extreme natural (such as hurricanes) or man-made (cyber-attacks) events. Although these events are rare, yet they compromise significantly the performance of power systems [41]. These types of disruptions need to be distinguished from other typical power system contingencies, as they have different characteristics [135]–[137]:

- Their duration and time of occurrence are extremely uncertain.

- They can provoke problems to any kind of components, making their repair and restoration complex and time-consuming.
- They can cause extreme component failure in a short time period.
- They cause significant damage to the utility territory and on other major infrastructure (e.g. natural gas system, communication network).

Resilience has the following characteristics (Figure 4.1) [41]:

- ✓ Continuous awareness of the situation. It enhances the comprehension of current situation and estimate the possibility of potential interruptions.
- ✓ Robustness and preparation before any extreme event. In this way the system becomes more resistant and less vulnerable to unexpected disruptions.
- ✓ Responsiveness and survivability against any extreme events. A resilient power system must be able to survive from an extreme event, maintaining a minimum level of functionality.
- ✓ Recoverability and rapidity after any extreme event. System must be able to recover quickly from the extreme event and come back to the condition before the event.

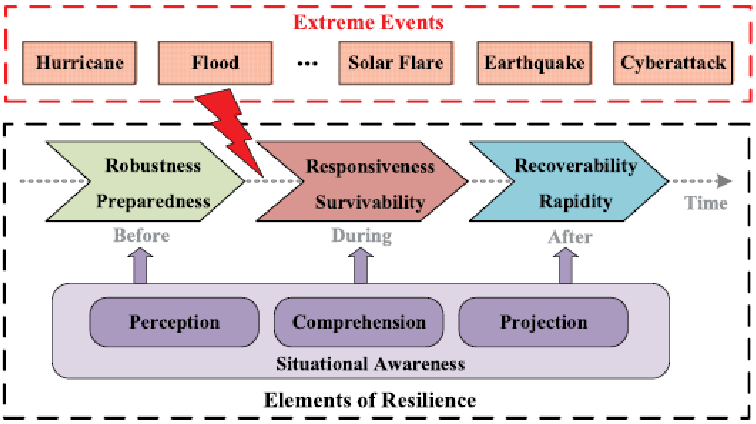

Figure 4.1: Conceptual composition of power systems resilience [41].

Resilience should not be confused with reliability. Reliability refers to the ability of the system to be able to deliver a sufficient range of electricity services to the customers [138]. High reliability of a power system mitigates fault occurrence. Thus, reliability is a way of preventing faults. In contrast, resilience is related to system ability to respond and recover when a fault has occurred [41]. The reliability of a system is measured based on frequency and duration of power disruptions, while resilience represents system behavior before, during and after fault [41]. Different metrics have been defined for reliability and resilience respectively. Most commonly used reliability indices are loss-of-load probability (LOLP), expected-energy-not-supplied (EENS), system-average-interruption-frequency index (SAIFI), and the system-average-interruption-duration index (SAIDI) [41], [139]. However, a high reliable power system might not be resilient, and vice versa [139]. Thus, reliability and resilience are two complementary concepts that need to be implemented in modern power systems [41].

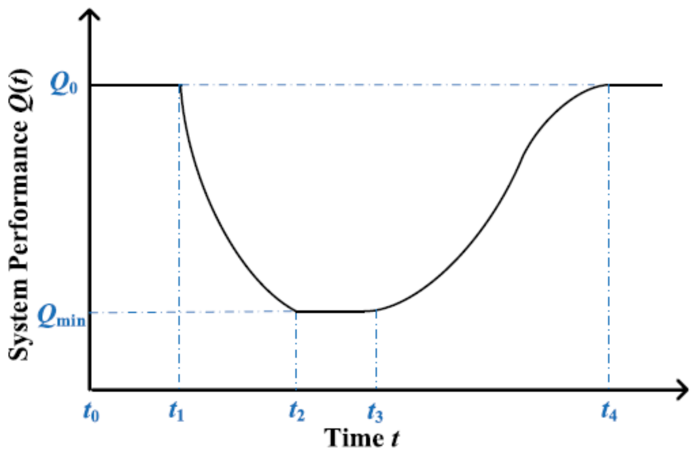

Figure 4.2: Typical evolution curve of system performance [41].

To quantify resilience in a rational way, different resilient metrics have been introduced. A typical evolution curve of system performance in case of an extreme event is presented in Figure 4.2. The level of system performance is considered as a function of time (Q(t) -Figure 4.2). When an extreme event occurs at time t_0, the system performance r $Q(t_0)$ remains almost idle, due to system resistant to initial disruptions (Figure 4.2). System performance gradually drops when the disruptions become more severe. The system reaches at a minimum level Q_{min} at time t_2 and system resilience starts increasing gradually as the system is partially restored (Figure 4.2).

At time t_4, system performance has reached at normal levels before the interruption, implying that the fault has been fully restored (Figure 4.2). The extreme event can be quantified as the reciprocal of system's loss of performance [41]. In this way, the system resilience can be quantified ranges theoretically from zero to infinity. Infinity represents the perfect resilience while zero means no resilience at all.

Different shapes have been introduced for resilience [140], [141]. Traditionally, most approaches use the resilience triangle (Figure 4.3) [140]. The shape of the triangle can vary (linear, triangular, exponential) based on the effectiveness of the recovery strategy [142]. However, this approach ignores highly significant factors of the fault process, such as how fast the resilience degrades or how much is the duration of different phases after fault [140].

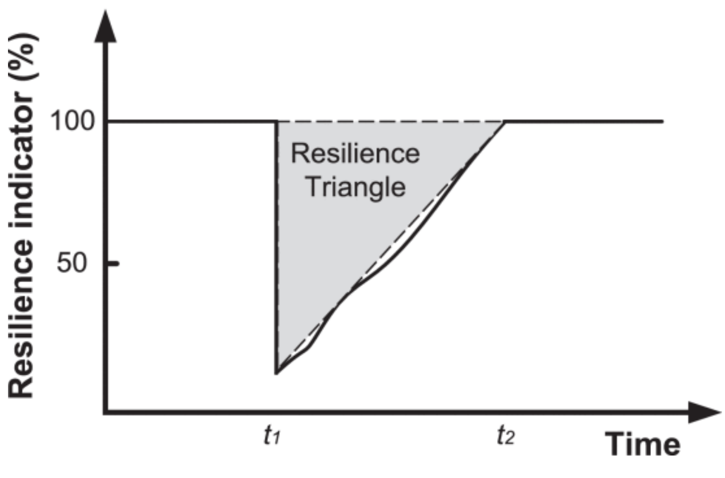

Figure 4.3: The resilience triangle [96].

These missing factors have led to the replacement of the resilience triangle with a trapezoid multi-phase trapezoid shape (Figure 4.4). The trapezoid shape depicts all phases during an extreme event, including the transition between them [140]. For this purpose, time-dependent operational and infrastructure resilience metrics are introduced [140].

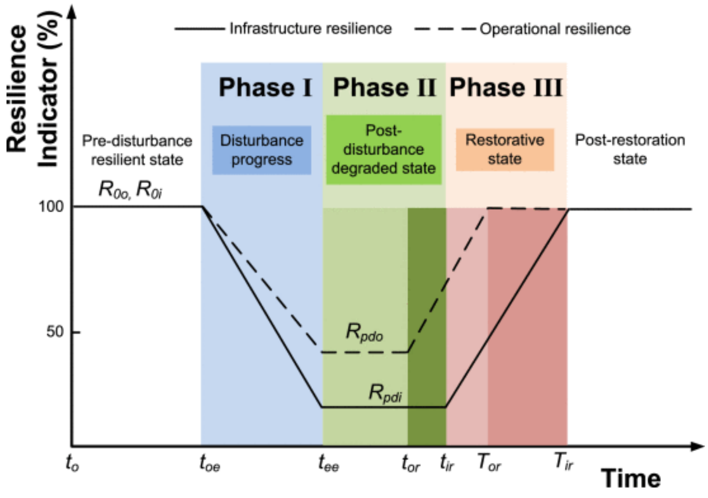

Figure 4.4: The multi-phase trapezoid [140].

In the multi-phase trapezoid, there is a pre disturbance phase where the resilient is considered as 100%, since the disturbance have not occurred yet (Figure 4.4). When the fault occurs, three different phases are distinguished. Phase I, represents the disturbance phase which is defined from the moment the fault occurs until the moment it ends, named disturbance progress phase (Figure 4.4). Phase II is the post-disturbance degraded state phase, which represents the phase from the moment that the event has ended, however the restoration process has not started yet (Figure 4.4). The restorative process occurs in phase III, where gradually the operation and infrastructure restoration occur (Figure 4.4). At the end of phase III, the resilience has reach again at 100% which is equal to the resilience before the fault event (Figure 4.4).

A set of metrics need to be defined in order to quantify resilience in power systems. Metrics (Φ) and (Λ) measure how fast and how low the resilience drops during phase I respectively. Metric (E) is used in order to quantify how extensive is the post is the post event degraded phase of phase II, and metric (Π) measures how promptly the fault is restored during phase III [140]. To quantify these resilience metrics particular different resilience indicators can be used. One of them, is the amount of generation capacity and load demand (in MW) are connected during the event. Another one, is the number of transmission lines that are online during the event [140].

In this work the resilience metrics used are presented in the table below:

Resilience metrics	Comments
Resilience (%) [140]	Defined as the percentage of total connected load (in kW) during fault, in respect to the initial connected load before the fault.
Number of customers disturbed [143]	Number of customers experience outages.
Duration of interruption [144]	Duration of disturbance the users experience (in minutes).
Level of disturbance (%)	Percentage of load each user loses, in respect to the initial load before the fault.

Table 4.1: Resilience metrics used in this work.

4.1.1. TYPE OF FAULTS

Two main type of faults are considered in power systems. Temporary faults and permanent faults [145]. Temporary faults, also known as transient faults, cause momentary disruptions without the intervention of protection strategies [97]. Permanent faults cause sustained disruptions which require the involvement of protection actions to restore system normal operation [146]. The most common permanent fault types are usually associated with wind, ice, loading thermal heating and sag [146]. Two main fault categories are electrical and communication faults [147]. Electrical faults occur, when one of system physical components is damaged or malfunction. The components could be a feeder, a transmission line or another component such as a transformer, or a cable. On the other hand, communication faults could occur in the communication network of modern power systems, These faults, compromise the effectiveness of the communication network, and occur as there might be data congestion, failure in one of the communication components, presence of corrupted data or malfunction of communication software due to cyber-attacks [147].

4.1.2. Resilience in Microgrids

Different strategies have been implemented in current literature in order to enhance resilience of MGs. The networked MGs is considered as a viable solution to improve their resilience against extreme events [148]–[150]. A self-healing strategy for a distribution system with both dispatchable and non-dispatchable DGs is presented in [148]. The aim is to minimize operating costs and maximize revenues, using a rolling-horizon optimization method. In the self-healing mode, is optimally split into networked self-supplied MGs. Stochastic programming techniques are used to tackle RES uncertainties. The methodology is tested in a 123-node distribution system, proving its effectiveness. In [149], an optimal MG scheduling is developed with dynamic network reconfiguration. The scheduling strategy has two different modes, one for grid-connected and one for islanded operation. The authors develop a suitable simulation model which proves the effectiveness of the introduced methodology. Power distribution network and water distribution network are tested, under earthquakes in [150]. The authors use stochastic techniques in order to enhance system resilience under these extreme conditions. A 33-node model is developed and tested for different scenarios in order to test the performance of the developed strategy. In [151], researchers implement flexible division and unification control strategies in order to enhance resilience in networked MGs. In extreme events the networked microgrids can switch to a division mode, where the active power sharing is regulated by local controllers without using assets and resources from the neighboring MGs. Moreover, the remaining MGs can use the unification mode and operate as one entity in order to mitigate the effects of the extreme event. The proposed strategy is a practical and cost-effective and is tested in by running time simulations. A resilience analysis framework is presented in [152], where the researchers investigate the fault ride-through capability of direct current (DC) MGs in unknown denial of service (DoS) cyber incidents. The authors examine if a DC MG is resilient against time-varying and unknown DoS attacks. For this purpose, a stability analysis is developed with randomly switching dynamics. To test the developed strategy simulation techniques are used using convex optimization. An optimization strategy is developed in [153], to enhance MG resilience and maintain the critical loads active during the extreme event. A resilience index is introduced to assess the ability of each MG to cover the critical loads. The uncertainties imposed by the RES integration are tackled by using robust optimization techniques. The developed method is tested in three different topologies under emergency conditions. A particular methodology is introduced in [154], to identify the vulnerable components of MGs to extreme events, mitigating their impact on existing infrastructure. The researchers investigate the electricity and natural gas infrastructures under extreme conditions. The results showed that the suggested methodology is effective for interconnected infrastructures.

4.2. P2P EXCHANGE

4.2.1. INTRODUCTION

P2P exchange can be defined as the process where energy customers with DERs can share their energy with their peers directly [155]. P2P exchange permits to the users to share their energy surplus or the flexibility of their demand with other end-users, providing a beneficial situation both for energy producers and consumers [156]. The high diversity of generation and load demand offers great potential for P2P sharing, providing incentives to end-users to participate [157]. Moreover, in most countries the feed-in tariffs are lower than the price for buying electricity from the grid, providing incentives to the users to trade energy with their peers rather than with the grid [157]. The ongoing decrease of the existing feed-in tariffs and the debate about their presence in modern smart grids, makes the potential of P2P even higher [158].

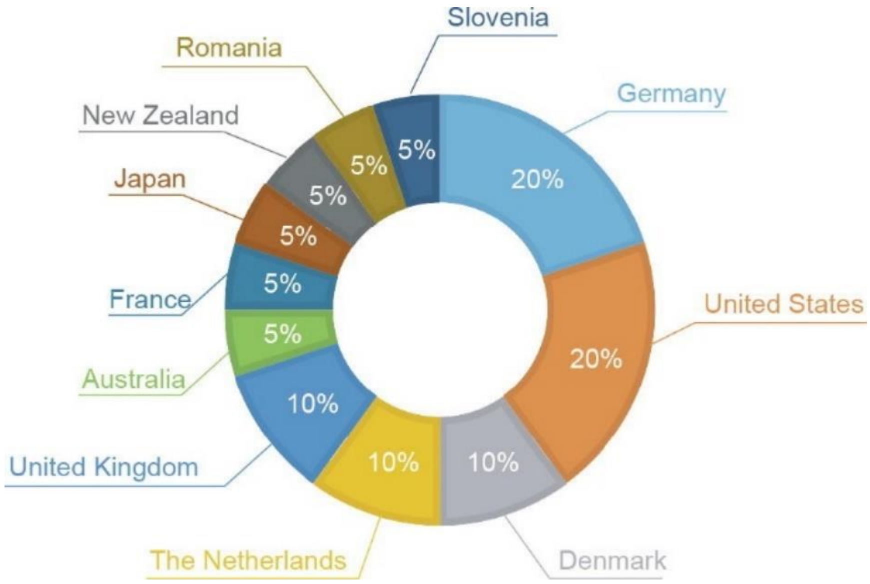

Figure 4.5: Proportion of P2P projects per country [155].

Different P2P exchange schemes have been implemented in different countries, including USA, New Zealand, United Kingdom, Spain, Portugal and Australia [158]. The proportion of P2P exchange projects per country is presented in (Figure 4.5).

Most of the implemented P2P projects are focused on the local level (70%), including distribution networks, MGs buildings and local communities (Figure 4.6). Only a small percentage (30%) is only focused on national level, enabling P2P exchange trading between generators and consumers in different areas or in the wholesale market [155] (Figure 4.6). Most of the implemented projects use the blockchain platform in order to facilitate energy trading among prosumers, making it as a promising approach. Some of the most key factors of P2P exchange are market design, trading platforms, physical and ICT infrastructure, social science perspectives, and policy [155]. P2P exchange attracts academic interest, as it is investigated in numerous published journal papers. An increasing number of papers is observed during last years, as it is shown in Figure 4.7 [155]. A great majority of the papers is focused on market design, followed by trading platforms, social science perspectives, ICT infrastructure and policy [155].

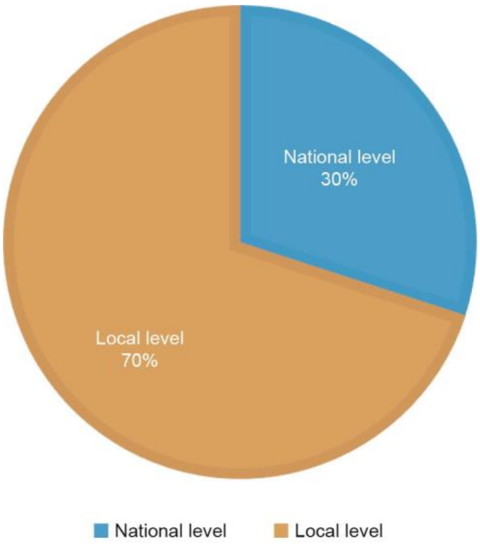

Figure 4.6: Proportion of P2P projects focused on local and national level respectively [155]**.**

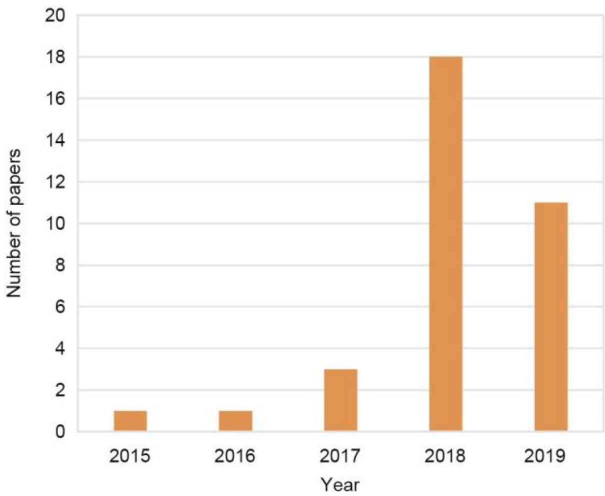

Figure 4.7:Number of journal papers on P2P energy trading by year [155]**.**

4.2.2. MARKET DESIGN

P2P exchange has introduced a new area of different market designs, capable of handling P2P interactions. Three different market designs are recognized: Centralized, decentralized and distributed markets [155]. Centralized markets include a coordinator which communicates with each peer, collecting information and coordinating the energy import/export of the peers [159]. The coordinator is also responsible for distributing the revenues among the peers following certain predefined rules [159]. The major advantage of centralized markets is their ability to maximize the social welfare of the whole community, and the power generation and consumption have less uncertainty [160], [161]. However, their disadvantage is the increased computational and communication burden, which is increased as the number of DER is increased [162]. Other disadvantages of centralized markets are autonomy/privacy issues and their vulnerability to single-point failures to the coordinator [155].

In contrast, decentralized markets have no coordinator and peers communicate directly with each other [163], [164]. This fact provides privacy protection and permits to the peers to full control their own devices. Another advantage of decentralized markets compared to the centralized ones, is the fact that they have better scalability, as it is easier to plug in and out users [163], [164]. However, the decentralized markets may not maximize community's social welfare, due to the absence of coordinator. Moreover, energy trading of decentralized systems might not visible or predictable for distribute network operators (DNOs) and transmission network operators (TSOs), thus the efficient control of the system may be compromised [165].

Distributed markets are a third market type which lies between centralized and decentralized markets. Distributed markets can combine the features of centralized and decentralized markets and provide compromised solutions in modern power systems [155].

4.2.3. Trading platforms

Trading platforms are indispensable part of P2P exchange schemes as it permits to the trade among peers based on particular market rules. Following the market design division they can also be categorized in centralized and decentralized platforms [155]. Blockchain is a popular platform suitable for P2P exchange schemes and has attracted considerable attention by researchers. Blockchain platform is a safe environment for peer trading in a decentralized manner. Blockchain is considered to be the main platform for energy trading in MGs [166]. The main benefits of Blockchain platform are summarized below [167]:

- There is no need for a third-party coordinator. Thus, it is a cost saving solution, where the risks caused by the misbehavior of the intermediate are reduced.
- The transactions are protected by cryptography. Consequently, the transaction records are transparent, tamper-proof, and robust to single-point failure.
- Blockchain supports smart contracts, which can be easily made and automatically executed.

However, Blockchain platform has its own disadvantages. One of them is the cost and time required to reach to consensus in public blockchain and the compromise of trustworthiness in consortium or private blockchains [155]. For this reason, cost benefit analysis should be conducted in order to decide which platform to use base on the particular characteristics of each P2P trading scheme [155].

4.2.4. Physical and ICT infrastructure

Since the trading agreements have been settled using market design and trading platforms, a number of metering and communication devices is necessary to put into practice the P2P trading. Two types of solutions can be applied [155]: a) private electric power networks and associated technical arrangements and b) public electric power networks and associated technical arrangements.

In private networks, private wires or networks among peers are constructed, enabling the physical peer-to-peer energy delivery. Private networks have high sunken costs and low marginal network operating costs [155]. Moreover, they are riskier as there are concerns in their long-term operation and have high uncertainty regarding future investment, supply security, climate change, and regulations [168]. As a consequence, constructing private networks in large scale is still not an economically viable solution, although it is technically feasible, and this seems to remain unchanged despite the development of P2P trading projects [155].

In public network solution, the existing public network is used to deliver the agreed energy to the peers, and it is the most common practice in existing P2P schemes [155]. In this case, the power network is used as a big pool where the electricity producers inject power into the pool, and electricity consumers receive power from the pool. The consumers do not need to know where the electricity physically comes from [155]. Therefore, P2P exchange in public networks is considered by many as a virtual energy trading rather a physical energy exchange [155]. A summary of the available two solution is depicted in Figure 4.8.

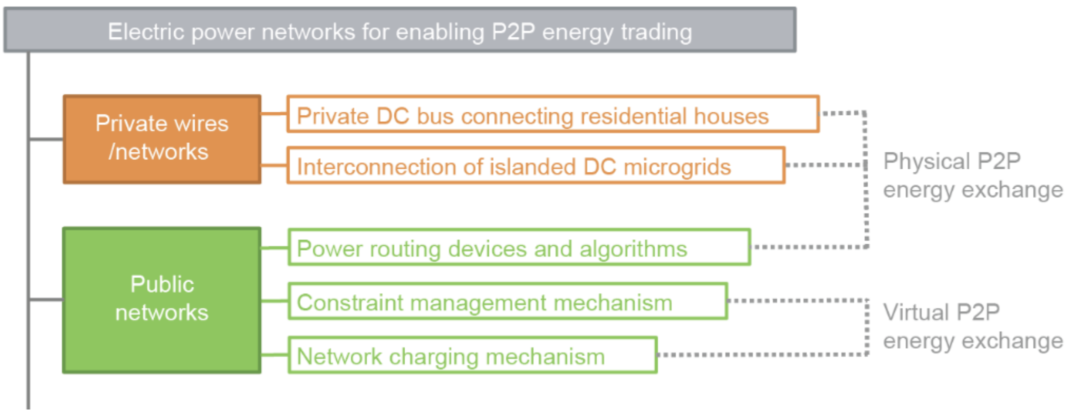

Figure 4.8: Available solutions for physical and ICT infrastructure [155].

4.2.5. SOCIAL SCIENCE PERSPECTIVES

As P2P exchange involves the interaction of several people, social aspects of it are investigated by researchers. A major direction is the use of anthropological methods, trying to simulate peoples' behavior in a more realistic way, without assuming that peoples' behavior is completely rational [155]. Despite the pure economical aspects, dynamic aspects of social interaction are investigated in the context of P2P trading [169]. Different types of trading were investigated despite the market energy exchange, named “mutual energy trading”. According to this term, mutual energy trading is “a social and personal transaction of energy between an energy giver and energy receiver, which is mutually structured and negotiated” [170]. Existing studies also investigate the association of peoples’ attitude with the terms of “autarky” and “autonomy”, and their impact on P2P exchange schemes [171]. It is also verified that P2P exchange is a consumer-centric scheme from a motivational psychology perspective [172]. Since the cultural backgrounds of these studies is limited more investigation is required to reveal social aspects of P2P trading [155].

4.2.6. POLICY

There is an increasing number of studies which investigate what kind of actions are required to modify the existing regulatory frameworks to facilitate P2P exchange implementation [155], [166], [173]. However, no radical changes in this field has been put into practice yet due to difficulties that emerge. First, the regulatory changes involve interests of large number of stakeholders and their modification needs to be done carefully. Second, the new technologies regarding P2P exchange scheme are developing fast and it not clear yet how these changes should be treated by the existing regulatory frameworks [109]. Certain directions have been identified for future policy development. These directions include: a) defining the role and responsibility of pro- sumers and P2P energy trading markets, b) exploring the relation- ship between P2P energy trading markets, existing electricity markets, and other evolving entities such as DSO, c) proposing appropriate schemes for the distribution of taxes and fees for P2P energy trading, d) incorporating and providing incentives for flexibility and e) protecting vulnerable customers in the context of P2P energy trading [109].

4.2.7. LITERATURE REVIEW

Competitive market approaches

P2P exchange has become a promising approach in modern power systems, attracting the interest of academic community. In a recent work, researchers developed an automated bilateral peer-to-peer exchange strategy [174]. Energy contracts of prosumers are evaluated through multiple social and environmental criteria, combined with their preferences over these criteria. The strategy promotes users' training in order to find the most appropriate peers that their energy contracts are closer to Nash equilibrium. Nash equilibrium is a concept of game theory which implies the optimal outcome of a game, where each player has no incentive to deviate from their initial strategy. The developed strategy is applied to real energy profiles, improving utilitarian social welfare and fairness. In [175], the researchers analyze two different market designs: a centralized market and a peer-to-peer exchange market where prosumers trading energy in local communities. The solution of the P2P market is characterized as Variational Equilibrium proving that its set coincides with the optimal solutions for social welfare for this market design. The impact of preferences on the network line congestion and renewable energy surplus is characterized for both examined market designs. The authors also present an example of a 14-bus system, where the energy trading under different prices can be simulated. The results showed that the preferences have a great impact on the trade structure, and the variational equilibrium is the optimum. Finally, the researchers discuss, the learning mechanisms in order a P2P market to reach to an equilibrium along with privacy issues. In [176], a decentralized approach based on transactive energy systems and P2P energy transactions is introduced. The researchers use distributed ledger technology (DLT) based on blockchain concept, in order to establish smart and safe contracts among prosumers. A new concept of Proof of Energy is suggested, as novel protocol for P2P exchange. The proposed infrastructure is applied to a virtual power plant aggregator, with a transactive controller for energy management of storage assets. The results showed that the applied protocol increased the self-consumption ration of prosumers, reducing significantly though power losses. In [161], two market designs are proposed for P2P exchange, focused on the role of energy storage. The researchers address particular questions related to the value of prosumers' batteries, the market features that are needed for system configuration, the market design that increases benefits for the prosumers. For this purpose, an optimization model is developed, representing a small community in London, UK. A comparison of distributed storage assets among the users is compared to a centralized storage scheme. The results showed that storage could produce 31% energy savings for end-users. A market design for P2P trading is established in [177], using blockchain approach. The methodology provides certain financial and socio-economic incentives to the participants, in order to integrate local renewable energy sources. However, an innovative information system is required in order to ensure system efficiency. Seven market components are defined to estimate market efficiency. The Brooklyn MG project is evaluated as a case study, which satisfies an important number of these components. The results showed that the blockchain approach is eligible for decentralized energy systems, highlighting also regulation barriers that need to overcome in many countries to facilitate P2P trading.

Cooperative market approaches

A game theory approach was used in [172], in order to investigate the participation of users in P2P trading scheme. The authors explored the social cooperation between prosumers by forming coalitions. The researchers also introduce relevant models of social phycology, which are satisfied by the proposed P2P scheme. The researchers prove that the proposed scheme is consumer-centric, giving numeric examples to highlight its benefits. P2P trading is investigated in [178] under the Blockchain concept. Coalition formation are used in order to establish energy trading among different MGs. The authors highlight the advantages of their approach. Synchronous and asynchronous execution of the coalition formations is one of the most significant advantages along with the quick convergence. Moreover, the suggested methodology enables local trading by mitigating security and privacy issues. A game theoretic approach is also used in [179], where the researchers examine the ideal incentive structure shaped by Shapley value axioms, in order to allocate payment among peers. Shapley value is a solution concept of game theory, which regulates a fair distribution of cost and benefits among different actors that participate in a coalition. Although there is high complexity, the authors prove that there is a fluid limit for large populations, which can be computed with different scenarios. The implementation of the approach could provide significant cost and energy savings. A direct electricity trading scheme is introduced in [180], where end users trade energy with small-scale energy suppliers. The cooperation between the stakeholders is established through coalitional game theory approach. The asymptotic Shapley values is used in order to maintain coalition stability. The implemented strategy can be enabled by using the number of users and statistical information about the electricity supply and consumption, making it practical in modern applications. The price of electricity is examined using different simulation scenarios, validating the asymptotic Shapley value analysis. The optimum ratio of different type pf small-scale electricity suppliers is also investigated. A two-stage aggregated control scheme is proposed in [159], for P2P energy sharing in MGs. In this method, the prosumers control their DER through a third entity, called as energy sharing coordinator. A constrained non-linear optimization, with rolling horizon is used in the first stage, in order to minimize energy costs. The second stage includes a rule-based control, which constantly updates the setpoints, according to real time measurements. The approach examined from community's and users' perspective. The approach is applied to residential communities with batteries and PVs. The results showed a 30% reduction of energy costs, increasing also the prosumers' income. A decentralized control system is developed in [181], using ICT concept and P2P networks in DC MGs. The energy trading occurs among different households, considering smaller entities named nanogrids. The developed approach increases flexibility and dependability of the system. The method is implemented in a real system of 19 inhabitants in Okinawa. The authors also run simulations to examine self-efficiency of the system, testing also in practice resilience, in case of blackouts. A theoretical study of energy production and distribution is presented in [182]. The authors analyze the evolution of energy systems and the role of RES, focusing on MGs. They also develop an alternative model that uses MGs in order to create a P2P trading scheme, discussing the necessary conditions for the "energy commons" concept. P2P trading in electric vehicles (EVs) is investigated in [183]. The authors develop an energy trading between two sets of EVs, reducing significantly the impact of charging process to the system, during business hours. The approach is implemented in Belgium, by using an activity-based model to predict the daily schedule of trips, for the EV owners. The results showed that the energy cost paid by the drivers of the particular area was reduced by 71%, for a particular time slot. In [184], an optimization model is introduced in order to maximize the economic benefits of rooftop PV-battery owners, in the context of a P2P trading scheme. A local community with 500 households is used as a case study, under real-word constraints regrading PV operation. The results showed that the energy savings of households are sensitive to various factors, such as PV scale and penetration and the presence of storage. An optimum P2P sharing is suggested in [185]. Two different prosumers are used, one residential and one commercial one, that are connected with power lines with each other. The model minimizes the prosumers' operating costs, maximizing the use of RES and distributing optimally the energy among the two prosumers. Moreover, the approach minimizes the electrical utility operating under particular ToU tariff scheme. A case study in south Africa is been used to test the practicality of the suggested method.

Criticism – Concluding remarks

A comprehensive review of the global development of P2P trading has been published based on the existing academic papers, research projects and industrial practice [155]. The researchers highlight the increasing interest of the academic community for P2P exchange strategies, in order to address the energy trilemma. A detailed review of the current literature, showed that most of the existing papers focus on market design approaches while other fields such as trading platforms, physical and ICT infrastructure, policy and social science perspectives, are less investigated [155]. In fact, most of the existing journal papers focus on market design and pricing mechanisms [172], [174]–[180]. The aim of the proposed P2P schemes is to maximize profits either in a competitive market where each user acts individually seeking for the best buying/selling price through auctions and biddings [174]–[177] or in a cooperative one, where the users act cooperatively to maximize the profit of the coalition, based on a particular set of rules which should be followed from all the members of the coalitions [172], [178]–[180]. The complexity of some market designs [174]–[176] require agent-based models, to simulate the different auctions and biddings among the peers. Some researchers use the coalitional game theory approach in order to split the users in small groups and ensure the fairness of the P2P trading [172], [178]–[180]. However, although these approaches require simpler market rules, there are concerns about the coalition's stability and core's condition (empty or not), which require further investigation. Fairness of P2P trading is main issue in coalitional game theory approach and Shapley value is used to address it. Although current research providing insights about market mechanisms, limited research has been conducted regarding technical aspects of P2P exchange. Moreover, in most approaches energy storage is not playing a primal role in the P2P trading. Only in few papers is included [159], [161], [184] and only in [161] it is considered as the main issue of their research. Technical aspects such as optimum battery size, battery degradation, system resilience in case of faults have not been examined yet, in the context of P2P trading. In this work technical aspects of P2P exchange, with particular interest on storage assets are investigated. The research examines the synergies of energy supplier(s), local DNO(s) and MG users in order to participate in P2P exchange and jointly gain benefits. The gained benefits are examined in terms of economic benefits for the stakeholders (profits), system resilience in case of faults, carbon emissions reduction and increase of batteries lifetime. The approach, provides a simplified market based on an existing ToU tariff scheme and the availability of storage devices, avoiding complex negotiations and auctions. In this work, the quantification of resilience introduced in [140] is been used.

4.3. THE CONCEPT OF ZONING

The concept of zoning in distribution networks was also investigated to appreciate its role in P2P exchange. In current literature, there are very few works which focus on this issue. The zoning concept has been defined in the context of small-scale energy zone (SSEZ) [186]–[188]. SSEZ is a conceptual configuration for low-voltage distribution networks, which contains controllable small-scale embedded generators, energy storage units, and consumer demands [188]. SSEZ is a concept similar and complementary to MGs [188]. While the research on MGs mainly focuses on alternative future network designs, SSEZs exclusively consider the addition of small-scale embedded generators to existing low-voltage networks [188]. The advantage of SSEZs is to overcome some grid constraints and achieve a number of operation goals [186]. In this way, resilience and reliability goals can be met using suitable control techniques [186]. In [187], the optimal operation of interconnected MGs is examined where each MG is considered as a SSEZ.

As an extension to this concept, a similar concept named “zoning” is been used in this work. As the main goal is to establish a P2P exchange trading in MGs, the zoning concept defines the area in which P2P exchange is enabled. The main difference compared to the existing literature is the fact that its boundaries are dynamic. As the number of users participating in the P2P exchange may vary for each timestep, the boundaries of the zone change accordingly. Since the P2P exchange can be expanded outside the MG boundaries, the zone could be a sub-area of the microgrid, an area that coincides with the MG boundaries, or it is extended beyond them. The zoning concepts makes defines an area where different rules are implemented compared to the rest MG. This allows resources to be allocated in a systematic process according to the established rules. The concept of zoning is described in two of our conference papers [189], [190] , which will be presented in the next section.

In this work a centralized market approach is used, as it fits better with the implemented strategy. Since we propose a P2P framework with rules that need to be followed by all participants, a centralized entity needs to collect all data and make decisions based on the defined rules.

4.4. PUBLISHED WORK

Based on the knowledge acquired for P2P exchange process, a novel methodology was developed and published in CIRED workshop in 2018 [189]. The methodology includes two steps: 1) user's categorization and 2) definition of a zone with dynamic boundaries where P2P is enabled [189]. A case study with 50 users is examined. The results showed that P2P exchange could provide significant benefits to the user mitigating carbon emissions at the same time [189].

The methodology is implemented under a particular ToU tariff scheme. Two different tariffs are considered, one low during the night and one high during the day. The main principle is that the users charge their batteries during the night and discharge them during the day [189]. P2P exchange occurs during the high tariff period. The MG users are categorized based on their available storage assets. The users who have batteries under their ownership are characterized as “Battery owners” (BO) while the rest of the users are “Grid-connected” (GC) users [189]. Each BO user has two options during the P2P exchange process: either use the grid or discharge their battery. The algorithm calculates the cost of each option and chooses the one with the lowest cost. A second categorization occurs regarding the BO users. A BO user that covers their needs only by using their battery during the P2P exchange period is characterized as an “energy-surplus” user. On the other hand, the BO users that use also the grid for the same period are characterized as “energy-deficient” users [189]. The “energy-surplus” users receive extra rewards in order to have incentive to reduce the grid usage as much as possible.

The concept of zone is used, which is defined as the area where P2P exchange process is enabled. The minimum area includes the “energy-surplus users”, but it can be extended outside the initial MG, as long as benefits are still gained. The P2P exchange facilitates an optimum discharging of the “energy-surplus” users’ batteries. Priority is given to the “energy-deficient” users of the MG. Initially, the zone includes the “energy-surplus” users and one “energy-deficient” user. The optimization runs, and checks if any benefits can be gained. In the case where benefits are gained, the zone starts expanding by adding one more “energy deficient” user at a time. If benefits are still gained, the zone expands to include users outside the MG. It is assumed that the grid users don’t have either PV panels or batteries installed. The benefits gained are divided equally between the grid and the “energy-surplus” user group. Profits are shared among the users according to the amount of energy each user provides. In this way, complex auctions among the stakeholders are avoided. A graphical representation of zone expansion is presented in Figure 4.9 [189].

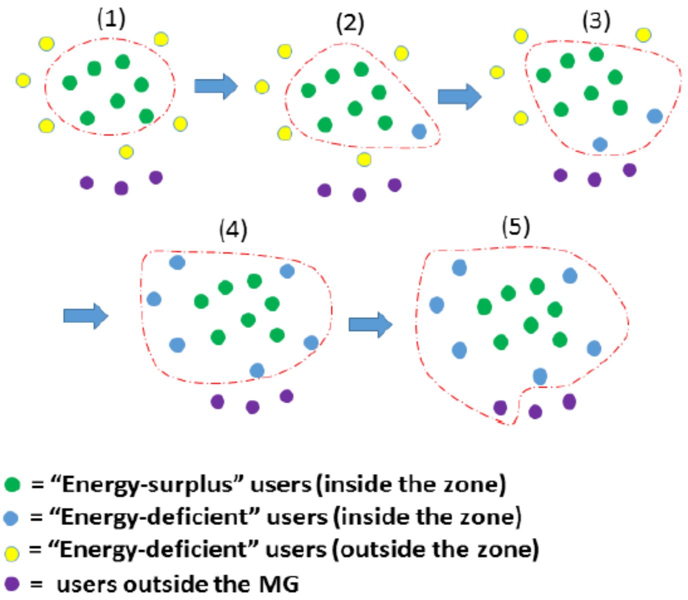

Figure 4.9: Zone expansion process [189].

An optimization process is implemented in MATLAB in order to jointly discharge the users' batteries. Examples of the behavior of "energy-surplus" and "energy-deficient" users, for the considered case study are presented below (Figure 4.10-Figure 4.11).

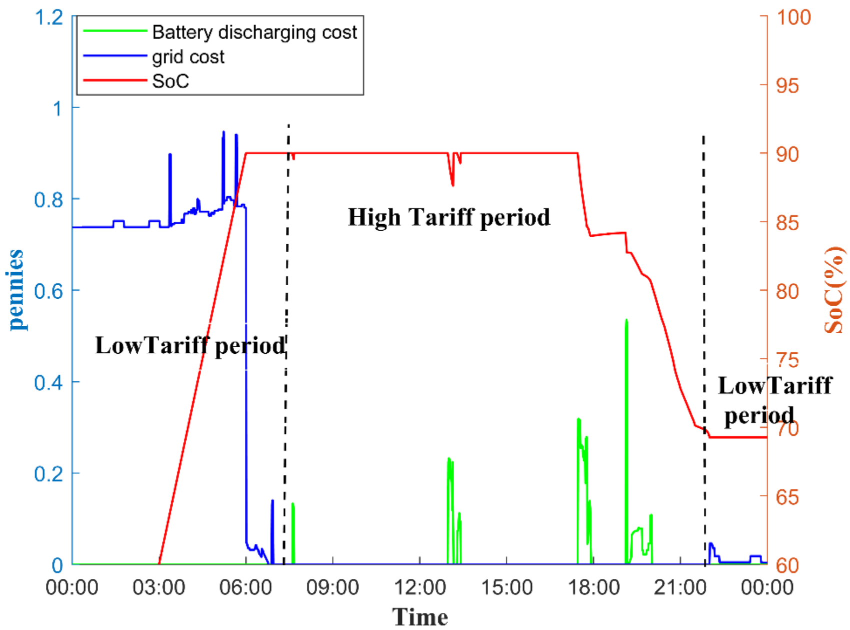

Figure 4.10: Example of "energy-surplus" user.

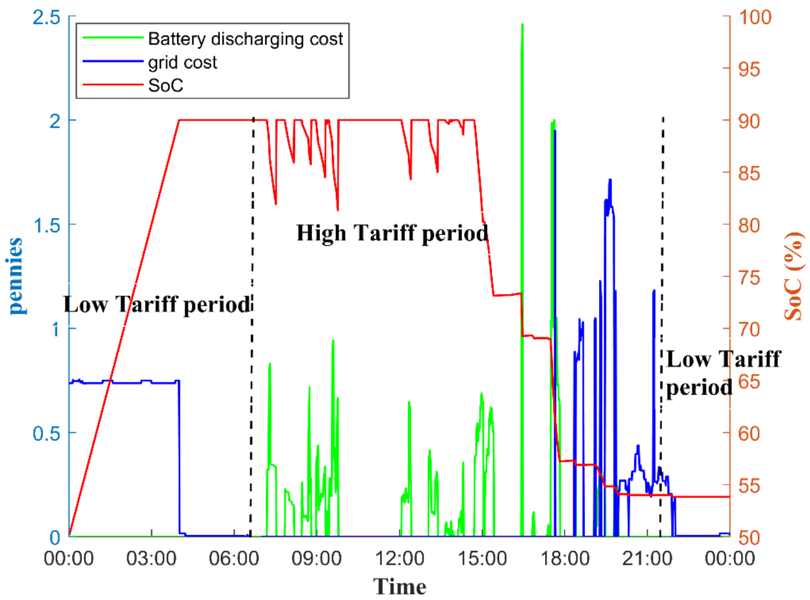

Figure 4.11:example of "energy-deficient" user.

In Figure 4.10, the behavior of an “energy-surplus” user is presented. The main feature of this type of user is the fact that their energy needs is covered entirely by their own assets (battery, PV) without using the grid during the high-tariff period. For this reason, there is no grid cost during that period (no blue line). When the battery is discharged there is a particular amount of degradation cost which varies depending on the discharging event and is represented with green line. There are also periods during the high-tariff period, where the battery remains idle. This means that for these timesteps the user needs are entirely covered by the PV panel. Before the start of the P2P exchange period, the battery is charged during the night (red line), increasing the grid cost for the user as it’s been charged by using the grid (blue line). When the P2P period ends, the battery remains idle and the user uses only the grid as the existing tariff is low during this period.

In contrast in Figure 4.11, the behavior of an “energy-deficient” user is presented. While their behavior is the same during the night, as they both charge their batteries, there is a major difference during the high-tariff period. The “energy-surplus” user has to use additionally the grid during this period to cover their needs (blue line). Especially, after 18:00 and until the high-tariff period ends, the user uses almost entirely the grid.

The results showed that considerable benefits can be gained both for the users and the grid, by reducing the CO_2 emissions at the same time. The methodology can be extended to multiple MGs and make a feasible case for future energy systems [189]. However, in this work there is not a particular user priority order according to which GC users are included in the zone. Moreover, the categorization of BO in "energy-surplus" and "energy-deficient" increases the complexity of the method and reduces the ability of the optimization to minimize battery degradation cost. This happens as the BO first discharge individually their batteries and then they are discharged jointly in the optimization process. Thus, this kind of categorization was not used further in our research.

An extension of the aforementioned work was presented in CIRED 2019 conference, using the same EMS zoning concept and optimization from but giving a special interest on the impact of P2P on system resilience [190]. Different fault scenarios are considered in order to specify the impact on system resilience. The faults occur either on physical network or on communication network. The obtained results showed that the implementation of this strategy can enhance system resilience without compromising the economic benefits and the carbon emissions reduction [190]. A suitable communication network is introduced to support the implementation of the developed methodology. The topology of the communication network is presented in [190].The MG server collects the data and runs the optimization, regarding the P2P exchange among the users of the MG. The MG server then communicates with the grid server to get information regarding the energy left in the batteries. If there is still energy left, the grid provides information about the load demand of users that are located outside the MG. Then the MG controller runs the optimization in order to cover as many users as possible. The electrical fault happens on the physical infrastructure on the grid and could be a cable fault or a fault in a system component (such as transformer). The communication fault is defined as a fault occurring in one of the communication channels so the user, cannot communicate with the MG server [190].

In case of electrical fault, the system will reconfigure zone boundaries in order to isolate the fault area and will continue the P2P exchange process with the remaining users. In case of a communication fault, some of the users fail to communicate properly with the MG server. Thus, the process is continued, excluding the fault users. If the fault occurs in one of the BO users, then there is less energy available for P2P exchange, thus the zone boundaries will be shrunk. On the other hand, if the fault occurs in a grid dependent user then this user will be excluded and the zone will cover another user, as the required energy will be reduced. The users that have a communication fault are just supplied by the grid and cover the energy needs without compromising the benefits to the rest of the users [190]. However, in this work the concept of resilience is generally described in the context of the implemented methodology, focusing on zone reconfiguration of the zone in case of faults. A further investigation is required in order to quantify resilience by using particular resilience metrics and explore the impact of faults in greater detail.

4.5. CHAPTER SUMMARY

In this chapter the concepts of resilience. P2P exchange and zoning were investigated. The concept of resilience was distinguished from that of reliability by identifying their major differences. Different approaches of resilience were examined along with their quantification using metrics suggested from the literature. The detailed literature review on P2P exchange, revealed gaps in the existing knowledge. Technical aspects of P2P exchange, such as optimum battery size, battery degradation, system resilience in case of faults have not yet been examined in the context of P2P trading.This work will examine the synergies local DNO(s) and MG users in order to participate in P2P exchange and jointly gain benefits. The gained benefits will be examined in terms of economic benefits for the stakeholders (profits), system resilience in case of faults, carbon emissions reduction and increase of batteries lifetime. A novel P2P exchange framework will be developed, based on an existing ToU tariff scheme and the availability of storage devices, avoiding complex negotiations and auctions.

Chapter 5. Methodology

In this chapter a novel P2P exchange framework for MGs will be presented. The synergies for the local DNO and MG users that could lead to participation in a P2P exchange scheme in which they both gain benefits, are investigated. These benefits are examined in terms of economic benefits for the stakeholders (profits), system resilience under fault scenarios, carbon emission reduction and increased battery lifetime. The approach provides a P2P framework that operates within an existing static ToU tariff scheme and makes use of storage devices that are available at customer premises. This approach avoids complex negotiations and auctions by working under agreed predetermined rules that maximize the system performance. Under fault conditions the overall performance is degraded to a lesser degree than would occur without a P2P exchange scheme in place.

5.1. METHODOLOGY OVERVIEW

The methodology implements a P2P exchange framework for sharing energy between participants in a MG. It Relies on a static ToU tariff scheme to value benefit in time-shifting demand to low cost periods. Two groups of stakeholders are considered: A) the local DNO and B) the MG users. The energy trading occurs under three principles: First, energy sharing occurs by using the storage and renewable assets of the MG. Second, P2P exchange is enabled during the high-tariff period. The storage assets are discharged during high-tariff period and charged during the low-tariff period. Third, it is based on the mutual benefits to the DNO and MG users. The stakeholders agree in advance to share the cost and benefits of P2P energy trading. The percentage of participation in the gained benefits is the same with the percentage participation in the cost. Energy sharing is regulated and followed by all participants according to the rules explained in each step, taking into consideration transformer and storage inverter power limits. The implemented methodology aims to achieve particular goals that are summarized below. These goals are:

- provide economic benefits to P2P exchange participants,
- reduce carbon emissions,
- improve system resilience, and
- increase battery lifetime.

5.2. METHODOLOGY - MAIN STEPS

To apply this methodology an energy management strategy is developed with particular steps. Each step describes certain rules that should be followed by all participants. These steps are summarized and described in detail below:

- Provide input data
- Battery sizing
- Users' categorization and priority order
- Zoning
- Optimum battery discharging
- Application of network and communication faults:
  - ✓ Network faults
  - ✓ Communication faults
  - ✓ Feeder faults
  - ✓ Transformer/infeed faults

5.2.1. PROVIDE INPUT DATA

To apply the presented methodology certain input parameters are required from the user. These parameters are presented in Table 5.1. The parameters describe the characteristics of the MG, including the number of MG users, number of feeders and number of users in each feeder (Table 5.1). Moreover, the number of users with PV panels is required along with the size of the installation (Table 5.1). The daily load demand and PV generation data of the MG users are also required (Table 5.1). The particular characteristics of the existing ToU tariff scheme are also required, including the low/high tariff periods and the tariffs for each of them. The participation of DNO and MG users in costs must be also specified along with power limits of the inverters and the transformer (TF) (Table 5.1). Existing feed-in-tariffs (FIT) for each kWh fed into the grid from the PV energy surplus need to be specified (if there are any).

Input data	
Number of MG users	ToU tariffs (p/kWh)
Number of MG feeders	TF export power limit
Number of users per feeder	Inverter power limit
Number of users with PV	DNO –MG participation (%)
PV installation size (kWh)	Battery prices (£/kWh)
Low tariff period (time)	Daily load demand (kW)
High tariff period (time)	Daily PV generation (kW)
PV surplus FIT (p/kWh)	

Table 5.1: Input data required

5.2.2. BATTERY SIZING

The methodology includes two different modes. One planning mode and one operation mode. In planning mode, the number and the size of storage assets is not defined in advance, thus a battery sizing process is required. In operation mode the storage assets are predefined thus the sizing process is skipped.

In planning mode, each MG user is willing to jointly buy a battery with the DNO in order to participate in P2P process, in case that benefits are gained. This will determine the total number of batteries and their size in the MG. The contribution of each stakeholder to the investment cost and the percentage of benefits gained, is settled in advance. The expected benefits for each potential battery owner are then estimated. Initially, it is assumed that all users have batteries. A cost-benefit analysis is performed for each of them, seeking the optimum battery size for which their benefits (if there are any) are maximized. For this purpose, the net present value (NPV) is the metric against which different battery sizes are assessed. With a positive NPV the user does not gain benefits for the considered parameters, thus the battery purchase is not a profitable option. Whereas for a negative NPV the user gain benefits after the payback period. If the benefits are satisfactory the user installs a battery asset. The equations used in the NPV calculation are as follows. The net power, $P_{net(t,k)}$ at an individual home is

$$P_{net(t,k)} = P_{L(t,k)} - P_{PV(t,k)} \tag{1}$$

where $P_{L(t,k)}$ is the load demand and $P_{PV(t,k)}$ is the power generated by the PV panel (in kW), for each timestep t and for each user k. The duration of P2P exchange process in minutes, ΔT_{P2P} is:

$$\Delta T_{P2P} = T_{P2P-end} - T_{P2P-start} \tag{2}$$

where $T_{P2P-end}$ is the time when P2P ends and $T_{P2P-start}$ is the time P2P starts (in minutes). The maximum energy that can be discharged from the inverter (in kWh), $E_{\max(k)}$ during the P2P period, ΔT_{P2P} is:

$$E_{\max(k)} = P_{inv(k)} \cdot \Delta T_{P2P} \tag{3}$$

where $P_{inv(k)}$ is the maximum power limit of each user's inverter device (in kW). As each user has one inverter connected both to the PV panel and the battery, the maximum energy that can be discharged from the battery (in kWh), $E_{max-batt(k)}$ is:

$$E_{max-batt(k)} = E_{\max(k)} - E_{PV(k,n)} \tag{4}$$

where $E_{PV(k,n)}$ is the energy produced from the PV panel of each user k, for each representative day n (in kWh) that passes through each inverter. The energy needed for self-consumption (in kWh), for each user k during the P2P exchange period, $E_{batt-sc(k)}$ is:

$$E_{batt-sc(k,n)} = E_{tot-P2P(k,n)} - E_{PVtot-P2P(k,n)} \tag{5}$$

where $E_{tot-P2P(k,n)}$ is the total energy required during the P2P exchange period by each user k and for each representative day n (in kWh). $E_{PVtot-P2P(k,n)}$ is the total energy produced by the PV panel during P2P exchange period, for each user k and for each representative day n (in kWh). The grid provides rewards to PV users for each kWh they provide from their PV surplus during the P2P exchange period. The benefits gained for each kWh that is provided to the grid from the surplus of each PV, of each user k, $B_{P2P-PV(k)}$ is:

$$B_{P2P-PV(k,n)} = E_{PV-surplus(k,n)} \cdot C_{PV-surplus} \tag{6}$$

where $E_{PV-surplus(k,n)}$ is the energy surplus produced from the PV (in kWh) of each user k during P2P exchange for each representative day n. $C_{PV-surplus}$ is the FIT provided for each kWh (in p/kWh). The energy surplus is defined by the equation below:

$$E_{PV-surplus(k,n)} = \sum_{t=1}^{T=\Delta T_{P2P}} \left(PV_{gen(k,n,t)} - E_{cons(k,n,t)} \right) \tag{7}$$

Where $PV_{gen(k,n,t)}$ is the PV energy generated (in kWh) for each user k, for each representative day n, for each time t, and $E_{cons(k,n,t)}$ is the energy consumption (in kWh) for each user k, for each representative day n, for each time t. The tariff paid for each kWh delivered during the P2P exchange, $C_{P2P-tariff}$ is:

$$C_{P2P-tariff} = ((C_{HT} - C_{LT} - r)\ /100) \cdot p \tag{8}$$

where C_{HT} and C_{LT} are the high and low tariffs of the existing ToU tariff scheme respectively (p/kWh). r is the reduction tariff (p/kWh) offered to the grid connected users for participating in the P2P process, and p is the percentage of participation of each user to cost and benefits (% percentage). The gained benefits from P2P for each user k, for each representative day n, $B_{P2P(k,n)}$ is:

$$B_{P2P(k,n)} = loss_{batt(k)} \cdot \left(E_{max-batt(k)} - E_{batt-sc(k,n)}\right) \cdot C_{P2P-tariff} \tag{9}$$

where $loss_{batt(k,n)}$ is the percentage of estimated battery losses for each battery k, for each representative day n. P2P exchange will achieve carbon emissions reduction, if the grid carbon intensity is lower during the low-tariff (LT) period and higher during the high-tariff (HT) period. This will happen as batteries are charged during the LT period and discharged during the HT period. The benefits gained due to carbon emissions savings for each user k, for each representative day n, $B_{P2P-CO2(k,n)}$ is:

$$B_{P2P-CO2(k,n)} = W_{CO2-saved(k,n)} \cdot C_{CO2-saved(k,n)} \tag{10}$$

Where $W_{CO2-saved(k,n)}$ is the amount of carbon emissions saved (in tons) from each user k, for each representative day n in tones, and $C_{CO2-saved(k,n)}$ is the tariff paid for each tone of carbon emissions that is saved (£/tn CO_2 saved). This tariff is specified by implemented carbon emission policies. The benefits gained (in £) from P2P exchange process for each user k, for each representative day n, will be:

$$B_{P2P-tot(k,n)} = B_{P2P-PV(k,n)} + B_{P2P(k,n)} + B_{P2P-CO2(k,n)} \tag{11}$$

The total cost (in £) for P2P exchange process for each user k, for each representative day n, $C_{P2P(k,n)}$ is:

$$C_{P2P(k,n)} = C_{grid-P2P(k,n)} - B_{P2P-tot(k,n)} \tag{12}$$

where $C_{grid-P2P(k,n)}$ is the total cost paid to the grid (in £) for P2P process by each user k, for each representative day n, including battery charging cost. To compare the impact of P2P exchange framework, a BAU scenario is considered as a baseline. In this scenario, it is considered that the same users have PV panels but no batteries. Thus, the benefits gained for each user k, for each representative day n, $B_{BAU(k,n)}$ are:

$$B_{BAU(k,n)} = E_{PV-surplus(k,n)} \cdot C_{PV-surplus(BAU)} \tag{13}$$

where $C_{PV-surplus(BAU)}$ is the FIT paid for each kWh fed into the grid by the PV. The total cost paid to the grid for BAU case by each user k for each representative day n, $C_{BAU(k,n)}$ is:

$$C_{BAU(k,n)} = C_{grid-BAU(k,n)} + P_{net-tot(k,n)} \cdot C_{HT} - B_{BAU(k,n)} \tag{14}$$

where $C_{grid-BAU(k,n)}$ is the cost paid to the grid by each user k, for each representative day n (in £), for the same period P2P exchange lasts in order the results to be comparable. $P_{net-tot(k,n)}$ is the total net power for the BAU scenario for each user k (in kW), for each representative day n, for the same period P2P lasts. The total benefits (in £) each user k gains for each representative day $n, B_{tot(k,n)}$ is:

$$B_{tot(k,n)} = C_{BAU(k,n)} - C_{P2P(k,n)} \tag{15}$$

The investment cost for each user $k, C_{invest(k)}$ is:

$$C_{invest(k)} = (C_{batt} \cdot Batt_{rated(k)} + C_{inv(k)}) \cdot p \tag{16}$$

where $Batt_{rated(k)}$ is the battery size (rated capacity) of each battery k (in kWh), C_{batt} is the current battery prices in £/kWh and $C_{inv(k)}$ is the inverter cost of each inverter k (in £). The net present value of each for each user k, after y years for each representative day n, $NPV_{(y,k,n)}$ is:

$$NPV_{(y,k,n)} = \sum_{1}^{y} \frac{(C_{invest(k)} - B_{tot(k,n)}}{(1+q)^{y}} \qquad (17)$$

where q is the discount rate after y years. The lowest value is selected, as it represents the maximum benefits. The NPV value is calculated on an annual base, using a certain amount of representative days for each user. For each representative day, a range of possible battery sizes ($Batt_{rated(k)}$) is tested. The optimum battery size will be the one for which the NPV value is minimized. The annual benefits will be the average value of the benefits gained for each representative day. In the same way, the battery size will be the average value of the optimum sizes of each representative day. A sensitivity analysis is also performed to test the validity of the average value.

5.2.3. USERS' CATEGORIZATION AND PRIORITY ORDER

The methodology is applied to MGs where users have batteries or/and PV under their ownership. The users who have batteries are characterized as "Battery owners" (BO), while the rest of them as "Grid-connected" (GC) users. The users' categorization is implemented regardless the PV ownership. BO charge their batteries during the low-tariff (LT) period and discharge them during the high-tariff (HT) period.

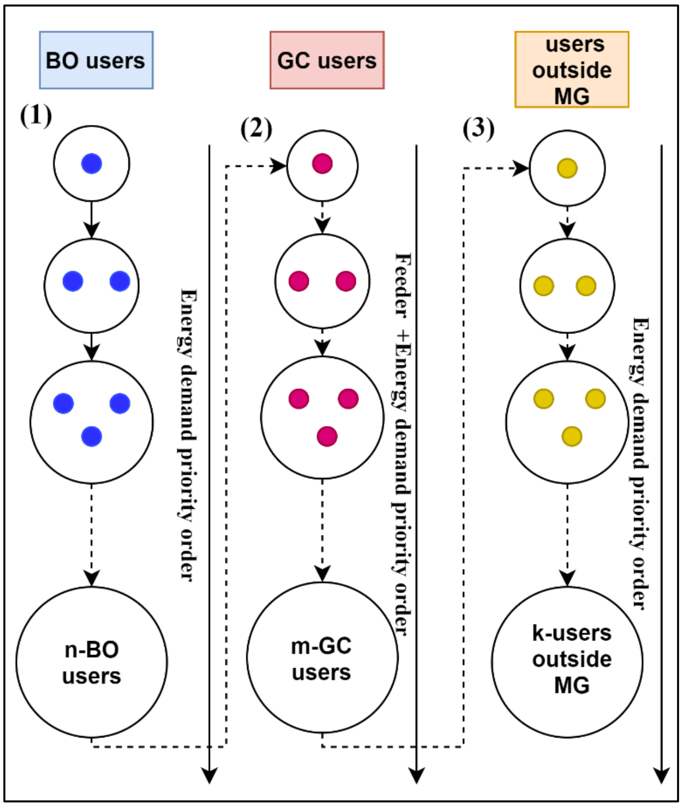

Figure 5.1: Users' priority order.

Users' prioritization process is shown in Figure 5.1. The users are prioritized in three stages, based on day-ahead demand and generation assumptions. First, the BO users are prioritized, as they are the key players of P2P process, starting from the one with the lowest energy demand until the one with the highest. Second, the GC users are prioritized. GC prioritization occurs based on the energy mismatch of each feeder for the P2P exchange period. The mismatch is calculated by subtracting the total stored energy in the batteries of the feeder, from the total net energy demand of the feeder's users. A negative mismatch means there is surplus energy in the batteries of the feeder, while a positive value shows a deficit. The MG feeders are prioritized from the lowest mismatch value to the highest. The GC users of the first-priority feeder have priority over the users of second priority feeder and so on. However, a second prioritization happens within each feeder, where the users are also prioritized from the lowest to the highest energy demand. The users that are not included in the P2P process continue to pay the HT as before.

The methodology is applied regardless of the internal structure of each feeder. For example, it can be applied to MG with different feeder structures and different number of users in each of them. Third, the "users outside the MG" are prioritized according to their energy demand, simply from the lowest to the highest. Finally, the model checks how many users can be served based on the availability of energy stored in the batteries and used in the P2P process.

5.2.4. ZONING

In this work, the concept of "zone" is used, which is defined as the area where P2P exchange is enabled. The users who participate in it gain privileges from the P2P process. The prioritization process is used to define the order of GC users. In this way, the way that the available generation units will be dispatched, is defined (UC process).

The energy sharing occurs within energy and power limits. Energy limit refers to the stored energy available in each timestep while power limit is given by the maximum transfer capacity of the inverters and transformers (TF). Zones are dynamically adjusted in order to include users that can be served within the energy and power limits, following the defined priority order.

As zone members gain benefits, all MG users have incentives to participate in the scheme. One of the goals is to provide economic benefits to the stakeholders. This is achieved by reducing the load demand during the HT period, as this mitigates the peak power and, in this way,, more energy will be available in the batteries to share it among peers. To implement this, the mismatch between users demand and the batteries' stored energy on each feeder for the P2P exchange period is calculated on a day ahead basis A negative mismatch means there is surplus energy in the batteries of the feeder, while a positive value shows a deficit. The MG feeders are sorted from the lowest mismatch value to the highest to set the zone expansion order for the day ahead.

In addition to the feeder order there is a user priority order along each feeder. As P2P exchange encourages users to reduce their load demand during HT period, the users with the lowest load demand are included by priority in the zone, leaving the users with higher load demand last to join the scheme.

An example of zoning expansion, according to a particular order, is presented in Figure 5.2. The zone area does not always coincide with a continuous geographical area, as some batteries might be in a feeder that does not participate in the zone, yet its BO do. If there is still energy available for P2P sharing, the zone can be expanded beyond the geographical limits of the MG.

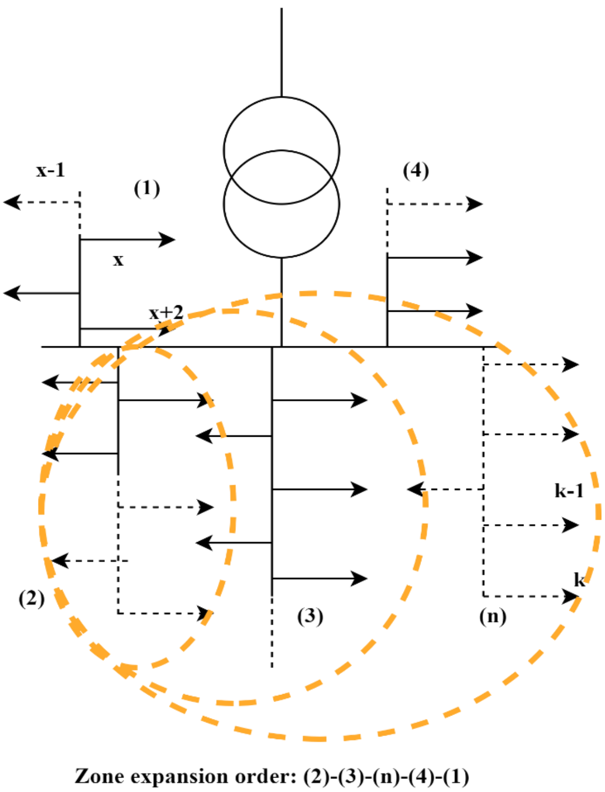

Figure 5.2: MG topology and zone expansion in time

The NPV described in (17), is initially calculated, without taking into consideration the TF power limit per user, as the amount of power used within the MG and the amount exported to the grid, cannot be estimated in advance. However, after the number of batteries is determined, the zone process runs again for the n representative days, this time including TF power limits. The model calculates how much energy remains in the batteries (if any) after the zoning process. If there is unused energy this is interpreted to mean that the batteries are oversized. Thus, the battery sizes of the existing batteries are corrected, and the NPV value is recalculated as well as the users' categorization and zoning processes (Figure 5.3).

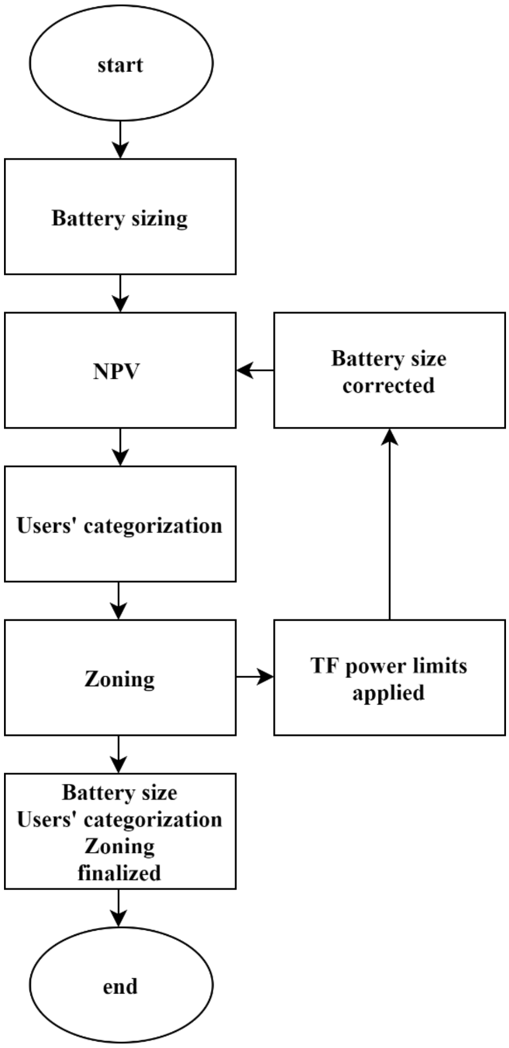

Figure 5.3: Battery correction process.

The battery sizing process itself is presented in the flowchart below:

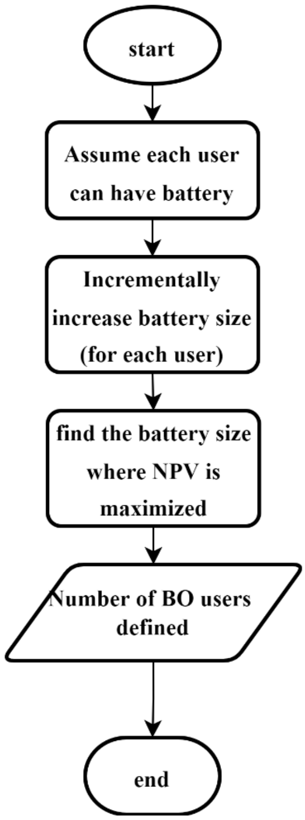

Figure 5.4: Battery sizing process flowchart.

5.2.5. OPTIMUM BATTERY DISCHARGING

After the zone boundaries have been defined for each timestep, the power required from users' batteries is calculated. A certain amount of power is available in the batteries to cover the energy needs of the users. This power will be used in the optimization section, where the batteries are jointly discharged in order to minimize the degradation cost. Sharing the power requirement prolongs battery lifetime compared to a one-by-one battery discharging in which each home covers its individual needs. In the joint discharge approach the power in each timestep is shared among k batteries resulting in lower discharging currents than individual batteries would see through one-by-one discharging. Lower discharging current means a lower degradation cost for each battery. Different models have been developed in current literature to estimate the degradation cost of lithium-ion batteries. In this work, the equations described in [111] are used. According to [111], the total cycle loss of lithium batteries, $Q_{total\ loss}$ can be described by the following equation:

$$Q_{total\ loss} = Q_{cycle\ loss} + Q_{calendar\ loss} \tag{18}$$

where $Q_{cycle\ loss}$ is the operation cycle loss and $Q_{calendar\ loss}$ is the calendar cycle loss. In this study, the calendar cycle loss is ignored. The operation cycle loss is described by the following equation:

$$Q_{cycle\ loss} = B_1 \cdot e^{B_2 \cdot I_{rate}} \cdot A_h \tag{19}$$

where I_{rate} is the charge/discharge rate (C-rate), A_h is the Ah-throughput and B_1, B_2 are:

$$B_1 = \alpha \cdot T^2 + b \cdot T + c \tag{20}$$

$$B_2 = d \cdot T + e \tag{21}$$

where T is the absolute temperature in K and α, b, c, d, e are the model coefficients described in [111]. According to [111], the degradation cost of a discharging event can be described by the equation :

$$C_{\deg(t,k)} = \frac{Q_{cycle\ loss\ \%}}{\eta\%} \cdot P_B \tag{22}$$

where $Q_{cycle\ loss\ \%}$ is the percentage of cycle loss of the discharging event, $\eta\%$ is the threshold of maximum cycle loss which is usually set to 20%-30% of the initial capacity. P_B is the price of the whole battery pack [111]. As the degradation cost is a non-linear function MATLAB fmincon is used to develop the optimum discharging algorithm. The aim is to minimize the total discharging cost of the batteries. The solver is able to find the global minima as it is convex. A proof of its convexity can be found in Appendix 2. The optimization problem is described below:

Minimize:

$$f = \sum_{1}^{K} C_{\deg(t,k)} \tag{23}$$

Where K is the total number of batteries of the BO users, included in the zone. This number remains constant after the battery sizing process has finished.
subject to:

$$SoC_{(t+1,k)} - SoC_{(t,k)} = I_{(t,k)} \cdot dt \tag{24}$$

$$\sum_{1}^{K} I_{(t,k)} = I_{tot}(t) \tag{25}$$

$$SoC_{\min(k)} \leq SoC_{(t,k)} \leq SoC_{\max(k)} \tag{26}$$

$$0 \leq I_{(t,k)} \leq I_{\max(k)} \tag{27}$$

where, $C_{\deg(t,k)}$ is the degradation cost, $SoC_{(t,k)}$ is the SoC (in Ah)and $I_{(t,k)}$ is the discharging current of each battery k for each timestep t , while $I_{tot}(t)$ is the discharging current of all batteries K, for each timestep t and $I_{\max(k)}$ is the maximum current that can be discharged from each battery k.

5.3. RESILIENCE AND FAULT SCENARIOS

Resilience can be defined as the ability of a power system to respond comprehensively and recover rapidly from faults due to extreme events [41]. The resilience of the system is tested in the context of the described methodology against a baseline scenario, called “No P2P” scenario. The baseline has the same number of batteries, but P2P is not enabled so that batteries operate independently, in the interests of the individual users. The implementation of the methodology requires a communication network to exchange information and make certain decisions according the rules explained in this paper. The structure of this network is described in Figure 5.5 based on our previous work in [190]. A centralized communication network is considered, where a central MG server collects all the information from MG users through communication channels. The server could be located in the local substation. The users send data regarding their SoC, their ID number, their type (BO or GC user) and the required energy during the P2P exchange process. Moreover, the MG server communicates also with the server of main grid, in order to receive information about the “users outside the MG” and their energy demand. The MG server receives all the information, prioritizes the users and run the optimization according to the developed methodology sending the suitable signals back to the users and to their storage devices. Besides the structure of the communication network, which is briefly described no further communication issues are investigated.

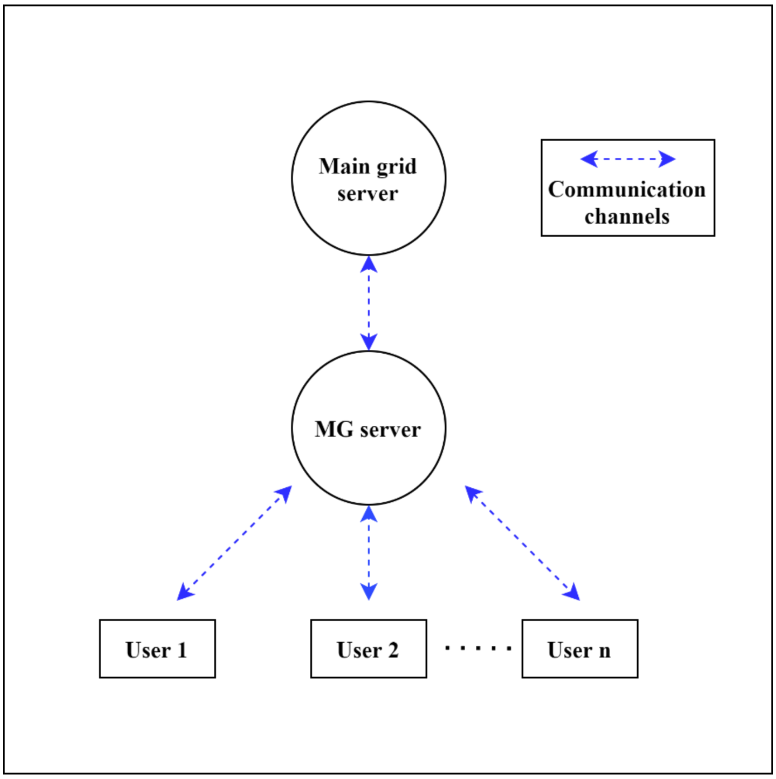

Figure 5.5: Communication structure based on [190].

To examine the impact the developed methodology on resilience, four fault scenarios are considered. The first scenario examines faults on the physical components of batteries, while the second one the faults on the communication system. A third scenario examines the electrical fault in one of system's feeders, while the fourth one the case where transformer/supply is lost. In the last two scenarios, the DNO is obliged to provide compensation as it is responsible to cover the energy needs of the end users. In the first two scenarios, no compensation is provided as DNO is not responsible for these faults. An equation for DNO compensation is created and used, based on data gathered from [144], [191].

$$\text{Compensation}=0.0119\cdot t_{\text{dist}}+17.5\cdot E_{\text{l}}+0.92 \tag{28}$$

where t_{dist} is the total minutes of disturbance of all users, and E_l is the total energy loss (kWh) due to fault. Each fault scenario is described in greater detail:

5.3.1. Battery fault scenario (FLT_{Batt})

In FLT_{Batt} scenario, batteries are unavailable due to faults. Fault incidents could occur before or during the HT period in which theP2P process occurs. Battery faults could occur in multiple batteries during the same day. Repair time is assumed to be 1-day, so the P2P exchange is reconfigured to continue without the faulted batteries. Users with a battery fault, can still communicate with the MG controller yet they are treated as simple GC users for that particular day. The zone expansion order is reconfigured with the available assets, excluding the fault batteries. After reconfiguration the number of batteries has changed which could change the zone expansion order. P2P exchange continues with the remaining batteries noting that the available energy for will be less, resulting in shrunken zone boundaries.

5.3.2. Communication fault scenario (FLT_{COM})

Multiple FLT_{COM} fault can happen during the same day, before or during the HT period. FLT_{COM} can occur either to BO or to GC users or to both user categories. Repair time is assumed to be 1-day. In this case, the faulted users are no longer visible by the MG controller, thus they are automatically excluded from zone.

5.3.3. Feeder fault scenario (FLT_{Feed})

FLT_{Feed} scenario considers that a whole feeder(s) is disconnected, due to faults in the electrical network components. One or more feeders can be disconnected from the substation leaving their users without supply. The zone is again reconfigured, by adjusting its boundaries to the new circumstances. The faulted feeders are automatically excluded from the zone along with their users. P2P exchange continues with the remaining users from the no fault feeders. The zone expansion order is changed, as the faulted feeders are excluded. Until the fault is restored, the DNO is obliged to provide compensation to the users off-supply, according to the duration and the level of disturbance.

5.3.4. TF FAULT SCENARIO (FLT_{TF})

In the FLT_{TF} scenario, it is assumed that the MG Transformer/supply is lost due to faults. However, it is assumed that there is back up system that keeps the communication network active. The resilience of the system is then tested in the context of the described methodology against a baseline scenario. The baseline scenario has the same number of batteries, but P2P is not enabled so that batteries operate independently, in the interests of the individual users. The zone is automatically reconfigured so that all MG users are included. P2P exchange attempts to mitigate the disturbance to users until a fault is restored (even partially). If the energy available in the batteries is sufficient to cover MG users' needs, for the expected fault duration, without violating PL, the users will remain undisturbed. However, it's very likely the energy available will be insufficient, or the PL will be violated in some time steps. In this case a load curtailment strategy is introduced to satisfy the energy and power limitations. All MG users have agreed in advance a priority list of devices, which represents the order of devices they are willing to lose in case of a TF/supply fault. The device priority list is shown in the table below:

Device priority list	
1	Group 1 appliances (Standby appliances +washing machine)
2	TVs
3	PCs
4	Oven
5	Fridge
6	Lights

Table 5.2: Device priority list

The load is curtailed gradually according to a load curtailment priority order. While in the zoning process there is a user priority order according to which the users are added in the zone, another priority order is defined for load curtailment process. The load curtailment priority order will be exactly the opposite of the users' priority list. In other words, the first user added in the zone will be the last curtailed. Initially, the first device in the priority list is curtailed, according to the load curtailment priority order until the point that the energy/power limits are not violated. If the limits are still violated the next device is curtailed in the same way and so on. A flowchart of the device curtailment process is shown in Figure 5.6. The overall methodology process is summarized in the flowchart presented in Figure 5.7.

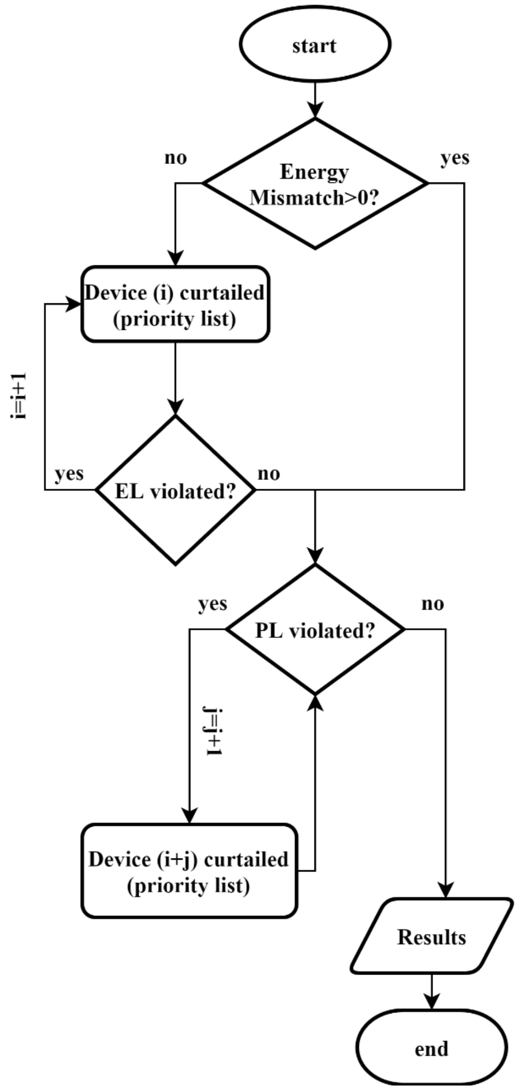

Figure 5.6: Load curtailment strategy sub process

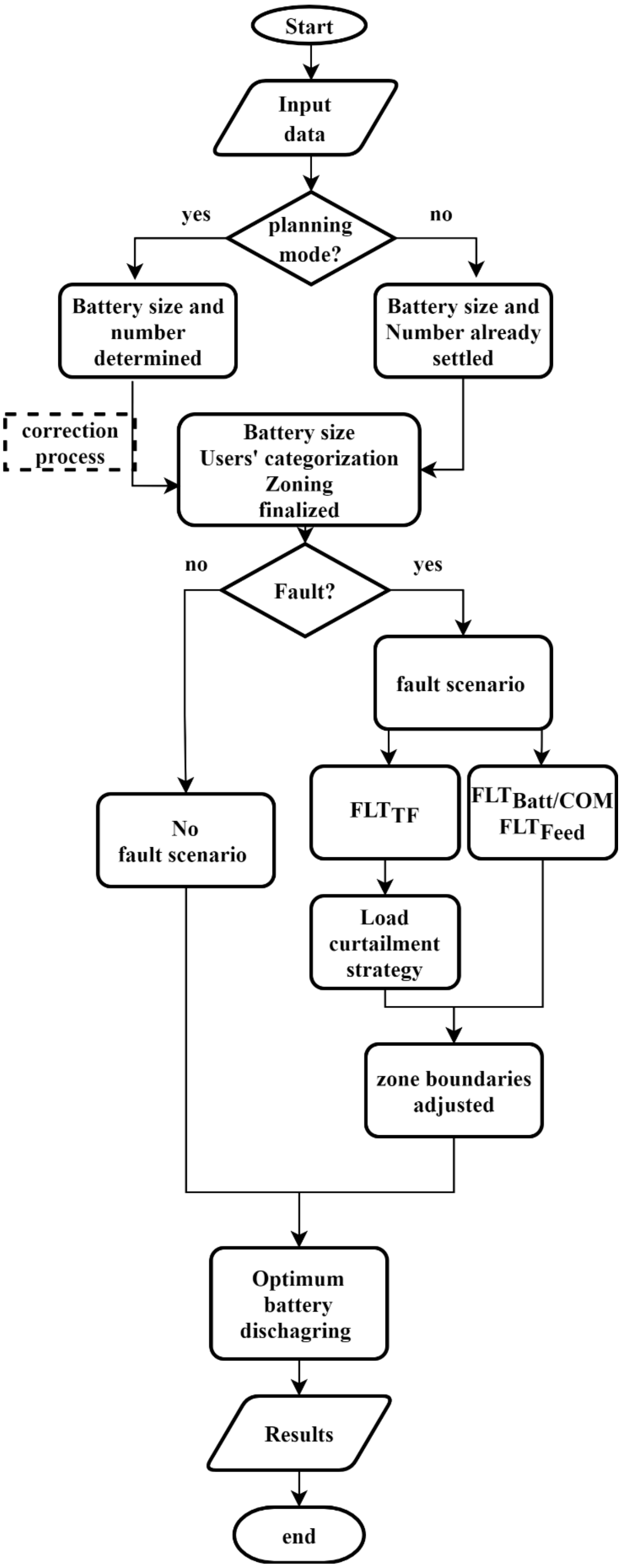

Figure 5.7: Flowchart of the developed methodology.

5.4. CHAPTER SUMMARY

In this chapter a novel framework for P2P exchange was presented. A detailed description of the required steps was provided. Since the input data are provided, a battery sizing process is implemented to find the number and the optimum size of the batteries. The next step includes a users' categorization process. The users are categorized (BO, GC. "users outside the MG") and prioritized under certain criteria. A zoning process is then applied putting users in it according to the priority order. P2P exchange is performed by jointly discharging BO's batteries in an optimum way to minimize degradation cost. Different fault scenarios are examined to quantify their impact on system resilience, assuming that faults occur at the physical or communication part of the system. A brief description of the communication structure is provided along with relative flowcharts that clarifies certain processes of the presented methodology.

Chapter 6. Case study-results

In this chapter the practicality of the developed methodology will be tested. A particular case study will be presented, using suitable input parameters and implementing all the methodology steps. Four representative days will be used from CREST model to size the system, and then a particular day in Winter will be examined for UK location. The obtained results will be described and discussed analytically for each examined scenario.

6.1. INPUT PARAMETERS

The practicality of the suggested methodology is tested on a particular case study. A particular MG with settled number of users and a ToU tariff scheme, are considered (Table 6.1). The MG is located in North East England in UK (Newcastle city). The examined MG consists of five parallel feeders where the users are equally distributed among them (Figure 6.1).

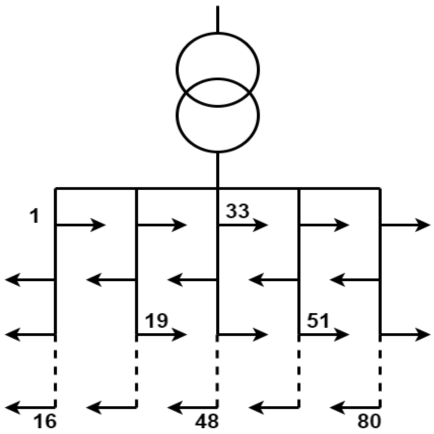

Figure 6.1: MG topology for the case study.

Some of the users have PV panels under their ownership, while some others not. For this case we assume that only half of the users have domestic PV installations of 3kW. Each PV installation produces the same amount of power for the same day, as they are located at the same place. It is assumed that the FIT is for P2P exchange is increased significantly by policy makers, in order to provide incentives to the users to participate. Thus, for this case study the FIT for P2P exchange is almost 3 times higher than the existing one for the BAU case (Table 6.1). The DNO and the MG users contribute 50% each to the investment cost and share the gained benefits. A particular price per kWh is assumed for lithium-ion batteries based on a recent study (Table 6.1). Inverter and local transformer power limits are also specified (Table 6.1). All MG users are domestic users, and their load data are obtained from CREST model [192].

Input parameters	**Values**
MG users	80 users
MG feeders	5 feeders
Users per feeder	16 users per feeder
Users with PV	40 users
PV installation size	3 kW (each)
PV cost	Not required as both scenarios (BAU and P2P) have the same PV device.
Low-tariff period	22:00-07:00
High-tariff period	07:00-22:00
ToU tariffs	Low tariff =2p/kWh High tariff=25p/kWh Tariff reduction (r)=2p/kWh
PV surplus FIT for P2P	12 p/kWh
PV surplus FIT for BAU	3.87 p/kWh [193].
TF export power limit	1.5 kW per user
Inverter power limit	3 kW per device
DNO-MG users participation	50%-50%
Inverter cost	800 £ per device (50% paid by each user)
Discount rate for NPV (q)	3.5 % [194].
Battery price	114 £/kWh [195].
Daily load demand/PV data	obtained by CREST model [192].
Number of representative days (n)	4 days
Time until portable generator is brought in the field	3 hours

Table 6.1: Input parameters.

A certain number of typical days is selected in order to represent the load and PV data for a whole year. These days are also known as representative days. Different approaches have been presented in literature on how to select these days [196]. In this work the simplest method is used, by selecting days from periods that present significant variability on load demand and PV data. CREST model provides data based on meteorological conditions and a particular occupancy model. As the aforementioned parameters vary on a seasonal basis, the model presents a significant seasonal variability [197]. Thus, four representative days were selected one for each season (Winter, Spring, Summer, Autumn). The system is sized based in these four days. In this work, it is considered that we have perfect forecasts, so the load demand and the PV generation are known a priori.

6.2. Battery sizing

Initially, the number and the size of the batteries is unknown. It is assumed that all users have batteries as described in the methodology section. Then the NPV value after five years is estimated for each user, for different battery sizes. The NPV value is compromised by the inverter and transformer limits. The NPV value is calculated using the equation (17), for four representative days, one for each season. An optimum battery size is being found for each day. The size for which the cost is minimized will be the optimum. The optimum battery size and NPV value will be the average value of the 4 representative days. A sensitivity analysis is also performed to test the validity of the average value. Six different other battery sizes are tested within a range from -30% to 30% of the average battery size for each user separately, and the NPV value is calculated again for each of them to test which of them give the minimum value (maximum benefits). An indicative example is presented in the table below and it is referred to User 1 (Table 6.2). The same process was followed for the rest of the MG users.

Battery sizes (kWh)		NPV(£)
Average battery size - 30%	34.2	123
Average battery size - 20%	39	-88
Average battery size - 10%	43.87	-142
Average battery size	**48.75**	**-226**
Average battery size +10%	53.62	-53
Average battery size +20%	58.5	152
Average battery size +30%	63.75	437

Table 6.2: Sensitivity analysis for battery sizing for User1. The maximum benefits are gained for the average battery size.

In Figure 6.2, an indicative graph with the cost function of a particular user is presented.

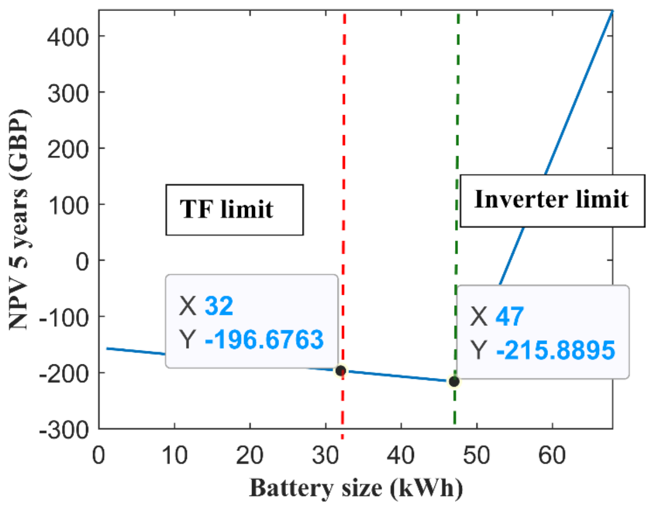

Figure 6.2: Cost function behavior example for one BO user.

The minimum cost is for this user is -215.88 £ (negative cost means benefits), where the battery size is 47kWh due to the inverter limits. However, the final optimum battery size will be 32kWh due to transformer power limits (Figure 6.2). If the transformer power limits are ignored in the sizing process, a part of the stored energy in the batteries will be always remain unused as it will not be possible to be delivered through the transformer. This fact means that the battery is oversized, as a part of the energy cannot be delivered through the transformer. Another issue is the fact that the inverter is connected both with the battery and the PV, meaning that a high PV generation will reduce the amount of power that can be delivered from the battery.

The initial optimum battery sizes are presented in the figures below for each MG user (Figure 6.3). The transformer power limits are not applied yet, as this is part of the correction process (see Figure 5.3). Only the inverter power limits are considered to this point. The results show, that 27 users have batteries with battery sizes close to 50 kWh, with only one exception that is around 55 kWh (Figure 6.3). The initial optimum battery size values are the average of the optimum values for each representative day, for each battery owner. The x-axis in this graph, shows only the absolute number of BO for this case.

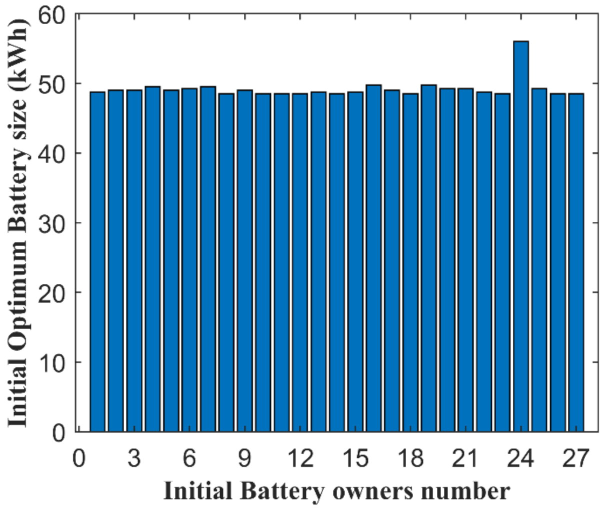

Figure 6.3: Initial optimum battery size for each battery owner.

The average NPV value after 5 years for each user is presented in Figure 6.4, in sorted order. A positive NPV value means that the user does not gain benefits after 5 years, while a negative one means that they do. Each user decides if the expected economic benefits are enough to invest money and buy a battery for P2P. In this case, we assume that the minimum of economic benefits that each user requires, is around 100£. Thus, the number of batteries will be initially 27 (Figure 6.4). Since the initial battery size is settled for the users that are going to have batteries, a correction of the battery sizes occurs taking into consideration the TF power limits, according to the process described in Figure 5.3. After the correction process, the number of BO is reduced from 27 to 18 (Figure 6.5).

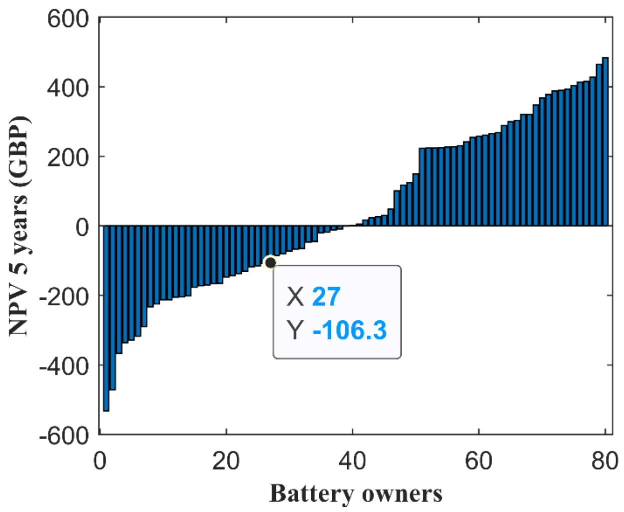

Figure 6.4: Average NPV value after 5 years for each MG user.

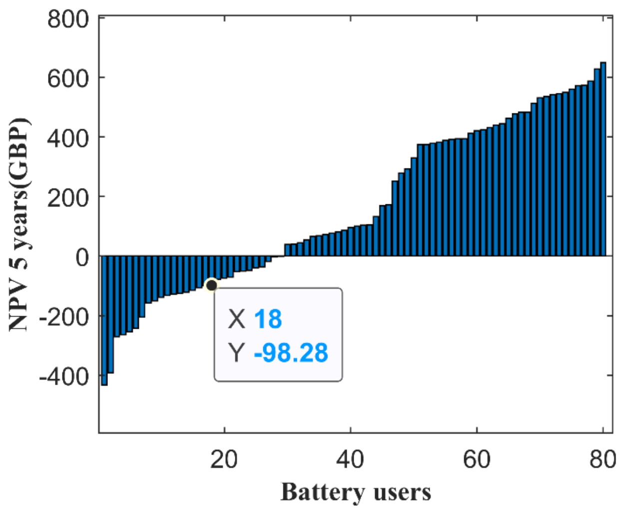

Figure 6.5: Average NPV value after battery correction.

Since the battery sizing process is terminated, the available assets of each MG user are finalized. In the figure below, the optimum battery sizes of the 18 batteries is shown (Figure 6.6). The x-axis in this graph, shows only the absolute number of BO for this case.

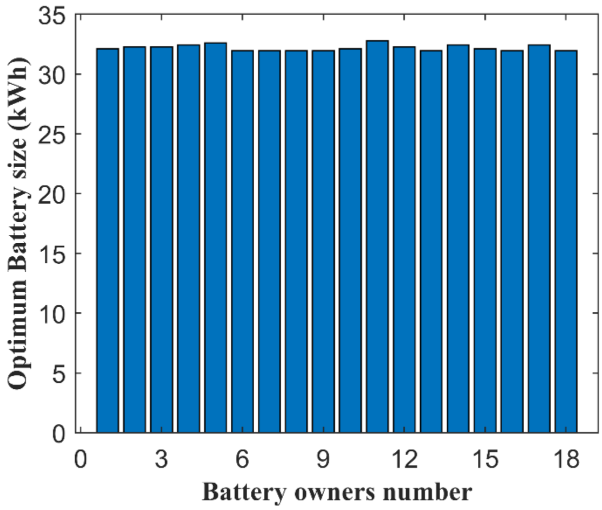

Figure 6.6: Optimum Battery size of the 18 BO.

6.3. USERS' CATEGORIZATION AND PRIORITY ORDER

Figure 6.7 shows exactly the users that have batteries and/or PVs and those that have not. In this way, the number of BO and GC users is settled for the particular case study. The PV ownership of each users is also specified. Users that have only PV are by definition GC users.

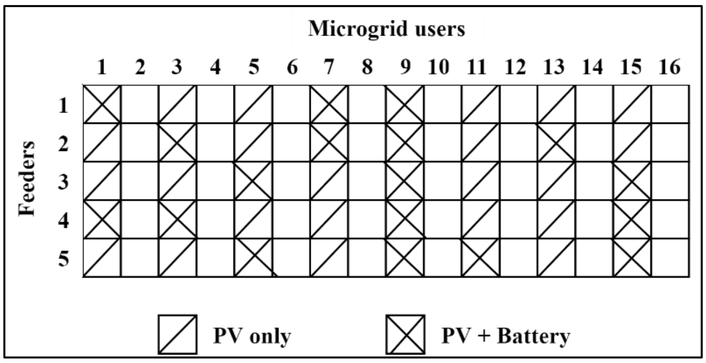

Figure 6.7: BO, GC users for the particular case study.

All the BO users have also a PV installation under their ownership. This happens as the PV installation reduces the net power of these users, leaving higher amount of available energy in their batteries to share. Moreover, it is assumed that for P2P exchange the FIT for PV is almost 3 times higher for this case (Table 6.1), increasing the benefits gained. Higher benefits gained for the user means that it is more likely to finally buy a battery based on the net present value process described above.

Comparing the initial number of batteries and their sizes, it is obvious that the correction process reduces the significantly the number and the size of the batteries, in relation to the first estimation. This fact also shows, that for some users a smaller battery (due to TF power limits) will finally produce no benefits, thus a battery purchase for P2P exchange is not a profitable option. An explanatory figure to clarify the battery sizing process for this case is presented below (Figure 6.8):

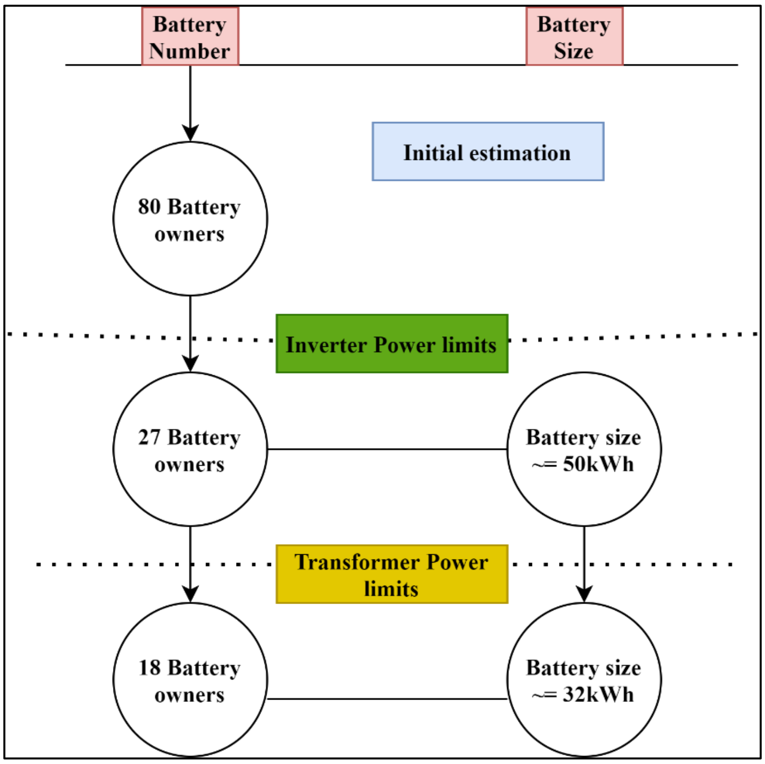

Figure 6.8: battery sizing process -explanatory graph.

To summarize, initially it is assumed that all the users of the MG have batteries (80 BO). Then the inverter power limits are applied, and the number of BO drops to 27, with a battery size around 50kWh for each user. This result is calculated based on the average NPV after 5 years for four representative days. Finally, the transformer power limits are applied, reducing the battery size to approximately 32 kWh for each user and the battery number to 18 batteries. If the power limits are ignored, then the batteries will be oversized, and a significant part of the stored energy will not be used.

6.4. ZONING

The zoning expansion order is based on the energy mismatch of each feeder, as it is described in methodology section. In this case the zone expansion starts from feeder 2 and ends in feeder 1 (Figure 6.9). Despite the zone expansion order per feeder, there is also user priority order within each feeder, it was described in methodology. The BO users are excluded from Figure 6.9, as they are all included in zone for this case.

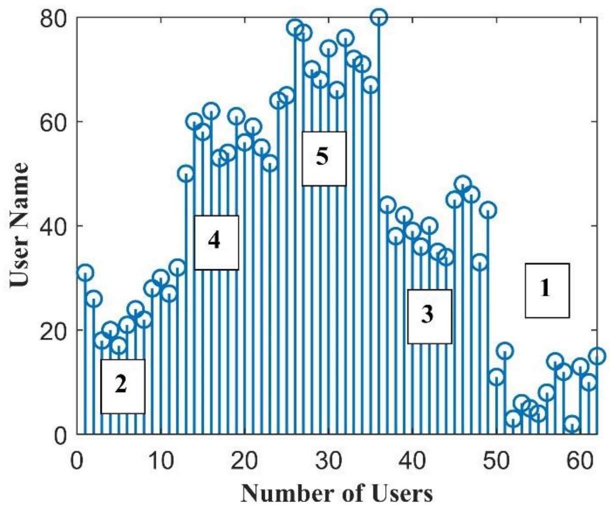

Figure 6.9: Users' priority order - no fault scenario.

As P2P exchange can be expanded outside MG, 100 extra "users outside MG" are considered with no PV and storage assets. For the users outside the MG the priority order is based only on their energy demand from the lowest to highest (Users 81-180). The load demand data of these users are also obtained from CREST model [192].The model calculates the total required power from inverters, checking if the power limits are violated (Figure 6.10). If PL are violated, the excess power is shifted to time steps where limits are not violated. In this way, the total power required from the inverters is calculated (Figure 6.10). Since each inverter is connected both to the PV and the battery, the required power from batteries is equal to the total inverter power minus the PV generation power. When the PL are violated P2P exchange cannot be expanded outside the MG, since only a part of the MG users demand is covered. Figure 6.11, shows the number of users included in zone for each time step. It is obvious that after 16:00 only a few users are included in zone and no power is exported through the local transformer, as PL are initially violated (Figure 6.10).

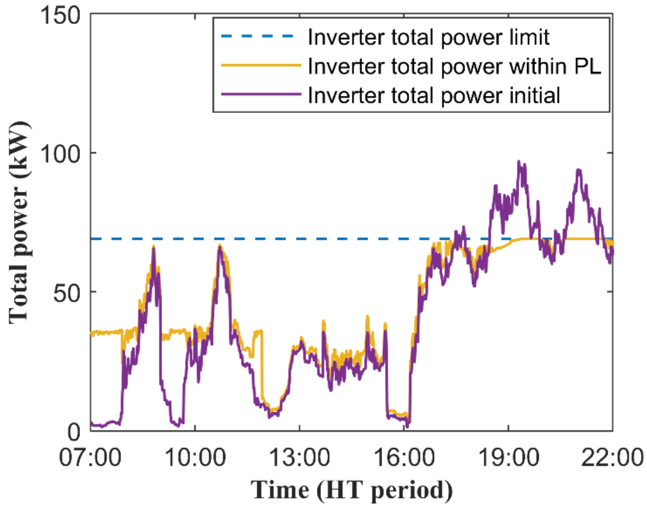

Figure 6.10: Total power covered by inverters/batteries.

As it is mentioned in methodology section, priority first given to BO users, then to the GC users within the MG and finally the grid users outside MG. The required power from batteries shown in Figure 6.10 is the power used in the optimization process. The equations used in the optimization are presented in methodology section (eq. (23)-(27)). Since the power covered by inverters is corrected in order to be within the power limits, the number of users included in the zone for each timestep is defined (Figure 6.11).

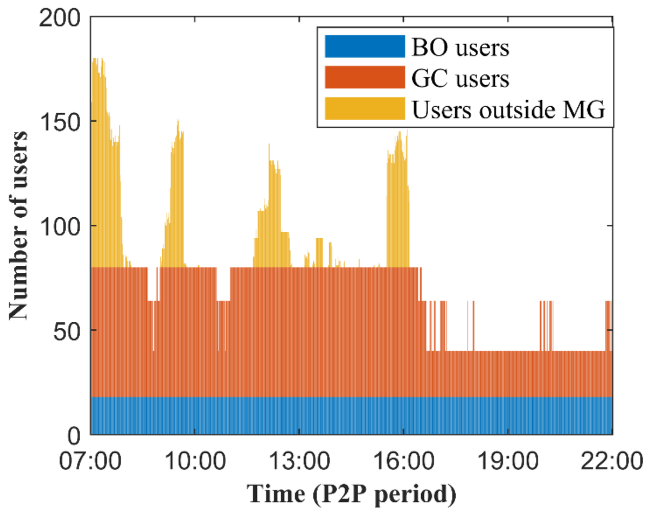

Figure 6.11: Number of users included in zone -no fault scenario.

Different colours are used for the different group of users. The blue colour represents the BO users, the red the GC users within the MG and with yellow colour the users outside MG (Figure 6.11). It is obvious that for the timesteps that PL are violated (Figure 6.10) the number of users included in zone are less than the total number of users within the MG (Figure 6.11).

6.5. Optimum Battery discharging

As the objective function described in (23) is non-linear, fmincon solver is selected in MATLAB software. The solver find the minimum of the objective function under equality and inequality constraints [198]. The constraints equations are eq. (24)-(27). MATLAB offers a range of fmincon algorithms depending on the characteristics of the optimization problem. The available algorithms are: a) ‘interior-point’, b) ‘trust-region-reflective’, c) ‘sqp’, d) ‘sqp-legacy’ and e) ‘active-set’ [199]. In this work, the ‘interior-point’ algorithm is selected as it can handle large, sparse problems, as well as small dense problems and it is recommended to be used first [199]. The software has different parameters to estimate if the solver has succeeded or failed to solve the problem, and different stopping criteria where the optimization ends if they are reached. The two most important parameters are first-order optimality and feasibility [200]. The closer these parameters are to zero the more accurate the solution is. In this work, the tolerance parameters are set to 10^{-3} and the optimization ends when these limits have been reached (Figure 6.12).

```
                                                  First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
    0      5383     0.000000e+00    8.507e+02     1.004e-07
    1     10766    -8.476618e-02    2.274e-12     2.939e-04    2.427e+03

Optimization stopped because the relative changes in all elements of x are
less than options.StepTolerance = 1.000000e-03, and the relative maximum constraint
violation, 2.672887e-15, is less than options.ConstraintTolerance = 1.000000e-03.
```

Figure 6.12: Screenshot from Matlab software, when the selected limits have been reached and the optimization ends.

In this case, the P2P exchange period lasts 15 hours with a timestep of 1 minute. Thus, the total optimization points will be 15*60=900. As the number of batteries and the number of points is increased, the optimization time is slowed down as the matrices become bigger, requiring also higher RAM. To accelerate the optimization process for the 18 batteries, the problem was broken in six sub-problems where the optimum values for 150 points were sought (900/6=150). The last values of each sub-problem are used as initial values to the next one. Each sub-problem is formulated as an optimization function with certain input and output parameters.

In this work, 18 batteries are used in the optimization problem. The (optimum) battery sizes selected by the battery sizing process is around 32kWh for all users, with small differences among them (Figure 6.6). Moreover, all batteries have the same SoC operating window (10%-90%) and are fully charged (SoC 90%). In addition, each battery has the same inverter type with the same power limits (3kW). For these reasons, the difference in cycle loss are negligible among them. This practically means that 18 same batteries are discharged together. For this reason, for each timestep the same amount of energy is been discharged from each of them to cover the P2P exchange energy needs. Thus, the optimum discharging curves and the optimum discharging currents coincide. In Figure 6.13, one of the optimum current and SoC curves is presented. The optimum cycle loss is during P2P exchange period is presented in Figure 6.14. It is obvious that cycle loss is increased as the DoD is increased (battery is discharged). However, the degradation cost will be different as the sizes are different (eq. (22)). The differences are small, following the battery size differences (same cycle loss) (Figure 6.15).A maximum threshold, $\eta = 20\%$ is selected for all batteries, meaning that each battery is practically replaced when the 20% of its initial capacity is lost.

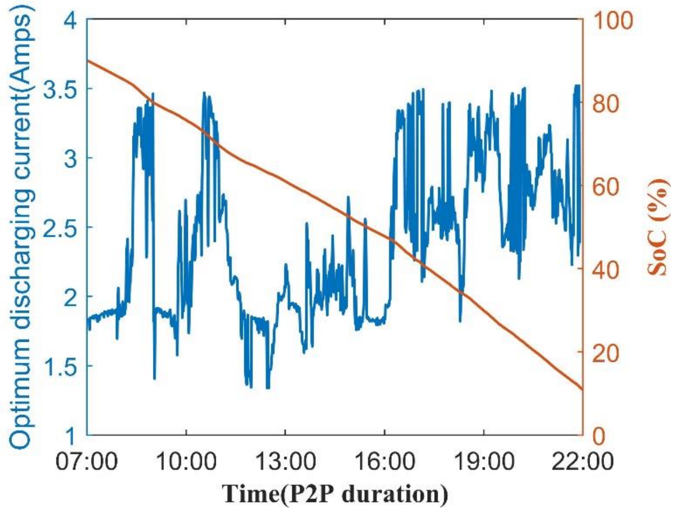

Figure 6.13: Optimum discharging current and Battery SoC.

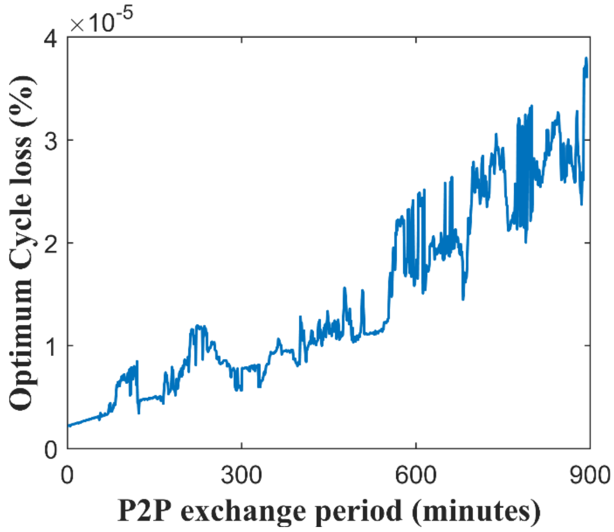

Figure 6.14: Optimum cycle loss for each battery, during the P2P exchange period.

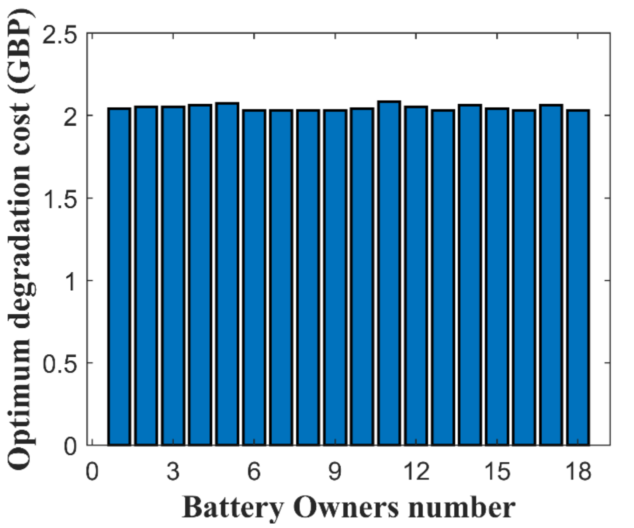

Figure 6.15: Optimum degradation cost during P2P exchange period.

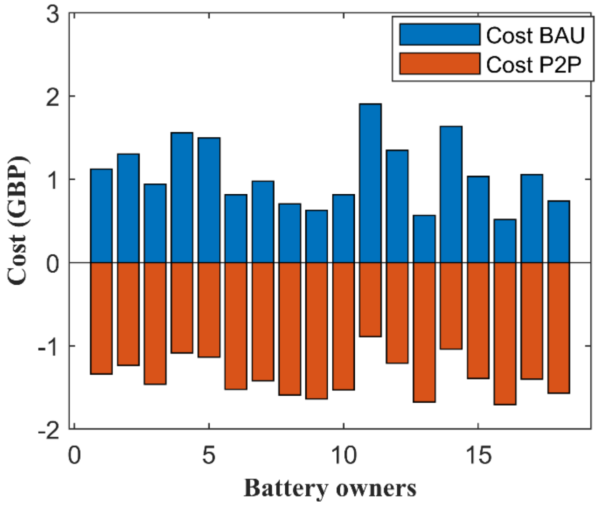

Figure 6.16: Daily cost comparison.

When the optimization process ends, the daily cost for P2P and BAU scenarios are calculated and compared using the equations (12) and (14). The cost comparison between the two scenarios is presented in Figure 6.16. The results show significant benefits gained for the BO, as it was estimated in the battery sizing process. The amount of daily benefits is essentially the difference between BAU and P2P cost (Figure 6.16). The obtained economic benefits are different for each user due to the daily load diversity, meaning that there is different amount of energy in each battery, available for P2P exchange.

6.6. FAULT SCENARIOS

For the examined fault scenarios described in methodology, we consider particular fault conditions, regarding the fault users, the fault time and the fault duration (Table 6.3). The fault conditions are chosen randomly as the model is generalized and provides results for any number of fault users, fault time and duration (within 1 day). Fault duration is considered the same for the first three scenarios, so that the results are comparable. For simplicity, it is assumed that faults in the FLT_{Batt} and FLT_{COM} scenarios, happen at the same time. In FLT_{Feed} and FLT_{TF} scenarios the fault duration is different (3 hours), as it is assumed that the DNO brings a portable diesel generator. Even if the fault is not fully restored, it is considered that the fault no longer exist for the users as their needs are covered by the portable generator.

Scenarios	Fault users	Fault time	Fault duration
Battery fault	1,12,13,79	09:40	09:40-22:00
COM fault	1,2,3,12	09:40	09:40-22:00
Feeder(s) fault	feeder 3	09:40	09:40-12:40
TF/supply fault	-	09:40	09:40-12:40

Table 6.3: Fault conditions for the considered scenarios.

6.7. ZONING RECONFIGURATION – USERS' PRIORITY ORDER

In Figure 6.9, the priority order of GC users is presented for the no fault scenario where the number of GC users is 62 since the BO users are 18 (the total number of MG users is 80). In the FLT_{Batt} scenario, the fault users (users 1, 12, 13, 79) become GC users after losing their batteries (Figure 6.16 – green colour). Thus, the number of GC users is increased to 66 and the number of BO users is reduced to 14. An interesting feature is the fact that the battery faults change the zone expansion order from "5-2-1-4-3" to "2-5-4-1-3" (Figure 6.9 and Figure 6.17). This happens, as the model re-runs the zoning process for the new conditions, without including the fault batteries. Thus, the energy mismatch for each feeder will be different, changing in the end the previous zoning expansion order.

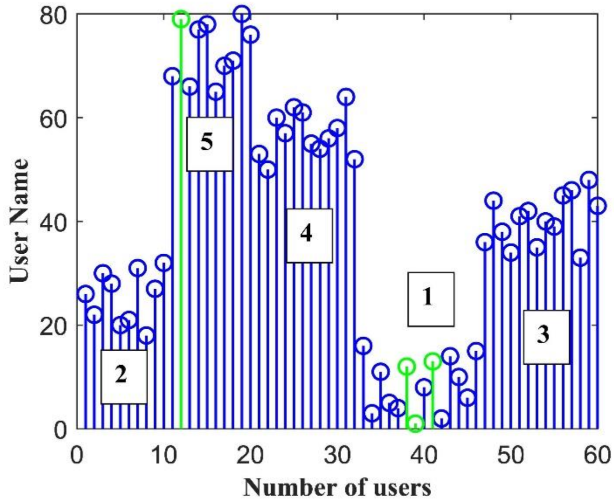

Figure 6.17: User priority order- FLT_{Batt} scenario.

In the FLT_{COM} scenario, the fault users (users 1, 2, 3, 12) are automatically excluded from the zone as they cannot communicate with the MG server (Figure 6.18 – red colour). In this case, the zone expansion order remains the same to the no fault scenario (Figure 6.9). This happens due to the fact that in the FLT_{COM} scenario, only one battery is disconnected, while in the FLT_{Batt} scenario four (batteries). As it was described in methodology section, BO users have greater impact on the energy mismatch than GC users, which explains why the impact of the particular communication faults is significantly less than the battery faults. If the communication faults occur in more BO users the zone expansion order can be also different.

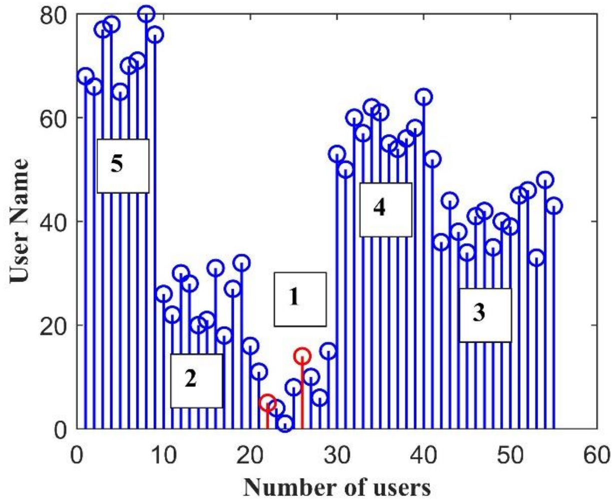

Figure 6.18: User priority order- FLT_{COM} scenario.

In Figure 6.19, the priority order of the GC users for the FLT_{Feed} scenario is presented, where the fault users that excluded from zone are marked with red colour. As the fault feeder is feeder 3, it excluded also from the expansion order which has only four feeders in this case (Figure 6.19). The zoning process runs only with the assets of these remaining feeders (Figure 6.19- blue colour).

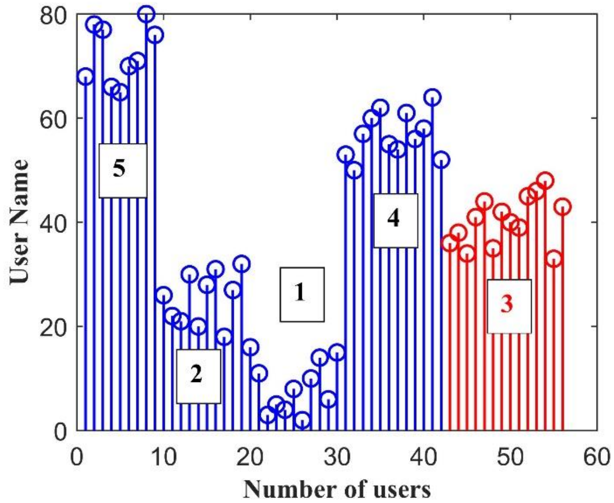

Figure 6.19: User priority order- FLT_{Feed} scenario.

In the FLT_{Batt} scenario, the number of users included in zone are significantly less after fault time, as the available batteries are 14 instead of 18 (Figure 6.20). This fact means that, less energy is available for P2P exchange. However, for some time steps after 16:00, the number of users is slightly higher, as the users' priority order is changed. Less energy available and different user order means that different amount of user will fulfill the energy and power requirements.

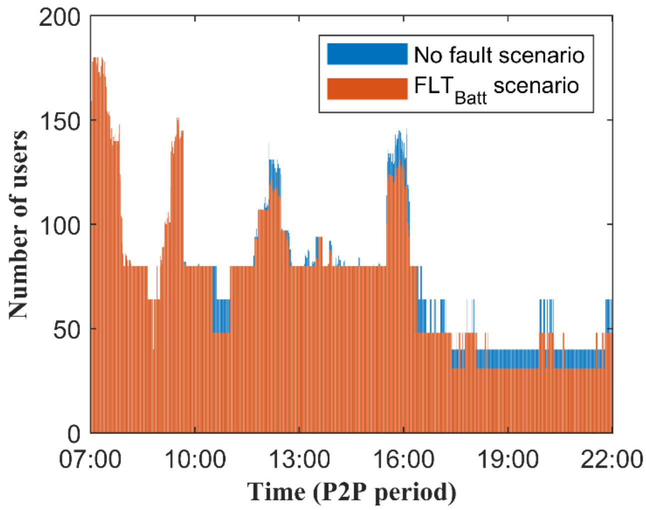

Figure 6.20: Number of users included in zone -FLT$_{Batt}$ scenario comparison.

In FLT$_{COM}$ scenario, the number of users included in zone are also less than the no fault scenario (Figure 6.21). However, the impact of the COM faults is less significant, in this case, than the battery fault scenario, as only one battery is out of order. The number of users included in zone is dominated by the total available energy in the batteries. Thus, impact on fault to P2P exchange is related to the number of batteries that are not available due to any kind of faults (electric/communication). In case the fault occurs to GC users, the impact is negligible for the zone expansion, as the fault GC users will be simply replaced by others that have no fault (according to the users' priority order).

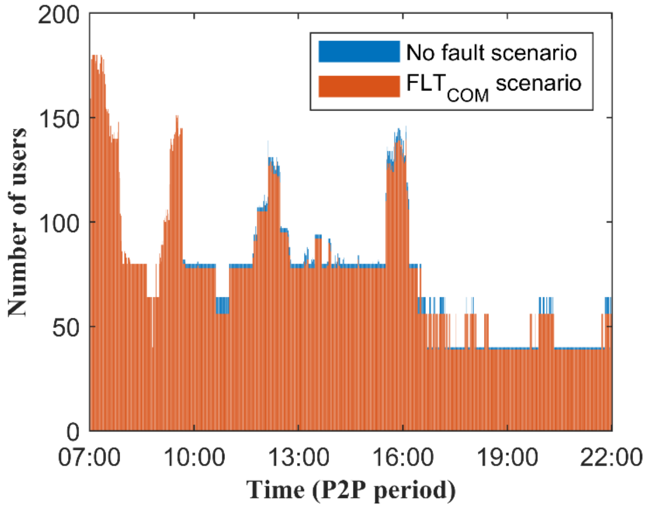

Figure 6.21: Number of users included in zone -FLT$_{COM}$ scenario comparison.

In FLT$_{Feed}$ scenario, feeder 3 is assumed to be disconnected due to electrical faults. Feeder 3 includes 2 BO and 14 GC users that are excluded from zone (Figure 6.22). An interesting feature is the fact that, the impact of fault is more significant to the number of users, compared to the battery fault scenario where 4 batteries are disconnected (the priority order remains the same). So, the crucial issue is not only how many batteries are disconnected, but how much of their energy is used for the P2P exchange. In this case, the available energy of the fault users is really high, and their individual load demand is low. In other words, a high amount of energy remains in the batteries and is not been used in the P2P exchange process.

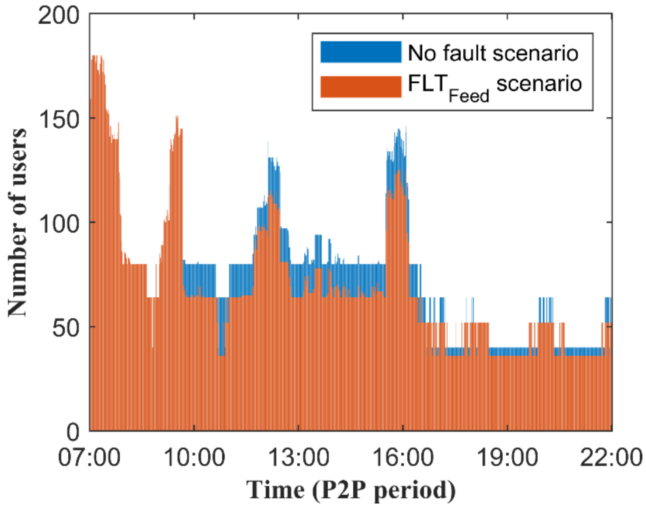

Figure 6.22: Number of users included in zone -FLT$_{Feed}$ scenario comparison.

6.8. BENEFITS GAINED

The average benefits that all BO users gain, for one day are presented in Figure 6.24 for three of the considered scenarios. Benefits of FLT_{TF} will be presented separately. Grid carbon intensity for the particular day is shown in Figure 6.23. The grid intensity data were obtained from [201]. As grid carbon intensity is lower during LT period (batteries charging), and higher during the HT period (P2P exchange period-batteries discarding), a reduction in carbon emissions will be achieved for that day.

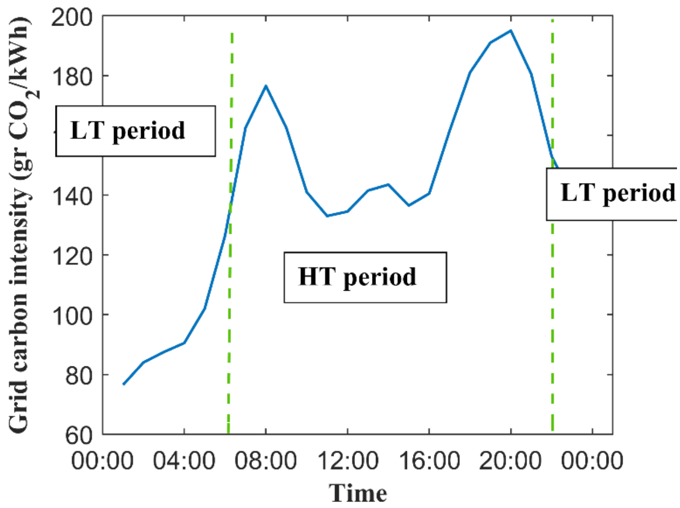

Figure 6.23: Grid carbon intensity for the particular case study.

Figure 6.24 shows the carbon emissions savings (in Kg) provided by the P2P exchange process. This valued is monetized based on carbon emissions policies, according to which a payment of £80 per ton of CO2 saved, is provided. This value is an average from the ones presented in [202]. This fact means that DNO and BO gain extra benefits for decarbonizing the grid. The total benefits gained are also shown in Figure 6.24 for the different examined scenarios. These benefits are the average value of all BO users, as there are small differences among them based on their individual characteristics. Benefits gained in the FLT_{COM} scenario are higher than battery fault scenario as two batteries are off instead of four. In feeder off scenario the average benefits are higher even than the no fault scenario, due to the compensation the DNO provides to the fault BO users (and in the fault GC users as well).

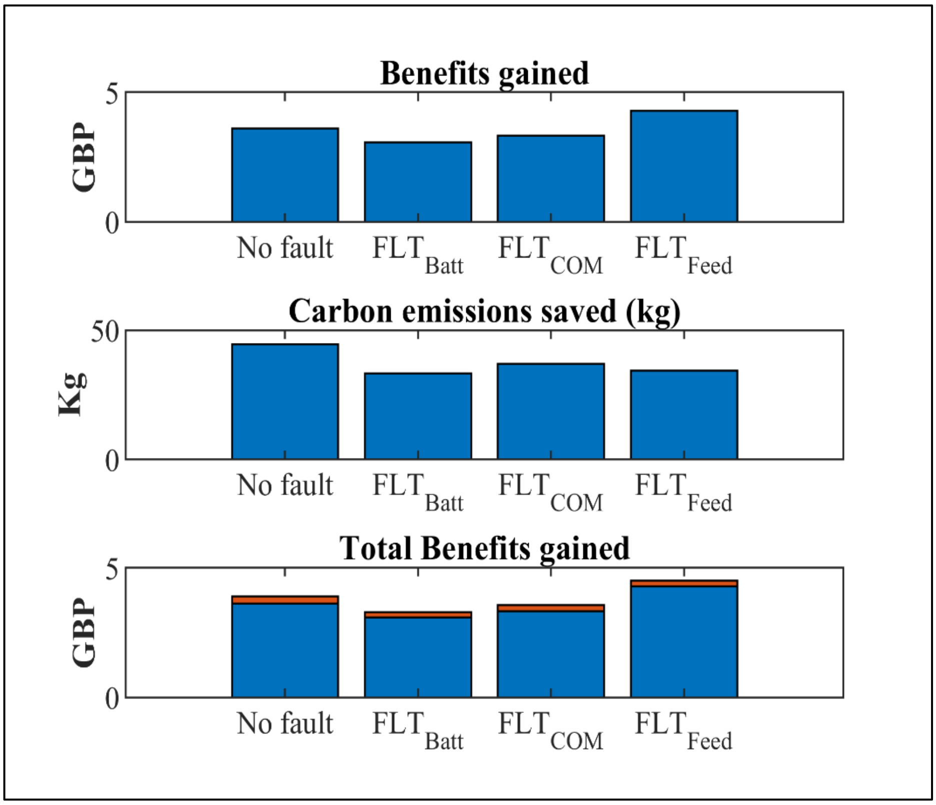

Figure 6.24: Average benefits gained for BO users, for different scenarios including carbon emissions reduction.

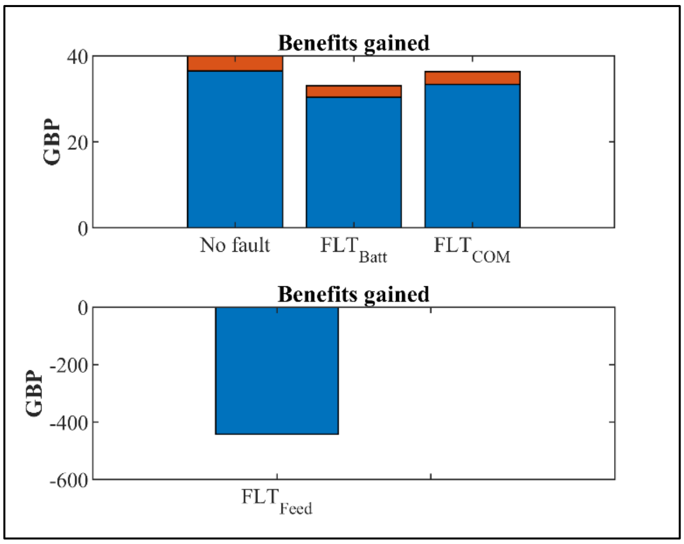

Figure 6.25: Benefits gained for the DNO.

The benefits DNO gains for the considered scenarios is presented in Figure 6.25. The benefits are provided as they participate by 50%, to the investment cost of the 18 batteries of the BO users. Thus, they share the benefits with them as explained in methodology section. For this reason, they follow the same pattern with the users' benefits, meaning that the highest benefits gained for the no fault scenario, followed by the FLT_{COM} and FLT_{Batt} scenarios. However, there is a significant difference for the FLT_{Feed} scenario as the DNO loses money (~400£) to provide compensation to the users that belong to the fault feeder.

6.9. FLT_{TF} SCENARIO

Since, the MG users are not responsible for the fault the users' priority order remains the same with the no fault scenario (Figure 6.9) regardless the fault time and duration. A in the batteries is used in after fault time, zone is automatically reconfigured in such a way to include all the MG users. As it was described in the methodology section, the available energy in batteries is used in order to cover the energy needs of the MG users. The load of users is covered only if the energy in the batteries is sufficient and the inverter power limits are not violated. In the opposite case, particular devices are curtailed based on a particular priority list. So, the devices curtailed according to a settled order, and the users of each curtailed device are also curtailed based on their user priority order. CREST model provides analytical demand data for each device making feasible the curtailment strategy.

After fault time, the zone is automatically reconfigured in order to include all the MG users. The difference between the FLT_{TF} scenario and the no fault scenario is presented in Figure 6.26. For some timesteps the number of users is more than the no fault scenario and for some other less. According to the implemented methodology, the available energy in the batteries is allocated in such a way in order to mitigate the disturbance within the MG.

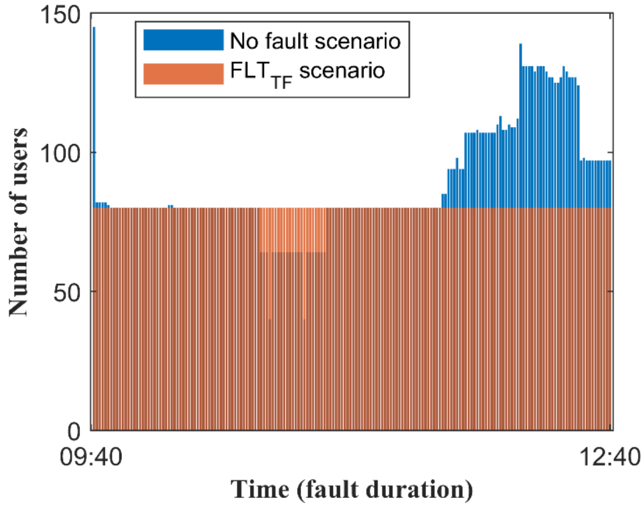

Figure 6.26: Number of users in Zone- FLT$_{TF}$ scenario.

In this case, the energy available in the batteries is sufficient to cover the energy needs of the MG users. However, the PL are violated for some time steps, thus some devices need to be curtailed (Figure 6.27). The priority order according to which device is curtailed, is exactly the opposite of the priority order they added in the zone. This fact means, that the first users included in zone will be the last disturbed for each device curtailed. After the device curtailment the power limits are not violated (Figure 6.27). The power covered from batteries is then used for the optimization process (Figure 6.27-yellow line).

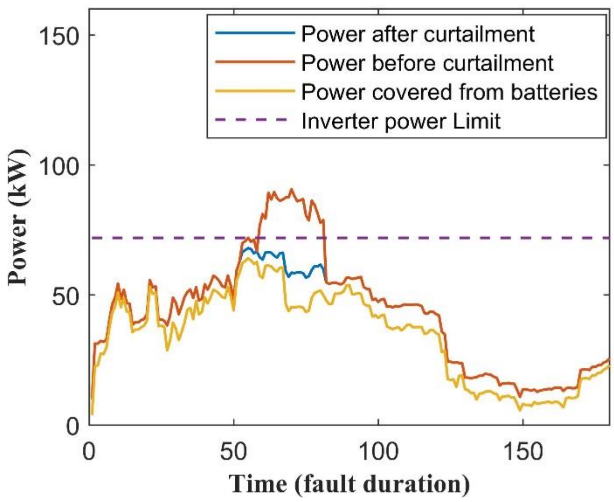

Figure 6.27: Power before, after curtailment – FLT$_{TF}$ scenario.

To highlight the impact of P2P exchange on system resilience, the obtained results are compared to another scenario named No P2P scenario. In this scenario, it is assumed that the system has exactly the same assets (PVs, batteries) yet P2P exchange is not enabled. The BO in this scenario use their batteries only to cover their individual energy needs.

The resilience of the system is measured by using a particular resilience metric, called Resilience (%). This metric quantifies resilience of the system based on the percentage of load that remains connected after fault [140]. The Resilience (%) during fault, for the two considered scenarios is presented in Figure 6.28. P2P exchange process improves significantly system resilience, in comparison to the No P2P scenario. As it is shown in Figure 6.28, resilience in No P2P scenario does not exceed 40%, and reaches at a minimum value of 6%. In contrast, in the P2P scenario, most of the fault period the users are not disturbed as resilience remains 100%. However, for the time steps the PL is violated the resilience drops a little, due to device curtailment, but it does not drop below 60% (Figure 6.28).

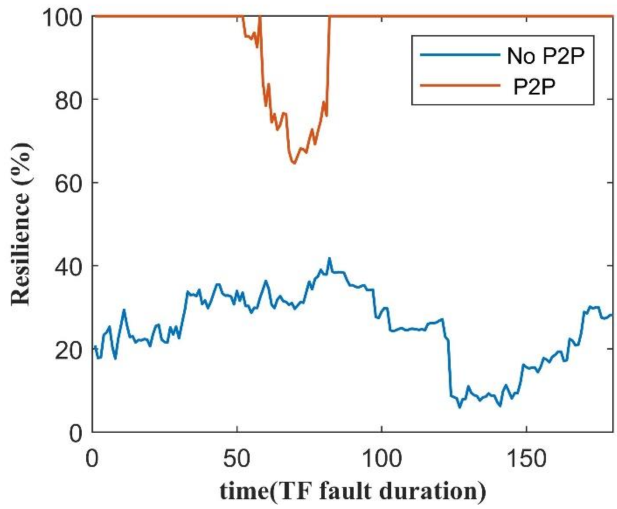

Figure 6.28: Resilience comparison - FLT$_{TF}$ scenario.

The average resilience is tremendously higher in the P2P exchange scenarios as it reaches at levels of 96.39 %, while in the no P2P is only 25.07 % (Figure 6.29). This fact proves that P2P exchange enhances significantly the resilience of the system, as it is compared with a scenario with the same assets but with no P2P exchange.

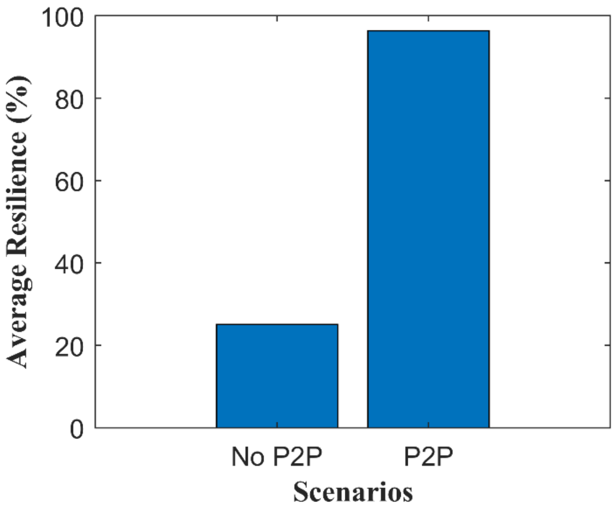

Figure 6.29: Comparison of average resilience between P2P and No P2P scenarios, for FLT_{TF} scenario.

Users that are low in users' priority order means that these users will be curtailed first. For this case, users of the feeders 2, 4 and 5 remain undisturbed while users that belong to feeders 3 and 1 experience a device curtailment. Figure 6.30, shows an indicative graph of the device curtailemnt for a particular user (User 43), which occurs during the period of the disturbance, as the power limits are violated (Figure 6.27).

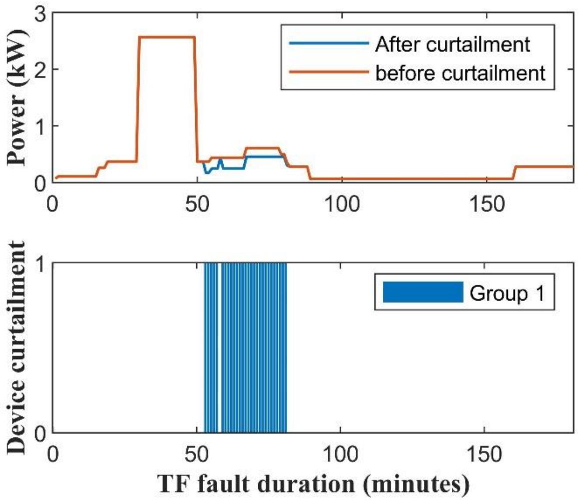

Figure 6.30: User 43 – Power and device curtailment.

User 43 belongs to feeder 3 which is low in users' priority order (Figure 6.9). In case of User 43 only the Group 1 devices are curtailed, which is first in the appliance priority list (Table 5.2). This happens as the total amount of load curtailment that is required is small (Figure 6.25), thus no more devices need to be disturbed.

The average level of distrurbance of all users, the duration of disturbance and the number of users disturbed, with and without P2P exchange, are presented in Figure 6.31. The boxplot shows these metrics for the minutes the fault lasts (180 minutes). The duration of disturbance is trendously lower in the P2P scenario compared to the no P2P scenario (mean value ~5minutes and ~150 minutes respectively). The average level of disturbance is around 10% with only a few users higher, at most reaching 60%. In contrast, the average level of disturbance in the no P2P scenario fluctuates from 10 up to 100%.

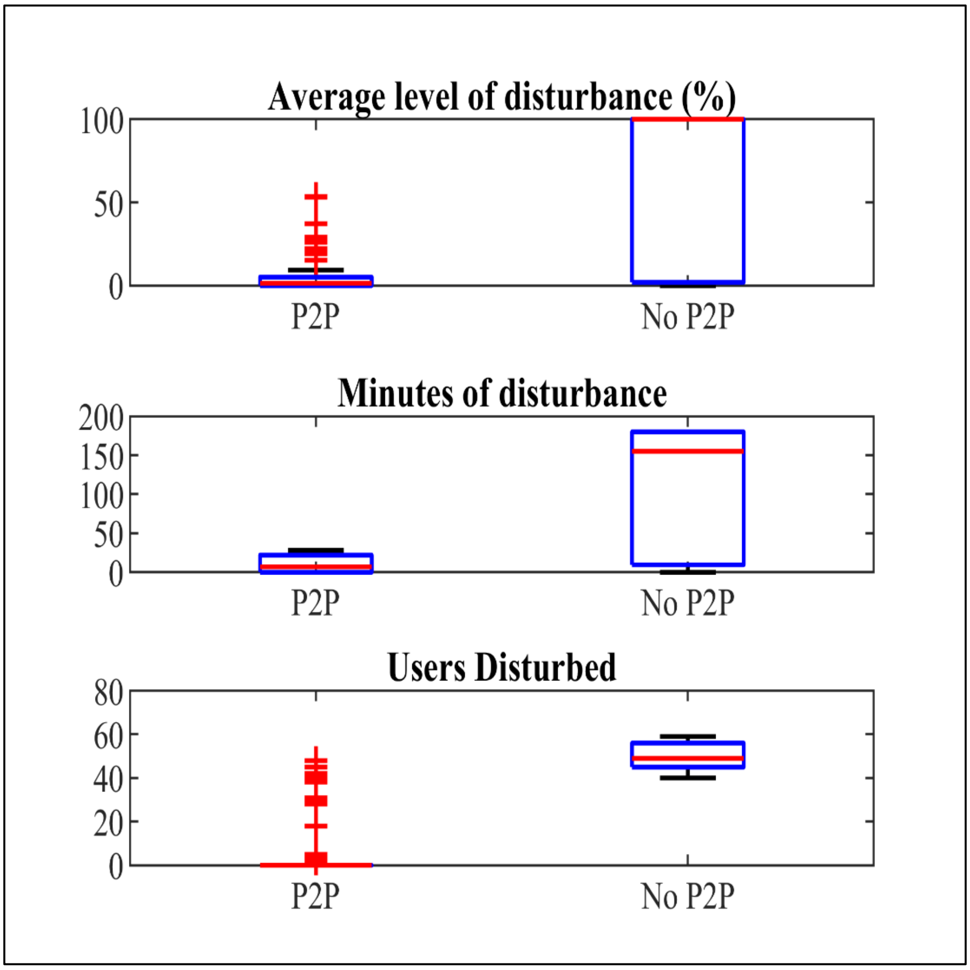

Figure 6.31: Resilience metrics comparison - FLT_{TF} scenario.

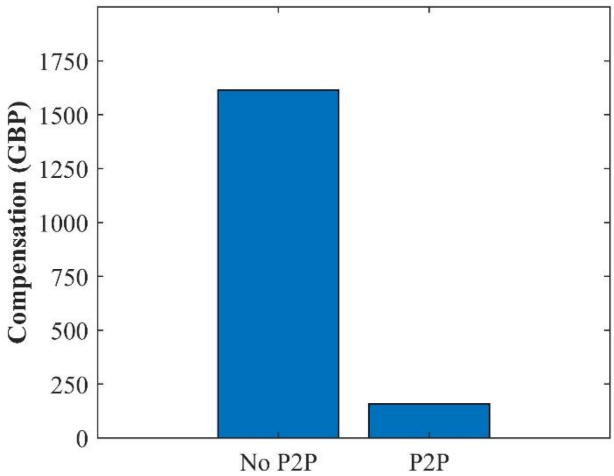

Figure 6.32: DNO compensation to the user's comparison.

In case where some of the users are disturbed the DNO is obliged to compensate them based on the loss of load and the duration of disturbance [144], [191]. The results in Figure 6.32 show that in P2P scenario the compensation money is below 250 £, while in the no P2P scenario is around 5 times higher (more than 1,500 £). The money saved by the DNO revelas the incentives of DNOs to participate in the P2P exchange scheme by participating in the investment cost and gain benefits.

To generalize the impact of P2P exchange to resilience enhancement, we examine a wide range of fault scenarios. More precisely, we examine 50 days with 48 different fault scenarios within each day (fault could occur every 30 minutes). This means that 2,400 scenarios are totally examined for this case study.

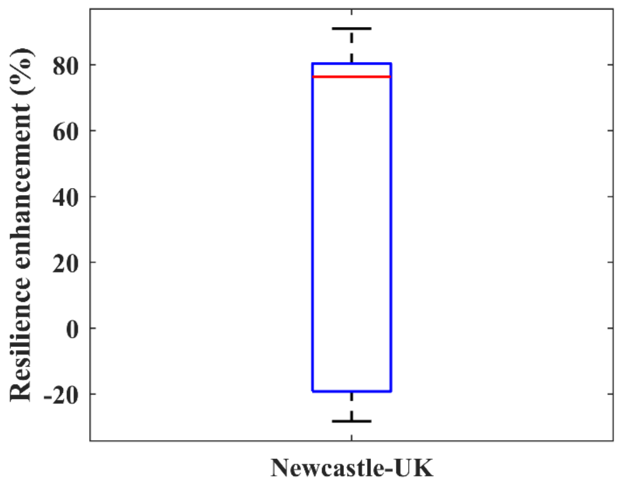

Figure 6.33: Resilience enhancement boxplot for the examined fault case.

The results are represented with a boxplot in Figure 6.33. In most case the resilience is enhanced, as in most cases it is positive. The range of enhancement is wide fluctuating between 0-80 %, while the median value is 78%. In a few cases, the resilience enhancement drops below zero which practically means that the resilience of the system is deteriorated. This happens as in some fault scenarios the fault occurs when the stored energy of the batteries is depleted. It is assumed that the faults are completely unexpected and have the same probability to happen. Thus, in some scenarios where the fault happens late during the day, the energy in the batteries has been depleted as the P2P exchange starts at 07:00 in the morning. Since the faults are considered as completely unexpected, P2P exchange process continues as usual until fault occurs. In reality, some days with extreme weather phenomena, there is higher probability of losing the TF or the supply. Thus, during these days, the P2P exchange EMS could be modified to operate in safe mode, so they save more energy by discharging less energy during P2P process. In this way, more energy is saved in the batteries in case of fault.

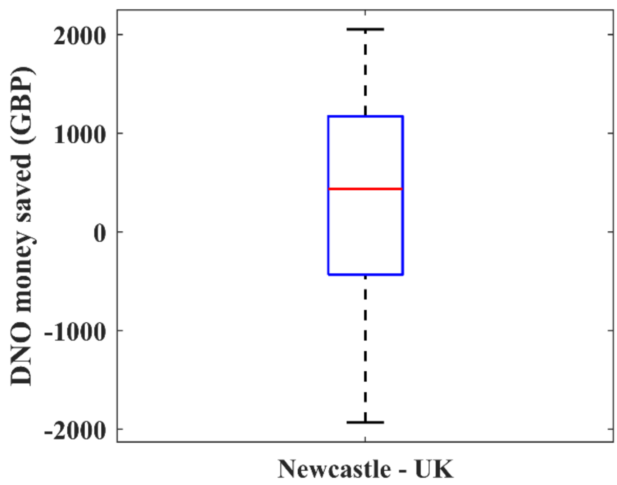

Figure 6.34: DNO money saved – boxplot for the examined fault cases.

When the resilience enhancement is positive, it practically means that the DNO saves money from compensation. The DNO money saved is presented in Figure 6.34. The money DNO saved fluctuates between 0-1100£. For the few cases, that the resilience is deteriorated (negative resilience enhancement) the money than the DNO money saved could reach up to 500£ (Figure 6.34).

6.10. MORE RESULTS

The simulation model is generalized and can simulate any case of the presented scenarios if the required input parameters are given. This means that thousands of scenarios can be tested with different fault times, different fault durations and different fault users. In this work only four representative days are used with certain load demand and PV generation obtained by CREST model. More, days can be tested if the required data are provided. We choose to provide some indicative results that are interesting and providing insights about the usability of this work. Some extra results are presented in this section to fulfill this purpose.

In case of battery, communication or feeder faults the results will be similar to the presented case. The main difference will be the different priority order of the users and the total number of users that will be included in the zone, depending on the amount and the type of the fault users. However, the logic remains the same.

A more interesting case is TF fault scenario, where the different fault time will have a different impact on resilience and load curtailment strategy, even if it is referred to the same day (same load and PV data). A fault that occurs at a different time will have different results, as the amount of the available energy for P2P will be different. For this reason, three more scenarios are presented where fault time occurs at 3PM and 5PM and 3AM. The impact on system resilience will be presented for the considered scenarios. Power before/after curtailment, including the power covered by the batteries are shown in Figure 6.35-Figure 6.36.

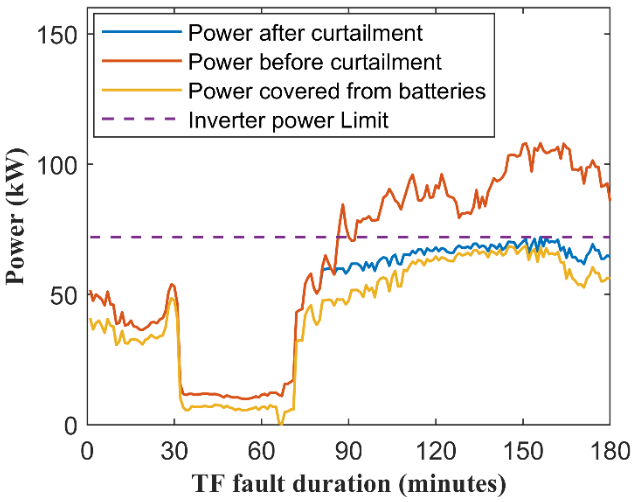

Figure 6.35: Power before/ after curtailment and power covered by the batteries for the 3PM scenario.

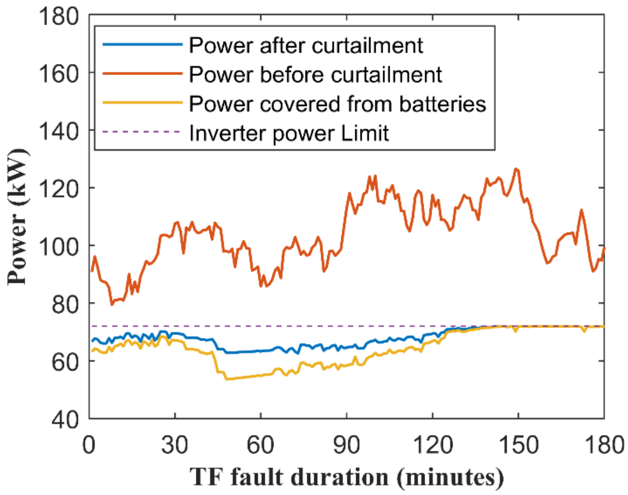

Figure 6.36: Power before/ after curtailment and power covered by the batteries for the 5PM scenario.

In 3PM fault scenario, total required power is exceeded for almost half of the duration period (Figure 6.35). This means, that more load need to be curtailed from users' devices compared to the FLT_{TF} scenario where the power limits were slightly exceeded only for around 30 minutes (Figure 6.27). In the 5PM fault scenario, the power limits are exceeded significantly during the whole fault duration period (Figure 6.36). In this case, the amount of load curtailment will be higher and longer than the 3PM fault scenario. It is obvious that, the later the fault occurs the higher and longer the device curtailment will be. This happens, as the available energy is depleted as the time passes due to P2P exchange process. Less energy available during fault, more device curtailment will be occurred. The device curtailment for User 43, is showed in Figure 6.37-Figure 6.38. It is obvious that in 3PM fault scenario more devices are curtailed and for longer time compared to the FLT_{TF} scenario. The duration and the number of devices curtailed is even higher for the 5PM scenario.

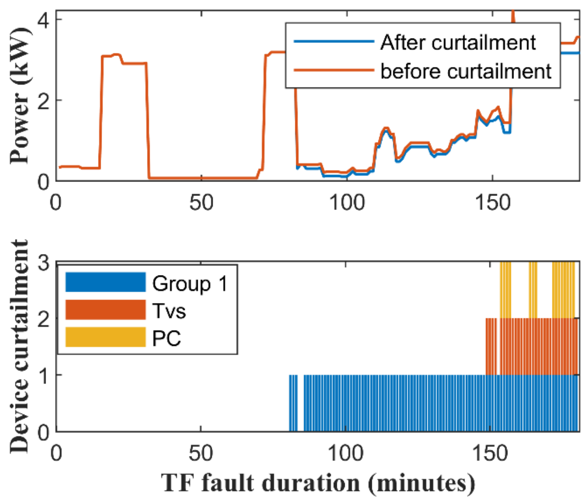

Figure 6.37: Device curtailment of User 43, 3PM fault scenario.

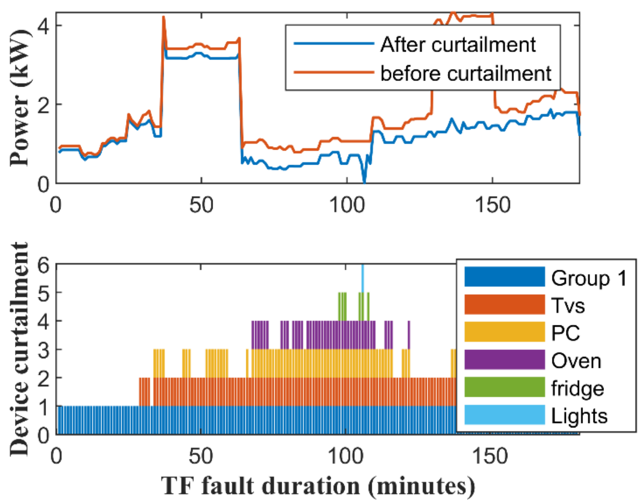

Figure 6.38: Device curtailment of User 43, 5PM fault scenario.

While in the FLT_{TF} scenario the users of feeders 2,4,5 were undisturbed, in the 3PM scenario even users from feeder 4 will experience some disturbance, yet lower and shorter than user 43. The device curtailment for User 68 is presented in Figure 6.39. In 5PM scenario users even from feeder 2 which is first in priority are disturbed. Figure 6.40 presents the device curtailment of User 32 for the 5PM scenario. One less device is curtailed compared to User 43 and for shorter time (Figure 6.38, Figure 6.40). However, in both examined fault scenarios, the resilience of the system is significantly better than No P2P scenario (Figure 6.41-Figure 6.42).

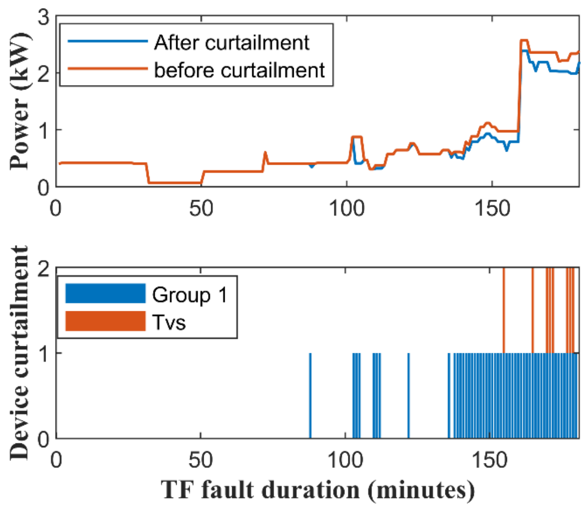

Figure 6.39: Device curtailment for User 68 – 3PM fault scenario.

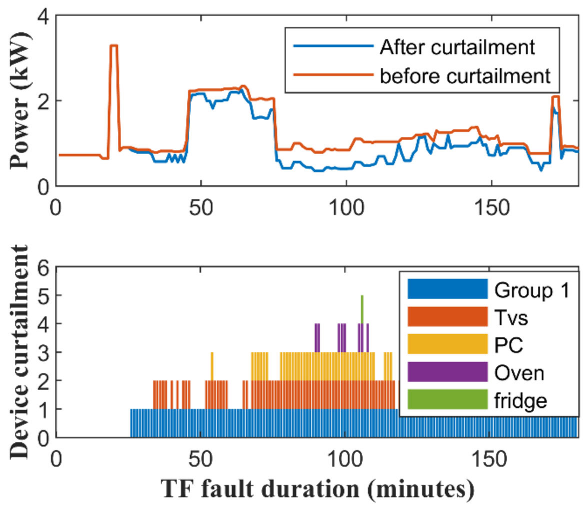

Figure 6.40: Device curtailment for User 32 – 5PM fault scenario.

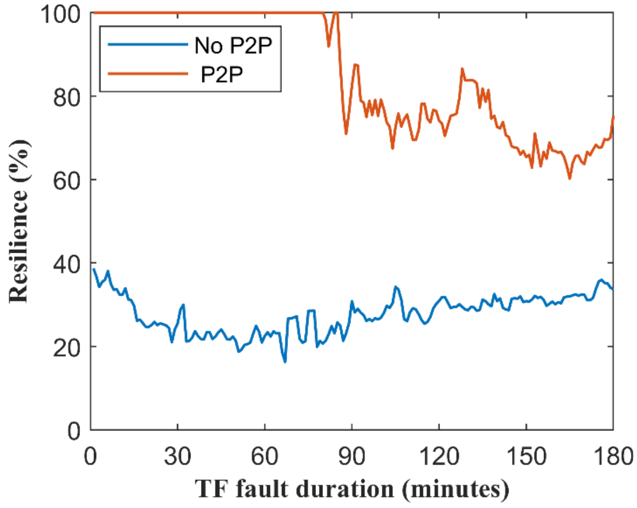

Figure 6.41:Resilience comparison between P2P and no P2P case, for 3PM fault scenario.

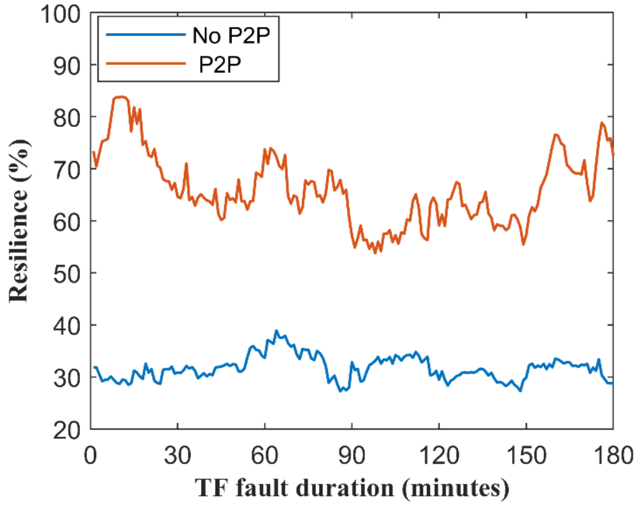

Figure 6.42: Resilience comparison between P2P and no P2P case, for 5PM fault scenario.

The fault can also occur during the night before the beginning of P2P exchange period. An extra scenario where fault occurs at 3AM is examined. During the night under normal conditions the batteries are charged. However, the charging process is unexpectedly interrupted by the fault. In this case, less energy is going to be available in the batteries since they have not fully charged. Nevertheless, the load demand is extremely low during this period, meaning that the partially charged batteries are still capable of covering the users' demand for the same fault duration (3hrs). The power discharged by the batteries is very low relatively to the maximum inverter limit (Figure 6.43). For this reason, the resilience is not dropped for the P2P exchange period, meaning that no device curtailment is needed (Figure 6.43). The results also show, the significant advantage that P2P exchange offers compared to the no P2P scenario (Figure 6.43).

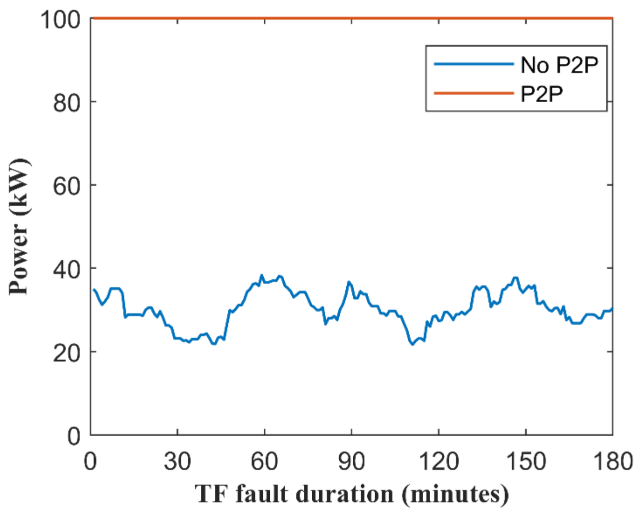

Figure 6.43:Power covered by the batteries for the 3AM fault scenario.

6.11. CHAPTER SUMMARY

In this chapter the practicality of the developed methodology was tested. Suitable input parameters were provided and all the described in the methodology chapter were followed. A MG in Newcastle, UK with 80 users and 5 parallel feeders was investigated. The users are equally distributed among the feeders. The battery sizing process was analytically described providing relevant graphs and explaining how the inverter and TF limits affect the process. For this case, P2P exchange is performed by 18 batteries (18 BO users). The rest of the MG users are GC users. 100 users outside MG was considered for this case. The user's priority order and the zone expansion order were presented for each examined scenario. Moreover, the number of users included in zone were also presented and compared with the no fault scenario. The benefits gained for local DNO and BO users were analytically explained and discussed, including DNO's compensation and carbon emissions reduction. The improvement on system resilience was highlighted for the FLT_{TF} scenario, providing relevant graphs regarding particular resilient metrics and users' device curtailment. The overall case study reveals the improvement in the economic and efficient operation of the MG, due to the implemented methodology.

Chapter 7. Different ToU tariff schemes and Locations

In this chapter the developed methodology will be applied to different locations and different ToU tariff schemes. Initially, the P2P framework is applied to different locations under the same ToU tariff scheme. The differences on system resilience will be highlighted due to the different characteristics of each location. Subsequently, the developed methodology is implemented for different locations and different ToU tariff schemes, seeking for the best ToU tariff for certain objectives. In this way the usefulness of the method will be revealed, as a general tool that could be applied to any location and provide insights about the potential benefits that can be gained for the stakeholders.

7.1. Comparison of resilience different locations, for the same ToU tariff scheme

The suggested methodology is applied also for three different locations, using the same ToU tariff scheme described in the case study section (Table 6.1). Locations with different load demand and weather conditions are selected (Athens, New Delhi and New Work). CREST model provides PV generation data for different locations, providing the longitude and latitude of each location. However, load profiles are not available. However, data about the average differences in load demand for the different countries are available. Thus, the load demand data were generated by adjusting the available data from UK [192], [203]. The existing load demand data for UK were modified by using suitable multipliers to represent the different locations. The multipliers were set based on the differences in average load demand for different countries presented in [204]. In this way, the required data were generated and used in the model. The multipliers used for each location are presented in the table below, UK data were used as a baseline.

Location	Load multiplier
Athens	1.14
New Delhi	0.4
New York	2.87

Table 7.1: Load multiplier selected for the different locations.

The rest of the input key parameters remain the same as the case study in Newcastle, UK. The suggested methodology described above is applied for the different locations, so the number of batteries for each case along with their size is defined (Table 7.2). The different load demand and PV generation data lead to different number of batteries and sizes, despite the same ToU tariff scheme. More analytically, in Athens there are 31 batteries, in New Delhi 21 and in New York 32, while in Newcastle, there are only 18 (Table 7.2). However, the differences of the average battery size are slightly different (Table 7.2). This fact mainly happens due to the same inverter and TF power limits that are considered for all cases.

Location	Number of batteries	Average battery size (kWh)	Total installed battery capacity (kWh)	Total Net energy consumption (kWh)
Newcastle-UK	18	32	576	365.15
Athens-Greece	31	29	899	170.09
New Delhi-India	21	30	651	-174.83
New York-USA	32	33	1056	239.28

Table 7.2: Number of batteries and Average battery size for different locations.

The resilience enhancement of the system is investigated comparing the P2P scenario with the No P2P scenario for the same ToU tariff scheme presented in case study section. The improvement of resilience is examined by simulating 2400 scenarios for each location. Each simulation represents a particular fault scenario, where the TF/Power supply is disabled. 48 fault scenarios are examined for each day, considering that the fault occurs in each 30- minute period. 50 different days are examined for each location ($48 \times 50 = 2400$ fault scenarios).

The impact on resilience is dependent mainly on two factors: a) Total installed battery capacity and b) Total net energy consumption of the system during P2P period. The total net energy consumption is calculated for the same day, for all locations. The higher the installed capacity is and the lower the net energy consumption is, the higher the resilience enhancement will be. This happens, as it is more likely the available stored energy to cover the energy needs of the users, mitigating their disturbance.

In Table 7.2, the total installed battery capacity and the total net energy consumption are presented for the examined locations. The differences in these values are depicted in the obtained results shown in Figure 7.1. New Delhi has the higher resilience enhancement, with a median value of 80 %, and a minimum value of 60%, as it has the lowest total net energy consumption and considerably significant installed battery capacity (Table 7.2). TF fault the system can better manage the disturbance. Athens follows, as it has similar characteristics with New Delhi, with a median of 68% and the majority of cases are above 60% (Figure 7.1). There are also a few cases that the resilience enhancement drops significantly and reaches for very few cases to negative values. Negative values mean that the No P2P scenario offers higher resilience, as the energy in the batteries has been depleted in the P2P scenario. New York has the highest installed battery capacity but also the highest total net energy consumption (Table 7.2). This fact leads to Resilience improvement between 20% - 60% for the majority of scenarios, with a median of 58% (Figure 7.1). Newcastle has the lowest installed capacity and the highest total energy consumption. For this reason, there is a high fluctuation in the resilience enhancement, for the majority of cases with a range of -20% - 80% (Figure 7.1).

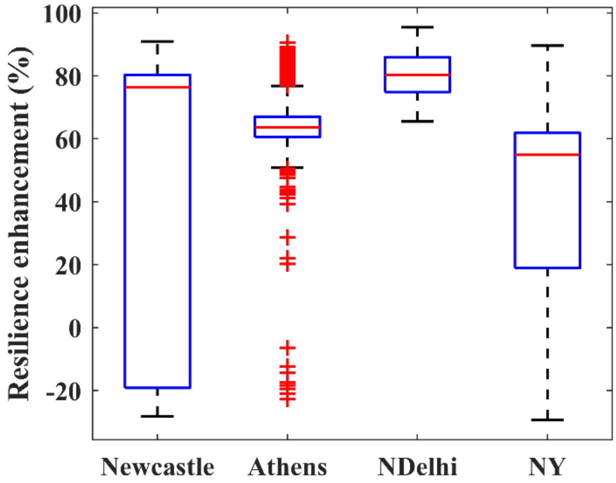

Figure 7.1: Resilience enhancement (%) for different locations.

DNO money saved for each location is shown in Figure 7.2. The results follow the same pattern with the resilience enhancement presented above. For the cases where the resilience enhancement is positive the DNO saves money, while in the opposite case they lose as the resilience is deteriorated. In most cases, the DNO saves money as the resilience is usually enhanced.

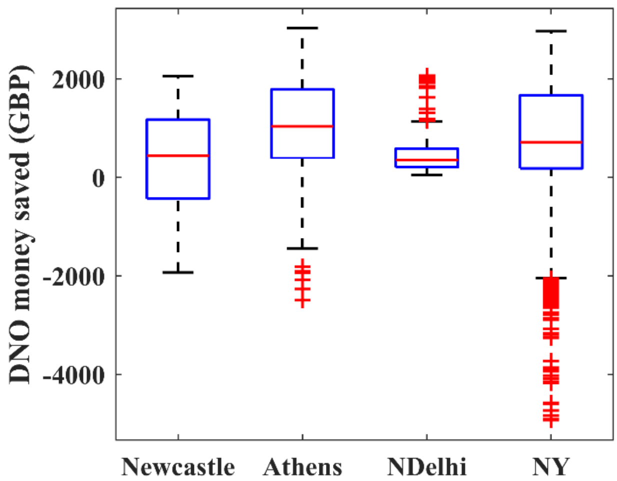

Figure 7.2: DNO money saved for different locations for the same ToU tariff scheme.

7.2. DIFFERENT LOCATIONS AND DIFFERENT TOU TARIFF SCHEMES

Different ToU tariff schemes are also examined for the selected locations (Table 7.3). The expected benefits for each case provide insights about the design of ToU tariff schemes that will be suitable for each location. The examination provides useful information to DNOs and MG users in order to make decisions about which ToU tariff design is the best for certain criteria. Two factors are changed in each scheme: the HT duration and the levels of high/low tariffs. Six different HT period schemes are examined, giving a particular number to each of them in order to distinguish them (Table 7.3). Six low/high tariffs schemes were also examined, and the top 3 of them are presented in this section (2-25p/kWh 6-30p/kWh and 6-35p/kWh) (Table 7.3).

<table>
<tr><th colspan="3">High/Low tariff schemes</th></tr>
<tr><th>Tariff (p/kWh)</th><th colspan="2">colour</th></tr>
<tr><td>2-25</td><td colspan="2">‘red’</td></tr>
<tr><td>6-30</td><td colspan="2">‘green’</td></tr>
<tr><td>6-35</td><td colspan="2">‘blue’</td></tr>
<tr><th colspan="3">HT period schemes</th></tr>
<tr><th>Number</th><th>HT duration</th><th>Symbol</th></tr>
<tr><td>1</td><td>07:00-22:00</td><td>‘x’</td></tr>
<tr><td>2</td><td>10:00-22:00</td><td>‘□’</td></tr>
<tr><td>3</td><td>12:00-22:00</td><td>‘▽’</td></tr>
<tr><td>4</td><td>07:00-20:00</td><td>‘*’</td></tr>
<tr><td>5</td><td>07:00-18:00</td><td>‘◊’</td></tr>
<tr><td>6</td><td>07:00-16:00</td><td>‘o’</td></tr>
</table>

Table 7.3: Different ToU tariff schemes examined.

Four different objectives were selected under which the ToU tariff schemes are tested. Annual total benefits gained, annual carbon emissions reduction, average resilience enhancement and DNO money saved. The selected objectives were split in two groups and different graphs were created for each of them. The first group includes the annual total benefits gained and the annual carbon emissions reduction, while the second one the remaining two.

The created graphs for the first group of objectives is shown in Figure 7.3-Figure 7.6, for four different locations. The objectives are the annual total benefits gained (in GBP) and the annual carbon emissions savings (in tons). For Athens and New Delhi the best solution for both objectives is the 6-30p/kWh tariff with HT duration 1 (Figure 7.3-22). For New York location, the best solution for the annual benefits objective is the 6-30p/kWh tariff with HT duration 3, while for the annual carbon emissions savings the same tariff with HT duration 1 (Figure 7.5). For Newcastle location, the best solution for the annual benefits gained is the 6-30p/kWh tariff with HT duration 3, while for the annual carbon emissions savings the 6-35p/kWh tariff with HT duration 1 (Figure 7.6). For some cases, the gained benefits and carbon savings are zero meaning that the developed methodology is not a profitable option for that set of parameters (Figure 7.3-Figure 7.6). For example, in Athens location the 2-25p/kWh tariff with HT duration 6 has no benefits for the stakeholders (Figure 7.3).

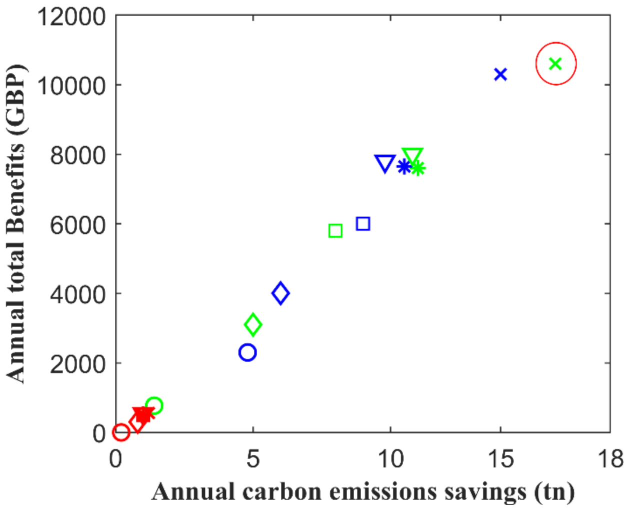

Figure 7.3: Annual total benefits and carbon emissions savings-location, Athens.

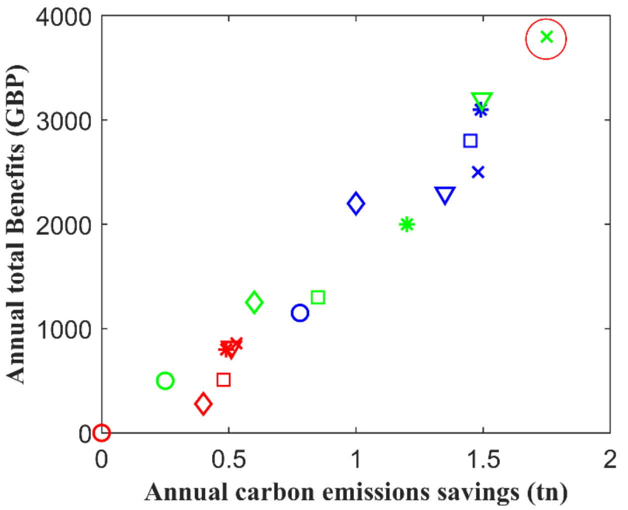

Figure 7.4: Annual total benefits and carbon emissions savings-location, New Delhi.

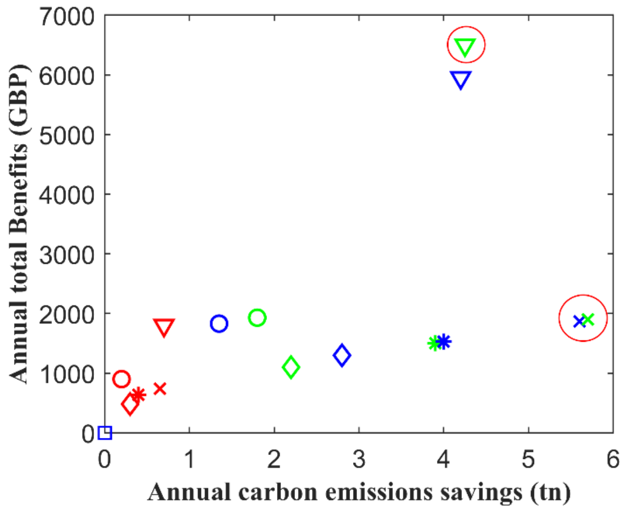

Figure 7.5: Annual total benefits and carbon emissions savings-location, New York.

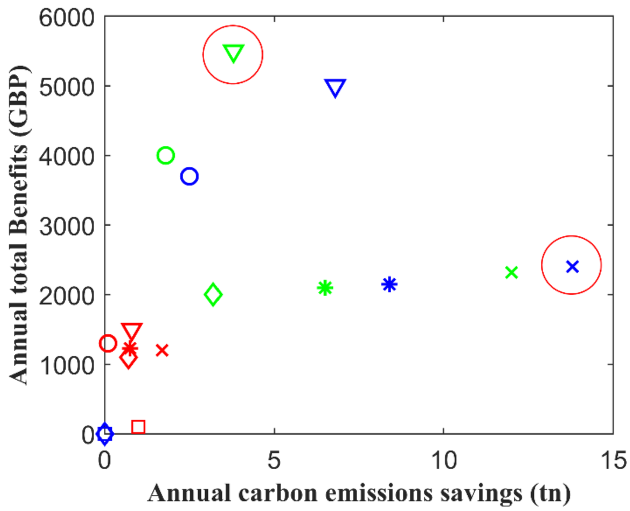

Figure 7.6: Annual total benefits and carbon emissions savings-location, Newcastle.

Similar graphs are also examined for the second group of objectives: average resilience enhancement and DNO money saved (Figure 7.7-Figure 7.10). These two objectives are related to the TF fault scenario and are dominated only from the HT duration. Thus, there are only 6 cases for each location. The obtained results show that for all locations the best solution is the HT duration 3.

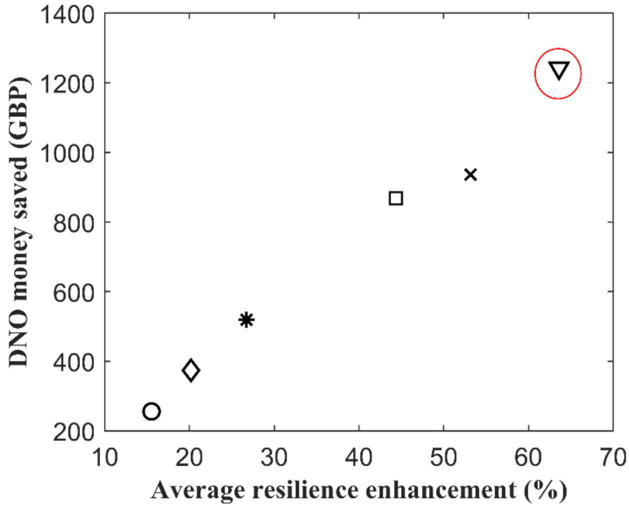

Figure 7.7: Resilience enhancement and DNO money saved, location Athens.

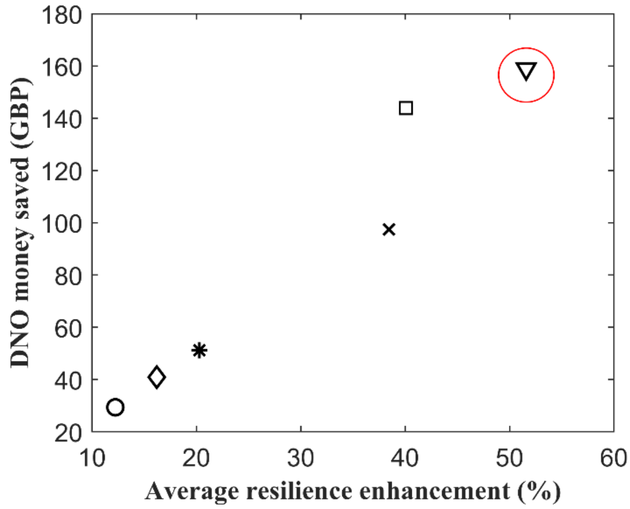

Figure 7.8: Resilience enhancement and DNO money saved, location New Delhi.

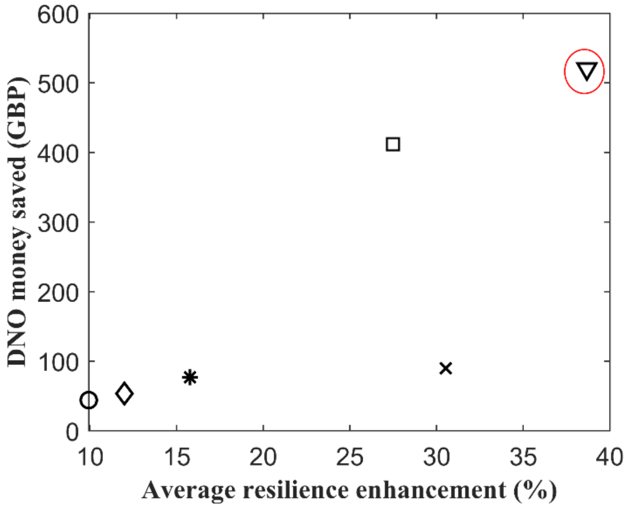

Figure 7.9: Resilience enhancement and DNO money saved, location New York.

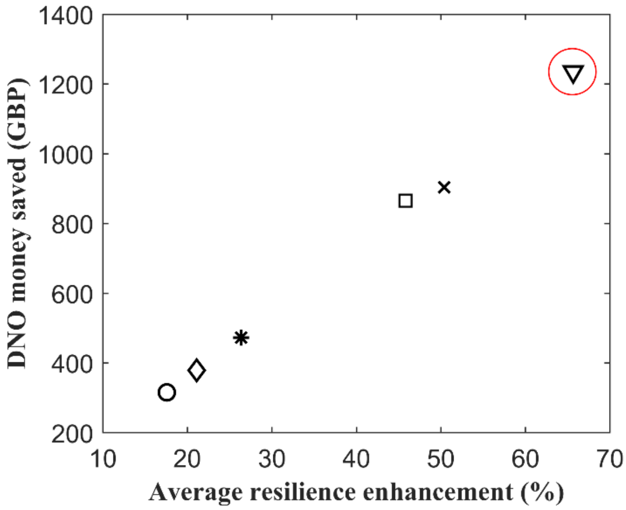

Figure 7.10: Resilience enhancement and DNO money saved, location Newcastle.

The graphs show that the developed methodology can be applied to any location providing different results according to the characteristics of each location. The examination provides insights to the stakeholders about the desired ToU tariff scheme according to their preferences (annual benefits, carbon savings etc.). More scenarios can be tested by changing also other input parameters such as battery price and inverter power limits. The results also showed that in some cases the implemented methodology will not provide any economic benefits to the stakeholders (Figure 7.3-Figure 7.6), meaning that the users have no incentives to participate.

7.3. CHAPTER SUMMARY

In this chapter, the implemented methodology was tested for different locations and different ToU tariffs. Different locations were tested under the same ToU tariff and compared. The results showed important differences regarding resilience enhancement due to the particular characteristics of each location. More tests were conducted for the same locations for different ToU tariff schemes, seeking for the best tariff scheme for particular objectives. Four different objectives were selected and categorized in two groups. Different graphs were created for each of them. The results showed that the developed framework is a useful generalized tool that could provide insights about the potential benefits gained for any location.

Chapter 8. Optimum Battery discharging and one-by-one discharging comparison

In the presented methodology an optimum battery discharging was introduced, where all the batteries were jointly discharged. In this chapter, the optimum discharging, will be compared to a random one-by-one discharging scheme to investigate which discharging strategy causes lower battery capacity loss. The data from Newcastle location will be used.

8.1. OPTIMUM BATTERY DISCHARGING AND ONE-BY-ONE DISCHARGING COMPARISON

Different discharging strategy will have different impact on battery cycle loss, as the major factors that affect cycle loss (C-rate and DoD) will be different. Since the same batteries are compared, the battery capacity will be the same, which practically means that the C-rate difference is practically the current difference (C-rate=Current/battery capacity). For simplicity, it is assumed that the battery temperature has the same behavior in both schemes. In the one-by-one discharging case, it is assumed that P2P is also enabled yet it happens only by pairing individual batteries with individual customers. As there are numerous ways of pairing the individual batteries, 100 random discharging scenarios are examined for each of them. In order the results to be comparable, the total energy discharged in the one-by-one case is the same with the energy discharged in the optimization case (for each battery). Four different days are examined, based on the four representative days, one for each season. By principle, when a group of batteries is jointly discharged to cover the aggregated load demand of a group of users, the discharging current will be smoother than one-by-one discharging as the joint discharging takes advantage of load diversity. In this way, extreme high currents are avoided. The aforementioned strategy is applied, to the Athens location for a particular ToU tariff scheme. The same strategy can be applied to any other case. The cycle loss comparison is only affected by the duration of the P2P exchange regardless the offered tariffs. The ToU tariff where the P2P exchange duration is 07:00-22:00 is selected. The number of BO for this case is 18. Thus, the optimum discharging of 18 batteries is compared with a 100 one-by-one discharging scenarios for the same batteries. A comparison of the two discharging strategies is presented in the table below:

Discharging strategy	1-by-1 discharging	Optimum discharging
Overview	Each battery is randomly paired with a GC users, and is discharged individually to cover their energy needs.	All batteries are optimum discharged together covering the same amount of energy with the 1-by-1 discharging strategy.
Battery Capacity (Ah)	45Ah	45Ah
SoC window (%)	10% -90 %	10% -90 %
Number of batteries	18	18
Amount of Energy discharged (kWh)	same	same
Number of representative days	4	4
Location	Athens	Athens
P2P duration	07:00-22:00	07:00-22:00

Table 8.1: Comparison of the 1-by-1 discharging with the optimum battery discharging.

The inverter maximum power is 3kW and the maximum current is 4.67 Amps. Two indicative discharging currents of one-by-one discharging and optimum discharging are shown for spring representative day, for the same battery (Figure 8.1). It is obvious that in one-by-one discharging the current increases suddenly reaching the maximum value multiple times, while in the optimum discharging the current follows a smooth fluctuation that does not exceed the 3.5 Amps. From the discharging currents, duration curves are created for each battery and for each representative day. For simplicity, the results of one battery are selected and presented (Battery 1). Similar results were obtained for the rest of the batteries.

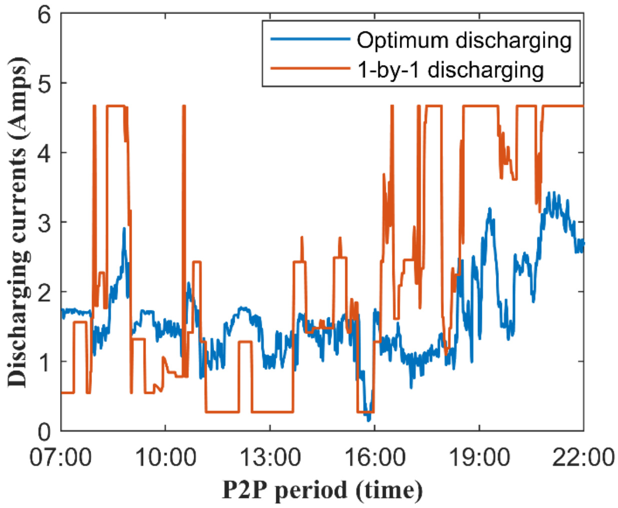

Figure 8.1: Comparison of discharging currents, between optimum and one-by-one discharging, for spring representative day.

In the figures below, the duration curves of battery 1 are presented for the four representative days, against 3 one-by-one discharging scenarios (Figure 8.2-Figure 8.5). The remaining scenarios are not depicted in the picture as the follow similar patterns but will make the figures too messy to interpret. The duration curves show that in optimum discharging the maximum current is never reached, while in one-by-one case the maximum current is reached in multiple timesteps (Figure 8.2-Figure 8.5).

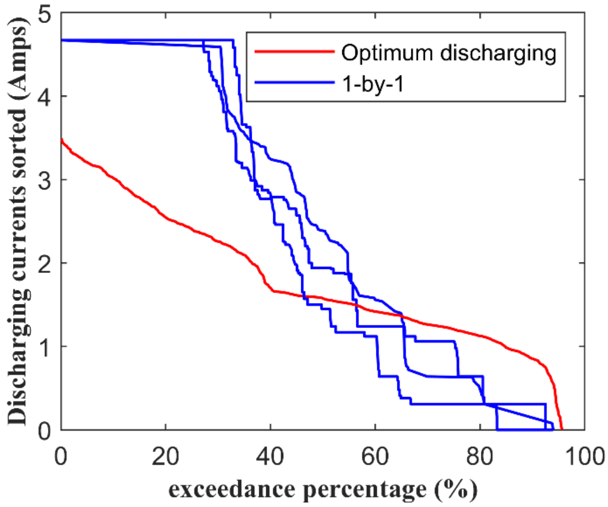

Figure 8.2: Winter duration curves, for optimum discharging and three random one-by-one discharging cases (Battery 1).

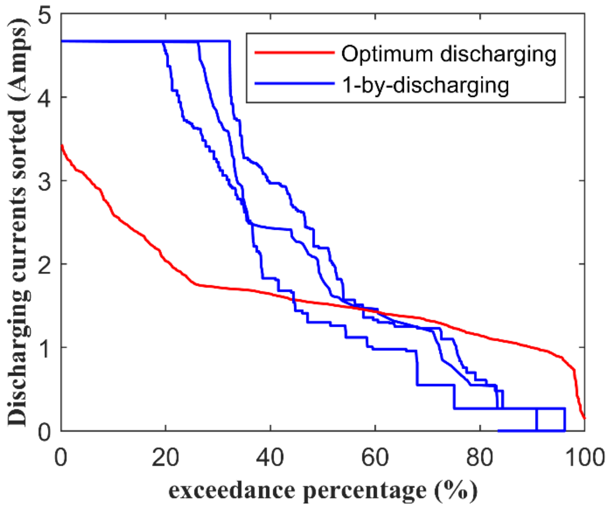

Figure 8.3: Spring duration curves, for optimum discharging and three random one-by-one discharging cases (Battery 1).

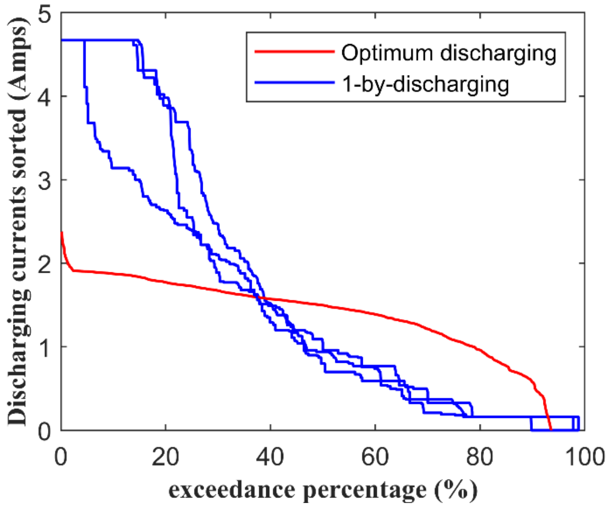

Figure 8.4: Summer duration curves, for optimum discharging and three random one-by-one discharging cases (Battery 1).

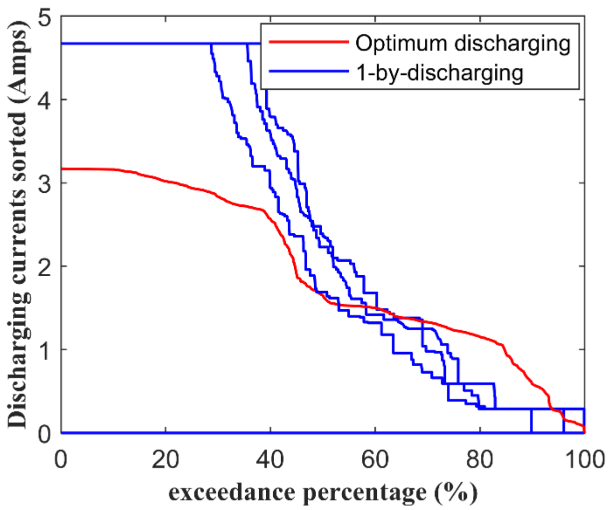

Figure 8.5: Autumn duration curves, for optimum discharging and three random one-by-one discharging cases (Battery 1).

Another interesting feature is the fact that for high currents the one-by-one discharging currents are significantly higher than the optimum ones. After a point, the optimum current becomes higher than one-by-one, but for much lower currents. Higher currents (higher c-rates) mean higher cycle loss, as the discharging current is the most significant factor (exponential impact-see equation 19).

From cycle loss equation the three important factors are c-rate, DoD and Temperature. For simplicity reasons it is assumed that the temperature is the same for optimum and one-by-one discharging. Thus, the remaining factors are c-rate (current) and DoD. Using the obtained data, curve fitting is used in MATLAB in order to find (by approximation) the correlation between the discharging current and the DoD. In this way, the DoD can be replaced in the equation so that it is only dependent on the discharging current. Using the cycle loss equations (19)-(21), we have:

$$\frac{C_{loss(k)}}{C_{loss\_opt(k)}} = -0.0026 \cdot e^{(0.3524 * I_{(k)} - I_{opt(k)})} \cdot \frac{DoD_{(k)} \cdot (1 - DoD_{(k)})}{DoD_{opt(k)} \cdot (1 - DoD_{opt(k)})} \Leftrightarrow$$

$$C_{loss\text{-}factor(k)} = -0.0026 \cdot e^{(0.3524 * I_{(k)} - I_{opt(k)})} \cdot \frac{DoD_{(k)} \cdot (1 - DoD_{(k)})}{DoD_{opt(k)} \cdot (1 - DoD_{opt(k)})} \tag{29}$$

$C_{loss\text{-}factor}$ shows the correlation between one-by-one and optimum discharging. If $C_{loss\text{-}factor(k)} > 1$, then the $C_{loss(k)} > C_{loss\_opt(k)}$, which means that optimum discharging is a better option than the one-by-one discharging as it causes lower cycle loss to the battery k. In contrast, if $C_{loss\text{-}factor(k)} < 1$ it means that the one-by-one discharging is better than the optimum one. For each representative day and each battery, the $C_{loss\text{-}factor}$ equation will be different, as the fitting curve that correlates the discharging currents with DoD will be different. For battery 1, the equations that represent this correlation, are presented for each representative day.

$$DoD_{winter(k)} = \alpha_1 \cdot e^{(b_1 \cdot I(k))} \tag{30}$$

$$DoD_{winter\text{-}opt(k)} = c_1 \cdot e^{(d_1 \cdot Iopt(k))} \tag{31}$$

$$DoD_{spring(k)} = \alpha_2 \cdot e^{(b_2 \cdot I(k))} \tag{32}$$

$$DoD_{spring\text{-}opt(k)}=c_2 \cdot e^{(d_2 \cdot Iopt(k))} \quad (33)$$

$$DoD_{summer(k)} = \alpha_3 \cdot e^{(b_3 \cdot I(k))} \quad (34)$$

$$DoD_{summer\text{-}opt(k)}=c_3 \cdot I_{opt}{}^{d_3} \quad (35)$$

$$DoD_{autumn(k)} = \alpha_4 \cdot e^{(b_4 \cdot I(k))} \quad (36)$$

$$\mathrm{DoD}_{\mathrm{autumn\text{-}opt(k)}}=\mathrm{c}_4 \cdot I_{opt}{}^{d_4} \quad (37)$$

Where $a_{1-4}, b_{1-4}, c_{1-4}, d_{1-4}$ are the coefficients obtained from curve fitting process and can be found in Appendix section. Putting the equations (30)-(37) to the equation (29), four equations are obtained where cycle loss (one-by-one and optimum) is dependent only on discharging current. In Figure 8.6, the cycle loss factor for Spring representative day is illustrated, along with the cycle loss enhancement that optimum discharging offers.

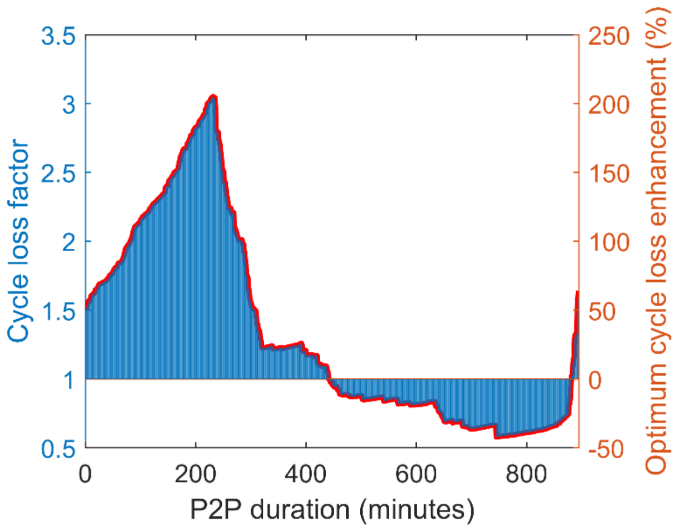

Figure 8.6: Cycle loss factor and Optimum cycle loss enhancement (%) for a particular case in Spring.

It is obvious that, when the cycle loss factor is higher than 1, the optimum cycle loss is a better option leading to a cycle loss enhancement up to 200%.

In contrast, after 400 minutes the cycle loss factor is lower than 1, meaning that for this period one-by-one discharging is better (negative cycle loss enhancement of optimum cycle loss). However, the average cycle loss factor is higher than 1, as the enhancement before 400 minutes is much higher than the negative enhancement (deterioration).Besides the particular case described above, the surfaces that represent the space of all possible solutions for each representative day, can be plotted. (Figure 8.7-Figure 8.10).

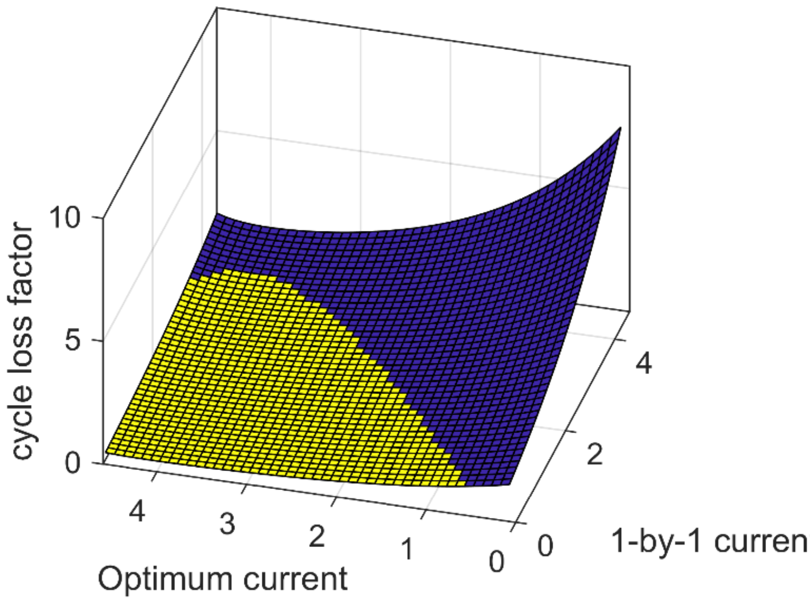

Figure 8.7: Cycle loss factor surface, Winter.

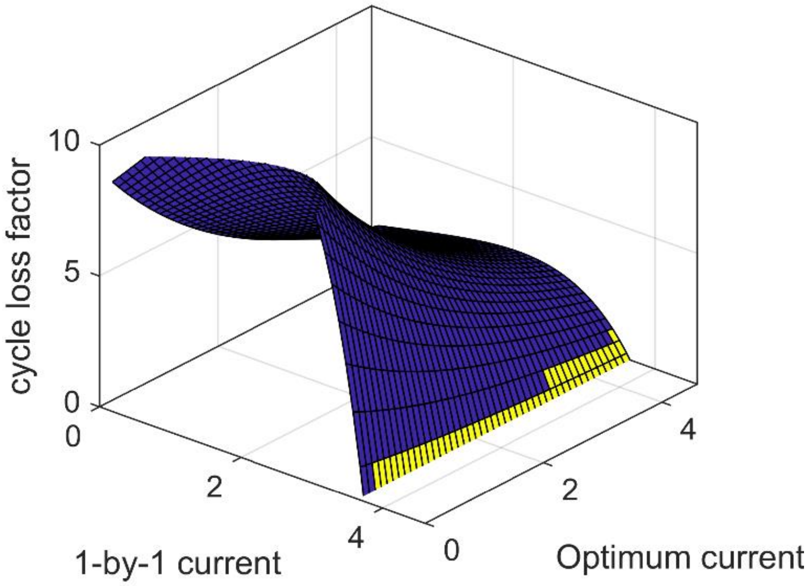

Figure 8.8: Cycle loss factor surface, Spring.

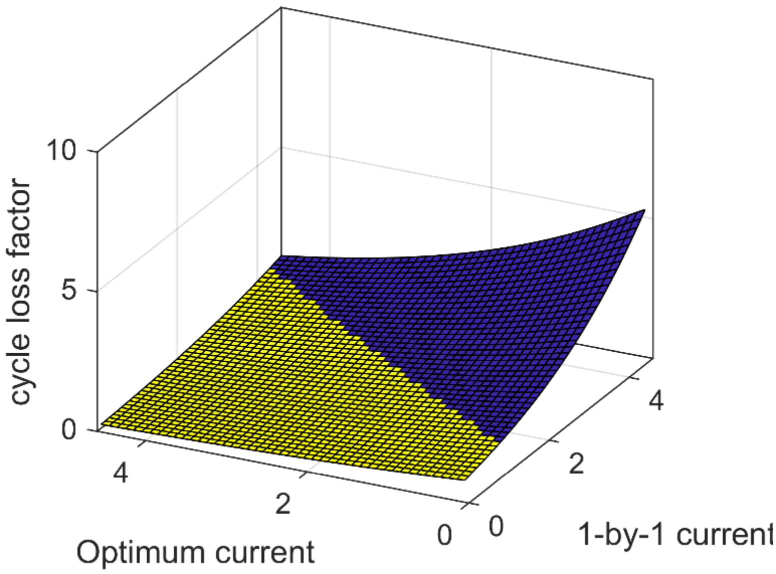

Figure 8.9: Cycle loss factor surface, Summer.

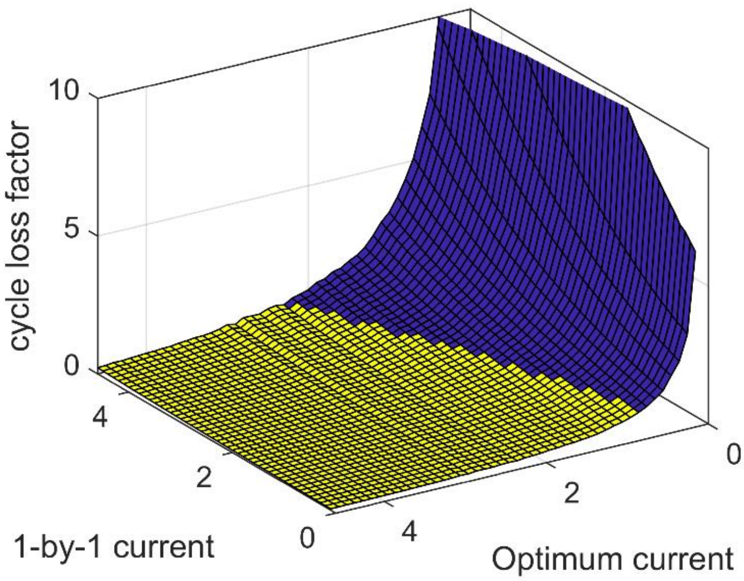

Figure 8.10:Cycle loss factor surface, Autumn.

In the above figures the surfaces of all possible solutions are illustrated. The higher the cycle loss above 1, the better the optimum discharging is compared to one-by-one discharging and vice versa. The yellow colour represents the solutions where cycle loss factor is lower than 1 (one-by-one better than optimum discharging), while the blue one the solutions that are higher than 1 (optimum better than one-by-one discharging). In all cases, it is obvious that the optimum discharging leads to much higher cycle loss factor values, meaning that the optimum discharging is much better than the one-by-one discharging. For example, for summer representative day, almost half of the possible solutions have cycle loss factor lower than one-by-one, while the rest of them is higher. However, it is obvious that the cycle loss factor is significantly higher in the optimum discharging case, meaning that the overall performance of optimum discharging is better than the one-by-one discharging. This fact means that P2P exchange with an optimum discharging strategy could prolong battery lifetime.

To explore this issue further investigation is required. In this work, an analytical method based on given equations from literature is followed to prove in a more general way the benefits an optimum discharging offers. To summarize, the results showed that for low currents, one-by-one discharging might be better than optimum discharging. However, for higher currents optimum discharging becomes tremendously better making the overall performance of optimum battery discharging better. Ideally, a combination of one-by-one and optimum discharging could be used, tracking for each timestep which one is better. However, the complexity of the phenomenon makes this practice infeasible. Thus, an optimum discharging can be selected for all cases having an overall better performance compared to one-by-one discharging.

8.2. Chapter summary

In this chapter, a comparison of jointly optimum discharging and one-by-one discharging was performed to investigate which discharging strategy causes lower battery capacity loss. The comparison was conducted for the four representative days, and the results for battery 1 were presented. Duration curves and curve fitting process were used to correlate the DoD and the discharging current for both examined scenarios. A cycle loss factor was introduced, which essentially shows which discharging scheme is better for a range of discharging currents. Based on this factor, different surface graphs were presented which depict the comparison between the two examined schemes, for all the possible discharging currents within certain limits (maximum current limit). The results showed that the overall performance of optimum discharging is much better than one-by-one, despite the fact for some cases with low currents, one-by-one discharging causes less degradation.

Chapter 9. Discussion

In this work, a framework for P2P exchange was presented as the main contribution to knowledge based on the existing literature. The presented methodology was developed after a detailed investigation of broader concepts and gradually narrowing down to the research gaps found in the current literature.

Initially, the concept of smart grids was investigated seeking their main characteristics compared to conventional power systems. The main functionalities of smart grids were identified, and their advantages compared to the traditional systems were highlighted. The significant benefits they offer are based on particular assets available such as renewable energy and storage systems. Wind power and PV panels are the most popular renewable technologies, that have developed fast during the last decades. The research progress and the increasing number of renewables applications make them cost-effective solutions for modern power systems. Smart grid encourages GHGs reduction leading to mitigation of climate change. Moreover, smart grids enhance system reliability and efficiency, increasing their security as well. Despite the important benefits they offer, there are some challenges that emerge. The main challenge is the tremendous amount of data and number of devices required to coordinate different domains at the same time and make decisions in real time. Thus, novel approaches are required to overcome communication burden using suitable smart devices and control strategies.

The next step was to identify the concept of MGs in the context of smart grids and the advantages they offer. Different energy management techniques in MGs were investigated and the active role of consumers was highlighted. An important characteristic of MGs is their ability to operate in two different modes: grid-connected and islanded. Another significant advantage of MGs is the fact that they can integrate RES that could be used locally in a decentralized way, reducing power losses and mitigating environmental impacts of climate change. Moreover, MGs connect local users to the main grid in such a way that they can be treated as a flexible, aggregated and controllable load. MGs have become a significant field of research from academic community as their deployment could significantly enhance resilience of modern power systems. For this reason, many studies focus on MGs' planning and operation. In this context, different energy management techniques in MGs were identified, where the most important ones are unit commitment (UC) and demand-side management (DSM). Unit commitment allocates the available resources in an economic and secure way. Unit commitment is formulated as an optimization problem, which varies depending on the mix of the available units and particular operating constraints. Different optimization techniques have been used to address the UC problem including, stochastic programming, MILP and robust optimization. However, the increasing integration of renewables pose new challenges to the UC problem due to the intermittent nature of renewables, as it is dominated by uncertainties. Demand side management (DSM) is defined as the modification of demand consumption patterns in order to increase efficiency and flexibility of power systems operation DSM becomes popular in modern power systems, offering frequency regulation, capacity provision, and market efficiency enhancement. However, DSM is posing new challenges to smart grids due to the complexity and information burden of these strategies. Time-of-use tariffs were also identified as an efficient way to provide incentives to the users to actively manage their consumption and participate in DSM techniques. Different ToU tariff schemes were also examined, making clear that the static ToU tariff schemes are the most preferred so far. Smart grid integrates the active role of consumers compared to a passive behavior in traditional power systems. As a consequence, a new type of users is defined, named prosumers. Prosumers both produce and consume renewable energy, modifying their consumption and gaining benefits. Different projects are implemented which are based on prosumers, developing novel business models and markets to permit their active participation. The role of prosumers encourages local energy production/consumption and local trading, promoting sustainability.

As energy storage applications have been identified as an important asset of smart grids, a more detailed investigation was implemented seeking cost-effective solutions for distribution networks. The investigation of literature revealed different energy storage technologies that can be implemented, with different advantages and disadvantages. Each technology offers a wide range of options for energy experts, based on their location, application scale, and the services provided such as frequency regulation and voltage control. Electrochemical storage technologies and especially batteries were identified as a suitable candidate for distribution networks, offering significant advantages compared to the rest of the available technologies. Lithium-ion batteries (LIBs) are identified as a reliable and mature storage technology with high potential of further improvement in the near future, which offer significant advantages compared to the other battery types. The chemistry of LIBs provides higher power and energy density and lower self-discharging rates compared to other chemistries. They have higher cycle life and higher efficiency making them suitable for a wide range of applications either stationary or portable (EVs, laptops, smart phones). However, the degradation effect was highlighted as a main concern of LIBs, which lead to capacity loss. The degradation effect is a complex phenomenon that occurs in battery technologies (such as lithium-ion, lead acid) due to irreversible chemical reactions that take place inside the battery. The degradation effect increases the internal resistance of the battery, causing a permanent capacity loss. Operation cycle loss can be mitigated by controlling particular parameters of battery operation. Different key factors that affect degradation effect have been recognized. The most important ones are charging/discharging current, temperature and the SoC window during operation. Another concern for LIBs is the environmental impact of their industrial production. Life-cycle analysis is a popular method used by researchers to investigate this impact.

The role of storage technologies in distribution networks was also investigated, highlighting their crucial role in modern power system due to the advantages they offer. The most important advantage for distribution networks is the ability to store energy and used when it is needed. Other significant advantages are, power quality enhancement, frequency regulation, load peak shaving/shifting, voltage control, facilitation of RES integration, reduction of system costs, increase of system reliability and resilience and mitigation of GHGs effect. However, storage applications pose important challenges for their implementation such as the sizing process and the energy management techniques that set the rules according to which the energy is stored and distributed to the system. The acquired knowledge up to this point led to the implementation of a simulation model which examined the potential benefits gained for domestic users under a ToU tariff scheme. This work was presented in UPEC conference in 2017.

The research was then focused on system resilience and P2P energy exchange approaches. The concepts of Resilience and P2P exchange were investigated in detail. The difference between resilience and reliability is clarified, and different type of faults were defined from the literature. The role of resilience in MGs were examined, and the main aspects of P2P exchange concept were covered. As the main issue examined in this thesis is P2P exchange for microgrids, to improve economic and resilience operation, a detailed literature review is conducted seeking the research gaps in the existing literature. The aim was to identify to what extent the concept of resilience was investigated in the context of P2P exchange process. The main aspects covered by literature on P2P exchange were investigated, looking for uncovered areas that this work could contribute to. Relevant parts of our published work were presented, regarding P2P exchange and resilience. The main aspects of these works were described, and critically reviewed. Based on the thorough investigation of the current literature, a novel method was presented in the next chapter.

The major contribution of this thesis was then presented, based on the research gaps identified in the existing literature. A novel P2P exchange framework for MGs was developed, to improve economic and resilient operation. The synergies for the local DNO and MG users that could lead to participation in a P2P exchange scheme in which they both gain benefits, were investigated. These benefits were examined in terms of economic benefits for the stakeholders (profits), system resilience under fault scenarios, carbon emission reduction and increased battery lifetime. The energy trading occurs under three principles:

- First, by using the storage and renewable assets of the MG.
- Second, P2P exchange is enabled during the high-tariff period and
- third, it is based on the mutual benefits to the DNO and MG users.

The stakeholders agree in advance to share the cost and benefits of P2P energy trading. The percentage share of the benefits gained is the same as the percentage participation in the cost. Energy sharing is regulated and followed by all participants according to the rules explained in each step, taking into consideration transformer and storage inverter power limits. The required steps to implement the developed methodology were described in detail. Since the input data are provided, a battery sizing process is implemented to find the number and the optimum size of the batteries. The next step includes a users' categorization process. The users are categorized (BO, GC. "users outside the MG") and prioritized under certain criteria. A zoning process is then applied putting users in it according to the priority order. P2P exchange is performed by jointly discharging BO's batteries in an optimum way to minimize degradation cost. Different fault scenarios are examined to quantify their impact on system resilience, considering faults that occur in the physical or communication part of the system. The physical faults include faults on one or more batteries of the system, on a whole feeder of the microgrid and on the MG transformer/supply. Communication faults include faults in the communication network that make it impossible for one or more MG users to communicate with the MG server. In all cases, the zone is reconfigured accordingly in order to mitigate the impact of the faults. In case of Transformer/supply fault, a device load curtailment strategy is implemented cutting off devices based on a device priority list that has been agreed by the users. The developed framework sets particular rules that should be followed by all participants. In this way, complex auctions and biddings among the MG users are avoided.

As a next step, the practicality of the developed methodology was tested. A particular case study was presented, using suitable input parameters and implementing all the methodology steps. Four representative days were used from the CREST demand model to size the system, and then a particular day in Winter was examined for a Newcastle location. The obtained results were presented analytically for each step described in the methodology chapter. A MG in Newcastle with 80 users and 5 parallel feeders was investigated. The users were equally distributed among the feeders. The battery sizing process was analytically described providing relevant graphs and explaining how the inverter and TF limits affect the process. For this case, P2P exchange is performed by 18 batteries (18 BO users). The rest of the MG users are GC users. 100 users outside MG were considered for this case. The users' priority order and the zone expansion order were presented for each examined scenario. Moreover, the number of users included in zone were also presented and compared with the no fault scenario. The benefits gained for local DNO and BO users were analytically explained and discussed, including DNO's compensation and carbon emissions reduction. The improvement on system resilience was highlighted for the transformer fault (FLT_{TF}) scenario, providing relevant graphs regarding particular resilience metrics and users' device curtailment. The overall case study reveals the improvement in the economic and efficient operation of the MG, due to the implemented methodology.

The developed framework was then expanded to different locations and different ToU tariff schemes. Initially, it was applied to different locations under the same ToU tariff scheme. The differences on system resilience were highlighted due to the different characteristics of each location. Then, the developed methodology was implemented for different locations and different ToU tariff schemes, seeking for the best ToU tariff for certain criteria. In this way the usefulness of the method was revealed, as a general tool that could be applied to any location and provide insights about the potential benefits that can be gained, under particular criteria. The results showed important differences regarding resilience enhancement due to the particular characteristics of each location. More tests were conducted for the same locations for different ToU tariff schemes, seeking for the best tariff scheme for particular objectives. Four different objectives were selected and categorized in two groups. Different graphs were created for each of them. The results showed that the developed framework is a useful generalized tool that could provide insights about the potential benefits gained for any location. Numerous extra scenarios can be tested, by changing more input data parameters. An interesting example will be to test different FIT tariff schemes for the PVs in order to identify which is the minimum FIT scheme that provides benefits to the stakeholders. A case where FIT tariffs are the same for BAU and P2P scenario would also be interesting. This information will be useful to policy makers in order to achieve certain sustainability goals. Another extension would be to change the battery prices, according to the expected future values in order to estimate the gained benefits in the near future.

Finally, a comparison of jointly optimum discharging and one-by-one discharging was performed to investigate which discharging strategy causes lower battery capacity loss. Duration curves and a curve fitting process were used to prove the advantages of optimum discharging. Different surface graphs were presented which present the comparison between the two examined schemes, for all the possible discharging currents within realistic limits (maximum current limit). The results showed that the overall performance of optimum discharging is much better than one-by-one, despite the fact for some cases with low currents, one-by-one discharging causes less degradation. This type of investigation can be expanded beyond the particular developed framework, as it addresses a general question on how a group of batteries should be discharged. A more thorough investigation of this issue is required, which can be part of a future work.

9.1. LIMITATIONS AND ASSUMPTIONS

To develop the presented P2P exchange framework and make progress in a novel investigation, several assumptions have been made to overcome a range of limitations and barriers. There are several issues that have been identified yet not investigated. Some of the most important ones are presented in this section.

The developed methodology can be applied to systems with an existing static ToU tariff scheme. Although, static ToU tariffs are mostly preferred at the moment [68], this work is not expanded to other ToU tariff scheme structures. More investigation is required for different tariff structures such as dynamic pricing, as the different pricing might change the P2P exchange process presented in this work. For a dynamic price tariff scheme the presented framework could be modified by setting a particular price limit above which P2P exchange will be enabled.

In case of transformer/supply fault the MG will need to be switched to islanded mode and reconnect back to the grid when the fault is fully restored. This process requires a synchronization of system frequency. The synchronization process needs some time (usually a few minutes) and suitable control techniques to be implemented. A battery from the MG can be used a reference point in order to synchronize its frequency. A different approach will be to synchronize the system by interconnecting it with other parts of the network or other MGs. To overcome this, it is assumed that the synchronization process happens instantaneously without having problems with system frequency. Several studies have been conducted for this issue to address this problem [205]–[208].

Computational burden during the optimization process is another issue that might compromise the implementation of the developed methodology. The number of batteries discharged and the number of timesteps the discharging occurs are the two main factors that increase the computational burden. An increase in the number of batteries and timesteps will increase significantly the required RAM and the simulation time. A way to partially handle this, is to break the optimization problem in smaller ones, including only a few timesteps each time. This will leave space to increase the number of batteries. In this work, some tests are performed with up to 300 batteries with a timestep of two (minutes) and the computational time was around 3-hrs. For a higher number of batteries probably a different set of computers is needed to handle the large amount of data. Moreover, the computational time must be reasonable and certainly less than 24-hrs as the developed methodology is based on a day-ahead scheduling. For the case study presented, there are 18 batteries and 900 timesteps. To accelerate computational time the problem was broken in 6 subproblems with 18 batteries and 150 timesteps each. The computational time was only 172 seconds which makes the optimization for this particular set of parameters fast enough for a quick evaluation using modest hardware. Another significant parameter that needs to be taken into consideration regarding the computational time is the initial value needed for each optimization section. Suitable values must be selected to avoid many iterations until the optimization converges. The used solver was the default of MATLAB software called “interior point”, which can handle large, sparse problems, as well as small dense problems. The algorithm satisfies bounds at all iterations. Other solvers such as “sqp”, “active-set” and “trust-region-reflective” could be also tested and compared to the selected one.

Another issue that is related to the implementation of the presented framework is the required control and communication structure. To perform a P2P exchange under the presented principles, a large amount of control and communication devices are needed to implement the decisions made by the algorithm. The MG server which is part of the communication structure runs all the processes – such as users' categorization, zoning and optimum discharging – by exchange data with the MG users. This fact requires a detailed and careful development of communication structure, increasing the complexity and the costs. IoT technology is a promising technology to support communication infrastructure in smart grids. These issues are investigated by other researchers [209]–[211] and are not part of this work.

In this work the investment cost includes the battery cost and the inverter cost. However, there are additional costs that are related to the required communication and control devices. These costs are not considered in this work.

Another limitation is related to degradation effect of Lithium-ion batteries. This phenomenon is quite complex and different models have been proposed by the researchers to estimate it. In this work the degradation effect simulated in the optimum discharging is modelled using the equations presented in [111]. However, in a real implementation the specific batteries used need to be tested to confirm that the model used is suitable. Based on test results new equation might be developed or the existing models could be modified accordingly. In this work, it is assumed that all the batteries are the same type and their degradation behavior is described by the equations presented in [111]. Moreover, for simplicity reasons the temperature of the battery it is assumed to remain constant, while in reality it would vary depending on charging/discharging current, internal resistance and other factors. Detailed studies if degradation effect of are presented in [112]–[119].

In this work, electric and communication faults were examined. For simplicity reasons it is assumed that the fault occurs at the same time in all devices. However, this is very unlikely to happen as different faults will happen in different times. Moreover, the model does not address the combination of faults occurring at the same time (for example battery and communication fault). To include all these, more coding needed increasing the complexity of the algorithm.

In the developed methodology it is assumed that all users participate at the same ToU tariff. However, each user may have an energy contract with a different energy supplier paying different tariffs according to their energy plan. Moreover, the low/high tariff periods may vary from contract to contract. This situation would significantly increase the complexity of the method but could be accommodated without significantly modifying the underlying code.

The device curtailment strategy is implemented by disconnecting particular devices according to a priority list. Normally, end-users receive specific benefits for participating in DR strategies. However, in this work, benefits from DR are received through the enabling effect it has on the overall P2P scheme. It is assumed that devices are switched off and on during the device curtailment period instantaneously. Moreover, it is assumed that after fault all the devices are connected back to the system instantaneously. Nevertheless, this process is not performed instantaneously by connecting back all the devices as this might cause imbalances to the grid (rebound effect). Thus, the device curtailment strategy needs to be carefully designed to avoid these issues. Several studies have been conducted regarding DSM and DR strategies [56]–[59], [212], [213].

Although P2P exchange is considered as a promising process for modern power systems, there are regulatory barriers as in most countries the legislative frameworks have not been modified to enable this type of projects. This fact might compromise the implementation of the developed framework. However, it is expected that these barriers will be overcome in the near future [155], [214].

The implementation of the presented framework requires exchange of personal data of the end users such as personal load demand, user ID, battery SoC etc. This fact rises concerns about the protection of their privacy. Users may refuse to provide sensitive information and compromise energy trading processes such as P2P exchange. The research community has shown an increasing interest about privacy issues for prosumers, looking for practical solutions to address this problem [215]–[217]. However, privacy issues are beyond the scope of this work and are not examined. It is assumed that this barrier has been overcome and user privacy concerns are accommodated during the P2P exchange process.

The developed methodology is implemented by following a particular users' priority order based on the energy mismatch of each feeder. The feeders with low energy mismatch have higher priority and vice versa. This means that users that belong to a feeder with more PV/battery assets and lower load demand have higher chances to get high priority and be part of the P2P exchange process. In some feeders there might be domestic and commercial loads that have different daily load profiles, in terms of the amount of load demand and peak hours. These issues might raise fairness concerns and pose questions if all end users are treated equally. In this work, it is assumed that all users are domestic ones and potential farness issues are not investigated. Fairness issues are the main focus of different studies [218]–[220].

In this work, it is assumed that the stakeholders (DNO and MG users) agree to cover equally (50%-50%) the investment cost of batteries (including the inverter costs) and share the gained benefits for P2P exchange. However, the engagement of the stakeholders in a P2P exchange project is a complex issue that is not investigated here. The agreement to cover a certain percentage of costs is complicated especially from DNO's side, as multiple factors regarding pricing and costs need to be considered in the decision-making process. This process requires deeper investigation itself which is beyond the scope of this thesis. The engagement of stakeholders in sustainable development projects, is investigated by researchers focusing on the development of methods and tools to encourage their participation [78], [221], [222].

Another concern regarding the implementation of the presented framework is the fact that grid constraints are not taken into consideration. Feeding power in the system from PVs and batteries might cause voltage imbalances to the grid or other problems such as line congestion. Power flow analysis within certain constraints will reveal any potential imbalances for the system. However, they are not included in this work. This thesis presents only the framework and the rules under which the energy management can be performed, without the examination of grid constraints.

Finally, the presented method is applied as a day ahead scheduling assuming that there is an accurate forecast regarding the expected load demand and PV generation of a particular day. However, to implement the method, a real time controller needs to be developed to correct any mismatches between the forecasted values and the actual ones. The presented work represents the forecasted values that are going to be used as a baseline in a real-time controller.

Conclusions and future work

In this work, a novel P2P exchange framework for MGs to improve economic and resilient operation was presented. The framework was implemented under certain principles in the context of an existing static ToU tariff scheme. The implementation of the method requires particular steps which were described in detail. Two groups of stakeholders were considered: Local DNO and MG users. Suitable input data are required, in order to estimate the number and the size of system batteries. Users were categorized based on their available assets and a particular priority order were established. P2P exchange is enabled within a zone, which is expanded according to the users' priority order. P2P exchange is based on the available assets of the microgrid (PVs, batteries), where the system batteries are jointly discharged in an optimum way. The concept of resilience is also investigated by examining different fault scenarios. The examined faults occur either on the physical components of the system (batteries, feeders or transformer) or on the existing communication network.

The practicality of the method was tested for a particular case study. A particular microgrid topology was selected with five parallel feeders, for a location in the North East of England. Suitable input parameters were provided for this case and the steps described in the methodology were followed. The results showed that the stakeholders gain significant benefits from the P2P exchange framework compared to the BAU and No P2P scenarios. These benefits were examined in the context of economic benefits, carbon emissions reduction, resilient enhancement and battery lifetime improvement.

The developed methodology was expanded for different ToU tariffs and different locations. Four different locations were selected (Athens, New Delhi, New York and Newcastle). The results showed a variability on system resilience based on the particular characteristics of each location. Different ToU tariff schemes were investigated for these locations seeking for the best tariff design for certain objectives (economic benefits, carbon emissions, average resilience and DNO money saved). For this purpose, different graphs were created. The results showed that, the presented framework is a generalized tool that provides insights about the potential benefits stakeholders can gain, for any location. Since the suitable input data are presented, the methodology provides answers for certain objectives.

Finally, a comparison of two different discharging schemes was presented. The optimum discharging performed in the methodology and a random one-by-one battery discharging, were compared in order to investigate which discharging strategy causes lower battery capacity loss. Duration curves and curve fitting were performed to compare these schemes. The results showed that the overall performance of a jointly optimum discharging is significantly better than the one-by-one discharging, although for some low discharging currents the one-by-one causes less capacity loss.

A more thorough investigation of this phenomenon can be part of a future work, as it is expanded beyond the limits of the developed P2P exchange framework. Experimental work could be performed using particular lithium-ion batteries in order to validate or modify the equations used from the literature. A thorough investigation of the battery temperature can be also investigated for the two examined discharging schemes. This work could address a general issue regarding the capacity loss of lithium-ion batteries and provide guidelines on how to discharge a group of batteries to minimize capacity loss.

Another part of future work will be to integrate also EVs to the developed methodology with V2G technology. This feature will expand this research, adding more challenges regarding the uncertainties of EVs and their efficient management in a P2P exchange scheme. Probabilistic methods and robust optimization could be used to address these challenges.

The integration of grid constraints could be also an interesting expansion of the work. Power flows could be conducted using suitable simulation tools in order to investigate the impact of P2P exchange on power quality. The impact of P2P exchange on certain grid components such as MG transformer, feeders could be investigated.

Another important expansion of this work will be to develop a real-time controller (e.g. model predictive control (MPC)). As the developed methodology is established as a day ahead scheduling, it can be used as the baseline using suitable forecasting methods. The controller will use these data to fix the power mismatches in a real-time operation.

Finally, a detailed investigation of suitable communication networks to support this framework will be useful. Different topologies, devices and equipment could be investigated along with a deeper investigation on communication faults and recovery strategies.

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Appendix 1: Curve fitting coefficients

Table A1.1: Curve fitting coefficients for each representative day.

Curve fitting coefficient	Value
Winter	
a_1	0.283
b_1	0.0773
c_1	0.1898
d_1	0.3186
Spring	
a_2	0.1735
b_2	0.1967
c_2	0.2
d_2	0.44
Summer	
a_3	0.1735
b_3	0.19
c_3	0.3283
d_3	-0.017
Autumn	
a_4	0.3992
b_4	0.02164
c_4	0.2285
d_4	0.6939

Appendix 2: Convexity proof

We prove that our problem is convex. Since all constraints are linear, it is sufficient to prove that the objective function is convex. The objective function is:

$$f = \sum c_{\deg(t,k)} \tag{1}$$

where

$$c_{\deg(t,k)} = \frac{Q_{\text{cycle loss}(\%)(t,k)}}{\eta\%} \cdot P_{\text{B}(k)} \tag{2}$$

Since $P_{\text{B}(k)}$ and $\eta\%$ are parameters, it is enough to prove that $h = Q_{\text{cycle loss}(\%)(t,k)}$ is convex. To do so, we show that the second derivative of h, $h'' > 0$.

$$h = Q_{\text{cycle loss}(\%)(t,k)} = B_1 \cdot e^{B_2 I_{\text{rate}}} \cdot \text{Ah} \tag{3}$$

where

$$\begin{aligned} B_1 &= aT^2 + bT + c \\ B_2 &= dT + e \end{aligned} \tag{4}$$

Moreover,

$$I_{\text{rate}} = \frac{I(t)}{\text{cell capacity}} \tag{5}$$

$$\text{Ah} = (\text{number of cycles}) \cdot \text{DoD} \cdot (\text{cell capacity}) \tag{6}$$

$$\text{number of cycles} = \frac{\Delta\text{SoC}}{2(\text{SoC}_{\text{max}} - \text{SoC}_{\text{min}})} \tag{7}$$

It is assumed that the operating SoC window of the battery is between 10%-90%, so:

$$\begin{aligned} \text{SoC}_{\text{max}} &= 0.9 \cdot (\text{cell capacity}) \\ \text{SoC}_{\text{min}} &= 0.1 \cdot (\text{cell capacity}) \end{aligned} \tag{8}$$

$$\Delta\text{SoC} = I \cdot \Delta t, \ (\text{SoC in Ah}) \tag{9}$$

Equation (7), using (8) and (9), becomes:

$$\text{number of cycles} = \frac{I(t)}{2 \cdot 0.8 \cdot (\text{cell capacity})} \tag{10}$$

$$\mathrm{DoD} = \frac{I(t)}{\text{cell capacity}}, \quad \left(I(t) \text{ in Ah}\right) \tag{11}$$

Equation (6), using (10) and (11), becomes:

$$\mathrm{Ah} = \frac{I^2(t)}{1.6 \cdot (\text{cell capacity})} \tag{12}$$

Equation (3), using (5) and (12), becomes:

$$h = B_1 \cdot e^{B_2 \frac{I(t)}{\text{cell capacity}}} \cdot \frac{I^2(t)}{1.6 \cdot (\text{cell capacity})} \tag{13}$$

We then show that $h'' > 0$, considering battery temperatures between 0 – 80 °C (or 273.15 K – 353.15 K), $I \in [SoC_{min}, SoC_{max}]$, and $a = 8.63 \cdot 10^{-6}$, $b = -0.00513$, $c = 0.7631$, $d = -0.0067$, $e = 2.35$ [223].

$$h' = B_1 \cdot e^{B_2 \frac{I(t)}{\text{cell capacity}}} \cdot \left(\frac{0.625 \cdot B_2 \cdot I^2(t)}{(\text{cell capacity})^2} + \frac{1.25 \cdot I(t)}{(\text{cell capacity})} \right) \tag{14}$$

$$h'' = B_1 \cdot e^{B_2 \frac{I(t)}{\text{cell capacity}}} \cdot \left(\frac{0.625 \cdot B_2^2 \cdot I^2(t)}{(\text{cell capacity})^3} + \frac{2.5 \cdot B_2 \cdot I(t)}{(\text{cell capacity})^2} + \frac{1.25}{(\text{cell capacity})} \right) \tag{15}$$

Functions h and h'' (i.e., $Q_{cycle\ loss}$ and its second derivative) are illustrated in Figure 0.1 for the above-mentioned temperature range, current range, and coefficient values. Since $h'' > 0$, h is convex. This means that $c_{deg(t,k)}$ in (2) is also convex, and, finally, the objective function (f) is convex, as a sum of convex functions.

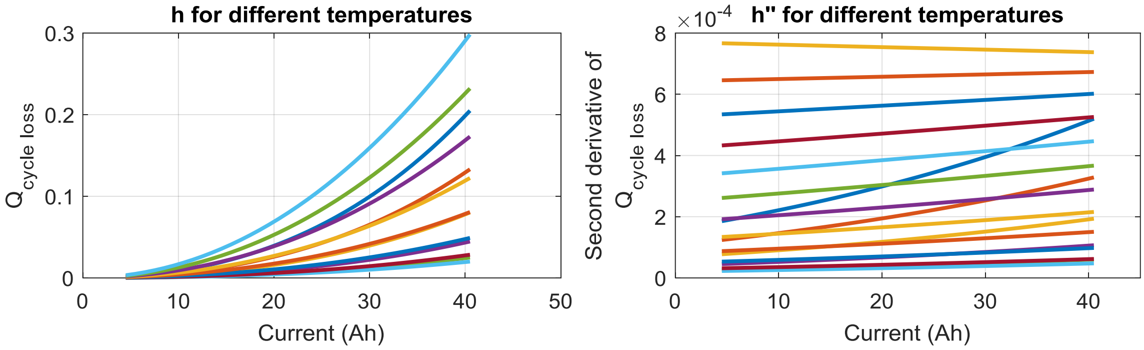

Figure 0.1: $Q_{cycle\ loss}$ and its second derivative for the considered temperature range, current range, and coefficient values.