DEPARTAMENT OF
ELECTRICAL AND COMPUTER ENGINEERING

THE USE OF COOPERATIVE FLEXIBILITY TO IMPROVE THE ENERGY COMMUNITIES' RESILIENCE

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Master in Electrical and Computer Engineering

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Para os meus Pais

Para a Avó Rosa e o Avô Brazuna

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisors, Professor João Martins and Professor Pedro Pereira, for their invaluable guidance, support, and mentorship throughout this research journey. Their expertise and encouragement were helpful in this work.

I am deeply indebted to the Thesis Accompanying Committee, represented by Professor Luís Camarinha-Matos and Professor Sílvio Mariano, for their constructive feedback and insightful suggestions, which significantly contributed to the improvement of this thesis.

I would like to acknowledge the support of NOVA School of Sciences and Technology, as well as the CTS-UNINOVA research center, for providing the necessary resources and environment conducive to research. I am also grateful to the secretariat of the Department of Electrical and Computer Engineering for their administrative assistance, and to Helena Inácio for her friendship and support.

To Januário, Pedro and Vilhena, to Carla, Gina and Maria João, with whom I was lucky to share this journey, thank you very much for all the moments of friendship, for your patience and for all your help and advice, you have undoubtedly made this journey easier.

I am eternally grateful to my friends Pombas, Chambel, Neves, Tiago, Catarina and Mariana, Hugo, Raquel, David and Joana, for their enduring friendship and support, who were essential in the most difficult moments of this journey.

My biggest thanks go to my family, my mother and father and my grandparents, thank you so much for all your love and affection, for teaching and supporting me throughout my life and for all your efforts to give me the best education and make me the person I am today. Thank you to my sister Vanessa and my beautiful nephews Aurora and Benjamim, who always manage to bring a smile to my face.

"Quem tem alma, não tem calma"

Fernando Pessoa

Abstract

The increasing integration of renewable energy sources into the power grid has prompted a paradigm shift towards sustainable and resilient energy systems. On the other hand, the energetic flexibility offered by shiftable loads or storage devices brings new win-win solutions for the grid, businesses, households, and the environment. This work explores the concept of Energy Communities (EnCs) cooperative flexibility as a strategic approach to bolstering EnCs resilience. EnCs can influence collaborative efforts among diverse energy stakeholders to optimize energy production, distribution, and consumption. This PhD thesis reviews the key components of EnCs, such as decentralized energy generation, smart grid technologies, and energy flexibility, highlighting their potential to enhance the overall reliability and adaptability of the power grid.

The existing literature exhibits a notable gap concerning the EnC resilience. Thus, this research endeavors not only to enhance the resilience of EnCs during faults or power deviations but also to discuss the concept of EnC resilience, incorporating energy flexibility as a pivotal component within the proposed methodology.

A community made up of 30 households is considered to conduct a group of use cases, where energy storage system as well as photovoltaic systems are installed. The EnC's resilience is quantified by key metrics, proposed for this thesis, that allow analyzing the community's behavior regarding the user's needs in different situations. The conducted use cases' results show that the proposed Energy Community framework improves the resilience of the community, benefiting not only the community's users as well as the Distribution System Operator (DSO).

Keywords: Energy Community, Renewable Sources, Energy Resilience, Genetic Algorithms.

Resumo

A crescente integração de fontes de energia renovável na rede elétrica tem provocado uma mudança de paradigma em direção a sistemas de energia sustentáveis e resilientes. Este trabalho explora o conceito de Comunidade Energética (EnCs) como uma abordagem estratégica para melhorar a resiliência da rede elétrica. As EnCs podem influenciar esforços colaborativos entre diversos *stakeholders* para otimizar a produção, distribuição e consumo de energia. Esta dissertação estuda a literatura principal das EnCs, como geração de energia descentraliza, *smartgrids* e flexibilidade energética, destacando o seu potencial para melhorar a confiabilidade e adaptabilidade da rede elétrica.

A literatura revela uma lacuna no que toca à resiliência das EnCs, assim, este estudo visa não só melhorar a resiliência da rede de baixa tensão durante falhas ou diminuições de energia, considerando a flexibilidade energética de uma EnC como elemento-chave na metodologia proposta, mas também proporcionar clareza sobre o conceito de resiliência das EnCs.

Uma comunidade composta por 30 habitações é considerada para realizar as simulações necessárias, onde um sistema de armazenamento de energia, bem como sistemas fotovoltaicos, são instalados na comunidade. A resiliência da EnC é quantificada por métricas, propostas para esta tese, que permitem analisar o comportamento da comunidade em relação às necessidades do utilizador em diferentes situações. As simulações realizadas demonstram que a *framework* proposta para a Comunidade de Energia melhora a resiliência da comunidade, beneficiando não apenas os utilizadores da comunidade, mas também o Operador de Rede de Distribuição (DSO).

Palavas chave: Comunidade de Energia Elétrica, Fontes de energia Renováveis, Resiliência da rede elétrica, Algoritmos Genéticos.

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ACRONYMS

AC	Alternating Current
ASME	American Society of Mechanical Engineers
CEC	Citizen Energy Community
CEP	Clean Energy Package
CES	Community Energy Storage
CHP	Combined Heat & Power
DG	Distributed Generation
DSO	Distribution System Operator
EA	Evolutionary Algorithms
EB	Event Based
EnC	Energy Community
EOD	End Of Day
EPBD	Energy Performance of Buildings Directive
EPG	Electrical Power Grid
ESS	Energy Storage System
EU	European Union
EV	Electrical Vehicle
FES	Flywheel
GA	Genetic Algorithm
GHG	Greenhouse Gases
H	Hypothesis
HESS	Hybrid Energy Storage System
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning

ICT	Information And Communication Technologies
KPI	Key Performance Indicator
LV	Low Voltage
MV	Medium Voltage
NIAC	National Infrastructure Advisory Council
NOCT	Nominal Operating Cell Temperature
NZEB	Nearly Zero Energy Building
NZEC	Nearly Zero Energy Community
PEB	Positive Energy Building
PEC	Positive Energy Community
PED	Positive Energy District
PHS	Pumped Hydro
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RAP	Resilience Analysis Process
REC	Renewable Energy Community
RQ	Research Question
SI	International System Units
SLES	Shared local energy storage
SRES	Shared residential energy storage
SRI	Smart Readiness Indicator
STC	Standart Test Conditions
SVES	Shared virtual energy storage
TC	Thermostatically Controlled
V2B	Vehicle to Building
V2C	Vehicle to Community
V2G	Vehicle To Grid
V2G	Vehicle to Grid
V2H	Vehicle to Home
V2L	Vehicle to Load
V2X	Vehicle to everything
ZEB	Zero Emission Building

SYMBOLS

E^b	Battery's Energy
E_{max}^b	Maximum Energy Capacity
E_{min}^b	Minimum Energy Capacity
G_{NOCT}	Solar Radiation at NOCT
PV_{Peak_Power}	PV System Peak Power
$P_c^b max$	Maximum Power Charge
$P_d^b max$	Maximum Power Discharge
$T_{a,NOCT}$	Ambient Temperature at NOCT
$T_{c,NOCT}$	Nominal Operating Cell Temperature
$T_{c.STC}$	Reference Cell Temperature at Standard Test Conditions
T_{cel}	The Temperature of The PV Panel Cells
X_A	Consideration A For Genetic Algorithm Cost Function
X_B	Consideration B For Genetic Algorithm Cost Function
a_n	Appliance Number
b^c	The Signals of Battery Charge
b^d	The Signals of Battery Discharge
w_n	Weight of Each Consideration for GA Cost Function
η_c^b	Efficiency of the Battery Charge Process (%)
η_d^b	Efficiency of the Battery Discharge Process (%)
A	PV Panel Area
G	Solar Radiation
N	Residential Houses' Number
P_{AC}	AC Power
S_N	Normal State of Power System

S_{tD}	Degradation State
T_{amb}	Ambient Temperature
t_D	Time of Degradation
Td	Community Total Demand
$t_{D'}$	Time For Restoration Process Starts
t_E	Time of Event
Tg	Community Total PV Generation
t_R	Time Where Normal State Is Achieved Again
ΔP	Liquid Power of System
ΔT	$t$ime Resolution (Hours)
η_{inv}	Inverter Efficiency
d	Demand Power
g	Generated Power
n	Time-step
α	Temperature Coefficient of The Maximum Output Power

1

Introduction

This chapter sets out the motivations and the main contributions of the research carried out. It also presents the proposed research problem and the general organization of the document.

1.1 Motivation

Climate change and the negative impact on the environment are amongst the most pressing challenges for the planet. Half of energy production (59.2%) comes from conventional energy sources including oil, coal and gas that are undergoing to a process of exhaustion and high pollution emissions, as shown in Figure 1.1. However, from 2021, renewable sources were responsible for 40.8% of energy production (European Union, 2023). Energy production and heat generation from conventional fuels are responsible for 52.6% of the European Union (EU) greenhouse gas emissions by the year 2020, as illustrated in Figure 1.2.

Renewable sources are seen as a solution by policymakers and governments for fostering a more competitive and sustainable energy system while mitigating the effects of climate change (Iddrisu & Bhattacharyya, 2015). In fact, European countries are committed to increase the share of renewable sources in Europe to 42.5% by 2030 (European Union, 2023). Although there is some resistance accepting certain changes related to renewable energy, promising approaches are emerging.

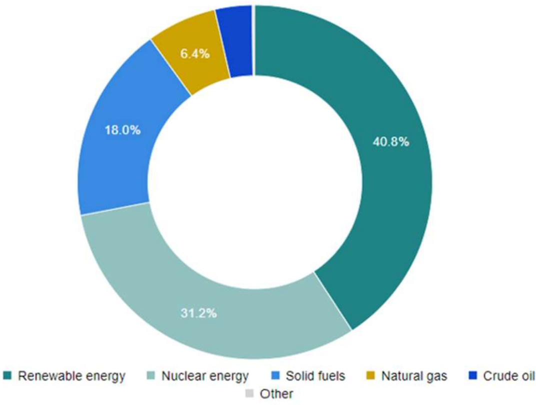


Figure 1.1 – Energy production by source in 2021, (European Union, 2023)

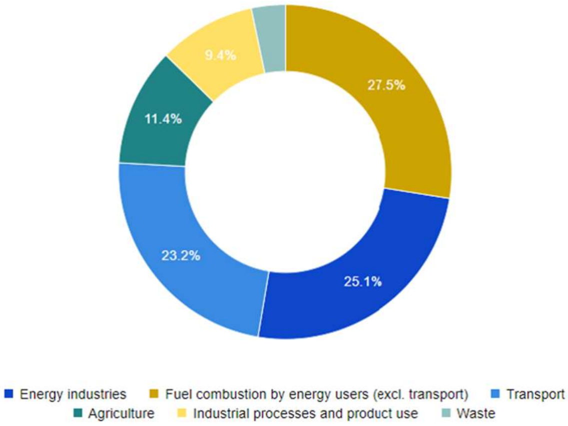


Figure 1.2 - Greenhouse gas emissions by source, in EU in 2020 (European Union, 2023)

For the European Commission, Energy Community (EnC) are characterized by groups of citizens, social entrepreneurs, public authorities and community organizations that participate in the energy production, trading, distribution and consumption of renewable energy (Azarova et al., 2019; Cohen et al., 2016). Conversely, in the event of a fault on the Electrical Power Grid (EPG), a power decrease or an outage, EnCs flexibility presents a solution not only to sustain power supply within the community but also to enhance the resilience of the EnC as a whole. This can be achieved by considering, for example, the energy flexibility of each house as well as of the entire community, or local renewable energy sources and storage systems.

Energy flexibility refers to the ability of an ecosystem, whether it's a household, a community, or the entire grid, to adjust its energy consumption or production patterns in response to changes in supply, demand, or external factors such as price signals or grid conditions.
In practical terms, energy flexibility enables the shifting of energy usage to times when renewable energy sources are abundant and cheap, or when grid demand is low, and conversely, reducing usage during peak demand periods or when energy prices are higher. This flexibility can be achieved through various means such as demand response programs, energy storage systems, smart appliances, among others. Overall, energy flexibility plays a crucial role in optimizing energy efficiency, improving grid stability, and facilitating the integration of renewable energy into the energy system.

This work explores the possibilities of using the community's energy flexibility to maintain the EnC users' energetic comfort whenever a fault occurs. Inside the community, each house may have renewable energy production as well as flexible consumption devices and storage systems that are possible to control. The main idea is to use each house’s energy flexibility in order to improve the EnC resilience.

1.2 Research Problem

The smart energy system concept has a new paradigm, and the integration of renewable energy sources has been discussed, for several years, from different points of view (Ceglia et al., 2020; Lund et al., 2017). Practical methods and technologies allow EPGs to self-regulate and reconfigure in case of failures, threats or disturbances (Amin & Wollenberg, 2005). Given EPG’s conceptual and technological advancements, conducting a comprehensive resilience assessment becomes crucial. Various approaches can be explored to enhance the EPG's resilience in the case of a fault.

With the increase of renewable energy, prosumers started to be considered as active players in the system. This type of consumer represents a user with double role: on one hand is a typical energy consumer, on the other is an energy producer that can share part of its energy with the local EPG. Having in mind the previous definition of a prosumer, energy communities should include prosumers, but they also involve broader community engagement, shared governance models, and collaborative energy initiatives aimed at achieving common objectives beyond individual energy production and consumption. In general, a community is a social unit that has something in common, for instance, a group of users that can have active participation in the consumption and production of energy, (Huang et al., 2017; IEC Technical Committee 1 (Terminology), 2018).

Energy communities serve as vital facilitators in the decentralization of the energy system, promoting local management of renewable energy. Additionally, these communities can enhance the local optimization of power flows and contribute to reducing energy losses. However, the sustained success of energy communities’ centers on their capacity to operate energy grids efficiently, ensuring cost-effectiveness and delivering benefits for all customers and the broader energy system in the long term.

For the European Commission, energy communities have the possibility to participate in network operations, either within the general regime (public grid) or as closed distribution system operators. When an energy community is designated as a distribution system operator (DSO), it becomes subject to identical rights and obligations as a traditional DSO, (Caramizaru et al., 2020). Three primary types of energy communities are worth considering for facilitating electricity transfers: energy communities within housing companies, energy communities that transcend property boundaries, and distributed energy communities (Caramizaru et al., 2020), namely:

Energy Community within a Housing Company:

This type of community refers to parties residing or operating within the same property, such as stakeholders in housing companies, collaborate to mutually benefit from self-consumption on their shared property. According to EU definitions, an energy community within a housing company exemplifies jointly undertaken renewable self-consumption, representing a distinct activity within the broader scope of an energy community.

Energy Community Crossing Property Boundaries:

This community is defined as a group of customers who seek access to renewable energy generated by a neighboring property located in close proximity to their own residences.

Distributed Energy Communities:

This community is characterized by customers who seek access to renewable energy production units located outside of their property or immediate vicinity, utilizing the existing power grid infrastructure for energy distribution and transmission.

These types of energy communities offer diverse models for collaboration and renewable energy usage, each with its distinct characteristics and geographical considerations.

Within the framework of the present thesis, the term "Energy Community" refers to a group of users connected to a local Low Voltage (LV) grid, outfitted with renewable energy generation, controllable consumption devices and storage units. Rather than solely using the produced

energy for individual consumption, users have the capability to store and share it within the Energy Community (EnC), making it accessible when needed. Additionally, leveraging the energy flexibility offered by the community members enables the management of the community's energy, enhancing the resilience of the Low Voltage grid.
This study was originated from one research question that is presented in the next sub-chapter as well as its correspondent hypothesis.

1.3 Research Question & Hypothesis

This work aims to develop a framework that, considering the energy community and energy flexibility concepts, will be able to improve the EnC resilience either during daily life, coping with DSO power curtailment needs, or during an extreme event that leads to an outage in the EnC. The following underlies the research question (RQ) that this work aims to address:

Research question:

RQ - Can Energy Community's resilience be improved considering Energy Community users' Energy Flexibility?

The following hypothesis (H) is considered to address the RQ presented above:

Hypothesis:

H – Energy Community's resilience is improved if the use of Energy Community's energy flexibility allows to maintain the EnC users' comfort level in case of a fault or a Distribution System Operator power curtailment event.

1.4 Adopted Research Methodology

The proposed work aimed at performing fundamental and applied research in the area of grid resilience and improve the resilience of Energy Communities in case of faulty events. The research methodology driving the progression of the work outlined in this thesis is presented in Figure 1.3 and follows the classic research method (Camarinha-Matos & Terminology, 2017).

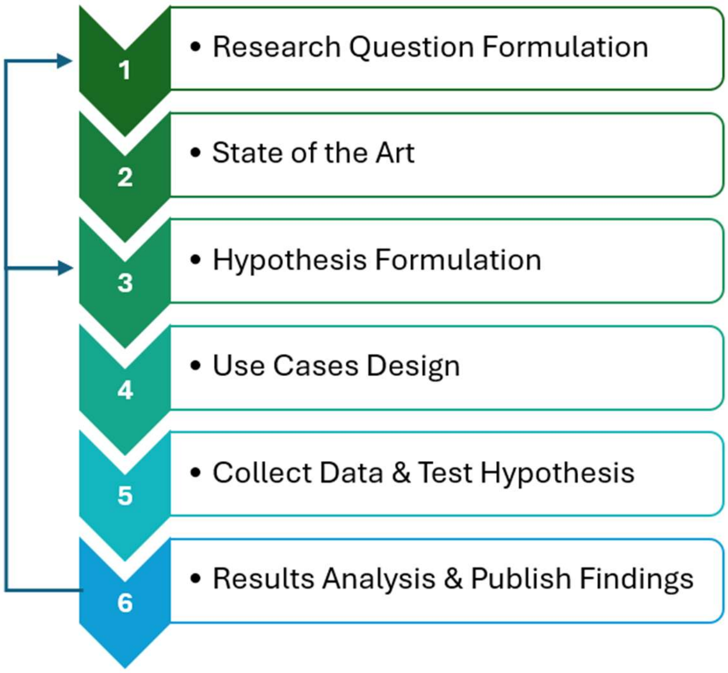


Figure 1.3 - Adopted Research Methodology for the thesis.

Behind this method, the research work was planned according to the six main phases as follows:

<u>Research Question Formulation:</u> In light of future considerations regarding energy resilience and the emergence of energy communities, this PhD thesis formulates one research question. It seeks to examine the enhancement of EnC resilience through the utilization of cooperative energy flexibility.

<u>State of the Art:</u> A comprehensive review of existing literature on energy communities and resilience methodologies was conducted to compile key findings published in this field. This review aimed to identify any existing gaps. One gap that was recognized pertained to the

applicability of resilience metrics that are better suited for MV/HV grids rather than LV grids and Energy Community levels.

Hypothesis Formulation: In alignment with the outlined research question and the findings presented, as well as the identified gaps in knowledge, the hypothesis was formulated.

Use Case Design: The use cases design is divided into two phases, first the formulation and development of a resilience framework, followed by the proposal of a set of metrics to measure EnC resilience. Second, the implementation of an EnC with different scenarios that will allow to test the proposed hypothesis, considering the different use cases and scenarios.

Collect Data & Test Hypothesis: Application of the proof-of-concept experiments to validation of use cases, leading to the collection of relevant data and the subsequent testing of the proposed hypothesis.

Results Analysis & Publish Findings: Results are collected and analysed, compared with the baseline scenario, to evaluate the proposed resilience framework.

Continuous publication of findings was considered during this research work, finishing in the present thesis. During the research work three research journal articles were published, among other conference articles:

- Mar, A.; Pereira, P.; F. Martins, J. A Survey on Power Grid Faults and Their Origins: A Contribution to Improving Power Grid Resilience. Energies 2019, 12, 4667 https://doi.org/10.3390/en12244667;
- Mar, A.; Pereira, P.; Martins, J. Energy Community Flexibility Solutions to Improve Users' Wellbeing. Energies 2021, 14, 3403. https://doi.org/10.3390/en14123403;
- Mar, A., Pereira, P., Martins, J. (2023). Storage System for Energy Communities. In: Camarinha-Matos, L.M., Ferrada, F. (eds) Technological Innovation for Connected Cyber Physical Spaces. DoCEIS 2023. IFIP Advances in Information and Communication Technology, vol 678. Springer, Cham. https://doi.org/10.1007/978-3-031-36007-7_3;
- A. Mar, P. Pereira and J. F. Martins, "Resilience Metrics applied to Renewable Energy Communities," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Tallinn, Estonia, 2023, pp. 1-5, doi: 10.1109/CPE-POWERENG58103.2023.10227398;
- Mar, A., Pereira, P. & Martins, J.F. Energy Community Resilience Improvement Through a Storage System. *SN COMPUT. SCI.* **5**, 794 (2024). https://doi.org/10.1007/s42979-024-03149-w.

1.4.1 Aimed Contributions & Objectives

As an emerging issue EnC resilience definition represents a lack in literature. This work aims not only to contribute to improve the resilience of the EnC when a fault or a power deviation occurs, taking into account the energy flexibility of an EnC as part of the proposed methodology, but also to clarify the concept of EnC resilience.

There are several goals that are expected to be addressed concerning the proposed RQ & H, namely:

- Definition of EnC resilience and associated metrics. Identifying the definitions and the metrics to evaluate Energy Community (EnC) resilience in the scenarios under examination is a crucial topic;
- Storage devices will be considered to understand how they can improve the EnC resilience when a fault occurs;
- Development of a resilience framework to manage the EnC and respective residential houses as well as user's flexibility;
- Use of optimization algorithms applied to the resilience framework in order to maintain the users' comfort when an anomaly occurs, and adjustments are necessary.

1.5 Thesis Outline

This thesis is structured in six chapters, including an introduction, four core chapters, and a conclusion. These chapters are further organized in various sections. Figures found within these chapters are labeled as (x.y), where 'x' denotes the chapter number and 'y' indicates the specific order number, tables and equations are numbered as (y) only. In-text citations for bibliographic references are provided in the format (Author, ..., Author, Year), where "Author" represents the surname of each author and "Year" signifies the publication year.
The work presented in the remaining of this thesis is structured into **5** chapters:

- <u>Chapter 2 - Electrical Power Grid and Resilience Assessment:</u> The foundational baseline for this research is established through a comprehensive review. A comprehensive analysis of grid faults and their underlying causes is presented, revealing potential weaknesses in the grid infrastructure. Additionally, an analysis of resilience strategies is conducted to identify and evaluate their effectiveness in improving the resilience of the EPG;

- Chapter 3 - Energy Communities and Resilience Assessment: This literature review offers a comprehensive study of energy communities with a particular focus on three key aspects: energy flexibility, household devices, and resilience assessment within energy communities;
- Chapter 4 - Framework to improve EnC resilience: This chapter presents the considered resilience framework to study and improve EnC resilience. It also introduces proposed resilience metrics aimed at evaluating the data gathered from experiment procedures;
- Chapter 5 - Use Case Design and Results Analysis: Outlines the use cases set up to test the hypothesis, detailing the considered EnC and delineating each scenario employed for data collection. Furthermore, presents and analyses the obtained results assessing the considered hypothesis;
- Chapter 6 - Conclusions: Provides a summary of the research conducted, emphasizing the principal activities undertaken and shedding light on key discoveries. Additionally, it outlines potential future research directions stemming from the findings of this study.

Thesis Conventions

The system of measurement units used, whenever possible, is the International System of Units (SI). In the mathematical symbols used, variables and scalars are represented in italics. Acronyms are presented in English nomenclature and are described in the list of acronyms.

2

Electrical Power Grid and Resilience Assessment

This chapter provides a comprehensive literature review centered on the analysis of EPG faults, and their underlying causes. Furthermore, it explores existing research on resilience across diverse fields of study, with a particular emphasis on the EPG.

2.1 Weaknesses in Electrical Power Grid

From a general point of view, the EPG, as illustrated in Figure 2.1, is a system that supports four main processes (generation, transmission, distribution and consumption). At any point of the grid a fault can occur, whether due to natural causes or operational errors. Furthermore, the evolution of the grid and the increased use of Information and Communication Technologies's (ICT) exposes the EPG to new threats, thus failures can also be due to physical or cyber-attacks.

Subchapter 2.1 and its subsections, highlights the weaknesses in EPG and reviews the related literature in order to understand which faults occur more often and what are their causes. The objective is to catalogue the knowledge identified in those studies, identify new research opportunities and relate them with EnC local grid

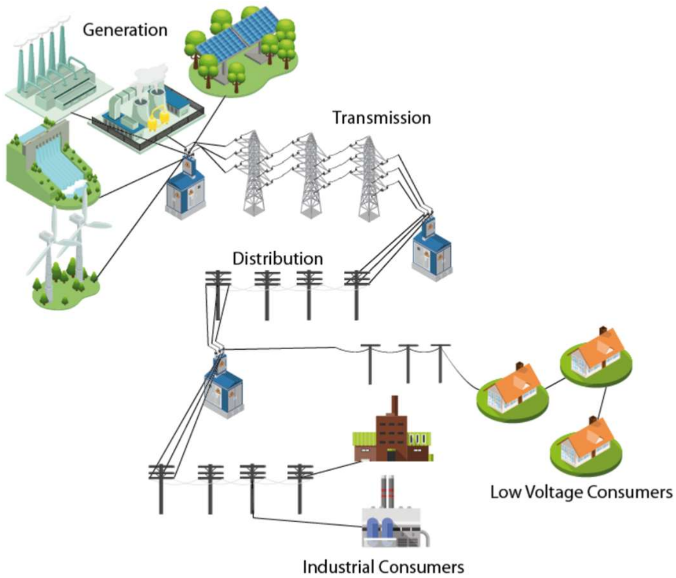


Figure 2.1 - EPG System

2.1.1 Faults and Related Causes

The nature of the cause will influence the respective consequences of the originated fault. If the cause origins a small-scale fault that will only affect some residential houses, it will be, most likely, easy to repair and could be solved in a few hours. Contrary, if it is a cause like a hurricane or a terrorist attack, that can origin a big-scale fault, like a black out or a cascading failure, it will affect a large geographical area and can take days or weeks to recover it. Big-scale faults also present serious economic and social consequences that will affect consumers. In case of an outage, a robust system is expected to recover and to have the capacity to restore to its initial state, when compared to a non-robust system. In the literature, three main causes clusters are reported:

- Natural Causes - different type of natural disasters that could lead to a fault on the EPG, such as hurricanes, storms, flooding's, earthquakes, tornados, heat waves or solar flares;
- Errors - causes related to human faults or equipment technical malfunction;
- Attacks - cyber-attacks like denial of service (must common), or human attacks such as terrorism.

These causes, when occur can lead to a wide variety of faults in the EPG. Different EPG faults referred in the literature are presented in Table 2.1, aggregated in three clusters that origin those faults: natural causes, where extreme events like hurricanes, storms or flooding are considered, errors, that can be due to a human or an equipment failure and attacks, of cyber or physical origin.

Table 2.1 - Faults reported in the literature.

Causes	Faults	Refs
Natural Causes	• Blackout • Cascading fault • Collapse of transmission towers • Damage and faults on substations • Downed wires • Lines disconnected • Fault currents • Fault of distribution and transmission lines • Fault of transformers • Faults and damages to overhead transmission and distribution lines • Flashover of transmission lines • Increase current • Line faults • Power loss • Line overloads • Localized blackouts and momentary interruptions • Short circuits • Stability limits exceeded • Substation flood • Thermal overloads • Transfer capability limited • Transformer slippage on the foundation and fall or complete collapse of the foundation • Underground cable loads affected • Voltage and frequency instabilities	(Abbey et al., 2014; Abi-Samra et al., 2010; Abi-Samra & Malcolm, 2011; Araneda et al., 2010; Bie et al., 2017; Billinton & Singh, 2006; Castillo, 2014; C. Chen et al., 2017; Ferreira & Barros, 2018; Gao et al., 2017; Hare et al., 2016; Hines, Apt, et al., 2009; Ji et al., 2017; Jufri et al., 2017; Z. Li et al., 2017; McClure et al., 2008; Mills et al., 2010; Nuti et al., 2007; Panteli et al., 2016; Panteli & Mancarella, 2015a, 2015b; Reilly et al., 2017; Shinozuka et al., 2007; Singh & Gupta, 2017; Y. Wang et al., 2016; Ward, 2013; Warnier et al., 2017; Xie & Zhu, 2011; Xu et al., 2015; Yates et al., 2014)
Errors	• Blackout • Cascading outages • Fault currents	(Andersson et al., 2005; Arghandeh et

	• Fault of transformers • Frequency deviation • Hidden faults of protection • Line faults • Line overloads • Voltage and frequency instabilities	al., 2016; Baldick et al., 2008; Colak et al., 2016; Hare et al., 2016; Hines, Balasubramaniam, et al., 2009; Kaitovic et al., 2015; W. Li & Zhang, 2014; Z. Li et al., 2017; Singh & Gupta, 2017; Vaiman et al., 2012; Y. Wang et al., 2016; Warnier et al., 2017)
Attacks	• Blackout • Cascading failures • Control infrastructures of Smart Grid affected • Delay, block or corrupt • Downed wires • Economic and social disruptions • Line faults • Localized blackouts and momentary interruptions • Power loss • Widespread damages	(Arghandeh et al., 2016; Bie et al., 2017; Castillo, 2014; C. Chen et al., 2017; Danzi et al., 2018; Erol-Kantarci & Mouftah, 2013; Fang et al., 2012; Hare et al., 2016; Kosut et al., 2011; Z. Li et al., 2017; J. Liu et al., 2012; Manandhar et al., 2014; Pagani & Aiello, 2013; Schuelke-Leech et al., 2015; W. Wang & Lu, 2013; Y. Wang et al., 2016; Zad Tootaghaj et al., 2018; Zhu et al., 2014)

In order to analyze any relation amongst causes and faults in EPG mentioned in the literature, a graphical representation using visualization software NodeXL was performed, following the strategy adopted in (Himelboim & Smith, 2017; M. A. Smith et al., 2009), and the size of the elements (squares and triangles) is proportional to the number of times they are discussed. With this analysis it is possible to understand the importance of studying the cause-fault relations and identify less studied areas. For this analysis, a total of 65 articles were studied and the same article can refer to different faults regarding one cause or vice versa, i.e, the same fault can be instigated by different causes. The performed analysis is translated into the graph presented in Figure 2.2, created using the Force Atlas algorithm (Jacomy et al., 2014). The blue squares denote causes, and the corresponding faults are denoted by the green triangles. in the surveyed literature.

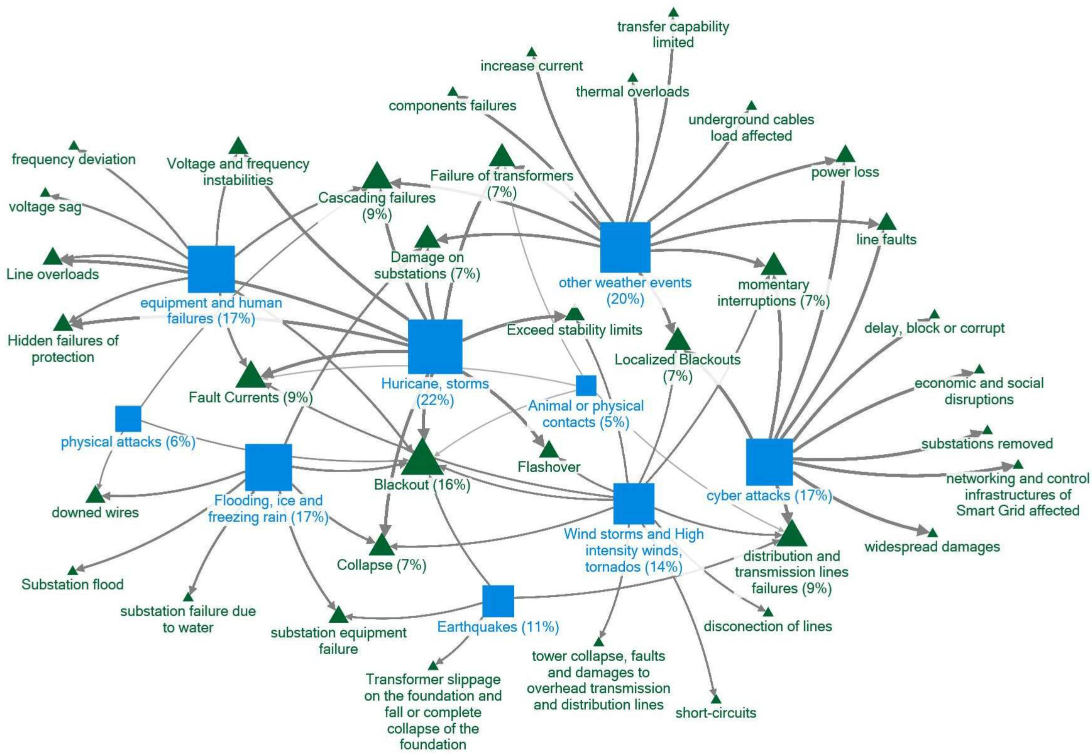


Figure 2.2. - Graph relationship of EPG's faults and causes.

Analyzing Figure 2.2 and considering the abovementioned clusters, the literature review shows 84% of articles mentioning faults due to natural causes. The most referenced natural causes are hurricanes and storms with 22% of articles where this cause is studied, followed by other natural events like heat waves or thunderstorms that were studied in 20% of all revised articles. Still considering the natural causes cluster, windstorms and tornados are addressed by 14% of the articles and earthquakes appears in 11% (Z. Li et al., 2017; Panteli & Mancarella, 2015a; Y. Wang et al., 2016; Xie & Zhu, 2011). Regarding the errors cluster, equipment errors and human failures were analyzed together and are mentioned in 17% of reviewed literature while animal or physical contacts with lines count only for 5% of the articles analyzed. Finally, in the attacks cluster, cyber-attacks are mentioned in 17% of considered articles. This is a higher percentage when compared with physical attacks that represents only 6% of studied literature for this work (Araneda et al., 2010; Xu et al., 2015).

The abovementioned causes are related to the resulting faults, represented in Figure 2.2 by green triangles. As seen before, the same fault can be originated by different causes. On Figure 2.2 the biggest triangles represent faults which are more mentioned in the literature. A blackout, that represents the biggest triangle in Figure 2.2, was referenced in 16% of the 65 articles studied to perform this analysis. The connection between hurricanes & storms and blackouts is denser than the line connecting physical attack and blackouts, meaning that in the range of studied articles, blackout is mostly related with hurricanes and storms rather than with physical attacks.

As mentioned before, different causes can originate the same type of errors. Looking into Figure 2.2, both "hurricane and storms" and "equipment and human failures", despite of different clusters, i.e, natural causes and errors, can origin the same type of faults such as Cascading failures and Fault currents, the second more referenced faults in studied articles, being mentioned in 9% of it.

2.1.2 Electrical Power Grid Resilience Approaches

Regarding the studied literature and causes-faults graph previously analyzed, some strategies are presented. Those strategies will improve the grid resilience trying to avoid some of the faults that occurred in other situations or decrease the magnitude of impact in the EPG. Figure 2.3 represents the relation between studied faults, presented in Figure 2.2, and different strategies. Considering the literature review, those strategies were categorized into four clusters:

- Prevention & management;
- Monitoring and fault detection;
- Smart grid-based solutions;
- Modelling and simulation.

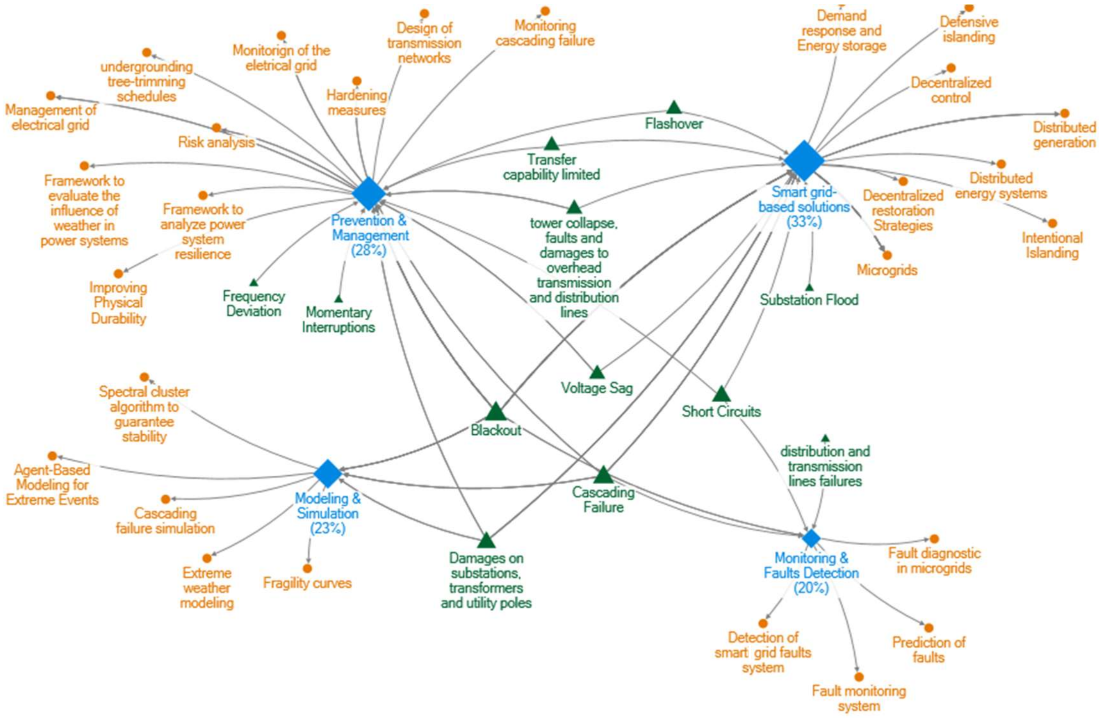


Figure 2.3. - Faults resolutions graph.

The four clusters are represented by blue squares and each of them are associated with a set of strategies that different authors have presented in their studies. Based on the performed literature review, which led to Figure 2.3, 28% belongs to “Prevention and management” strategies and are correlated with almost every fault represented in Figure 2.2. This type of strategy is normally carried out to perform an easiest knowledge of the power system as well as to increase the security of the grid before an outage. Also, “Smart Grid-based strategies” that are referenced in 33% of the analysed articles, had an increase of applications and many of the authors refers them as a viable way to improve the quality of EPG and decrease the consequences of a fault.

Monitoring the system and detecting faults as soon as possible is also an important approach to increase EPG resilience. From the carried out analysis, 20% of the authors consider monitoring and fault detection methods in order to guarantee that issues are detected before the outage or in time to be solved without an extreme consequence.

Blackouts and cascading failures, two extensively studied faults in the articles reviewed for this study, can have significant repercussions, resulting in outages that impact a large number of people. As shown in Figure 2.3, modelling and simulation are considered as a solution for 23% of the authors mentioned in this literature review, and is one of the considered methods to identify possible solutions and preventive actions to apply when a blackout or a cascading failure occurs.

A. Prevention & management

As it is possible to observe in the Figure 2.3, almost every fault, represented by green triangles, has as a possible solution prevention, management and monitoring. Some of the most common actions of prevention are presented in this subchapter, keeping in mind that some events are possible to be predicted and/or prevented, while others do not.

Structural changes in the infrastructures of EPG can make it less susceptible to damage, so reinforce the utility poles and overhead lines can be an option to prevent damages in case of extreme events (Electric Institute, 2014; Xu et al., 2015). One construction approach to avoid damage to EPG during floods is to elevate the substations. Also, the risk management of EPG will help to understand what can be changed or improved in order to decrease the faults and susceptibilities of the electrical grid (Kaitovic et al., 2015; Papic et al., 2011; Shiwen et al., 2017).

The technique of undergrounding the overhead distribution grid is the most obvious solution and would avoid storms, lightning strikes or even falling trees from destroy lines and poles. However, this solution has high costs and it is not recommended since does not guarantee total reliability of the system (Davis et al., 2014; Electric Institute, 2014; McGranaghan et al., 2013). Another challenge associated with this solution is that in underground distribution systems, restoration times may be prolonged due to the challenges of accessing the cables. The most viable solution is to choose the distribution lines areas where it could be more dangerous and more propitious to affect the line and underground just those portions.

On the other hand, for those that would not be underground, the structural reinforcement of distribution grid is other used hardening solution. Some of the suggested practices are to install guy wires or use steel or composite poles in order to reinforce the existent ones (Davis et al., 2014). Also, to prevent and combat equipment damage due to flooding or strong rains the application of hydrophobic coatings or the application of grade B[1] construction, that are the stronger standard of construction, are mentioned in (Brown, 2010).

[1] **Grade B** - The NESC recognizes three grades of construction which may be used in different areas: N, C, and B. Using Grade B construction results in the highest strength and largest safety factors construction.

Another important topic related to prevention and management is risk analysis and maintenance of the EPG components, as seen in Figure 2.3. The EPG assessment evaluates the electrical and mechanical health condition of the distribution system as well as of the electrical equipment. This will enable the determination of the intended operational lifespan as initially designed and installed. The process entails the identification and resolution of any defects, deficiencies, hazards, or weaknesses within the electrical power system, ensuring its continued performance without compromising reliability (Davis et al., 2014; Sharifi & Yamagata, 2016; Waterer, 2012).

As part of their management duties, grid distribution system operators (DSOs) are responsible to support power flow and ensure quality of supply, for maintain and reinforce the reliability of the EPG as well as for a fast and secure grid restoration when a fault occurs (P. Hinkel et al., 2019; Poudineh & Jamasb, 2014). The DSOs are able to interact with the distributed energy resources and coordinate the EPG depending on the actual needs. Procedures addressing EPG reconfiguration, monitoring and fault detection are also controlled by DSOs (Madureira et al., 2013). Nowadays the role of grid operators is more discussed regarding the huge deployment of renewable energy sources and consequent deployment of distributed energy technologies. In (Prostejovsky et al., 2019) authors carry out a series of studies in order to understand how necessary and fundamental human work is related to the grid control, concluding that, when dealing with extreme events and abnormal situations that can occur in EPG, human intuition is considered indispensable.

In Portugal, the core objectives of the main DSO (E-REDES) are as follows:

- Ensure the provision of electricity to all consumers with quality, safety, and efficiency;
- Promote the development of the distribution network to support the energy transition;
- Ensure, impartially, the availability of services to market agents;
- Maintain the distribution network and ensure the security of supply; ensure compliance with quality standards;
- Enable the integration of renewable production into the distribution network: support the increase of energy efficiency in consumption;
- Provide services to consumers, retailers, and other agents in the electrical sector.

B. Monitoring and Fault Detection

Monitoring is a method that could be used to predict faults or to monitoring in real-time the performance of the EPG (Shiwen et al., 2017). In (McGranaghan et al., 2013), a distributed computation method is used to near real-time monitoring of grid robustness in order to detect cascade failures. Moreover, in (Davis et al., 2014), authors have developed a system to detect fault location and makes fault monitoring in real-time in order to be able to manage the EPG during faults. They created three different monitoring systems that only monitor the electric current but have different locations for the sensors used on the EPG. This will allow quickly identify faults, enabling grid operators to make informed decisions and improve grid management. By reducing outage times and enhancing grid resilience, this system can contribute to improved safety and overall grid efficiency.

Fault detection and its location also have an important role in the restoration of the system and will help to improve the resilience of the EPG since the faster the fault is located faster will be repaired. Fault location methods are applied to transmission and distribution systems and use different approaches that typically consists of two categories: model-based and data-driven approaches (Hare et al., 2014; Yates et al., 2014).

C. Smart grid-based solutions

Smart grid technologies integrate advanced communication, control, and monitoring capabilities into traditional power grids, enabling real-time data collection and analysis. By leveraging sensors, meters, and automation, smart grids optimize energy distribution, improve reliability, and facilitate the integration of renewable energy sources. These solutions enable utilities to better manage grid operations, respond to outages more rapidly, and empower consumers with greater control over their energy usage.

A microgrid encompasses small-scale Electrical Power Grids (EPGs), Low Voltage (LV) distribution systems, distributed energy resources (such as microturbines, photovoltaic (PV) systems, fuel cells, etc.), along with storage devices (including batteries, energy capacitors, etc.). Microgrids can indeed be considered a smart grid-based solution since incorporate many elements of smart grid technology, such as advanced communication, control, and monitoring systems, to optimize their operation and enhance their functionality. Microgrids can operate in a non-autonomous way, where they operate connected to the main grid, or in an autonomous way, the island mode, where the system is disconnected from the main grid and is able to work by itself (Davis et al., 2014; Hatziargyriou, 2013). Furthermore, microgrids can act as the physical backbone of EnCs.

The implementation of microgrids has multiple advantages from different points of view. From a utility standpoint, on one hand microgrid can improve available generation providing more power to a larger area. On the other hand, the proximity of distributed generation to loads yields two significant benefits: the reduction of losses and the ability to be a substitute for network resources, due to the reduction of power flows in transmission and distributions lines (Davis et al., 2014; Hatziargyriou, 2013). Some advantages from grid operator's and customers point of view are presented in Figure 2.4.

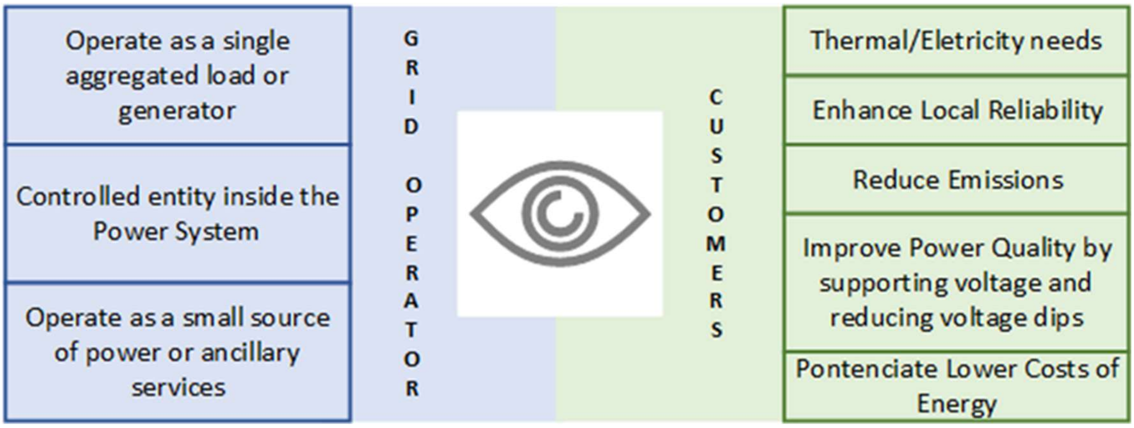


Figure 2.4. - Grid operator's and Customer's point of view regarding Microgrid.

Creating an EPG formed only by interconnected microgrids, known as networked microgrids, is one approach that uses microgrids to improve the resilience of power systems. This methodology consists in establishing a group of microgrids connected between them and able to support each other with local generation capacity and to actuate to support an emergency microgrid. When in normal operation, microgrids are autonomous systems without power interactions with the main grid or other microgrids. During emergency mode, a failing microgrid can be supplied by other microgrids, thereby mitigating the failure and ensuring continued supply for customers dependent on it during the repair period. (Z. Li et al., 2017).

Regarding the resilience of EPG, microgrids are used to perform load control, dispatchable and non-dispatchable units and energy storage units. Additionally, research suggests that integrating microgrids into EPGs enhances the overall resilience of the system (Kelly-Pitou et al., 2017; Khodaei, 2014). It is crucial to conceptualize the frameworks in which a microgrid can be beneficial, considering its potential, to comprehend how to leverage it for optimizing the operation of the Electrical Power Grid (EPG) (A. Peiravi, 2009).

The intentional islanding consists of split the EPG into stable islands, defining, in real-time, the branches that should be disconnected from the main grid, in order to isolate affected components whose failure would trigger cascading events (Brodzki et al., 2015; Ding et al., 2013). The schemes of islanding are delineated according to graph partitioning and should be used only as last resource, after the failure been detected but before the system becomes uncontrollable. To realize the islanding, some constraints are important to take into account to guarantee the functionality of the islanded grid. Those constraints are generators coherency, load generation balance, voltage and frequency stability, among others (Ding et al., 2013; Zeineldin et al., 2005).

This method, that helps to protect the EPG during an outage and consequently guarantees their functionality during the failure event, can also be used to improve the quality of supply indices, to optimize load scheduling and prevent the big scale blackouts, consequently, improves the reliability of the grid (Esmaeilian & Kezunovic, 2017). The islanding approach can be solved using different methods and considering diverse constraints. The constrained spectral clustering, (H. Zhang et al., 2017), the multilevel kernel K, (Brodzki et al., 2015) or artificial bee colony algorithm, (Kezunovic, 2011) are examples of it.

Despite Distributed Generation (DG) has been mentioned, at the beginning of this work, as a possible weak point in the EPG, brings many advantages to distribution grids and can be a usable source of power when the islanding method is applied to some branches of the grid (Mohammadi et al., 2015). Although some concerns like the frequency of connection and disconnection from the EPG, regarding renewable sources-based, or the change of the main aspects of the radial distribution network, DG presents a considerable number of advantages concerning the integration on EPG (Ates et al., 2016; Norshahrani et al., 2017). In addition to its economic benefits, the installation of DG can enhance the voltage and power quality of the EPG while alleviating transmission system congestions that may occur (Caramia et al., 2017; Torrent-Fontbona & López, 2016). Also, with the use of DGs the need to build new transmission lines decreased and it is possible to increase grid's flexibility throughout load balancing, integration of diversified energy sources and decentralized power generation.

Overall, the deployment of DG technologies introduces versatility and adaptability into the grid, allowing it to better accommodate fluctuations in supply and demand, integrate renewable energy sources, and respond to dynamic operational requirements.

D. Modelling and simulation

Modelling the EPG and simulating events together with other type of simulation, like weather forecast, is an approach that helps to understand how a grid is affected in fault moments and will help to decrease the consequences of it. For instance, in 2012, the Hurricane Sandy caused a catastrophic impact in New Jersey, with US$68 billion in damages, affecting the entire Atlantic coastline electrical infrastructure, with 69 and 102 electric substations damaged due to floods, 2500 transformers repaired, more than 4400 distribution poles replaced, and 286 lives taken (Abbey et al., 2014; Chang & Wu, 2011). After this catastrophe, a control simulation and weather model were developed to try to understand the storm and future aspects to improve. With this model was possible to simulate what would happen if another storm occurred, like the estimated number of substations affected by flooding or damages caused by winds in the EPG.

Also, regarding cascading failures, normally simulation of cascading failures is done to understand what grid branches will be more affected and where solutions like island mode can be applied to decrease the cascade failure effect (Singh & Gupta, 2017; H. Zhang et al., 2017).

2.2 Resilience Concept

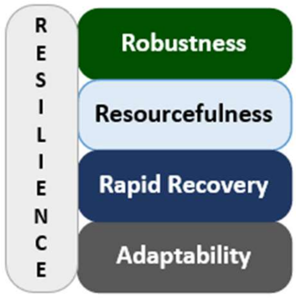
When discussing resilient systems and considering authors who incorporate the term "resilience" into their research, various definitions are employed within the literature. Within Physics research area, resilience means “the capacity of a body to recover the original shape after suffering shock or deformation” or “the ability to overcome or recover from adversities”. Some authors argue that the widest definition of the resilience concept must be assumed since it had become a term with different definitions along the years (Hodgson et al., 2015).

Different terms like robustness, risk assessment, reliability, adaptability, among others, are commonly used without differentiation, which may be misleading, since these concepts may be partial characteristics of a resilient system without replacing the concept of resilience itself (Arghandeh et al., 2016; Bishop et al., 2011; Francis & Bekera, 2014; Hodgson et al., 2015; X. Liu et al., 2017; Madni & Jackson, 2009; Panteli & Mancarella, 2015b). Some of those terms are listed below:

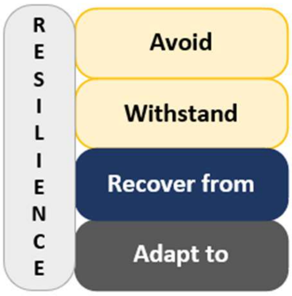
- Robustness/Resistance refers to the ability of having strength in order to resist to changes without losing stability, i.e., a robust system continues its operation, during attacks or failure events, and can resist to low probability events but with large consequence. In a robust system, if a damage occurs the system will resist but the damage will stay until it is repaired. Consequently, and from an engineering point of view, the robust system can be more fragile than others with different features such as the capacity to recover after an event;
- Reliability refers to the system's capacity to ensure components' performance under specific conditions and over a specific period of time. Reliability is related with the accuracy of the system and if the components are working in a range of conditions, then the system security will be assured;
- Adaptability of control systems aims proper functioning by adjusting their control parameters and algorithms according to uncertain changes. These disturbances can be regarded as undesirable incidents at the process layer and the system is supposed to adapt itself to those changes.

Four different groups of main characteristics, considered important for the creation of a resilient system by two different authors with relevant work in resilience area and government identities, are illustrated in Figure 2.5.

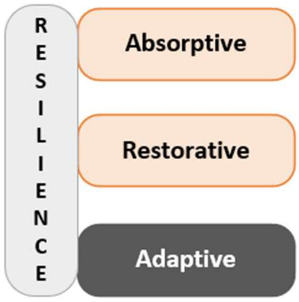
a) Main Characteristics from the point of view of Cabinet Office U.K, adapted from (Panteli & Mancarella, 2015b).



b) Main Characteristics by National Infrastructure Advisory Council USA, adapted from (Panteli & Mancarella, 2015b).



c) Features of a resilient system, adapted from (Madni & Jackson, 2009)



d) Main characteristics that form the resilience capacity of a system, adapted from (Francis & Bekera, 2014)

Figure 2.5 - Different Perspectives of Main Features of a Resilient System

The Cabinet Office [2]defines a resilient system as a system with resistance to anticipate and prevent the outage or damages and with the necessary reliability to guarantee the operation of the system under certain conditions, Figure 2.5a). According to them, should also be a system with a rapid and active recovery from an outage (Panteli & Mancarella, 2015b)

Figure 2.5b) illustrates the point of view of National Infrastructure Advisory Council (NIAC), USA, a resilient system should be robust, resourceful, with rapid recovery and adaptable, (Berkeley, 2010). With this characterization, NIAC, states that a resilient system, more than a system that have the capacity to operate during an outage, prioritizing the options and able to back to normal operation fast, should be a system able to learn with the outages, in order to reinforce the system and introduce new tools or technologies, preventing or mitigating similar events in the future. Analyzing Figure 2.5c) and Figure 2.5d), both combine similar

[2] Cabinet Office - The Cabinet Office is a ministerial department of the Government of the United Kingdom.

characteristics shared by different authors. For example, both, (Madni & Jackson, 2009) and (Francis & Bekera, 2014) defend that a resilient system needs to adapt to the occurred events and reconfigure the system after the failures. Additionally, in Figure 2.5c), the author argues that it is essential to avoid disruptions through anticipation and predictive capabilities, as well as to withstand disruptions through the robustness of the system. In Figure 2.5d), besides the adaptative capacity of the system, Francis & Bereka, mention that a system should also be able to absorb the impacts of perturbations as well as the capability to adjust to undesirable situations. This means that a system resilience is not only a specific feature, but it is based on a group of different characteristics that make the system able to adapt during an outage and to recover quickly.

Aforementioned, resilience is the ability of a system to recover as fast as possible from an adversity, however this could take different views and applications regarding the knowledge field where resilience is being considered. Different areas of application will be analyzed in the next subchapters, defining the necessary to modulate a more complete resilient system. Resilience is a concept that could be applied to a wide range of disciplines whether scientific, social, human or physical knowledge fields (Molyneaux et al., 2016), with different approaches but with a common goal: "resilience is the ability to face adversity" (Southwick & Charney, 2018). Some resilience views, in different fields of knowlegde, are described as follows.

<u>Ecology</u>

Holling, responsible for introducing the resilience concept into the ecology discipline, stated that resilience implies the capability of a system to preserve its behavior after some perturbation, i.e., the ability to withstand any change during a trouble and shift from one stability domain to another in order to maintain diversity (Holling, 1973). Twenty years later, Holling stated that disturbances can saw their magnitude absorbed before the system changes to another equilibrium state (Holling, 1992). On the contrary, other authors argue that resilience represents the recovering process of a system after some disturbance (Grimm & Wissel, 1997; Standish et al., 2014). On the other hand, Walker claims that a resilient system should be able to self-organize itself during a perturbation, (B. Walker et al., 2002). Ecological resilience can then be defined as a system's ability to absorb changes during a perturbation, maintaining its own characteristics and functionalities.

Organizational

For business ecosystems, Shefii has defined organizational resilience as the capacity to keep or recover to a steady state, allowing to continue normal operations, (Sheffi, 2006). Also, Nemeth considered company's resilience as the speed that companies can return to normal performance after a business change, such as a disruptive event like an inventory (Nemeth & Olivier, 2017). On the other hand, Patterson defends Collaborative Cross-Checking as a strategy that would improve organizations' resilience (Patterson et al., 2007).

Engineering

Opposite to ecological resilience, that considers the unpredictability of hazards, engineering resilience considers that natural disasters can be predicted, and prediction systems are reliable enough to forecast those events.

Although all of them are addressing the engineering knowledge field, several authors consider different meanings for the resilience concept. Marjolein states that engineering resilience is focused on predictability and efficiency, considering that a resilient system has resistance to disturbance and has high speed of return to stable state (Sterk et al., 2017). Although, for Sharifi engineering resilience is based on risk assessment as well as on management of systems and intends to improve the robustness of critical infrastructures, providing a rapid recovery to the initial point (Sharifi & Yamagata, 2016). The American Society of Mechanical Engineers (ASME), considers the resilience of a system as the ability to withstand internal and external disturbances without compromise its performance (ASME Innovative Technologies Institute., 2009). For the NIAC the ability of a system to predict, adapt and quickly recover from an unexpected event is what defines its resilience (Bush, 2009). Youn defined resilience of an engineering system as the result of the combination between reliability and restoration of that system (Youn B et al., 2011).

Summing up, an engineering system resilience is, on one hand, a system with the ability to maintain its performance during the outage, providing reliability and adaptability. On the other hand, it is a robust system with resistance to disturbances and with the ability to make a quick recovery after the outage.

2.2.1 Electrical Power Grid Resilience Framework

The EPG faces now greater and more frequent risks of interruption, owing to extreme weather events, human faults or attacks, aging and due to the astonishing rate at which the electric grid diversifies its energy resources and technology. Centralized power plants, transmission lines, substations and power transformers as well as DG are considered potential weak points since even a minor incident can cause a power outage.

As stated before, resilience can have different criteria and meanings. A clear resilient system's definition in each field is important in order to apply the actions that increase the resilience of the system in each area, from management through construction actions or other system recovering strategies. Arghandeh attempted to clarify and standardize the definition of resilience within EPG (Arghandeh et al., 2016). For this purpose, the author carried out a study of the different terms used, and often confused with resilience, in the literature. This study concluded that a resilient system should evaluate risks and perform a set of actions, over a period of time, to ensure its functionality against risks, attacks or faults. For the Cabinet Office, infrastructure resilience is obtained from a good system and network design in order to ensure the needed resistance, reliability and the capability to switch or divide the system into other parts (redundancy), to maintain the continuity of services during an outage (Cabinet Office, 2011). Also, to present a good resilience, the system should acquire the capability to respond and recover. For Jufri, EPG resilience is assessed based on the amount of damage caused by an extreme event on the grid or by the capability that the grid has to keep functioning during damage conditions (Jufri et al., 2017).

The EPG resilience framework presented above has two typical structures: assessment and improvement. On one hand, in the grid assessment the conditions of the grid are studied, and the risks are evaluated. On the other hand, the EPG system is improved in order to maintain the continuity of service during an outage and reduce the required time to return to its normal state.

Several authors have tried to characterize the resilience at system using a temporal line. Figure 2.6 and Figure 2.7 present the so-called resilience triangle and trapezoid, respectively. The resilience triangle was introduced by Bruneau (Bruneau et al., 2003; Ouyang et al., 2012), considering that the system does not have a degraded state. This curve was first used to study systems resilience considering the states presented in Figure 2.6. Panteli and Mancarella, argued that the resilience triangle approach could not be able to capture some critical resilience dimensions experienced by power systems, for example how long the infrastructure remains in one post degraded state before starts the restoration state (Panteli, Trakas, et al., 2017).

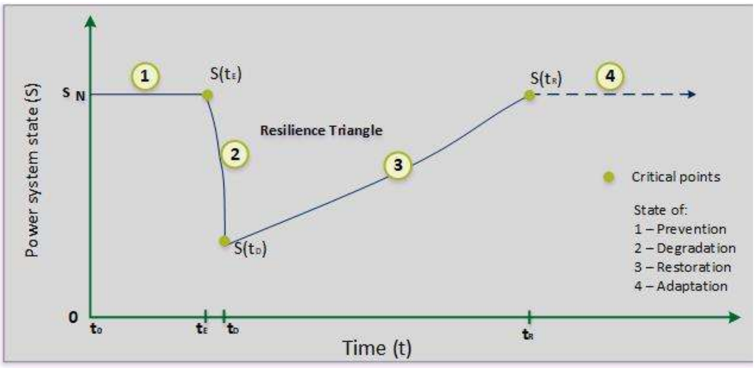


Figure 2.6 - Grid conditions associated with an extreme event , resilience triangle, (adapted from (Jufri et al., 2019)).

In 2017, Panteli argued that for a system to be able to deal efficiently with the conditions associated with a fault, it must present the characteristics of the resilience trapezoid, presented in Figure 2.7. In this case it is possible to represent the different states that electrical power systems experience through during an event as well as the transitions between them (Lu et al., 2018; Panteli, Mancarella, et al., 2017).

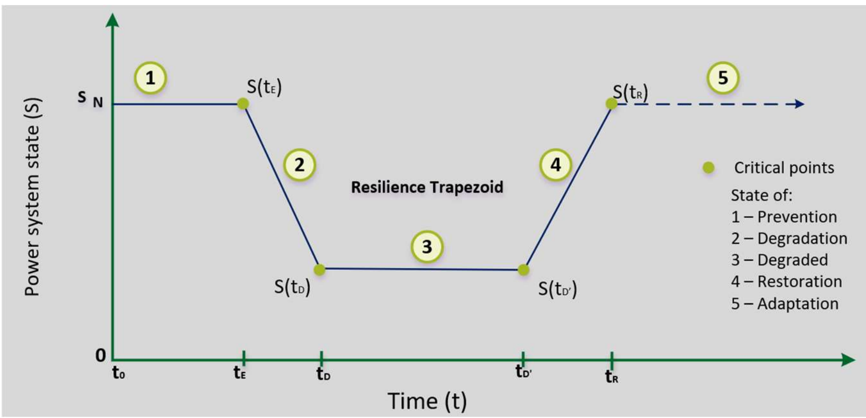


Figure 2.7 - Resilience Curve of EPG , (adapted from (Jufri et al., 2019), [57]).

Initially, the grid is under normal conditions, S_N, until an extreme event occurs at time t_E as presented in Figure 2.7. When an extreme event occurs, the grid functionality goes to the degradation state until time t_D, the worst condition of the system, S_{tD}). If no restoring actions are carried out the system will remain in a degraded state until the implementation of restoring actions. At time, $t_{D'}$, the restoration process will start and continues until the system reaches initial state of functionality, at time t_R.

2.2.2 Electrical Power Grid Faults Resolutions vs. Resilience Curve

Different states of grid conditions presented by the trapezoid resilience curve figured in Figure 2.7 suggests different approaches in order to improve the resilience of EPG. Considering the fault resolution clusters above mentioned, it is possible to correlate them with the states of the mentioned curve. This correlation is shown in Figure 2.8 and explained below.

- Prevention state - At this state, the grid is operating under normal conditions, being applied the preventive and management actions. This type of actions, presented in Figure 2.3, will help the system to deal successfully with future events. Moreover, monitoring actions as well as modeling and simulation can be applied at this stage since this kind of actions can be helpful to understand how the system will react to an event or to take some pre-event actions (Davis et al., 2014);
- Degradation state - This state reflects the progressive deterioration of the grid, ultimately reaching its worst state. As explained in Figure 2.7, at this state the magnitude of fault is represented and can be calculated with the evaluation of the failure state of grid components during the event. To do that, monitoring and fault detection actions will be taken into consideration so the faults can be located, and grid components can be monitored. If the intensity of the event exceeds the withstanding capability of the grid components, the damaged part could lead to a cascading failure event being important to know where the faults have occurred (Cadini et al., 2017; Chang & Wu, 2011);
- Restoration state - When a restoration action is taken, this state begins. In this state occurs the transition between the damaged grid condition and its pre-event condition, the prevention state. Different types of actions can be applied to restore the grid to its initial state. However, the use of microgrids and/or demand response actions have been mentioned in a considerable number of reviewed papers. As mentioned above, microgrids can be used to isolate the affected area from the main grid and avoid a cascading failure event;

- **Adaptation state** - Ultimately, the adaptation phase occurs when the grid is fully restored, and the preventive measures mentioned in this subsection are once again implemented on Figure 2.3.

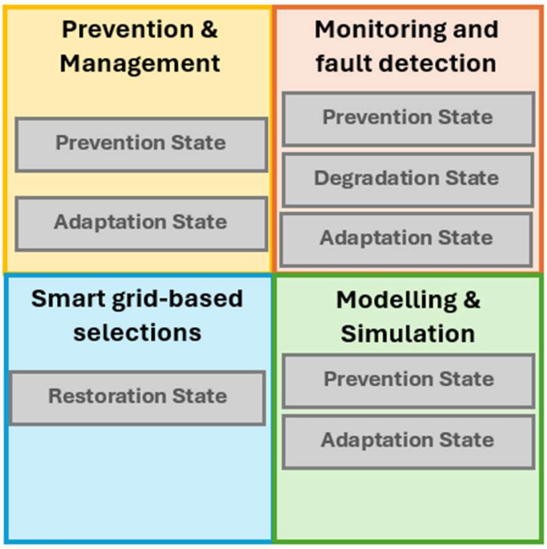


Figure 2.8. - Fault resolution clusters and Resilience curve relation.

In this thesis the focus will be on the restoration state of the resilience curve, understanding how to improve the resilience of EnCs, during the restoration state, without using energy from the main grid.

3

Energy Communities and Resilience Assessment

This chapter provides a comprehensive literature review centered on Energy communities, underlying several types of communities. Furthermore, it explores existing research on resilience metrics for EnCs resilience assessment.

3.1 Energy Communities

The European Union (EU) introduced the concept of energy community into the EU law through the Clean Energy Package (CEP) (Lowitzsch et al., 2020). The concept of energy community, as viewed by the CEP, comprises two main categories: Citizen Energy Community (CEC) and Renewable Energy Community (REC), as outlined in EU Directives 2019/944 and 2018/2001 respectively. The CEC, as defined by the EU, is a voluntary legal entity at the local level, engaging in various energy-related activities including electricity generation, distribution, supply, consumption, aggregation, energy efficiency services, Peer-to-Peer (P2P) energy trading, and electric vehicles (EVs) and energy storage. While the definitions of CEC and REC are similar, there are differences in focus. For instance, REC includes various energy carriers such as electricity, thermal, gas, and water, while CEC primarily centers on electricity. Additionally, REC emphasizes renewable energy generation for local consumption, whereas CEC activities may extend to distribution, aggregation, energy efficiency services, and P2P energy trading (Dorahaki et al., 2023).

An Energy Community (EnC) embodies a collective approach to energy management and consumption, where individuals, residential houses, businesses, or even entire communities collaborate to optimize their energy resources and practices. Key topics of the energy community may include:

- **Decentralization:** EnCs often operate at a local or community level, promoting decentralized energy production and distribution. This decentralization can enhance energy resilience, reduce transmission losses, and increase energy autonomy;
- **Renewable Energy Integration**: EnCs prioritize the use of renewable energy sources such as solar, wind, hydro, and biomass. By harnessing locally available renewable resources, EnCs reduce reliance on fossil fuels, lower carbon emissions, and contribute to environmental sustainability;
- **Demand-Side Management**: EnCs employ strategies to manage energy demand efficiently, including load shifting, demand response programs, and energy efficiency measures. By optimizing energy consumption patterns, EnCs can reduce peak demand, minimize costs, and alleviate strain on the grid;
- **Community Engagement**: EnCs foster active participation and collaboration among community members, encouraging shared responsibility for energy decision-making and resource management. Community engagement initiatives may include education campaigns, energy cooperatives, and community-owned energy projects;
- **Resilience and Self-Sufficiency**: EnCs aim to enhance energy resilience by diversifying energy sources, improving infrastructure robustness, and implementing contingency plans for emergencies. By building resilience, EnCs can better withstand disruptions such as natural disasters, grid outages, or supply chain disruptions.

Overall, the EnC concept represents a holistic approach to energy transition, emphasizing sustainability, resilience, and community empowerment. As societies seek to address climate change, energy security, and socio-economic disparities, the adoption of energy community principles offers promising pathways towards a more sustainable and equitable energy future (Yiasoumas et al., 2023). Also plays a crucial role in reinforcing robust social norms and encouraging active citizen involvement in the energy system. These initiatives share common

characteristics, including a dedicated commitment to locality and community participation in both the processes and outcomes (A. Smith et al., 2016).
In accordance with EU legislation, their primary objective is to foster social innovation by engaging in economic activities that extend beyond mere profit-making (Caramizaru et al., 2020).

Energy Communities (EnCs), especially those based on microgrids, are recognized as pivotal stakeholders in modern Energy Prosumer Grids. The operation of a microgrid-based EnC poses significant challenges due to the inherent uncertainties, complexities, and often conflicting objectives involved. An EnC microgrid-based denotes an Energy Community operating within a microgrid framework. Microgrids are decentralized energy systems capable of autonomous operation or integration with the main grid. Within an EnC microgrid-based framework, participants collaborate to manage and distribute energy resources, including renewable energy generation, energy storage, and demand-side management, within the microgrid's boundaries. This localized approach enhances autonomy, resilience, and efficiency in energy distribution and consumption, while concurrently fostering sustainability and community empowerment (Trivedi et al., 2022).

EnCs are established by including energy conversion, transmission and consumption on a community scale. Energy flow balancing, reducing peak load during peak hours, territorial energy planning, interconnection of different energy carriers or mitigation of environmental impacts are relevant items that EnC can cover under the energy context (Ceglia et al., 2019). On the other hand, when a fault occurs in the EPG, with consequent power decrease or power outage, EnC can be a solution not only to maintain the power supply inside the community as well as to improve the resilience of EPG as an all. The focus of this work will be the study within the EnC in order to have an understanding of the use of energy flexibility by users within the community.

3.1.1 Energy Communities and Flexibility

A fundamental tool that EnCs can use to help their energy management is the usage of their energy flexibility. The concept of energy flexibility encompasses the ability of energy systems, whether they are part of a power grid, buildings, or industrial facilities, to adapt their energy consumption, production, or storage in response to changes in supply, demand, or grid conditions. Energy flexibility enables these systems to effectively accommodate fluctuations in renewable energy generation, shifts in energy prices, grid limitations, or alterations in demand patterns while upholding stability and reliability.

Achieving energy flexibility entails employing various strategies, including demand response initiatives, energy storage technologies, smart grid solutions, flexible generation resources, and advanced control systems. By enhancing flexibility, energy systems can optimize their performance, minimize costs, enhance grid stability, and facilitate the seamless integration of renewable energy sources. This contributes to the development of a more sustainable and resilient energy infrastructure.

Within both, buildings and communities, several loads can be controllable, leveraging their flexibility to ensure additional power controllability during specific times of the day or in the event of faults. The building sector exerts significant influence on energy flexibility, driven by a multitude of factors. These factors encompass occupants' behavior and comfort preferences, the deployment of technologies such as heating or storage equipment, and the integration of control systems facilitating user interactions. Together, these elements shape the dynamic landscape of energy consumption and management within buildings and EnCs, defining their capacity to respond to unexpected energy demands and external circumstances (Junker et al., 2018).

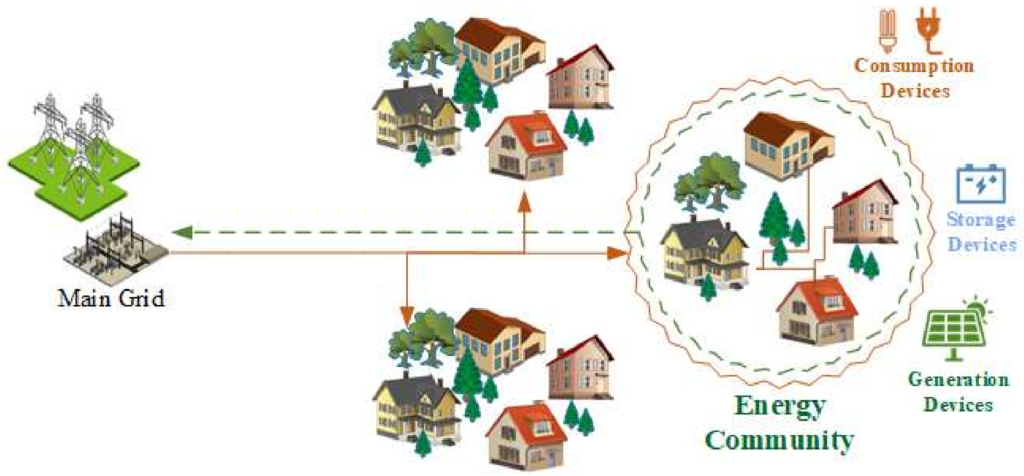


Figure 3.1 - Energy community scheme.

In this work, the term Energy Community refers to a group of users interconnected by a local Low Voltage (LV) grid, as depicted in Figure 3.1. On an EnC, besides the possibility of storage devices, each residential house can have renewable energy production as well as consumption devices that are possible to control. Instead of use the production for their own consumption, the user can store and share it with the EnC in order to be used when it's necessary. On the other hand, considering consumption devices' energy flexibility, it is possible to manage the community's energy to improve the EnC resilience when a change occurs in the main grid.

3.1.2 Zero Emission Buildings

The concept of Nearly Zero Energy Buildings (NZEBs) emerged as a cornerstone in the EU's strategy to decarbonize the building sector. Introduced by the Energy Performance of Buildings Directive (EPBD) in 2010 and revised in 2018, NZEBs mandate that all new buildings from 2020 must exhibit exceptionally high energy performance and cover nearly all their energy consumption from on-site or nearby renewable sources. This directive marked a significant step towards reducing the building sector's environmental footprint.

NZEBs contribute to lowering greenhouse gas emissions, decreasing reliance on fossil fuels, and enhancing energy security. By prioritizing energy efficiency and renewable energy integration, these buildings optimize resource utilization and minimize operational costs.
Different types of energy communities are mentioned in the literature. Some of them consider NZEBs in their composition (Burduhos et al., 2018); Positive Energy Buildings (PEBs) (Paci & Bertoldi, 2020); regular houses with controllable devices and renewable energy production that are aggregated using their combined flexibility in the community (Pontes Luz & Amaro E Silva, 2021); prosumers; or even plain consumers (Sarfarazi et al., 2020). The variety of houses' type that can coexist inside an EnC is illustrated in Figure 3.2.
NZEBs epitomize structures with exceptionally high energy performance, capable of both generating and consuming energy. These buildings are typically connected to the grid, allowing them to export surplus energy during favorable conditions and import energy from the grid or storage during periods of high demand or low generation. For instance, a photovoltaic (PV) based NZEB may exhibit an energy importing profile during winter and an energy exporting profile during summer months (Jaysawal et al., 2022; Kurnitski et al., 2011).

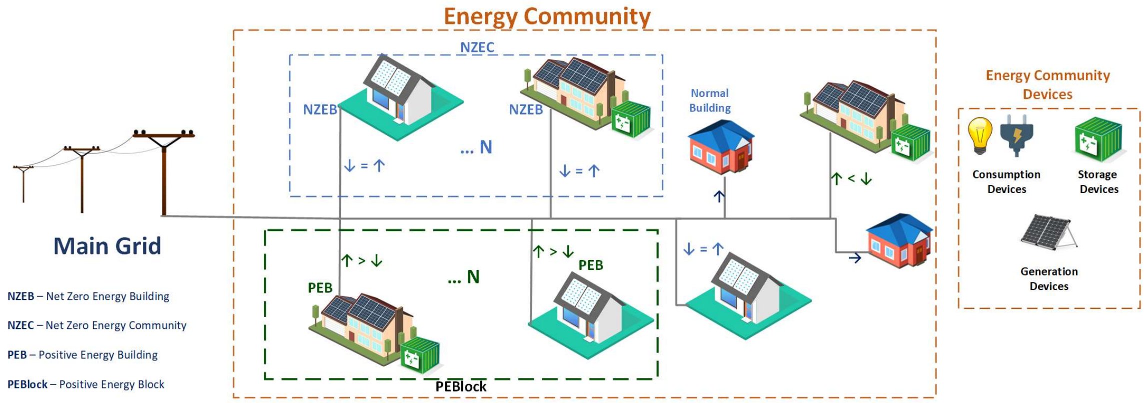


Figure 3.2 - Energy community's different categories of houses.

Normally, a period of one year is considered by the entities that use NZEB concept, in order to cover the different meteorological conditions (Athienitis & O'Brien, 2015). Considering that, in order to implement the NZEB concept in the buildings and standards used in construction, a uniform definition and a methodology to support the energy balance in this type of buildings were presented (Marszal et al., 2011; Sartori et al., 2012). To a better understand, (Sartori et al., 2012) defined the terminology to use, described at Table 3.1.

Table 3.1 - Terminology of NZEB system, (Sartori et al., 2012).

Building System Boundary - divides into physical boundary and balance boundary and compares the energy flow entering and leaving the system. It can include only a building or a group of buildings, Physical boundary, and determines the renewable sources that are on and off site. On the other hand, it determines what type of energy is included in the energy balance (heating, hot water, lighting, etc.), balance boundary.
Energy grid - as the name says, energy grid represents the supply system of energy, coming from electricity, natural gas, biomass among other fuels. The grid normally delivers energy to a building but, can also receive energy from it. In that case, it is named as a two-way grid.
Delivered Energy - Represents the energy delivered from the grid to buildings (kWh/y).
Exported Energy - Contrarily to the exported energy is the energy delivered from buildings to the grid (kWh/y).
Load - represents the building's demand of energy. Regarding the energy production on-site, the load may not be equal to the energy delivered since the self-consumption of the building.
Generation - energy generated by the building. After self-consumption of the building the oversupply is exported to the grid, which may not coincide with the amount of energy generation.

Weighting System - converts the physical units of different energy supplies into a uniform metric to be able to analyse and evaluate the global energy chain. The weighting system is divided into two parts: The Weighted Demand and Weighted Supply. The weighted demand is the sum of all load (or delivered energy) while weighted supply represents the sum of all generation (or exported energy).
NZEB Balance - represents the balance between delivered/load and exported/generation energy. The net ZEB balance is calculated as the difference between weighted supply and weighted demand and is accomplished when weighted supply is equal or greater than weighted demand over a period of time, normally a year.

A computational study in North America shows that the use photovoltaic panels, in the cost-effective way, can convert passive buildings into a net zero energy building (Alajmi et al., 2018),(Yildirim & Bilir, 2017).

However, the EU's climate ambitions have evolved. Recognizing that NZEBs represent an essential but intermediate step, the bloc is now setting its sights on an even more ambitious target: Zero-Emission Buildings (ZEBs). The revised EPBD of 2024, (Office of the European Union, 2024), introduces a stricter standard, demanding the complete elimination of on-site fossil fuel carbon emissions. The 2024 revision sets forth ZEBs as the new benchmark for newly constructed buildings. According to the agreement, all newly built residential and non-residential structures must achieve zero on-site emissions from fossil fuels. This requirement is mandated to take effect as of 1 January 2028 for publicly owned buildings and as of 1 January 2030 for all other newly constructed buildings, with potential exemptions allowed under specific circumstances.

The revised directive introduces a stringent definition of ZEBs, characterized by the complete elimination of on-site fossil fuel carbon emissions and the attainment of exceptionally high energy performance standards. This regulatory framework aligns the building sector with the EU's overarching climate neutrality objective for 2050, emphasizing the primacy of energy efficiency.

3.1.3 Positive Energy Buildings & Communities

Along with ZEB technologies and related solutions development, international efforts have increasingly focused on the development and adoption of positive energy buildings. According to European Commission, positive energy communities consists of several buildings that actively manage their energy consumption and the energy flow between them and the wider energy system as well as presenting an annual positive energy balance (Bartholmes, 2017). When the exported energy of a building, during a pre-defined period of time, is higher than the imported energy, the building is called positive-energy building (PEB) (H. ur Rehman et al., 2019). In line with this, a positive energy block or positive energy community (PEC) is defined as an area with different buildings interconnected where the annual energy demand is lower than the annual energy supply from local renewable energy sources (Ala-Juusela et al., 2016). For Walker (S. Walker et al., 2017), a building cannot be studied as an isolated unit, so in his work he considered benefic the study of buildings as a unit together with their connected systems, in order to achieve the energy positivity at a community level. In the literature is also possible to find a set of key performance indicators (KPIs) to assess the performance of a PEC. Considering not only the balance between local energy supply and demand in a community but also avoiding peak energy demand problems (Ala-Juusela et al., 2016). Those KPIs are presented in Table 3.2, noticing that they are suggested for each energy form (*x*), where *x* denotes either heating, cooling or electricity.

Table 3.2 - KPIs to assess PEC quality.

KPI	Definition
On-site Energy Ratio (OER*x*)	Used to measure the balance between energy demand and renewable energy supply in a community.
Annual Mismatch Ratio (AMR*x*)	Measure the amount of energy imported into the community, per year.
Maximum Hourly Surplus (MHS*x*)	Measure what is the maximum value on how much bigger the hourly local renewable supply is than the demand during that hour (per year).
Maximum Hourly Deficit (MHD*x*)	Measure what is the maximum value on how much bigger the hourly local demand is compared to the local renewable supply during that hour (per year).
Monthly Ratio of Peak hourly demand to Lowes hourly demand (RPL*x*)	Measure how big is the peak power demand.

Despite the KPIs, the more recent Energy Performance of Buildings Directive (EPBD) states that buildings should also include a Smart Readiness Indicator (SRI) in order to be employed to evaluate the capability of buildings to integrate ICTs and electronic systems. This integration is essential for adapting building operations to the needs of both occupants and the energy grid, as well as enhancing energy efficiency and overall building performance. The SRI is intended to increase awareness among building owners and occupants regarding the benefits of building automation and the electronic monitoring of technical systems. Furthermore, it aims to give confidence in occupants regarding the tangible energy savings and improved functionalities brought about by these advanced technologies (Office of the European Union, 2024).

In 2018 the European Parliament described SRI as follows: "The smart readiness indicator should be used to measure the capacity of buildings to use information and communication technologies (ICT) and electronic systems to adapt the operation of buildings to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings.". Moreover, the normative says that the SRI is based on (Eloranta, 2020; Official Journal of the European Union, 2018) three key building functions:

1 – Energy Consumption adaptation based on renewable energy source output;

2 – Operation mode adaptation based on occupants needs;

3 – Electricity demand flexibility based on electric grid status.

Furthermore, from a city point of view, PEB and PEC can be scaled up to district level named Positive Energy Districts (PED). Based on PEB and PEC definitions, PED is defined as an urban area with clear boundaries, consisting of different EnC of different types: normal consumption, Nearly Zero Energy Community (NZEC) or PEC, together with not residential buildings and buildings of other topologies, (Alpagut et al., 2019). Regarding the different topologies that constitute a PED, some specificities, like district's boundaries or the balance between the energy production and consumption, should be taken into account while considering improving system's resilience or the application of KPI and SRI to PEB and PEC (Paci & Bertoldi, 2020).

For Panteli & Mancarella, besides the PEC/PED, it is important to study the flexible neighborhood /community level since reliability and resilience can be provided by the flexible neighborhood / community level demand-side resources (Panteli & Mancarella, 2015c). Also, for Monti et. Al, a PEC will be able to use flexibility if different flexible resources are exploited inside the PEC (Monti et al., 2016). Considering these two contributions, the presented PhD work follows a line of research in order to understand how to achieve a suitable solution to improve the resilience of an EnC after a main grid outage, during the restoration process with the aim of maintain the EnC user's comfort.

3.2 Energy Flexibility & Household Devices

The energy flexibility concept has different focus as identified by (Reynders et al., 2018). Reynders identified, in literature, five different focus points: on energy infrastructure, on systems interaction with building, on energy price, on building performances and on electricity. LeDréau mentioned that energy flexibility was representative of the ability to change the energy usage from high to low price periods (Le Dréau & Heiselberg, 2016). Hong presented energy flexibility as a time window maximization where heat pumping operation time can be shifted without affect the comfort and hot water supply temperatures for the end-user (Le Dréau & Heiselberg, 2016).

The energy flexibility can also be characterized as a static function at every time instant, however Junker proposed a methodology that characterizes the energy flexibility as a dynamic function that allows grid operators to control the demand through the use of penalty signals, for example price or CO_2 emissions (Junker et al., 2018). Reynders have also presented a list of different methodologies to quantify energy flexibility (Reynders et al., 2018), which are summarized in Table 3.3. Han Li presented a work with an overview of methodologies for quantifying energy flexibility, arguing that in addition to metrics calculation, control and energy management strategies can be used to achieved energy flexibility. (H. Li et al., 2021a). Han Li identifies a wide variety of performance metrics used in literature to quantify energy flexibility, covering aspects such as energy, power, cost, duration, emission, and comfort. Also outlines several key performance indicators (KPIs) for measuring various aspects of energy flexibility in buildings (H. Li et al., 2023), such as:

- The ability to shift energy usage in response to external;
- The impact on peak demand reduction;

- Cost savings achieved through flexible energy use;
- Reduction in GHG emissions due to optimized energy use;
- Maintenance of indoor comfort and IEQ during flexible operations.

In (Akbari et al., 2024) authors introduce a new flexibility indicator based on the characteristics of energy curves in energy-time profiles. This indicator aims to reflect the potential for energy flexibility by modulating the area under the curves, considering energy, time and power metrics simultaneously.

Table 3.3 - Quantification methodologies for energy flexibility.

Flexibility Quantification Methodology	References
A – Number of hours that energy consumption can be delayed or anticipated (temporal flexibility).	(Nuytten et al., 2013)
B – The power will increase or decrease, combined with how long these changes can be maintained (power flexibility).	(D'hulst et al., 2015)
C – Combines both temporal and power flexibility, together with energy flexibility.	(Stinner et al., 2016)
D – The amount of energy that can be shifted at a specific moment and the respective cost compared to a reference plan.	(De Coninck & Helsen, 2016)
E – Available storage capacity, storage efficiency and the power shifting potential	(Reynders, 2015)
F - Use of control and energy management strategies to achieve energy flexibility	(H. Li et al., 2021b)
G - Performance metrics to quantify energy flexibility	(H. Li et al., 2023)
H - New flexibility indicator based on energy curves in energy-time profiles	(Akbari et al., 2024)
I - White-box, black-box & gray-box models for quantifying buildings flexibility	(Luo et al., 2022)
J - General Quantitative Model for Flexible Resources	(Bai et al., 2023)

Regarding the methodologies presented above, different types of household devices can be considered in order to adapt its behavior to quantify the residential house's flexibility. Those devices can be consumption or production devices and with or without storage. Moreover, those devices have different characteristics, presented in Table 3.4 and studied in the next subchapters, that will give different possibilities to manage the EnC's flexibility.

Table 3.4 - Household devices' type , based on (Luo et al., 2022)

Supply-side	Generation	Renewable production (uncontrolled)	Solar Photovoltaic Wind turbines Ocean production...	
		Other on-site production (controlled)	Combined cooling, healing Fuel cell Biomass H2	
	Operation/sys-tem	Active energy storage	Batteries Thermal storage	
		Passive Energy storage	Building thermal mass Phase change wallboard	
		Advanced technologies	Power-to-gas Power-to-hydrogen	
Demand - side	Demand/ load	Without temporal displacement	Can be turned off	Lights TVs Computers...
			Can't be turned off	Security sys-tems.
		Non-thermostatically controlled devices (Event-based devices)	Washing machines dishwashers dryer machines ...	
		Thermostatically controlled devices	HVAC Refrigerators Electric water heaters ...	
		Stochastic Devices	Electrical Vehicles.	

3.2.1 Household Devices

A. Non-thermostatically controlled devices (Event-Based Devices)

An Event Based (EB) device is characterized by its fixed electricity demand profile, which is based on working cycles, ranging between minutes to hours. Examples of EB devices are:

- Washing Machine;
- Dryer Machine;
- Dishwasher.

Table 3.5 - Generic electricity demand profile for event-based devices , from (Lopes, 2107)

Working State	Washing Machine	Clothes Dryer	Dishwasher
1 Power (W):	Water pumping 100	Air heating & forced flow. 2000	Water pumping & spraying arm rotation. 80
2 Power (W):	Water heating & drum rotation 2000	Air heating & forced flow. 2000	Water heating & spraying arm rotation. 2000
3 Power (W):	Water heating & drum rotation 900	Air heating & forced flow. 2000	Spraying arm rotation 80
4 Power (W):	Low speed drum rotation 100	Air heating & forced flow. 1600	Spraying arm rotation 80
5 Power (W):	Low speed drum rotation & water pumping 100	Air heating & forced flow. 1300	Spraying arm rotation 80
6 Power (W):	High speed drum rotation 300	Air heating & forced flow. 940	Water heating & spraying arm rotation. 2000
7 Power (W):	Water pumping + residual power consumption 50	-	Water pumping 300
8 Power (W):	-	-	Residual power consumption 150

Generally, the demand profile of an EB device depends on selected working program load, and technical characteristics. On (Lopes, 2017), Lopes presented a table with the generic characteristics of the demand profile for mentioned devices, based in (Staats et al., 2017).
This information is presented in Table 3.5. Also, regarding the EB device and the user's permissions, the starting time can be advanced or delayed if necessary, contributing to the energy flexibility of the house/building.

B. Thermostatically Controlled Devices

A thermostatically controlled (TC) device consists of a device where its energy consumption is related to the registered temperature on a certain system. The electricity load of TC devices can be reduced or shifted to the off-peak hour, helping in the management of load community and with little impact on costumer comfort (Jazaeri et al., 2019; P. Wang et al., 2020). Examples of TC devices are the following:

- Air conditioners;
- Heat pumps;

- Refrigerators;
- Electric water heaters.

This type of devices can represent an alternative to energy storage systems, that have application limitations due to high investment costs. Moreover, the flexibility of TC devices can significantly contribute to overall community flexibility due to their ability to rapidly adjust energy consumption patterns in response to grid conditions. By modulating the power consumption of individual TC devices and adjusting temperatures within user comfort thresholds, the community's power response can be rapidly Improved (Y. Wang et al., 2020).

C. Stochastic Devices

Finally, the integration of Electric Vehicles (EVs) with household energy systems can further enhance energy efficiency and grid stability. By optimizing charging schedules and potentially discharging energy back to the grid during peak demand periods, EVs can play a vital role in the decarbonization of the overall energy system.

The transportation sector has been a primary driver of global energy consumption, exacerbated by economic expansion and population growth. Electrification of the transportation sector, characterized by the use of electric motors and batteries for propulsion, offers a potential solution to mitigate these challenges. EVs, emitting no tailpipe pollutants and boasting lower operational costs compared to conventional vehicles, exemplify this paradigm shift. Advancements in lithium-ion battery technology and charging infrastructure are accelerating the widespread adoption of EVs (Thompson & Perez, 2020). Their battery charging processes present a significant opportunity to improve grid responsiveness operating in dual capacities: as distributed energy resources and flexible loads (Y. Wang et al., 2019).

In their role as distributed energy sources, EVs equipped with Vehicle-to-Grid (V2G) technology can discharge energy back to the grid during periods of peak demand, providing valuable grid support. Conversely, as flexible loads, EV charging can be strategically managed based on user preferences and grid conditions. By optimizing charging times to coincide with periods of low demand, EVs contribute to load leveling and grid stability. Furthermore, the integration of EVs with photovoltaic (PV) systems can create synergistic benefits, where the PV system supplies energy for EV charging, space heating, cooling, and other building loads, as demonstrated by (Roselli & Sasso, 2016).

More recently, the term Vehicle-to-everything (V2X) has become more popular. The term refers to the practice of using the batteries of EVs to offer energy services and derive extra value from the battery asset during times of non-use.

V2X is a comprehensive framework encompassing the bidirectional exchange of energy between EVs and other entities. This concept extends beyond traditional charging, enabling EVs to serve as both energy consumers and providers. V2X applications, Illustrated In Figure 3.3, span various scales and configurations, including Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Load (V2L), (M. A. Rehman et al., 2023; Thompson & Perez, 2020). Moreover, studies by (Noel et al., 2019; Yamagata et al., 2016), underscore the potential of Vehicle-to-Community (V2C) applications in providing local energy storage. By leveraging electric vehicle batteries, V2C can contribute to the creation of self-sufficient and resilient communities.

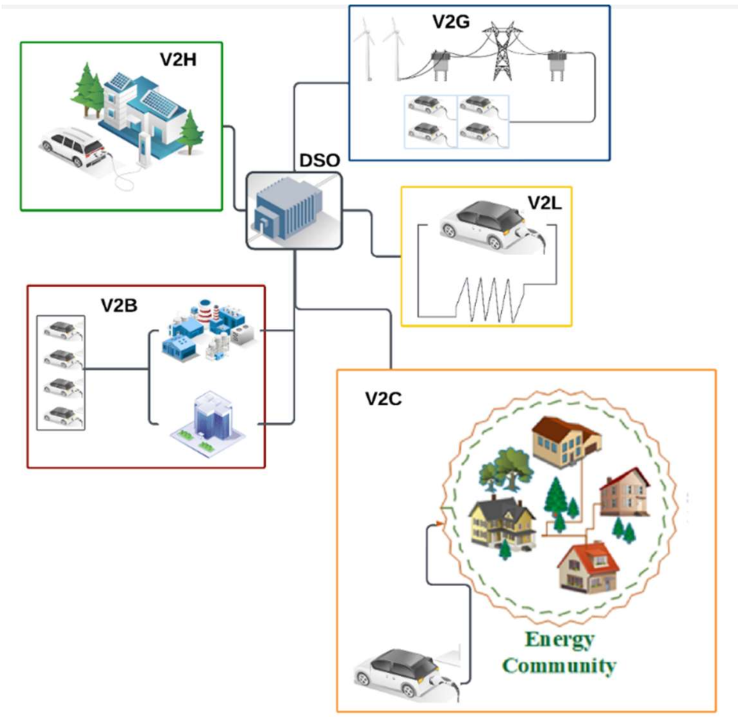


Figure 3.3 - V2X different applications, adapted from (Thompson & Perez, 2020; Yu et al., 2022).

Through V2X, EV batteries can be utilized as distributed energy resources, offering grid services such as peak shaving, load shifting, and frequency regulation. By participating in energy markets, EVs can generate revenue for their owners while contributing to grid stability. Moreover, V2X applications can provide backup power to buildings and homes, enhancing energy resilience (Pearre & Ribberink, 2019).

The realization of V2X's full potential necessitates advanced battery technologies, intelligent charging management systems, and supportive regulatory frameworks. As the electrification of transportation accelerates, V2X is poised to play a pivotal role in transforming the energy landscape (Yu et al., 2022).

3.2.2 Energy Storage Systems

Energy storage consists of a process of converting electrical energy into different forms of energy that can be stored for converting again into electrical energy when necessary. There are many different storage technologies that can be catalogued in different ways according to the type of storage (mechanical, electromechanical, electrical, chemical or thermal), the storage duration (short-term or long-term storage), capital cost, capacity, efficiency or environmental impact (Argyrou et al., 2018). In this work technologies will be categorized into storage types, as shown in Figure 3.4.

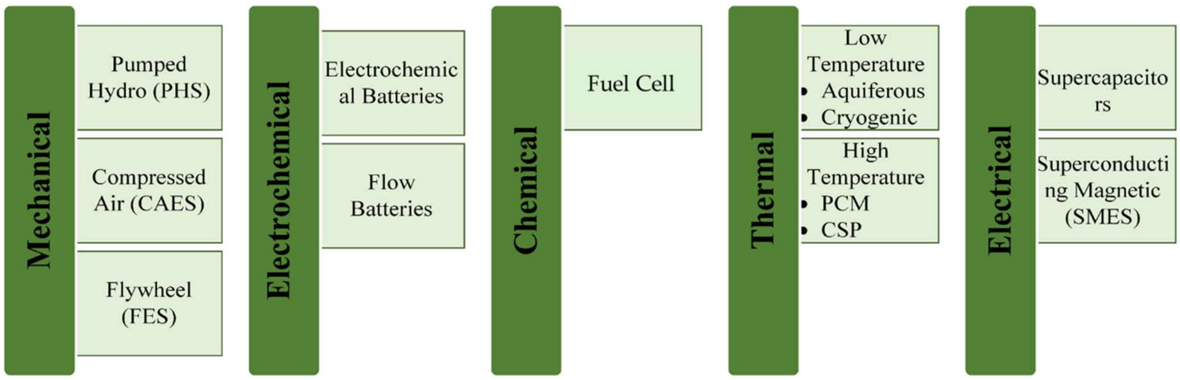


Figure 3.4 - Energy Storage Technologies.

The choice of which storage method should be used depends on several factors such as the amount stored, the time of storage (short-term or long-term), portability, efficiency, costs among others. Flywheels or supercapacitors are used in short-term applications, on the other hand Compressed-air Energy Storage (CAES) or flow batteries are suitable for peak-hour load leveling when high energy storage is required. Different characteristics of the storage methods presented above are compered in Table 3.6.

Table 3.6 - Comparison of technical characteristics of energy storage systems *.

		Efficiency	Response Time	Power Capacity	Lifetime	Discharge time	Capital Cost
Mechanical	PHS	65 – 85 %	< 1 min	100 – 10000 MW	30 - 60 years	Hours - days	500 – 4600 $/kW

	CAES	70 – 80 %	Sec - min	100 – 300 MW	~40 years	Hours - days	400 – 800 $/kW
	FES	90 – 95 %	Very fast (< ms)	< 250 kW	15 – 20 years	seconds	100 - 350 €/kW
Electro-chemical	Lead Acid	60 – 78 %	< 5 ms	0 – 20 MW	3 – 15 years	Seconds - hours	300 - 600 $/kW
	Lithium ion	85 – 97 %	< 5 ms	0.1 – 50 MW	5 – 15 years	Minutes - hours	1200 – 4000 $/kW
	Sodium-based	75 – 90 %	< 5 ms	0.05 – 10 MW	10 – 15 years	Seconds - hours	1000 – 3000 $/ kW
	Nickel-based	60 – 70 %	< 5 ms	0 – 40 MW	10 – 20 years	Seconds - hours	500 – 1500 $/kW
Flow	Redox Flow	75 – 85 %	< 5 ms	0.3 – 15 MW	5 -20 years	Seconds – 10 hours	600 – 1500 $/kW
	Hybrid Flow	60 – 80 %	< 5 ms	0.05 – 10 MW	5 – 20 years	Seconds – 10 hours	400 – 2500 $/kW
Chemical - Fuel Cell		20 – 50 %	< 5ms	0.001 – 50 MW	5 – 20 years	Minutes - hours	500 – 10k $/kW
Thermal	Low temperature	~60 %	< 1 min	0 – 5 MW	10 – 20 years	hours	
	High Tempera-ture	30 – 60 %	Not for rapid response	0.1 – 300 MW	5 – 40 years	hours	100 – 400 $/kW
Electrical	Supercapacitors	85 – 98 %	< 5ms	0.01 – 1 MW	10 – 20 years	Seconds-minutes	100 – 300 $/kW
	SMES	90 – 95 %	5ms	0.1 – 10 MW	20 – 30 years	Seconds-30minutes	200 – 300 $/kW

*(Denholm & Holloway, 2005; Denholm & Kulcinski, 2004; Hadjipaschalis et al., 2009; Kaldellis & Zafirakis, 2007; Kousksou et al., 2014; Mahlia et al., 2014; Poullikkas, 2013) (Bilgili et al., 2015; H. Chen et al., 2009; Denholm et al., 2011) (Bolund et al., 2007; Evans et al., 2012; H. Liu & Jiang, 2007; Mahlia et al., 2014; Mousavi G et al., 2017; Sebastián & Peña Alzola, 2012)

3.2.2.1 Hybrid Energy Storage systems

Hybrid Energy Storage systems (HESS) consider two or more different energy storage technologies and, normally, one technology is dedicated to cover the “high power” demand, transients and fast load fluctuations, being characterized by a fast response time as well as high efficiency (Argyrou et al., 2018; Bocklisch, 2015). The other technology acts as the “high energy” storage characterized by a low self-discharge rate and lower energy installation costs. It is important to choose a good combination of energy storage systems takin into account the system requirements. Figure 3.5, presents possible combinations of ES technologies.

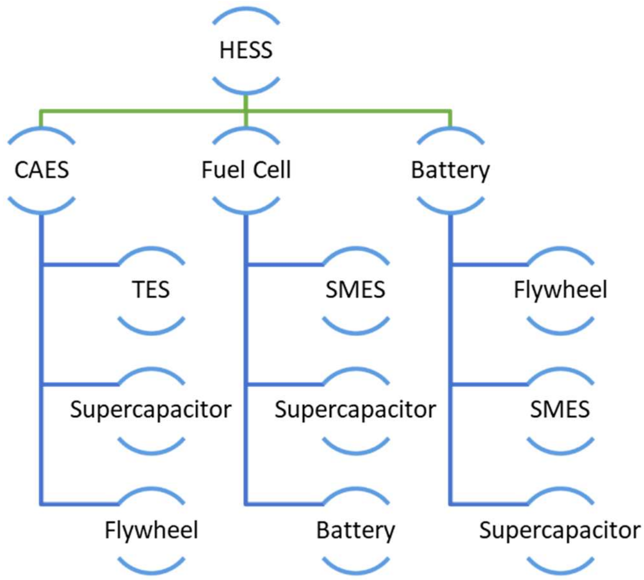


Figure 3.5 - Possible combinations of ES technologies.

Technologies like CAES, Fuel Cells and high energy batteries have long duration of storage and high energy rates, contrary to Superconducting Magnetic Energy Storage (SMES), supercapacitors, flywheels or high-power batteries that present high power rate and short discharge duration.

This type of combinations has some advantages such as (Bocklisch, 2015):

- The reduction of total investment costs;
- Increase of storage and system lifetime;
- Increase of total system efficiency.

The combination of battery and supercapacitor is an example of HESS which combines high storage capacity with very fast response time (Kuperman & Aharon, 2011). Different authors have proposed potential solutions involving battery and supercapacitor storage systems for buildings or microgrids equipped with renewable energy generation, as well as hybrid systems that use electric vehicles as storage source, aiming to enhance performance, increase efficiency, and extending battery lifespan.(Cao & Emadi, 2012; Kanchev et al., 2011; G. Zhang et al., 2010).

3.2.2.2 Community Energy Storage Systems

Storage devices are suitable to absorb surplus generation to use in periods where demand is higher than the available power. Community energy storage (CES) systems are getting more attention as a suitable solution of innovation for sustainable energy transition. Parra et.

al advocate the deployment of a CES system at the consumption site, highlighting its positive implications for both EnC users and network operators. Strategic placement of CES not only bolsters local energy autonomy and resilience for EnCs but also contributes to overall grid stability and efficiency. By reducing transmission and distribution losses, this approach aligns with broader sustainability and reliability goals within the energy sector (Parra et al., 2016).

More focused on community engagement, Van der Stelt, mentioned CES as a system located on the consumption site but with the capability to perform multiple applications in order to manage demand and supply, having positive impacts for both, consumers and DSOs (van der Stelt et al., 2018). Also, for Van Oost Koirala, CES is defined as *"an energy storage system with community ownership and governance for generating collective socio-economic benefits such as higher penetration and self-consumption of renewables*" (Koirala et al., 2018). Koirala also claims that CES, as defined, will reduce dependence on fossil fuels, energy bills and increase local economy. Moreover, Barbour and Parra concluded that CES is a more effective system than residential energy storage and presents benefits from the economic point of view, reducing the life-cycle cost of energy storage by 37% when compared to individual household storage (Barbour et al., 2018; Parra et al., 2015). Koirala, (Koirala et al., 2018), presented different CES configurations that are described below, as well as some cases of different CES configurations that are summarized in Table 3.7.

Shared residential energy storage (SRES): In this configuration each user can have his own energy storage, up to 20kWh, in their own premises and the energy can be shared among the community users, using the local physical grid.

Shared local energy storage (SLES): The local configuration energy storage has a capacity of tens to hundreds of kWh and it is installed in the local neighborhood, is shared by physical grid and has community ownership. This type of CES configuration provides multiple benefits, namely higher flexibility and energy security.

Shared virtual energy storage (SVES): This type of community is different from the other two mentioned since this is a virtual community, i.e., the energy storage is installed at different locations, inside or outside of EnC, and have independent ownership and governance. The energy storage is aggregated and virtually shared through the main grid considering the market design and regulations.

Table 3.7 - Some cases of CES configuration application.

CES configuration	Size	Number of households	Characteristics	Ref
SRES	120 kWh (24 household equipped with 5kWh each	47 total, 24 equipped	Can share energy storage for collective benefits.	(GridFlex, 2018)
	7.7 kWh each	15	Local users are able to monitor their electricity consumption and export but do not have responsibilities.	(Takata, 2017)
SLES	128 kWh	35	Maximize the usage of self-consumption of local generation.	(Liander, 2017)
	10MWh	37	All energy demand meets locally, and surplus generation is sold to national grid.	(NEFF, 2016)
SVES	2 to 16 kWh energy storage units	Virtual community of 10000 members	Members can share self-produced energy with other members of the sonnen Community. Since the user are exclusively using energy from the community, there is no need for a conventional energy provider anymore.	(Sonnen, 2016)

3.3 Resilience Assessment

In Chapter 2, an analysis of the resilience concept was undertaken. Resilience, being multifaceted and dynamic, is a complex concept, posing challenges to straightforward measurement. Nevertheless, the quantification of resilience is imperative for the evaluation of resilience strategies and subsequent adjustments. In assessing system resilience effectively, factors including robustness, recovery, and adaptive capacity must be taken into account. Despite these considerations, it is typical only one or two of these factors to be quantified, underscoring the intricate nature of comprehensive resilience assessment.

According to (Eshghi et al., 2015) "Resilience seeks to optimize, when possible, but to never sacrifice, operational minimums that risk large consequences through unintentional introduction of brittleness.". Authors in (Cutter et al., 2008; Moreno & Shaw, 2019) defined community resilience as "the ability of a social system to respond and recover from disasters and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event". (Roege et al., 2014) considered community resilience as a conceptual framework to analyze the community responses to power outages.

Given the critical role of EnCs in modern power systems, a comprehensive assessment of system resilience is essential. To this end, the following sub-chapters will address a Resilient Analysis Process (RAP) and proposed quantification methods for resilience metrics in power systems.

3.3.1 Resilience Metrics

A. Resilience Analysis Process

Watson et al. (2015) introduced the RAP, depicted in Figure 3.6, as a conceptual framework designed to assist decision-makers and stakeholders in developing resilience metrics and evaluating the baseline performance of a system in terms of resilience (Watson et al., 2015). In this type of processes, a periodic re-evaluation of system resilience is mandatory to consider because:

- It is necessary a validation of resilience analysis methodology and a validation of models against actual incident data;
- It is important to update resilience assessments with new technology.

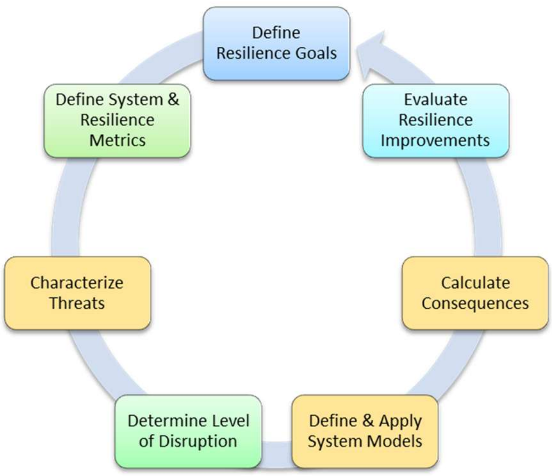


Figure 3.6 -Resilience Analysis Process , (adapted from (Watson et al., 2015).)

Also, defended that a resilience metric must have, at least, three attributes: threat, likelihood and consequence. To ensure a more complete analysis of the system and a better accuracy of the applied metrics, each RAP step, shown in Figure 3.6 and described in Table 3.8, should be fulfilled.

Table 3.8 - Description of RAP steps

1st - Define Resilience Goals	The first step is to define the main resilience goals of the system. The defined goals will be the basis for the whole analysis process.
2nd - Define System and Resilience Metrics	This step determines the scope of the analysis. System's geographic boundaries, relevant time periods or components can be identified. The type of consequences that are more important should be discussed at this step.
3rd - Characterize Threats	Threats and consequences are used to comprehend which system vulnerabilities are most important to address, in order to reduce the consequences associated with the threat. It should be established how capable the system should be to absorb and adapt to attacks or natural disasters.
4th - Determine Level of Disruption	The attributes of each threat are used to quantify the amount of damage to the system. Expectations about structural damage or other system impacts that influence the performance should be defined.
5th - Define and Apply System Models	Damages states defined in the previous stage are used as an input of system models. More than one system model could be required to capture all the important aspects of the system and dependencies between models should be considered.
6th - Calculate Consequence	System resilience evaluation should consider not only the direct use of energy, generation and distribution, but also social implications. The outputs are transformed in resilience metrics, as defined in the 2nd RAP step.
7th - Evaluate Resilience Improvements	Upon completing a baseline RAP through the previously outlined steps, it becomes both feasible and advantageous to apply the metrics to an alternative system configuration. This allows for a comparative analysis to determine which configuration would yield superior resilience. This improvement could be a physical, policy or procedural change.

After the first RAP definition, an extension of the RAP was proposed in order to improve the measurement of resilience in power systems, (Vugrin et al., 2017). The schematic representation of this extension is presented in Figure 3.7 where the differences from Figure 3.6 are presented in orange. This extension intends to provide flexibility and the capability to customize metrics for a specific analysis with some additional details:

- Instead using only computational models to generate the effects of hazards, Vugrin proposes to use other sources to quantify grid impacts;
- Watson was focus on forward, looking analyses and predictions, while Vugrin defended that retrospective analyses should be done, for example including historical data as a source;

- In addition to probabilistic analyses, Vugrin also includes a deterministic analysis of the system resilience.

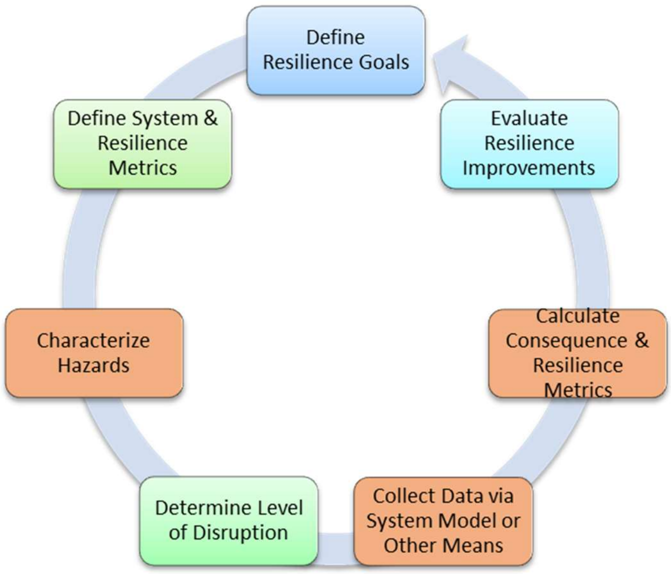


Figure 3.7 - Extension of Resilience Analysis Process, (adapted from(Vugrin et al., 2017))

There are several approaches reported in the literature to evaluate the resilience of a system considering different actions and approaches. Some proposed quantification methods for resilience metrics in power systems are listed below.

B. Short-Term & Long-Term Metrics

Panteli and Macarella explain that although it is a hard process, due to the complexity of resilience, it is important and necessary to quantify the resilience of the system that is often measured considering only certain parameters such as the degree of robustness to the initial disturbance, the functionality reached during the failure or the post event recovery time (Panteli & Mancarella, 2015c).

In the context of EnCs, a system characterized by continuous evolution and change as well as for the necessity to maintain users' comfort, it is essential to quantitatively assess short-term resilience and implement long-term strategies aimed at enhancing system resilience, as illustrated in Figure 3.8. Resilience metrics must possess the following attributes:

- Quantify the number of customers disconnected and, per each customer, the frequency and duration of disconnections, during an event;
- Provide global resilience indexes to the entire power infrastructure;
- Provide area and component-specific indexes;

- Incorporate time dimension in order to measure the ability of the system to slowly degrading and fast recovering back to the original state.

In the short-term, measurements should be made before, during and after the event, using the resilience curve, as explained in Figure 2.6 and Figure 2.7, to quantify the system resilience at each part of the event.

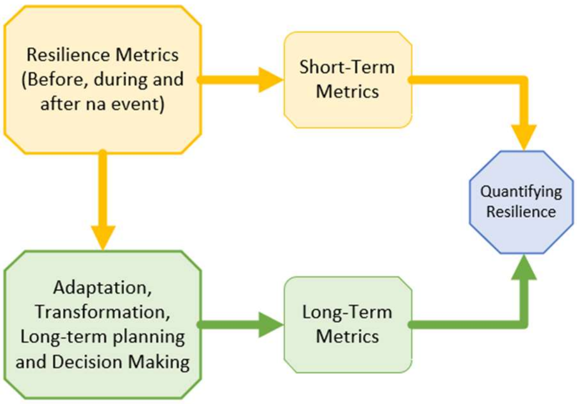


Figure 3.8 – Quantifying Resilience, adapted from (Panteli & Mancarella, 2015c).

As a long-term metric, it is important to consider the ongoing process of resilience improvement, using about past events knowledge to analyze existent measures and update them. As Figure 3.9 illustrates, this is a continuous process that continuously uses decision making and he analyses of the system behavior to improve the resilience and the way to act in case of failure.

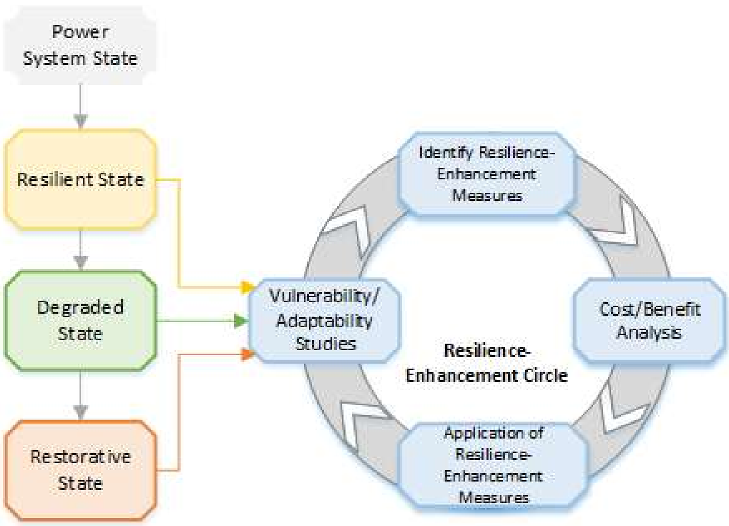


Figure 3.9 – Long-term resilience framework, adapted from (Panteli & Mancarella, 2015c)

C. Data and Time Measures

Eshghi mentions that performance of a system can be established by applying system integrity metrics and presented four metrics to take into account when the subject is power systems resilience, (Eshghi et al., 2015). To identify an event, attributes are measured in terms of time and/or data:

- Small signal stability (Data): to this type of metric, the evaluation of global system performance is done during the planning stage. By applying small disturbances at specific locations, it is possible to understand how the power system will react and its capability to keep synchronism facing a set of feasible operating conditions;
- Transient Stability (Data): to be a transiently stable system, it should maintain synchronism during an event/outage response. To measure the margin between stable and unstable states can be unsustainable due to limitations of computational power. So, it is necessary to find other mechanisms to understand what the global optima is to determine when a given operation condition is near the limit of stability;
- Communication Latency (Time): the time of response of a system depends on the latency in communication and computational processes of the system. In this case it is important to know what the maximum acceptable latency for the power system is;
- Physical Degradation (Data and Time): ensure system features and the total capacity to respond quickly in cases of failure depends on the physical state of the system. If there is degradation of the system or lack of maintenance, the control capacity as well as the response can be affected, consequently affecting the system's resilience.

Based on the comprehensive literature reviews conducted in Chapters 2 and 3, Chapter 4 will introduce various metrics aimed at quantifying the resilience of EnCs. These metrics will be aligned with the conceptual framework outlined in the subsequent chapter.

3.4 SoA's summary and gaps

Chapters 2 and 3 provided the foundational context for this work. Chapter 2 presented a survey of the topics that motivated this research, while Chapter 3 delves into the specific subjects addressed during the development of this study. Considering these two chapters, and the knowledge from the study of state of the art, certain gaps have been identified, namely:

- Existing resilience metrics primarily focus on broader energy systems rather than addressing the specific context of EnCs;
- A clear and universally accepted definition of EnC resilience is currently lacking;

To address these gaps, this research proposes a framework to improve EnCs resilience as well as a dedicated set of measurement metrics for assessing it, thereby improving users' comfort. These metrics will be employed to evaluate the proposed strategies in alignment with the research objectives outlined in sub-chapter 1.4.1, "Aimed Contributions & Objectives".

EnC's household appliances energy flexibility will be considered, combined with the use of available renewable energy and stored energy, whenever possible, in order to improve the EnC resilience. This will assess the RQ "*Can Energy Community's resilience be improved considering Energy Community users' Energy Flexibility?*".

Furthermore, by employing optimization algorithms that leverage energy flexibility, as detailed in subsequent sections, this research aims to enhance the resilience of the EnC. This optimization will enable both DSOs and EnC users to more effectively utilize available energy resources.

3.4.1 Important Concepts & Definitions

Finally, after the comprehensive study of the literature, it is important to mention and clarify some definitions that will be important for understanding the remaining document and comprehension of the presented work, namely:

EPG's Resilience - the resilience of electrical power grid is the ability of the grid to withstand, adapt to, and recover from various disturbances, disruptions, or challenges while maintaining its essential functions. Resilience in the context of electrical power grids involves the capability to absorb dangers, such as natural disasters, cyber-attacks, equipment failures, or other unforeseen events, and to quickly return to normal operation.

EnC's resilience - Energy community resilience refers to the ability of a community to withstand, recover from, and adapt to disruptions or challenges related to its energy infrastructure. This definition encompasses the community's capacity to maintain essential energy services, such as electricity, or heating, in the face of various stressors just like in EPG's resilience definition. Specifically in this work, the definition of EnC's resilience means the ability of a community to maintain users' comfort.

Key components of EPG or EnC resilience include:

- **Reliability**: The grid's ability to consistently provide electricity to consumers without interruptions, minimizing downtime even in the face of disturbances;
- **Robustness**: The capacity of the grid to resist and endure disturbances without significant damage or degradation in performance;
- **Redundancy**: The presence of backup systems, alternative routes, and additional resources to ensure the continued functioning of the grid during disruptions;
- **Adaptability**: The ability to quickly adjust and reconfigure the grid to changing conditions, such as through smart grid technologies, to optimize performance and mitigate the impact of disturbances;
- **Recovery**: The speed and effectiveness with which the power grid can return to normal operation following a disruption, minimizing the duration and extent of outages.

Finally, key strategies for energy community resilience improvement include:

- **Diversification of Energy Sources:** A resilient community often relies on a diverse mix of energy sources, including renewable energy, to reduce vulnerability to disruptions in any single source;
- **Decentralization of Energy Systems:** Distributing energy generation and storage resources across the community helps mitigate the impact of localized disruptions and improves overall system resilience;
- **Community Engagement and Planning:** Involving the community in energy planning and decision-making processes fosters awareness, preparedness, and collaboration.

This can include developing emergency response plans and promoting energy-efficient practices;

- Infrastructure Robustness: Ensuring that energy infrastructure is designed and built to withstand the impacts of various hazards, such as storms, floods, or earthquakes, contributes to community resilience;
- Smart Technologies: Integrating smart technologies, such as smart grids and advanced metering systems, can enhance the efficiency, flexibility, and responsiveness of energy systems, aiding in quicker recovery from disruptions;
- Energy Storage: Deploying energy storage solutions, such as batteries, allows communities to store excess energy during normal conditions and use it during outages or periods of high demand.

User comfort - is defined as the ability to maintain user wellbeing in relation to energy consumption, specifically by keeping the operation of desired equipment as specified by the user.

These concepts will help for a better understanding of the framework and use case design as well as for the analysis of results of this work.

4

Framework to improve EnC resilience

This chapter offers a concise overview of the research methodology and provides a comprehensive description of the framework to improve EnC resilience. Finally, it presents metrics to measure the EnC resilience.

An energy community is essential for developing a resilience framework by providing a detailed understanding of system dynamics and enabling comprehensive risk assessments through scenario analysis. It informs the design of robust infrastructure and optimizes resource allocation, ensuring efficient use of resources for maintaining operations during disruptions. Modelling enhances operational strategies, integrates renewable energy, and facilitates stakeholder coordination, improving emergency preparedness and response. These aspects are crucial for ensuring that energy communities can withstand, adapt to, and recover from disruptions, thereby maintaining a reliable energy supply.

4.1 Energy Community Resilience Framework

In the developed methodology for this work, three layers were considered, denoting the different stages of the framework aimed at studying the resilience of the energy community, as illustrated in Figure 4.1. One of the core components of the methodology is the "Orchestrator," which aggregates and analyzes data related to load and energy production profiles. Additionally, the Orchestrator serves as a decision support entity, overseeing configuration, coordination, and management processes.

The framework depicted in Figure 4.1 calculates the energy flexibility of the EnC under analysis. These calculations are subsequently used to evaluate the resilience metrics and to validate the resilience enhancements achieved through the adoption of the current methodology. The framework effectively oversees the entire EnC, encompassing user devices, energy production, available storage, and power load.

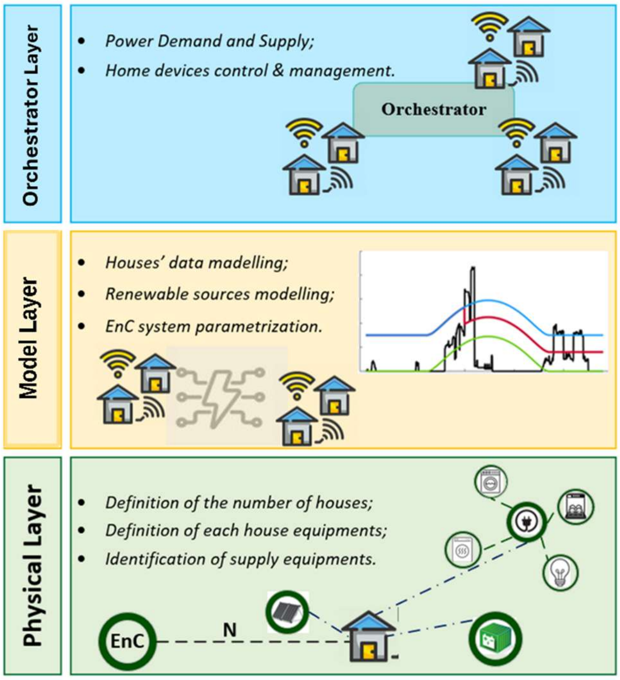


Figure 4.1 – Layers of Resilience framework.

The three layers aforementioned are described as follows:

- Physical Layer - provides a comprehensive description of the community, detailing the number of buildings, occupants, and installed equipment. This includes the total number of residential houses within the energy community, public buildings, their occupancy, and the installed equipment, such as loads, storage and production devices;
- Model Layer - it is responsible for the parametrization of the data collected from first layer as well as the modelling of the renewable sources, load devices and load diagrams that reflect users' behavior;
- Orchestrator Layer - The demand, supply storage and flexibility of each building as well as the entire EnC will be managed at the orchestrator layer, in order to improve the EnC resilience. In the orchestrator the metrics defined will be calculated to analyze the resilience of EnC within the framework applied.

4.1.1 Physical and Model Layer

Regarding physical and model layer, in this subchapter are presented the different systems that can be considered for EnC resilience framework. Considering an Energy Community, connected by a LV grid, consisting of **Y** residential houses, each equipped with a range of appliances. These appliances encompass both non-controllable devices such as lightning, laptops, and TVs, as well as controllable ones, including appliances like washing machines or dishwashers. Additionally, each residential house can be equipped with renewable systems like photovoltaic or wind production systems, while the ESS can be configured considering one of the three possible configurations mentioned in 3.2.2.

The developed framework for the EnC considers a 24-hour active power diagram that combines demand, generation and storage and is given by equation (1), (2) and (3) respectively (where d denotes demand power, g generated power and s storage power).

$$d_N \equiv [d_N(1) \cdots d_N(n)], n \in [0 - 1440] \quad (1)$$

$$g_N \equiv [g_N(1) \cdots g_N(n)], n \in [0 - 1440] \quad (2)$$

$$S_N \equiv [S_N(1) \cdots S_N(n)], n \in [0 - 1440] \quad (3)$$

where N denotes the number of the considered EnC's residential house and n the time-step. Moreover, the community's total demand (T_d), generation (T_g) and storage (T_s) are given by equation (4), equation (5) and equation (6), where the corresponding power of each house for 24-hours is added:

$$T_d = \sum_1^N (g_N) \quad (4)$$

$$T_g = \sum_1^N (g_N) \quad (5)$$

$$T_s = \sum_1^N (s_N) \quad (6)$$

The orchestrator layer will manage the demand and supply loads, including their flexibility, for individual households and the EnC as a whole. Equations (4) and (5) model the total load consumption and generation of each residential house. The storage, equation (6) can be considered for each house or for the entire EnC depending on the type of ESS chosen.

An illustrative example is depicted in Figure 4.2, where T_d and T_g are represented by the black and red line respectively. The figure also illustrates the load profiles of lighting and three controllable household appliances. For instance, the washing machine operates from 9:00 with a peak consumption of 2.5 kW, while the dishwasher and dryer consume 2 kW each, initiating cycles at 18:00 and 14:00, respectively.

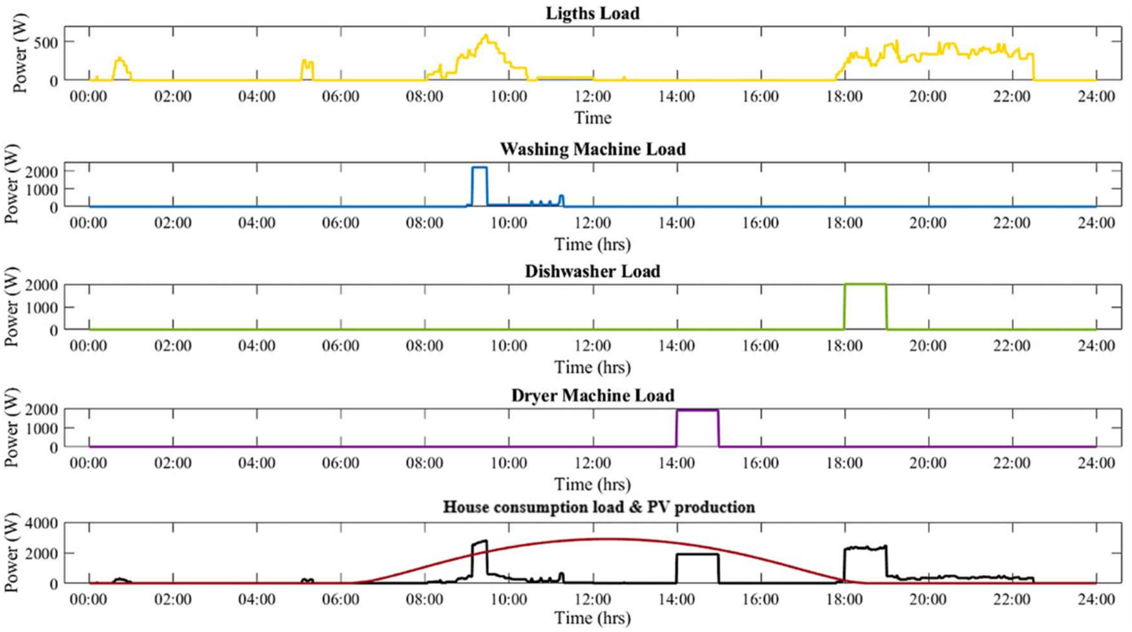


Figure 4.2 - Example appliances load.

4.1.1.1 Generation System

Energy communities empower households to transition from passive consumers to active prosumers, participating directly in the energy production process. This decentralized approach facilitates the integration of diverse generation technologies within the EnC. PV systems remain the most prevalent option, converting solar energy into electricity. In regions with consistent wind speeds, wind turbines can be effectively deployed. Bioenergy systems, using biomass resources such as wood chips, offer the potential for heat and electricity generation. Small-scale hydropower is suitable for areas with abundant water resources. Additionally, Combined Heat and Power (CHP) systems enhance energy efficiency by producing both electricity and heat from a single fuel source.

The selection of generation systems is influenced by various factors. Geographic location determines the availability of solar and wind resources. Household size and energy consumption influence the required generation capacity. Economic factors, including initial investment and operational costs, play a crucial role. Additionally, government policies and grid connection availability impact system feasibility.

By strategically combining these generation systems, EnCs can optimize energy production and consumption, reducing grid reliance.

Photovoltaic System

For this doctoral research, a PV system was considered as generation system, renewable one, and was modeled using Equation (7). The model incorporates parameters such as the specific PV panel characteristics, power inverter specifications, ambient temperature (T_{amb}) and solar radiation (G).

$$P_{PV\_dc} = PV_{Peak\_Power} - \left(\alpha \times PV_{Peak\_Power}\right) \times (T_{cel} - T_{c.STC}) \tag{7}$$

where:

- PV_{Peak_Power} denotes the PV system peak power;
- α the temperature coefficient of the maximum output power;
- T_{cel} the temperature of the PV panel cells;
- $T_{c.STC}$ the reference cell temperature at standard test conditions (STC).

The peak power of the PV system and the temperature of PV cells are given by equation (8) and equation (9), respectively:

$$PV_{Peak\_Power} = \frac{G}{1000} \times P_p \tag{8}$$

$$T_{cel} = T_{amb} + \left(\frac{\left(T_{c,NOCT} - T_{a,NOCT}\right)}{G_{NOCT}}\right) \times \frac{G}{1000} \tag{9}$$

where:

- G is the solar radiation;
- P_p is the peak power of the solar panel;
- T_{amb} is the ambient temperature;
- $T_{c,NOCT}$ is the nominal operating cell temperature (NOCT);
- $T_{a,NOCT}$ and G_{NOCT} is the ambient temperature and the solar radiation at NOCT, respectively.

4.1.1.2 Energy Storage System

As presented in chapter 3.2.2, there are different types of storage systems that can be used. In this work a battery was chosen as a storage system. The energy storage is represented by equation (10), where $E^b(n)$ is battery's energy on time-step n (kWh), $E^b(n-1)$ is battery's energy on time-step n-1 (kWh), η_c^b the efficiency of the battery charging process (%) and η_d^b the efficiency of the battery discharging process (%). b^c and b^d denote the battery control signals for charge and discharge respectively. Finally, $P(n)$ is the net power of system on time-step n (kW) and ΔT the time-step resolution.

$$E^b(n) = E^b(n-1) + \left(\eta_c^b\, P(n)\Delta T b_c + \frac{P(n)\Delta T}{\eta_d^b}\, b_d\right), n \in [0 - 1440] \tag{10}$$

It is also important to consider the charge & discharge constraints, presented below:

- Power Limitation:

$$\{ P_{\mathrm{max}_{\mathrm{dis}}} \leq P(n) \leq P_{\mathrm{max}_{\mathrm{ch}}} \tag{11}$$

- Charge & Discharge:

$$\begin{cases} b_c + b_d = 1, & b \in [0\,, 1] \\ b_c = 1 \text{ and } b_d = 0, & if\ \Delta P(n) > 0 \\ b_d = 1 \text{ and } b_c = 0, & if\ \Delta P(n) < 0 \end{cases} \tag{12}$$

Power constraints, as defined by Equation (11), ensure that the battery's charging and discharging rates remain within their respective nominal limits. Charge and discharge constraints, outlined in Equation (12), guarantee that the battery isn't charging and discharging at the same time. These constraints collectively safeguard the battery from damage due to overcharging or excessive discharge.

4.1.1.3 Household Devices

This study focuses on event-based household appliances that can be externally controlled. Given their diverse usage patterns, these controllable appliances were modeled as state machines, as depicted in Figure 4.3. The state machine comprises four different states ("Machine OFF", "Machine Ready", "Machine ON" and "Machine Complete"). Transitions between these states are triggered by signals that are specific to the selected program and appliance operation. The signals 'Ready_work' and 'Time_ON' govern state changes, while

'Appliance_Time' is derived from the appliance's characteristics and the chosen program. To illustrate the state machine concept, consider the following example as depicted in Figure 4.3:

- The initial state is "machine OFF", when the appliance is turned off;
- Once an appliance is ready to work the state changes to "Machine Ready" through the signal "ready_work", and the appliance will be prepared to start its cycle when the time arrives;
- The signal "Time_ON" is triggered when the clock equals the starting time chosen by the user, changing the state to "Machine_ON";
- On "Machine_ON" state is simulated the pattern for variable consumption;
- The appliance will work during the time providing by the signal "Appliance_Time" and the power that this appliance is consuming during its operation time will change inside the "Machine_ON" state, the output of the state machine will be the consumption of that appliance;
- When the appliance finishes its work a signal, "complete" is triggered changing the appliance to "Machine_Complete" state;
- Finally, if the machine expects other cycle the signal "cont_work" will be triggered and the state machine will stay in " Machine_Ready" state until the new signal to start working;
- Otherwise, the state "OFF" will be turned off the machine and change the state to "machine_OFF".

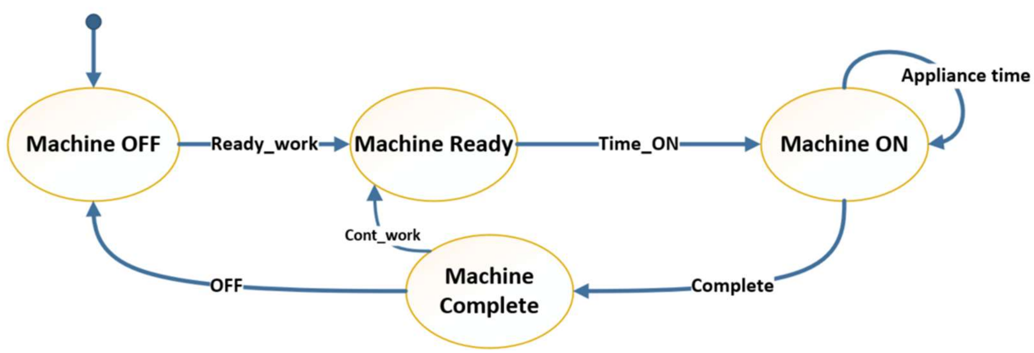


Figure 4.3 - Appliances' finite state machine.

Richardson's high-resolution domestic building occupancy model (Richardson et al., 2008) provides a detailed representation of household behavior by simulating the activities of residents and generating respective demand profiles with 1 minute resolution. This model is crucial for accurately predicting energy consumption patterns, enabling the development of effective energy demand management strategies.

For this work, Richardson model was employed to generate the household non-controllable load profiles, since the event-based appliances load was defined by the users and rescheduled when necessary during the resilience framework application.

4.1.2 Orchestrator Layer

The orchestrator serves as an important component of the proposed framework, responsible for analyzing energy consumption, storage and generation data from diverse household devices. This data is meticulously transformed into detailed load profiles and generation balances, as visualized in Figure 4.4, providing the foundation for comprehensive EnC management. The orchestrator also plays an important role in crisis management, i.e. when there are power faults, the orchestrator manages the EnC in order to optimize the use of resources and maintain user comfort.

This integrated approach empowers the EnC to effectively respond to grid faults or DSO requests by taking the necessary measures to mitigate the effects of faults, improving EnC's resilience and optimizing energy utilization.

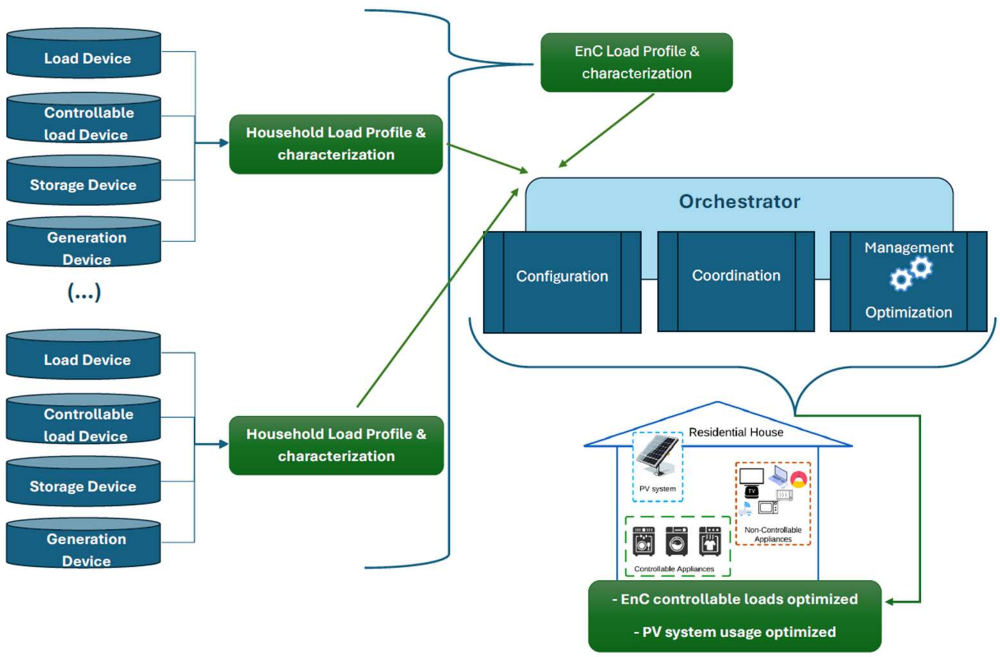


Figure 4.4 - EnC decision support entity.

By leveraging this data-driven approach, the orchestrator optimizes system performance through the dynamic management of energy distribution, storage, and generation.
Initially, the system configuration is established based on detailed household and EnC characteristics from physical and model layers, as well as the EnC's connection to the main grid. Subsequently, a coordination process evaluates system conditions to determine the necessity for demand adjustments. Finally, the management stage employs optimization approaches, such as Genetic Algorithms (GAs), detailed in subchapter 4.1.3, to allocate appliance loads optimally based on available renewable energy or storage resources.

4.1.3 Optimization Approaches

Optimization is a computational discipline dedicated to determining optimal solutions within predefined constraints. It quantifies solution quality numerically and seeks to maximize or minimize a defined objective function. This methodology is pervasive across fields like economics, physics, engineering, and more.
Core components of an optimization problem include:

- **Cost function:** A mathematical expression quantifying the problem's goal;
- **Decision parameters:** Parameters influencing the objective function's value;
- **Constraints:** Limitations defining the feasible solution space;
- **Feasible region:** The subset of solutions satisfying all constraints;
- **Optimal solution:** The best feasible solution maximizing or minimizing the objective function.

Optimization methods can be classified as linear or nonlinear methods depending on the type of problem being addressed, as shown in Figure 4.5. In the case of linear methods, where problems can be modeled using linear combinations of their decision variables and constraints, simple linear programming methods are used to obtain the optimum. However, in most engineering problems, the cost function and/or the imposed constraints exhibit nonlinear characteristics, requiring the use of nonlinear optimization methods.

Nonlinear programming encompasses a broad spectrum of optimization techniques, which can be categorized into three primary groups: classical, enumerative, and stochastic methods. Classical optimization methods employ deterministic approaches to identify optimal

solutions. These techniques often requires information about gradients or higher-order derivatives, rendering them unsuitable for many analog circuit sizing problems where such data is inaccessible. Enumerative methods, on the other hand, exhaustively explore the entire solution space, which can be computationally prohibitive for complex problems.
Stochastic search methods introduce randomness to the solution process, enabling exploration of a wider solution space. This randomized approach mitigates the risk of becoming trapped in suboptimal solutions.

Metaheuristic algorithms, inspired by natural processes, provide robust and adaptable frameworks for addressing complex optimization problems. These algorithms are excellent at exploring vast solution spaces, often yielding near-optimal or optimal solutions. Genetic algorithms, a prominent example, mimic the principles of biological evolution, iteratively improving solutions through mechanisms akin to selection, crossover, and mutation.
Unlike traditional deterministic methods, metaheuristics do not require explicit knowledge of problem derivatives. Instead, they rely on heuristic information derived from the problem itself, making them suitable for black-box optimization scenarios. This characteristic enables their application to a wide range of complex and ill-defined problems. The primary objective is to create algorithms that explore the search space effectively, aiming to locate high-quality solutions that may correspond to the optimal solution, based on metaheuristics.

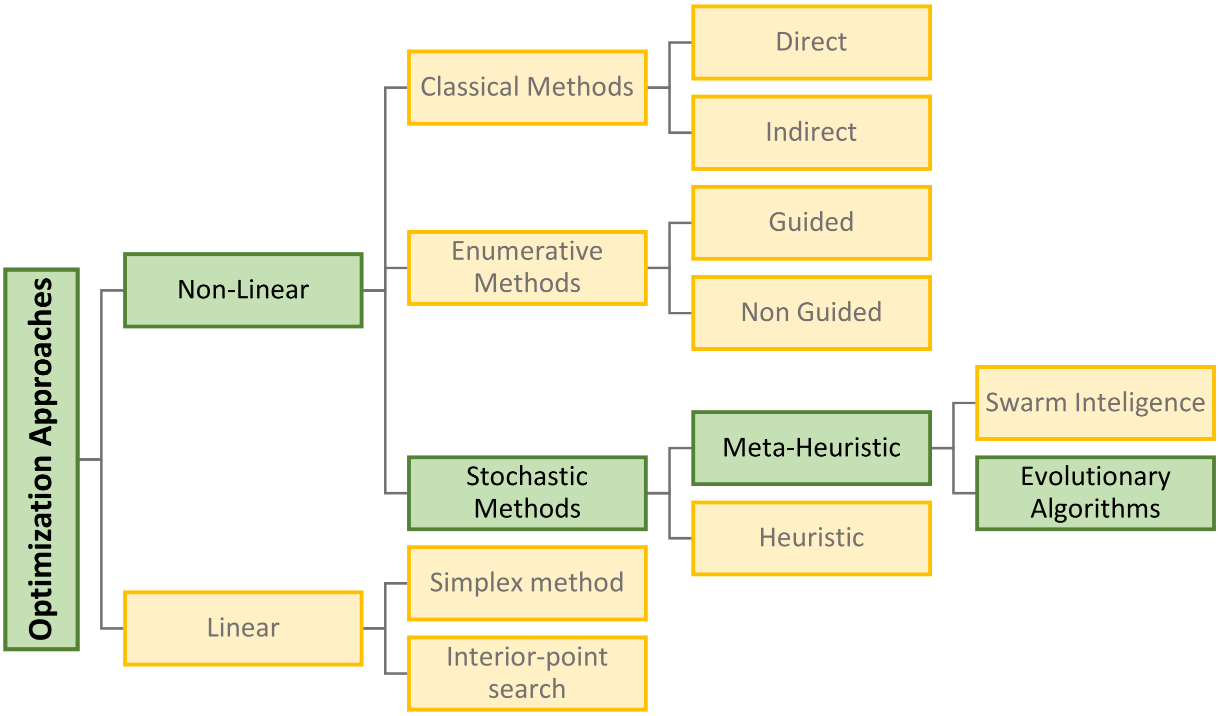


Figure 4.5 - Optimization Approaches , based on (Gil & Januário, 2016; Janga Reddy & Nagesh Kumar, 2020; Pereira, 2013)

A heuristic is a practical rule derived from experience. There is no conclusive proof of its validity, and it is expected that the heuristic technique will work most of the time. A heuristic, in general, helps to find good solutions, but not necessarily optimal ones. Natural methods are iterative procedures that attempt to simulate the processes used in nature to solve difficult problems.

Among the most commonly used techniques are evolutionary algorithms, e.g. genetic algorithms or differential evolution, and algorithms based on swarm intelligence like particle swarm or ant colony, as illustrated in Figure 4.6. Evolutionary Algorithms are population-based metaheuristics that employ stochastic search strategies to explore complex solution spaces. A population of candidate solutions undergoes an iterative process of selection, recombination, and mutation, simulating natural evolution.

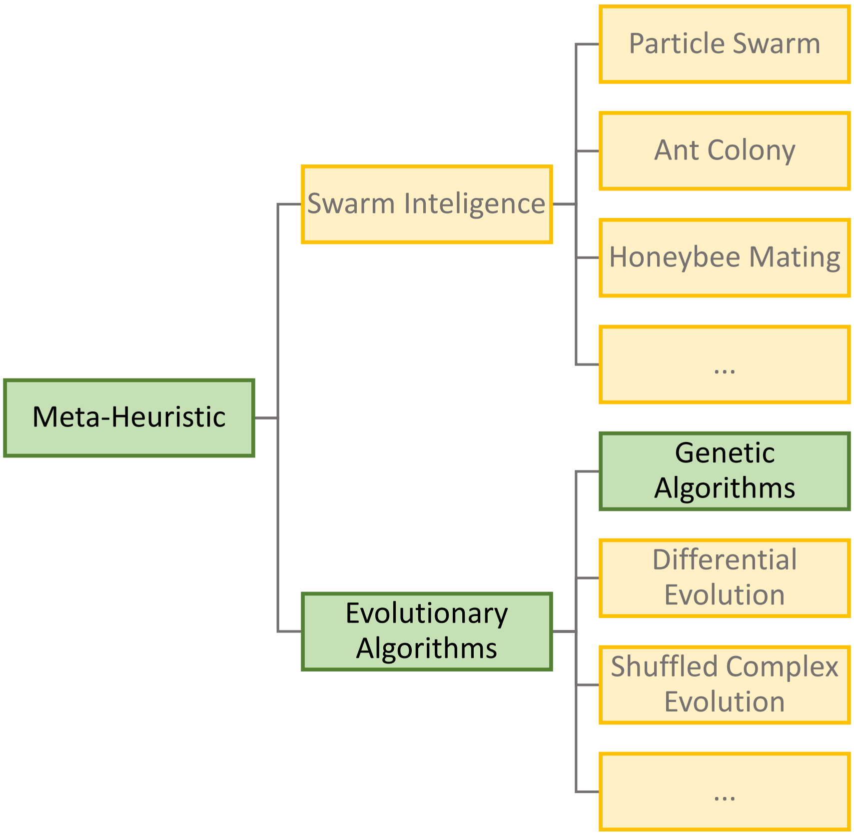


Figure 4.6 - Meta-Heuristic optimization , based on (Gil & Januário, 2016; Janga Reddy & Nagesh Kumar, 2020; Pereira, 2013)

Each individual in the population represents a potential solution, and their fitness is evaluated based on a predefined objective function. Higher-fitness individuals have a greater probability of contributing to the subsequent generation, promoting the exploration of promising regions of the search space. Over successive generations, the population converges towards optimal or near-optimal solutions. While various EA implementations exist, their underlying principles remain consistent (Kumar & Manne, 2010; Roni et al., 2022).

GAs, inspired by biological evolution, are population-based meta-heuristics that excel in solving complex optimization problems. Pioneered by Holland in the 1970s, (Holland, 1975), GAs simulates natural selection processes such as reproduction, mutation, and survival of the fittest. By encoding potential solutions as individuals within a population, GAs iteratively explores the solution space to identify optimal or near-optimal outcomes. Typically begins with a randomly initialized population. Individuals are evaluated based on a fitness function, determining their contribution to the subsequent generation. Selected individuals undergo genetic operators, including crossover (recombination) and mutation, to create offspring. This process balances exploration of the search space with exploitation of promising regions. The algorithm iterates until a termination criterion is met. GAs are incredibly versatile and reliable tools that have found their way into many different fields. Their adaptability and effectiveness make them a great fit for the proposed resilience framework.

Rescheduling optimization applied to Resilience Framework

In this work, when the orchestrator actuates, the aim is to reschedule the event-based appliances inside the EnC in order to a better use of the available power when faulty events happen. For that, contemplate a set of *n* considerations that will measure the problem's goal true the cost function. These considerations represent necessities that should be satisfied in order to optimize the appliances' rescheduling and maintain users' comfort. The specific considerations for this work are two, as follows:

1 – **Time variance**, represented by $\boldsymbol{X_A}$ and formulated in equation (13), that sums the difference between the initial time chosen by house users to start their appliances and the starting time changed by the algorithm.

2 – **Power Variance**, represented by $\boldsymbol{X_B}$ and formulated in equation (1), presents the difference between the power consumption and the power available inside the solar curve, when the difference is minimized, it means that the power used by photovoltaic is maximized.

The cost function, presented in equation (15), is the mathematical expression that aims to minimize a combination of the two specific considerations, Time and Power variance, and will be applied for genetic algorithms optimization considered by the orchestrator when resilience framework actuates in the EnC.

$$\begin{cases} X_A = \sum \left| Ap_{initial}(h,a) - Ap_{final}(h,a) \right| \\ Ap_{initial}(h,a) = hour_{initial}(h,a) * 60 + minute_{initial}(h,a), in\ minutes \\ Ap_{final}(h,a) = hour_{final}(h,a) * 60 + minute_{final}(h,a), in\ minutes \end{cases} \quad (13)$$

$$X_B = \left| \left(\sum Power_{available}(\mathrm{n}) \right) - \left(\sum Power_{consumption}(\mathrm{n}) \right) \right| \quad (14)$$

$$f_{cost} = \min \left((X_A * w_a) + (X_B * w_b) \ldots + (X_{\ldots} * w_{\ldots} \right) \quad (15)$$

Considering:

$h - represents\ the\ house\ number;$

$a - represents\ appliance\ number;$

$\mathrm{n} - represents\ solar\ window, \mathrm{n} \in\ [10\ am; 6pm];$

$w_a, w_b, \dots, -represents\ the\ weight\ of\ each\ category$ (%);

For the use cases of this work the cost function considered the minimization of Time variance as well as power variance with a combination of weights considered as follows:

$$f_{cost1} = \min\left((X_A * 50\%) + (X_B * 50\%)\right) \qquad (16)$$

For different setups each of these considerations, $X_A\ and\ X_B$ can have different weights, combining 100%. More considerations can be added to the cost function depending on what it is intended to minimize.

4.2 Energy Resilience Metrics

To assess the orchestrator's effectiveness in enhancing EnC resilience, a comprehensive evaluation of resilience metrics is essential. By calculating these metrics, the impact of the proposed framework on EnC resilience can be determined.

Energy resilience metrics are crucial indicators that assess the ability of an energy system, such as an EnC, to withstand and swiftly recover from various disturbances or disruptions. These metrics help evaluate the EnC's capacity to maintain a consistent and reliable energy supply under adverse conditions, such as power outages, fluctuations in demand, or unforeseen changes in energy availability. Commonly used energy resilience metrics include measures of system robustness, such as the ability to maintain power supply during peak demand periods, manage fluctuations in energy generation, and swiftly adapt to changes in energy flow. Additionally, metrics related to energy storage capacity, load management efficiency, and the EnC's capability to integrate renewable energy sources effectively are vital in assessing overall energy resilience, as studied on chapters 2 and 3.

Resilience Analysis Process, presented in subchapter 3.3.1, is a framework used to evaluate and enhance the resilience, in the case of an EnC, ensuring their ability to withstand and swiftly recover from a disruptive event or just to shift to remotely work, disconnected from main grid and, as defined for this work, with the ability to maintain the user's energetic comfort using renewable sources or ESS, without necessity to use main grid's power.

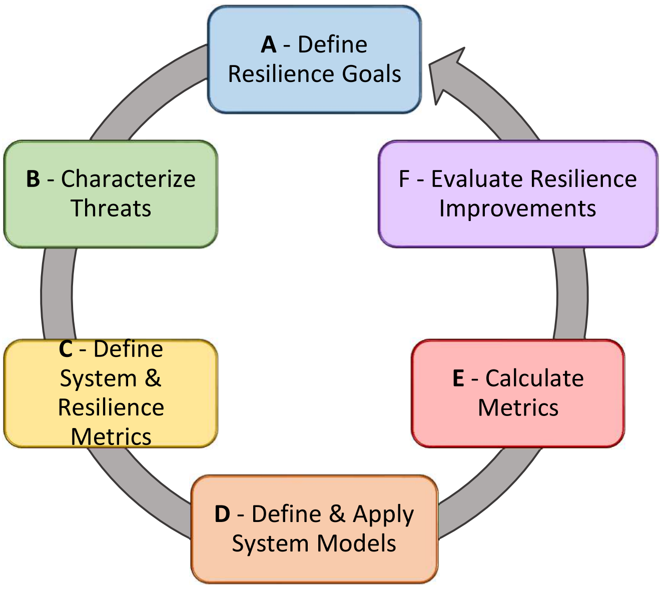


Figure 4.7 - RAP adapted to EnC resilience.

Key elements of the Resilience Analysis Process, adapted for this work, are presented in Figure 4.7 and include:

- A - Define Resilience Goals: The main task of this work is to present a structure that helps maintain the comfort of EnC users, taking into account the flexibility of EnC and, consequently, improving energy resilience;
- B - Characterize Threats: regarding the normal working of the EnC, the unexpected faults regarding natural disasters, cyber threats are considered as well as the supply chain disruptions that can be unexpected or planned by the DSO;
- C - Define System & Resilience metrics: This step involves creating a comprehensive energy system within the community, highlighting key components such as power generation facilities, ESS and household appliances. A clear understanding of the interconnectedness and interdependencies of these components is crucial for effective resilience planning. On this step is also defined the metrics to calculate the resilience of different EnC scenarios;

- D - Define & Apply System models: This step includes creating the framework for the EnC under study and presenting the modeling of the community along with the interconnections between its various components. Were also defined the different scenarios to study the improvement of EnC resilience;
- E - Calculate Metrics & F - Evaluate Resilience Improvements: In this step the metrics defined for this work will be calculated in order to evaluate the efficacy of the EnC resilience. The resilience of energy communities is an ongoing process that requires continuous monitoring and adaptation. Regular evaluations and updates to the resilience plan are essential to account for changes in the community's energy needs, technological advancements, and evolving risk landscapes.

In the review of current literature, resilience metrics are typically applied to EPG measures rather than providing an insight into the EnC itself.

This thesis considers the application of six specific metrics to evaluate the overall performance of EnC resilience specifically in instances where a fault occurs, or the available energy falls short of the EnC users' demand. These metrics are as follows:

Metric 1 – Number of appliances working during PV power availability

Solar time is considered as a working time window where irradiation exists, and PV systems can work. Depending on the month of the year, a larger or shorter window can be obtained. This metric counts the number of appliances that, after the orchestrator optimization process, have their working time inside solar time window.

Metric 2 – Community load unsupplied

To assess the EnC's energy self-sufficiency, it is essential to determine the percentage of daily consumption that cannot be satisfied by the combined resources of renewable energy and the ESS, compared to the baseline consumption pattern. This metric represents the necessary increase of the ESS and generation system to bridge this gap.

Metric 3 – Storage Capacity Indicator (SCI)

Metric 3, given by equation (17), allows to understand if the storage capacity is enough to support EnC during blackouts and guarantee users' comfort when changes occur and photovoltaic isn't available or it is not sufficient.

$$SCI(\%) = \frac{\sum_{\mathrm{i}}^{\mathrm{N}} E_{\mathrm{a_i}}(n)}{\sum_{\mathrm{i}}^{\mathrm{N}} E_{\mathrm{C_{i\,MAX}}}(n)}\ , n \in [0 - 1440] \quad (17)$$

It is given by the equation (14), where N is the number of correspondent house, E_a is the available energy at time-step n and $E_{\mathrm{C_{i\,MAX}}}$ the maximum battery capacity of the ESS.

Metric 4 – Average daily value of storage capacity

The average daily value of storage capacity, SC, along with Metric 3, will enable an assessment of whether the current storage capacity is sufficient or if it is inadequate. This metric represents a framework management metric since will help in decisions regarding potential updates to the storage capacity.

The metric is computed using equation (18) and considers N as the number of correspondent house, $\bar{E}_{\mathrm{day}}$ as the average of daily battery capacity used, as well as the maximum battery capacity, $E_{\mathrm{C_{i\,MAX}}}$.

$$SC(\%) = \frac{\sum_{\mathrm{i}}^{\mathrm{N}} \bar{E}_{\mathrm{day_i}}}{\sum_{\mathrm{i}}^{\mathrm{N}} E_{\mathrm{C_{i\,MAX}}}} \quad (18)$$

Metric 5 - Surplus Energy in EoD

Metric 5 studies the surplus energy by the end of the day. Surplus energy refers to the excess energy generated within the EnC that remains unused by the community members or stored by the end of the day. Managing surplus energy by the end of the day in an Energy Community involves implementing strategies and technologies to ensure efficient utilization and distribution of excess energy, namely increasing the ESS capacity, selling to the EPG or charging other type of assets like EVs.

Metric 6 - Consumed Energy during PV power availability

Metric 6 quantifies the energy consumption of controllable appliances operating within the solar generation window. This metric, combined with metric 1, when compared to the baseline scenario, which did not consider the resilience framework, allows to assess the amount of energy that was successfully rescheduled within the EnC in order to maintain the user comfort thus improving EnC's resilience.

Next chapter presents the use case design specifications, including a detailed description of the various use cases and scenarios, the data collected during the simulations, and the corresponding results, where the proposed metrics will be applied.

The design and modelling of the EnC system for this simualtions will be carried out using MATLAB software and considering collected data from renewable production from **P**hotovoltaic **G**eographical **I**nformation **S**ystem (PVGIS), (*JRC Photovoltaic Geographical Information System (PVGIS) - European Commission*, 2017).

5

USE CASE DESIGN AND RESULTS ANALYSIS

This chapter outlines the specifications of use cases design. Provides a comprehensive description of the various scenarios, presents the data collected during the described use cases and respective results.

5.1 The Energy Community under study

Considering the resilience framework presented in Chapter 4, the research design aims at specifying a set of use cases that allow to access the effectiveness of the developed methodology. To establish a foundation for use cases analysis, an EnC was considered. Each household is equipped with a set of appliances as detailed in Table 3.8 and interconnected via the EnC's LV grid. Figure 5.1 illustrates a single residential household, while Figure 5.2 presents the overall EnC configuration, considering 30 households and a shared local energy storage (SLES) as ESS.

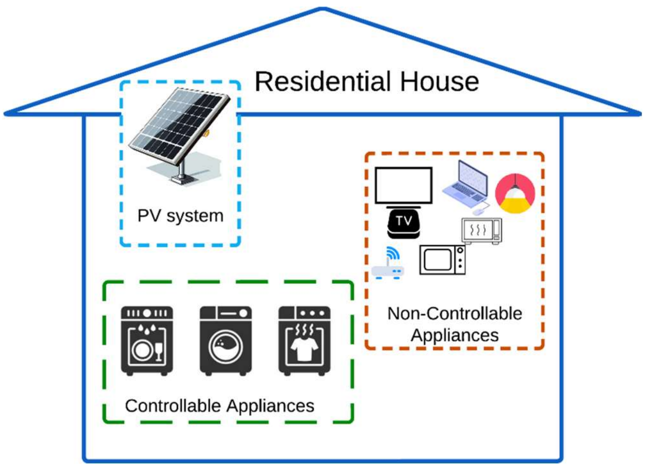


Figure 5.1 - Residential House considered for this work.

Table 5.1 – Electrical appliances considered in this study.

Appliance	Average Cycle Duration [min]	Standby Power [W]	Average Cycle Power [W]	Controllable
Laptop	300	5	141	No
TV	73	3	124	No
TV box	15	15	27	No
Wi-Fi	60	9	100	No
Microwave	30	2	1250	No
Electric oven	27	3	2125	No
Lights	Usage dependent	0	Usage dependent	No
Washing Machine	137	1	401	Yes
Dishwasher	59	0	[P1 - 2000; P2 - 1859; P3- 2150]*	Yes
Dry washer	59	1	[P1 - 1900; P2 - 2333; P3 - 2000]*	Yes

*Dishwasher and Dry washer mean cycle power can have different values depending on the chosen program (P1, P2 or P3).

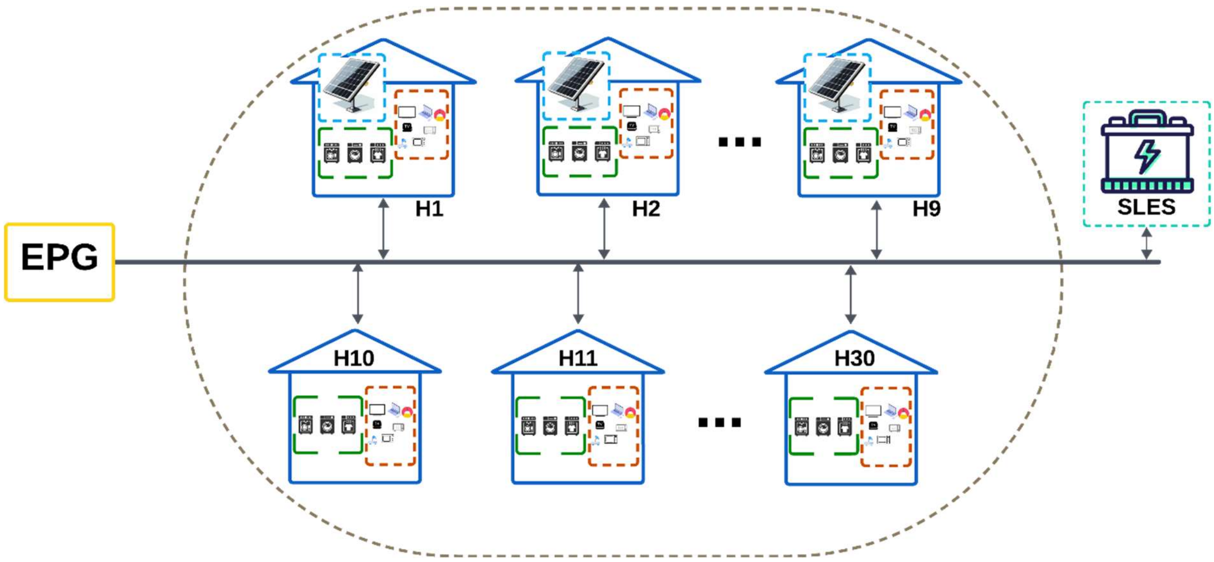


Figure 5.2 - Generic EnC considered for the use cases.

To consider the renewable energy generation, a certain number of residential households were equipped with PV systems, depending on the scenario. The specific characteristics of this PV system are detailed in Table 5.2. Ambient temperature (T_{amb}) and solar radiation (G) data necessary for PV system modeling were obtained from the photovoltaic geographical information system (PVGIS) database for the location of NOVA School of Science and Technology (38° 39' 36'' N/9° 12' 11'' W).

Table 5.2 - PV model & Inverter parameters used for the reference system with 4kWp.

	Parameters	Value	Unit
PV	A	1,60	m^2
	P_{MPPT}	285	W_p
	$T_{c,NOCT}$	46	^oC
	G_{NOCT}	800	Wm^{-2}
	α	-0.003	$^oC^{-1}$
	$T_{a,NOCT}$	20	^oC
	$T_{c,STC}$	25	^oC
	P_P	4000	W
Sunny Tripower 4.0 Inverter	η_{inv}	97.1	%
	P_{AC}	4000	W

Finally, the ESS was configured as a SLES, implying that there is a single storage system shared among all households in the EnC, as shown in Figure 5.2. Table 5.3 presents the characteristics considered on the use cases. It should be noted that the maximum SLES capacity will be defined for each scenario as different capacities for the SLES will be tested. Regarding the initial SoC, a value of 60% of the maximum capacity was considered in order to start the experiment with the battery at an intermediate capacity level.

Table 5.3 – SLES Characteristics considered for this work.

	Battery Characteristics
Maximum capacity (Emax) [Wh]	To be defined on Scenarios.
Minimum Capacity (Emin) [Wh]	5%*Emax
Initial SoC [Wh]	60%*Emax
Battery charging efficiency	80%
Battery discharging efficiency	85%

Subsequently, using the *MATLAB* environment, the framework presented on chapter 4 was considered, encompassing all appliances and characteristics of the EnC, as illustrated in Figure 5.3. For use cases design the scenarios will consider a full day window.

Leveraging user-supplied data on active appliances, the system constructs a comprehensive load profile, meticulously balancing energy production and storage. This analysis facilitates precise household characterization and overall EnC profiling. With this in-depth understanding, the orchestrator configures, coordinates, optimizes, and manages the EnC's flexibility and demands in case of fault. To refine the optimization process within this experimental framework, several constraints were considered, including:

- Each residential house has a maximum of 3 controllable appliances: Washing machine, Dish washer and Dryer machine;
- When the optimization process starts, rescheduling the loads, the system considers that any appliances already started will end their cycles;
- Appliances supposed to work after the orchestrator starts whenever a fault occurs, will be rescheduled using their flexibility.

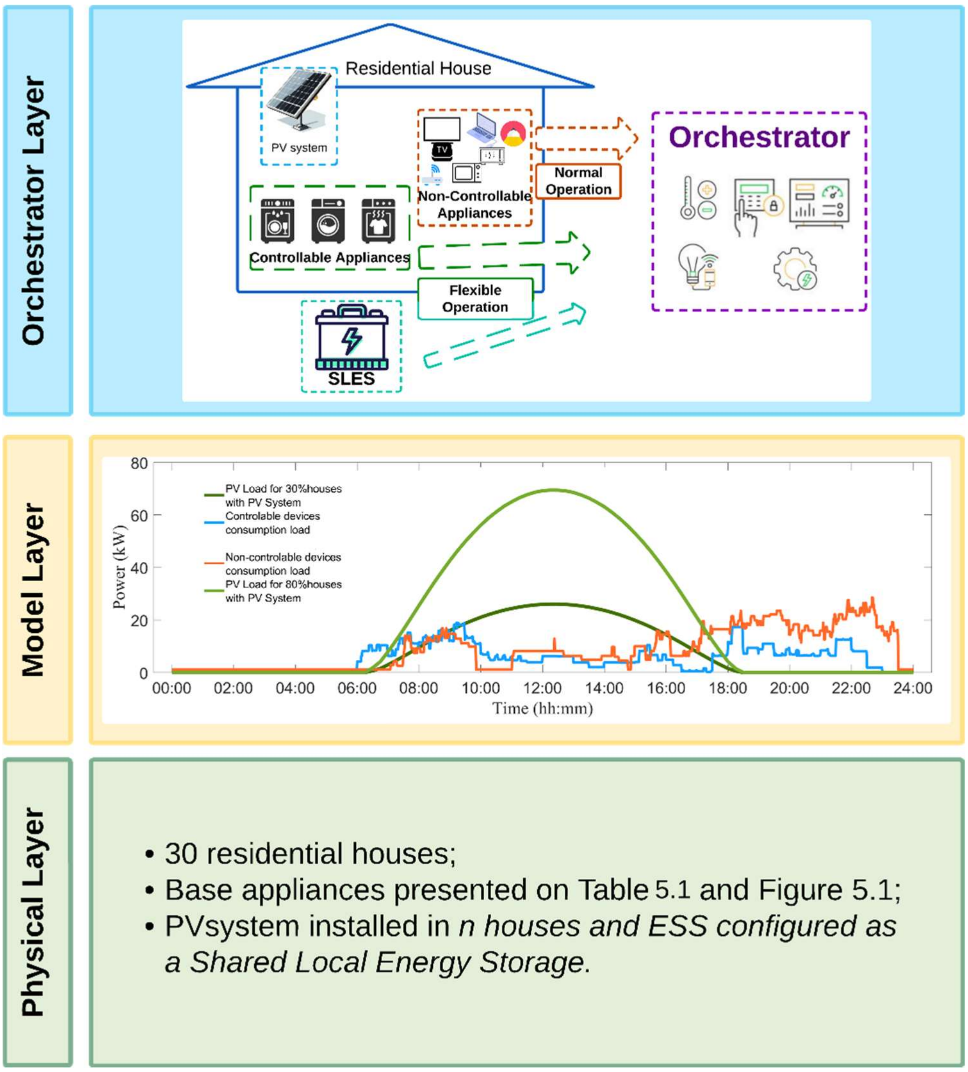


Figure 5.3 - Resilience Framework defined for this work.

At the physical layer, each user can designate which controllable appliances will be considered and their corresponding start times, adhering to the stipulated constraints of one of each controllable appliance per household and a single daily operation. Table 5.4 outlines these specifications in each household unit for the experimental period. The aggregate consumption profile, encompassing both controllable appliances and non-controllable appliances, is represented in Figure 5.4 denoted by the blue line, as well as the consumption of the controllable loads denoted by the red line. This red line represents the part of the load that will be adjusted in each use case, considering the flexibility of each appliance. Regarding this flexibility, of these three appliances per household, it is assumed that it can be rescheduled to any time, provided that their operating cycles can be completed within the considered 24-hour window.

Table 5.4 – Initial time for each controllable appliance

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
House #2	8h30	10h30	14h00
House #3	15h15	X	22h00
House #4	15h45	17h30	18h00
House #5	18h00	20h00	21h30
House #6	7h00	X	21h30
House #7	6h30	X	14h30
House #8	19h00	12h00	X
House #9	9h00	21h00	21h00
House #10	18h00	11h30	13h30
House #11	8h15	8h00	17h30
House #12	8h45	8h30	20h00
House #13	15h00	15h00	X
House #14	15h00	15h30	X
House #15	18h30	18h00	12h30
House #16	7h15	7h00	21h30
House #17	6h00	6h00	7h30
House #18	X	19h00	6h00
House #19	9h00	9h00	19h00
House #20	X	18h30	9h30
House #21	7h30	X	7h15
House #22	6h15	12h30	6h45
House #23	19h45	21h00	X
House #24	9h00	11h30	9h00
House #25	18h00	8h00	X
House #26	8h30	10h30	7h20
House #27	8h15	X	6h10
House #28	X	17h30	19h00
House #29	X	20h15	9h15
House #30	X	X	8h45

* X means that the house #n does not have that appliance.

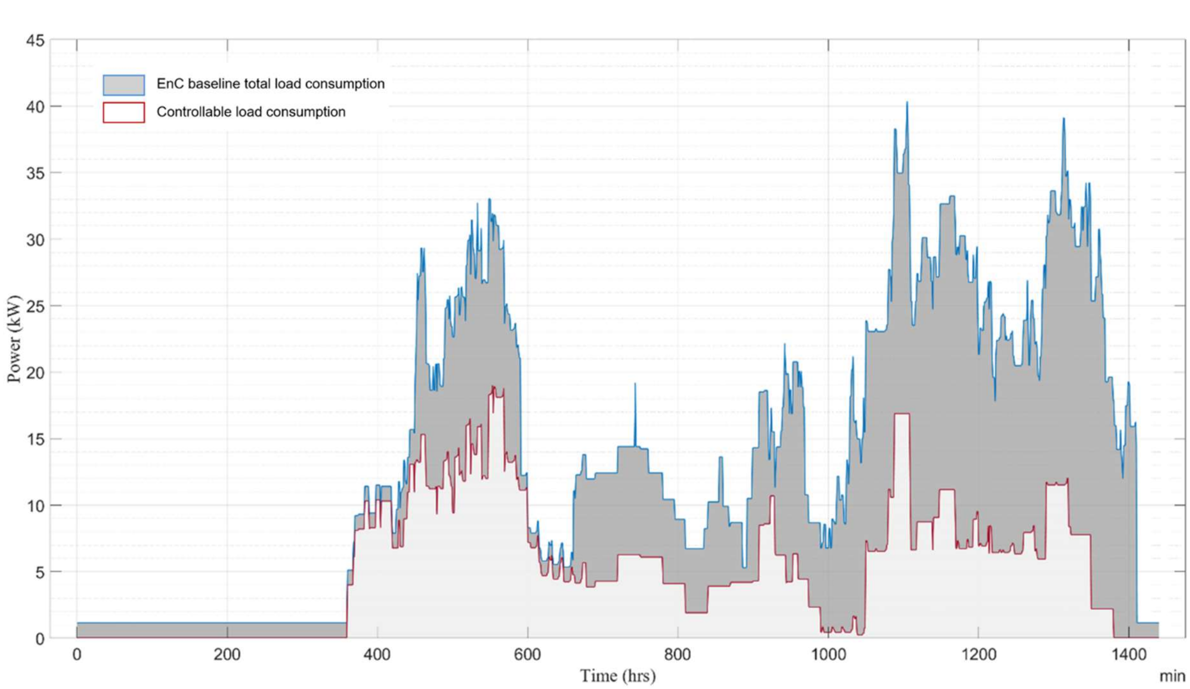


Figure 5.4 - EnC baseline total load consumption.

Analyzing the load profile, it reveals a consistent pattern of energy usage throughout the day, with consumption peaks occurring in the morning and late evening/night. There is a noticeable decrease in consumption during daytime hours, as users typically leave their homes for work. Paradoxically, these daytime hours also coincide with the high solar irradiance, resulting in maximum PV production. The load of non-controllable appliances was generated using the Richardson model and considering Laptop, TV, TVbox, Wi-fi router, Microwave, Electric oven and Lights. Some of these appliances have static standby consumptions, which results in a horizontal line from midnight to approximately 6am.

5.2 The Use Cases

For the use cases that are presented below, the EnC presented on subchapter 5.1 is considered (see Figure 5.1 and Figure 5.2).

The load profile depicted in Figure 5.4 serves as the baseline consumption pattern for all subsequent EnC use cases (#1, #2, and #3), which will be examined in detail in the following subchapters. Prior to presenting these use cases, it is worthwhile mentioning that two primary disturbance approaches were considered. The first one considers a disconnection from EPG due to a blackout, representing an unforeseen interruption from the main energy supply. This highlights the EnC's ability to autonomously reorganize its energy resources, highlighting the critical importance of flexibility. The second considered disturbance involves DSO-imposed constraints, where the orchestrator possesses prior knowledge of the foreseen maximum power constrains, including start time and duration. This enables proactive management of EnC resources, such as increasing energy storage and reallocating controllable appliances. Given these considerations, use cases design encompasses the following:

- Use Case #1: Long-term Blackout - In the first use case the EnC will be tested considering an unforeseen long-term blackout, meaning that EnC will be totally disconnected from the main grid for a 24h period;
- Use Case #2: Short-term Blackout - This use case considers a total disconnection of EnC from EPG for a period of 3hours. Like the use-case #1, this is also an unforeseen event, triggering post-fault optimization approaches;
- Use Case #3: DSO constraints -This use case considers a foreseen reduction in the EPG power availability. It is assumed that the orchestrator is informed, by the DSO, about the starting time and duration of the power limitation, giving it the opportunity to prepare and manage the EnC resources having an optimization approach pre-fault.

For each of these use cases, different scenarios, as presented in Figure 5.5, were considered to evaluate different approaches and real-life situations, namely:

- Scenario 1: 9 of the 30 houses inside the community have PV system installed (30%) and the SLES has a capacity of 30kWh;
- Scenario 2: 9 of the 30 houses inside the community have PV system installed (30%) and the SLES has a capacity of 100kWh;
- Scenario 3: 24 of the 30 houses inside the community have PV system installed (80%) and the SLES has a capacity of 30kWh;
- Scenario 4: 24 of the 30 houses inside the community have PV system installed (80%) and the SLES has a capacity of 100kWh.

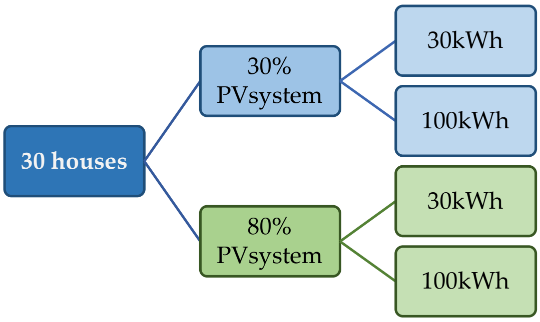


Figure 5.5 - Different scenarios of SLES and PVsystem.

Finally, to facilitate a comprehensive understanding and analysis of the work presented and subsequent results, it is important to revisit some definitions introduced in subchapter 3.4. The proposed use cases will be evaluated considering the resilience framework outlined in Chapter 4 and detailed in Figure 5.3. The use cases design will follow these specified rules. The ensuing subchapters present the specific use cases developed to assess and quantify EnC resilience under various conditions.

The subsequent subsections, 5.2.1 to 5.2.3, establish the baseline for the various use cases presented. Moreover, subchapter 5.3 delves into the presented methodology of this research, specifically the application of the resilience framework and the performance optimization of the orchestrator.

5.2.1 Use Case #1, Long-term Blackout

Energy communities able to operate in a disconnected state from the main grid can become increasingly relevant in the energy sector presenting a high resilience level, also when a fault occurs. In order to operate independently, these communities need to increase their resilience. This means that they should continue working even in the event of power outages or other disruptions in the main grid. This form of energy independence is often achieved through the implementation of local energy generation (desirable renewable energy sources like solar panels, wind turbines, and small-scale hydroelectric power), combined with the integration of energy storage systems, such as batteries or other energy storage technologies, together with the usage of user's energy flexibility. This approach not only improves the energy supply reliability within the community but also promotes higher self-sufficiency and resilience, reducing dependency on external suppliers

In this use case, presented on Figure 5.6, the idea is to test the EnC's ability to maintain its working conditions when it is completely disconnected from the main grid because of a fault that has caused a blackout on the EPG. This case is also relevant to scenarios where the EnC aims to operate autonomously, minimizing dependency on external energy sources.

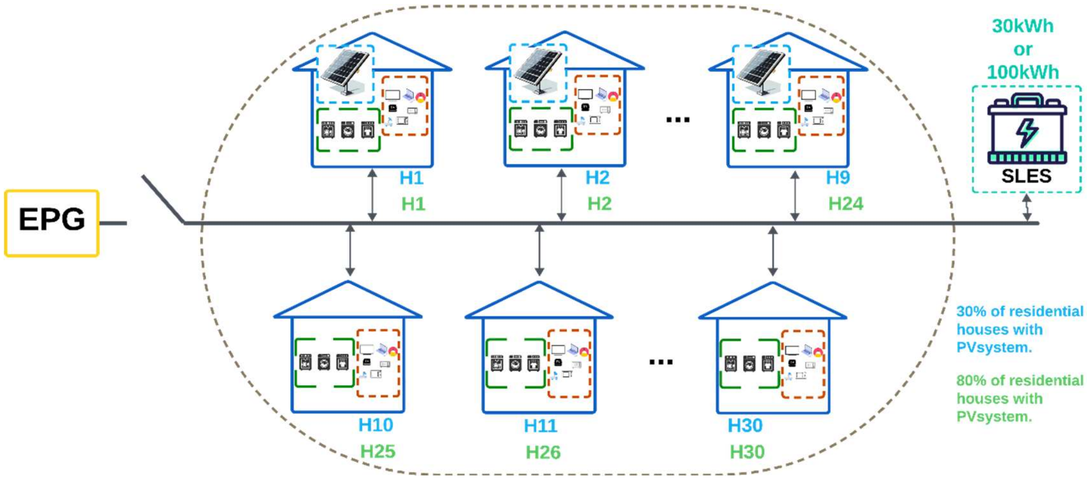


Figure 5.6 - EnC for use case#1 with different scenarios of PVsystem and SLES.

The results for the four different scenarios are presented in Figure 5.7, where PV production is represented by green line, the EnC baseline consumption by the red line and SLES energy by the blue line.

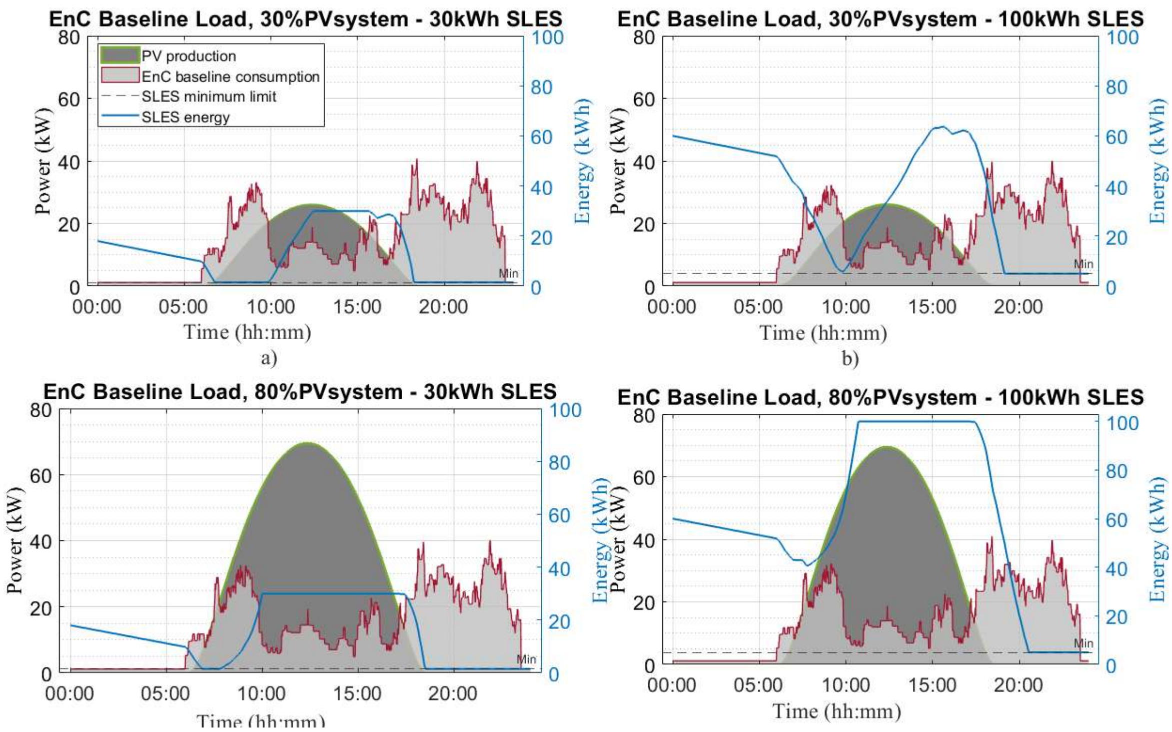


Figure 5.7 - Energy community baseline load for each scenario of use case #1, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

These results will allow to evaluate the impact that a bigger photovoltaic production will have to the EnC and its resilience. Different scenarios will also consider different SLES capacity, as presented in Figure 5.6, specifically 30 and 100 kWh.

As illustrated in Figure 5.7 and Figure 5.8, all four scenarios demonstrated the EnC's inability to maintain user comfort when operating in complete isolation from the EPG for 24 hours. A significant portion of the appliances within the EnC operate outside of the solar generation time window, relying solely on the available SLES capacity, which proved insufficient to meet the community's energy demands, represented by grey rectangles on Figure 5.8.

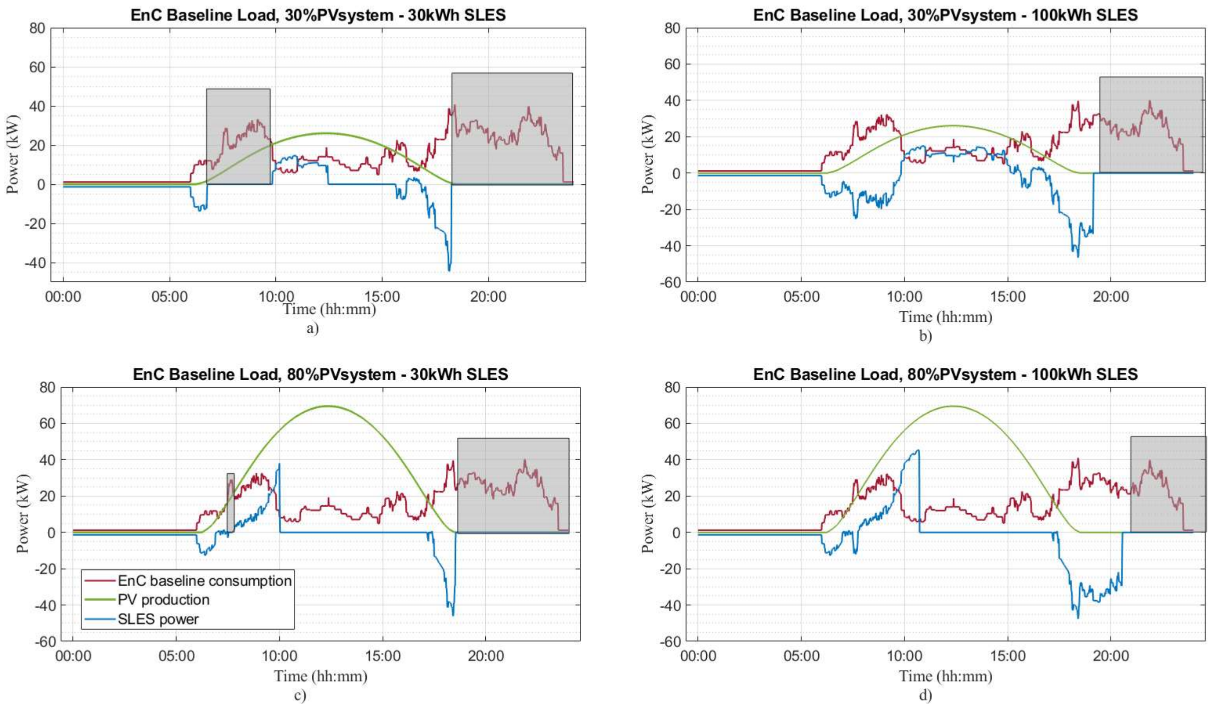


Figure 5.8 - EnC baseline load for each scenario with SLES power for use case #1, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

The main objective of the developed resilience framework is to maintain user's energy comfort even in case of a fault. The EnC resilience can be assessed using the defined metrics, ad presented in Table 5.5.

Table 5.5 - Metrics for baseline use case #1.

Scenario PV [%] / SLES [kWh]	Metric 1 Number of appliances working on solar time	Metric 2 Unsupplied Community load (%)	Metric 3 Battery capacity in EoD (%)	Metric 4 Average daily value of battery capacity (%)	Metric 5 Surplus Energy in EoD (kWh)	Metric 6 Consumed Energy inside solar window (kWh)
30 / 30	34 of 73	62,96	5,00	41,75	36,85	50,11
30 / 100	34 of 73	34,65	5,00	35,30	0,00	50,11
80 / 30	34 of 73	42,26	5,00	50,63	319,99	50,11
80 / 100	34 of 73	22,83	5,00	60,18	281,41	50,11

5.2.2 Use Case #2, Short-term Blackout

This use case, illustrated on Figure 5.9, assesses the EnC capacity to preserve user comfort during short-term grid blackouts. By subjecting the EnC to unforeseen grid disruptions, this use case evaluates its resilience in maintaining operations while prioritizing user well-being. The EnC's ability to balance energy supply and demand under these constrained conditions underscores its overall robustness and effectiveness.

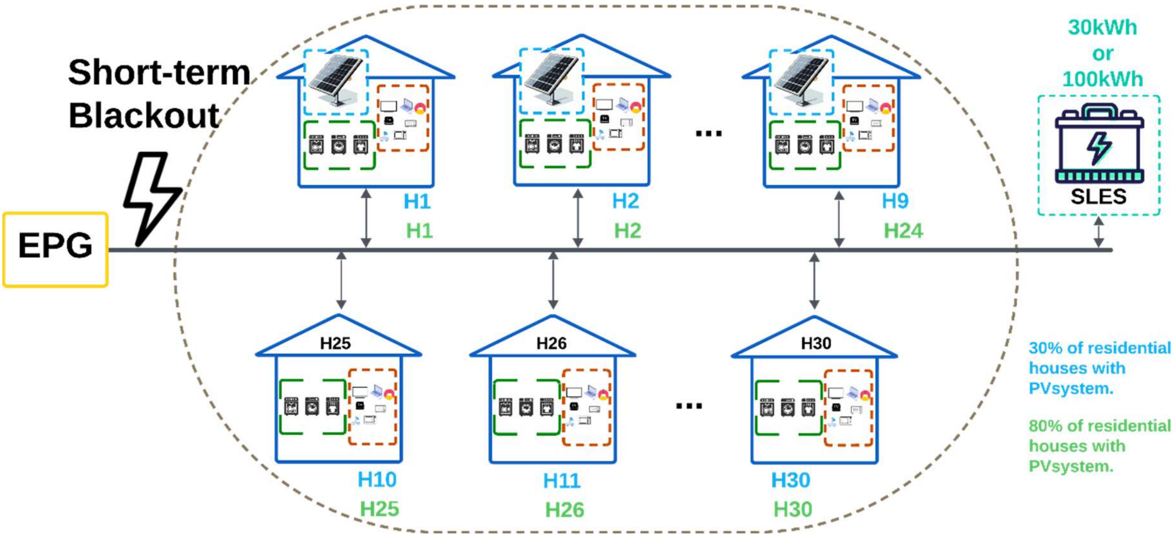


Figure 5.9 - EnC for use case#2 with different scenarios of PVsystem and SLES.

For visualization purposes the following reasoning was considered. Given the average annual per capita electricity consumption in Portugal of 1326,8 kWh (DGEG – Direção Geral de Energia e Geologia, 2023; PORDATA, 2024), the daily consumption per household is approximately 3,5 kWh per person. Considering the EnC consists of 30 households with diverse consumption patterns, it is assumed that the main grid can supply the EnC with a maximum of 250 kW for this use case.

As depicted in Figure 5.10, represented by the purple rectangle, a short-term fault occurred between 7h00 and 12h00, resulting in a complete outage of EPG. As seen in Figure 5.10 and Figure 5.11, during this period, the EnC relied solely on its PV system and SLES. In this case, when the day starts the EnC works connected to the grid but given priority to PV system production and SLES since it is an unforeseen fault, there’s no idea if or when it will occur.

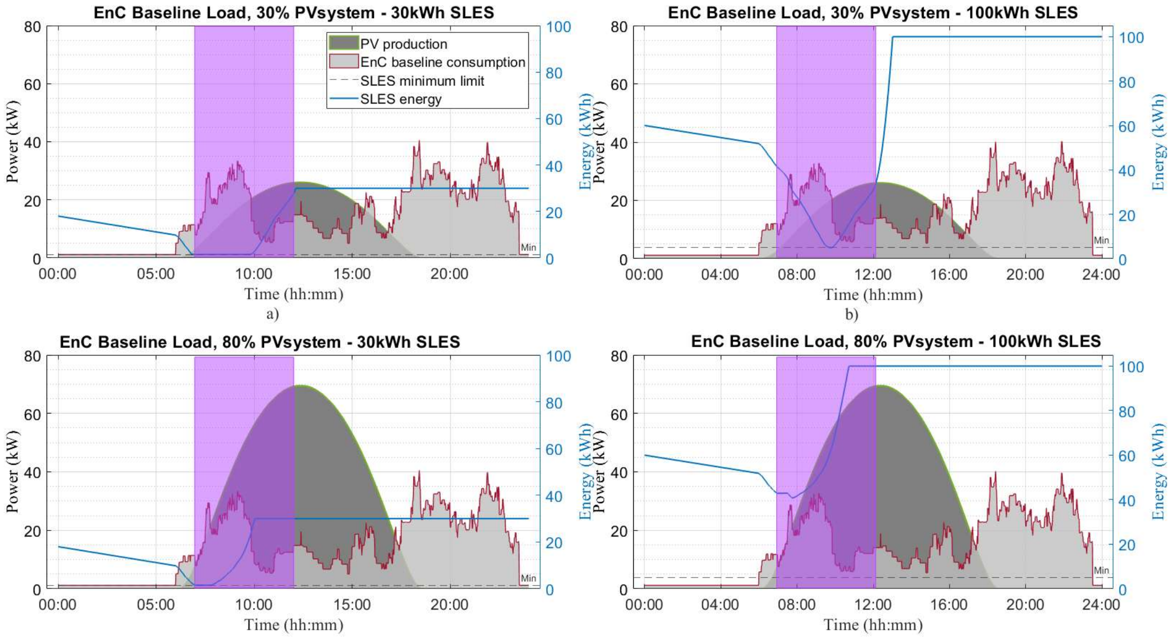


Figure 5.10 - Energy community baseline load for each scenario of use case #2, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

After the fault disappears, and the EnC is reconnected to the EPG, the EnC will maintain the SLES full in case of a second fault occurs and consume from PV system production or directly from EPG when necessary. Given the early occurrence of the fault, the EnC's stored energy was depleted during the initial hours of the day due to the lack of PV production. This resulted in an unsupplied community load in scenarios #1, #2, and #3.

The EnC resilience can be assessed using the defined metrics, as presented in Table 5.6. A surplus of energy production was particularly pronounced in scenarios with 80% PV system penetration, as the higher generation capacity exceeded consumption during the hours of peak solar irradiation. Since this is an unforeseen fault, the optimization algorithm will only be activated to reschedule appliances once the fault occurs.

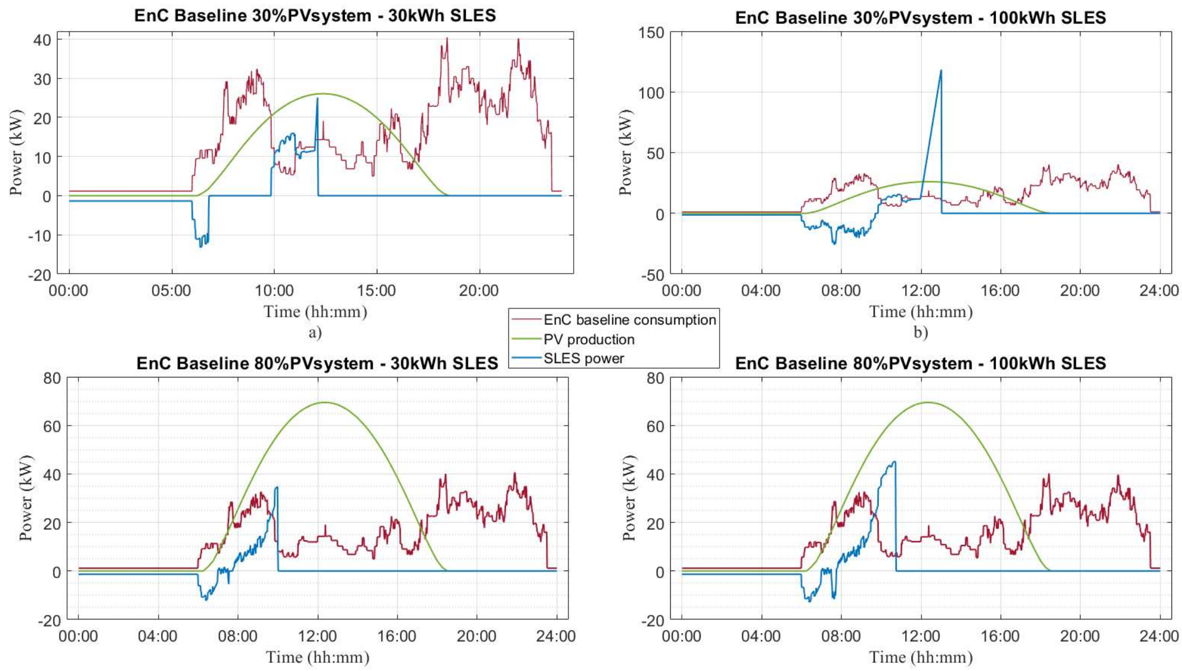


Figure 5.11 - EnC baseline load for each scenario with SLES power for use case #2, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

What is expected for the optimization in this use case is to decrease the surplus of unused energy production as well as the not supplied energy consumption of the EnC due to the short-term fault. Is it's also expected due to the early timing of the fault that a higher number of appliances works inside the solar window, leading to a higher energy consumption inside that solar window.

Table 5.6 - Metrics for baseline use case #2.

Scenario PV [%] / SLES [kWh]	Metric 1 Number of appliances working on solar time	Metric 2 Unsupplied Community load (%)	Metric 3 Battery capacity in EoD (%)	Metric 4 Average daily value of battery capacity (%)	Metric 5 Surplus Energy in EoD (kWh)	Metric 6 Consumed Energy inside solar window (kWh)
30 / 30	34 of 73	20,55	100	66,96	44,09	50,11
30 / 100	34 of 73	0,77	100	69,60	40,92	50,11
80 / 30	34 of 73	1,79	100	74,21	320,89	50,11
80 / 100	34 of 73	0	100	79,80	282,48	50,11

5.2.3 Use Case #3, DSO constraints

For this use case, in Figure 5.12, the objective is to test the capacity of the EnC to maintain the users' comfort during a foreseen event. The considered use case assumes a DSO need to divert energy to other users connected to the main grid, decreasing the maximum power supplied to EnC. As in the use case #2, this one will consider that the main grid is able to supply the EnC with 250kW.

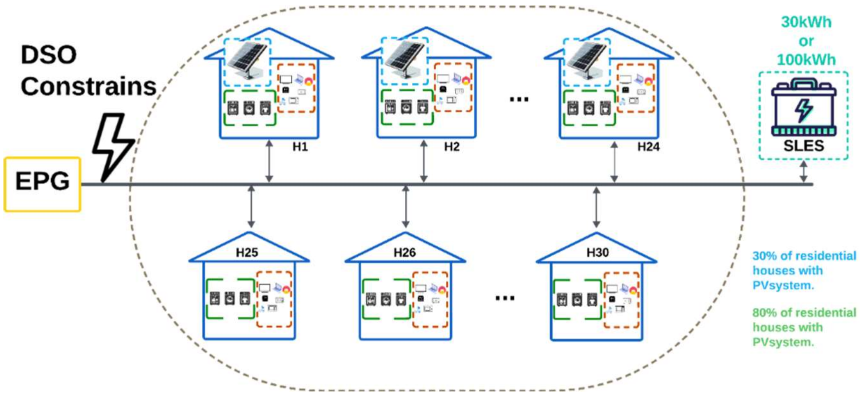


Figure 5.12 - EnC for use case#3 with different scenarios of PVsystem and SLES.

Given that the DSO will inform about the required power reduction and at what time will happen, it is feasible to implement a load scheduling strategy that considers the timing of the demand response event and reschedule the appliances outside of that time, considering also important to have SLES charged on that moment. This procedure is included in the developed framework and it will be assessed in section 5.3.

As depicted in Figure 5.13, DSO informs that the main grid is able to supply the EnC with 10kW, represented by the yellow rectangle, between 14h00 and 20h00, due to constraints imposed by the DSO.

By analyzing Table 5.7 and Figure 5.13 and Figure 5.14, it becomes clear that unlike use case 1, which operates in complete disconnection from the EPG, use case 3 has the option to consume power from the main grid although limited. As a result, scenarios 2 and 4, Figure 5.13 b) and d), demonstrate the EnC's ability to sustain user comfort during this faulty event, even without optimization considered in the developed framework.

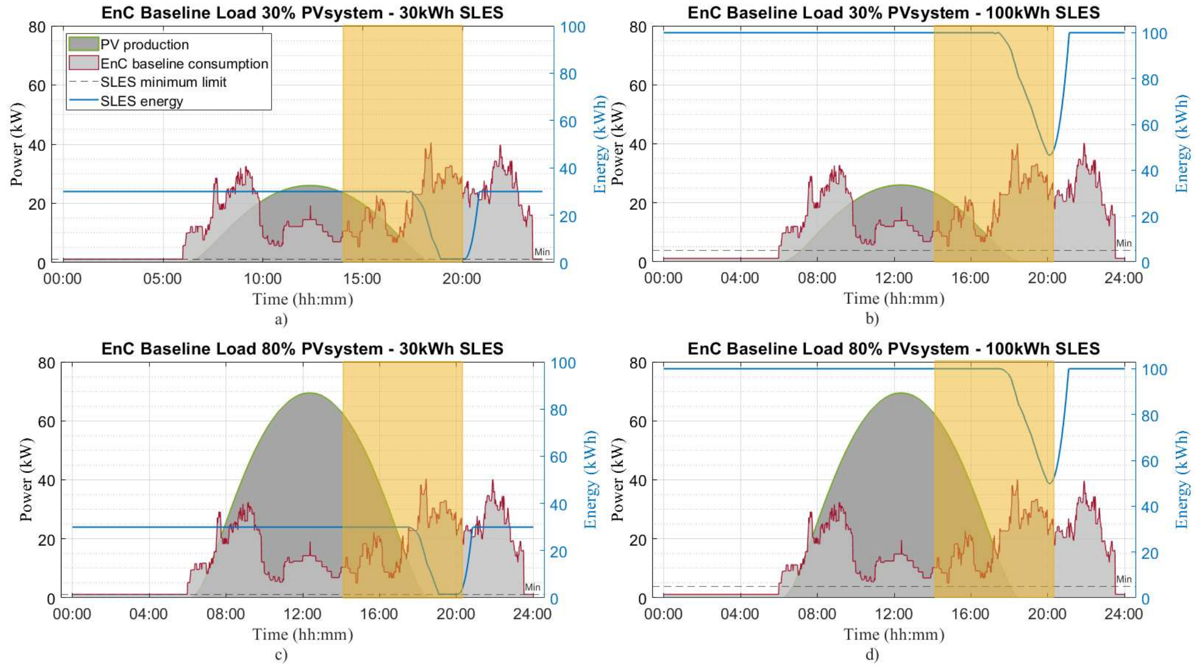


Figure 5.13 - Energy community baseline load for each scenario of use case #3, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

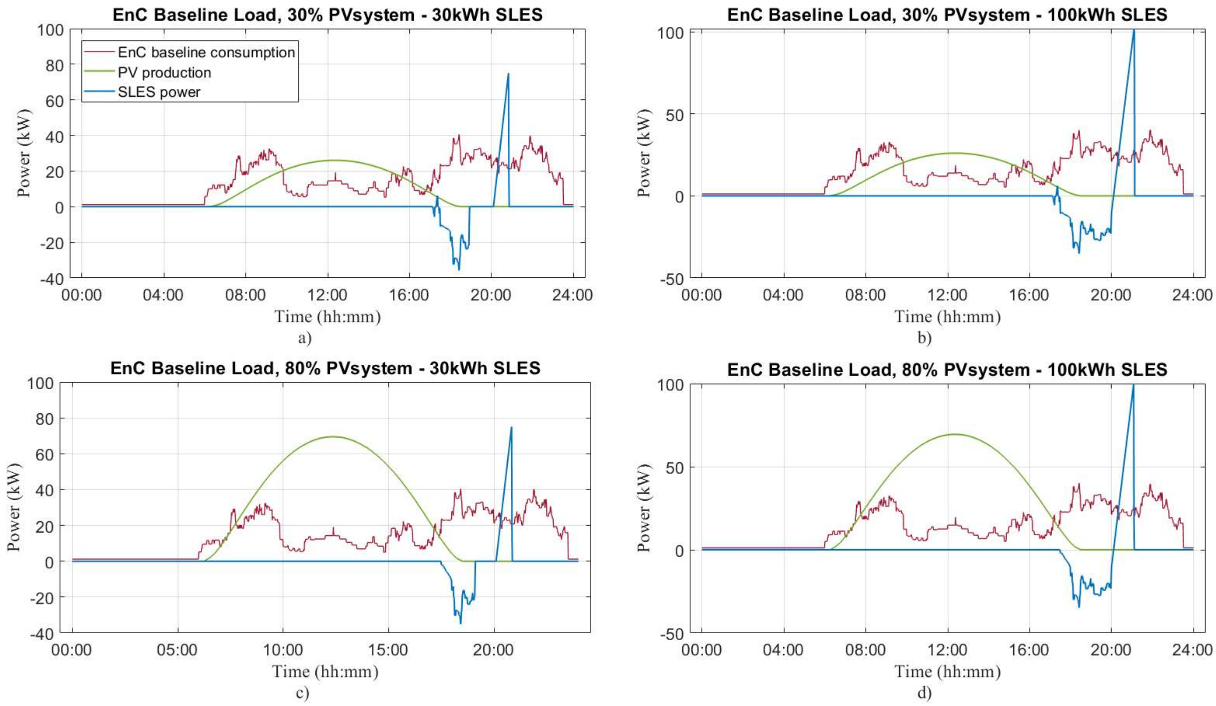


Figure 5.14 - EnC baseline load for each scenario with SLES power for use case #3, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

In scenarios 1 and 3, Figure 5.13 a) and b), which considers lower SLES capacity, the EnC exhibits an unsupplied community load of 9.58% and 8.18%, respectively. Given the forecasted nature of the fault in this use case, with the DSO providing information on the timing and magnitude of the power reduction, the EnC can proactively manage its energy consumption. Prior to the fault, the SLES prioritizes storing energy, while the EnC optimizes its consumption to maximize the utilization of PV production and grid power when necessary, ensuring a fully charged SLES at the time of the fault.

In scenarios where the EnC's energy needs are fulfilled, even with supplemental power from the EPG, the primary optimization objective will be to minimize EPG consumption and maximize the utilization of PVsystem production. This will be achieved by strategically scheduling appliances within the solar generation window to reduce excess energy at the EoD, as presented in section 5.3.

Table 5.7 - Metrics for baseline use case #3.

Scenario PV [%] / SLES [kWh]	**Metric 1** Number of appliances working on solar time	**Metric 2** Unsupplied Community load (%)	**Metric 3** Battery capacity in EoD (%)	**Metric 4** Average daily value of battery capacity (%)	**Metric 5** Surplus Energy in EoD (kWh)	**Metric 6** Consumed Energy inside solar window (kWh)
30 / 30	34 of 73	9,58	100	92,89	74,72	50,11
30 / 100	34 of 73	0	100	96,89	75,05	50,11
80 / 30	34 of 73	8,18	100	93,61	356,24	50,11
80 / 100	34 of 73	0	100	97,38	354,85	50,11

5.3 Resilience Framework Results

Subchapter 5.3 presents the results obtained from simulating the considered use cases and corresponding scenarios, as detailed in Subchapter 5.2, by applying the developed resilience framework to the EnC. These simulations explore the impact of varying SLES capacity, and the number of households equipped with PV systems.

5.3.1 Use Case #1

In this use case, where the EnC operates in complete isolation from the EPG, the resilience framework optimization algorithm is proactively initiated at midnight to manage loads throughout the day and ensure that user comfort will remain as high as possible. This proactive approach is essential because peak consumption periods frequently occur outside of the solar generation time window. Even with flexible load shifting within the solar generation window, a significant off-peak consumption gap often persists, necessitating the use of the SLES. However, the effectiveness of this approach varies depending on the specific circumstances of the EnC, including the availability of PV production and the storage capacity of the SLES. The following section discusses the diverse scenarios that emerged from optimization in use case #1 and Figure 5.15 Illustrates the results for each scenario.

In general, it is possible to observe that in graphs a) and c), where the installed photovoltaic system covers only 30% of the community's houses, there is always a maximum usage of stored energy, regardless of whether the storage capacity is 30 or 100 kWh. As illustrated in Figure 5.15 b) and d), where 80% of the community's houses are equipped with PV systems, an unused surplus of PV energy production becomes evident due to the insufficient capacity of the SLES to accommodate all excess generation.

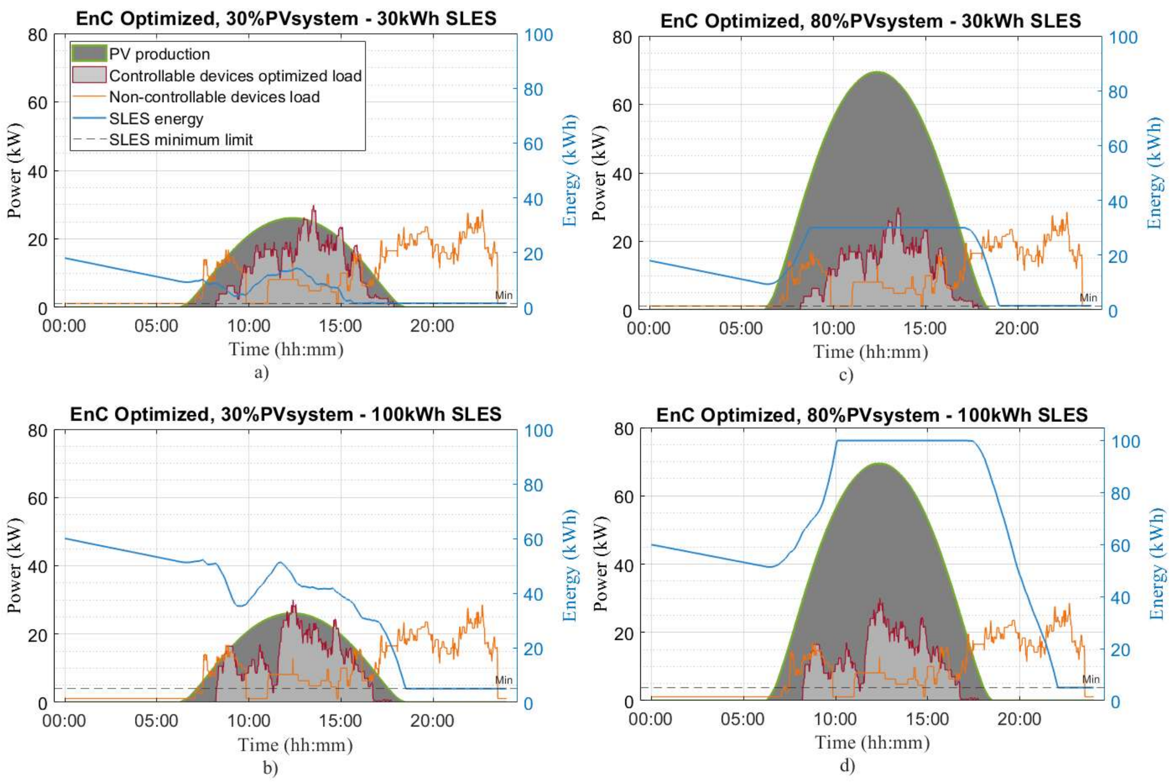


Figure 5.15 - Resilience framework results overview for use case #1 - Long-term Blackout, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

Figure 5.16 displays the EnC consumption load, depicted by a green line, alongside the available power from the PV system and SLES, represented by blue and red lines. The power output of the EnC's SLES is negative during discharge and positive during charging. A power output of zero indicates that the SLES has reached its maximum or minimum SoC. By analyzing both Figure 5.15 and Figure 5.16, it becomes evident that the system was unable to meet in 100% the EnC's needs with the available resources, even after the resilience framework optimization of appliances scheduling.

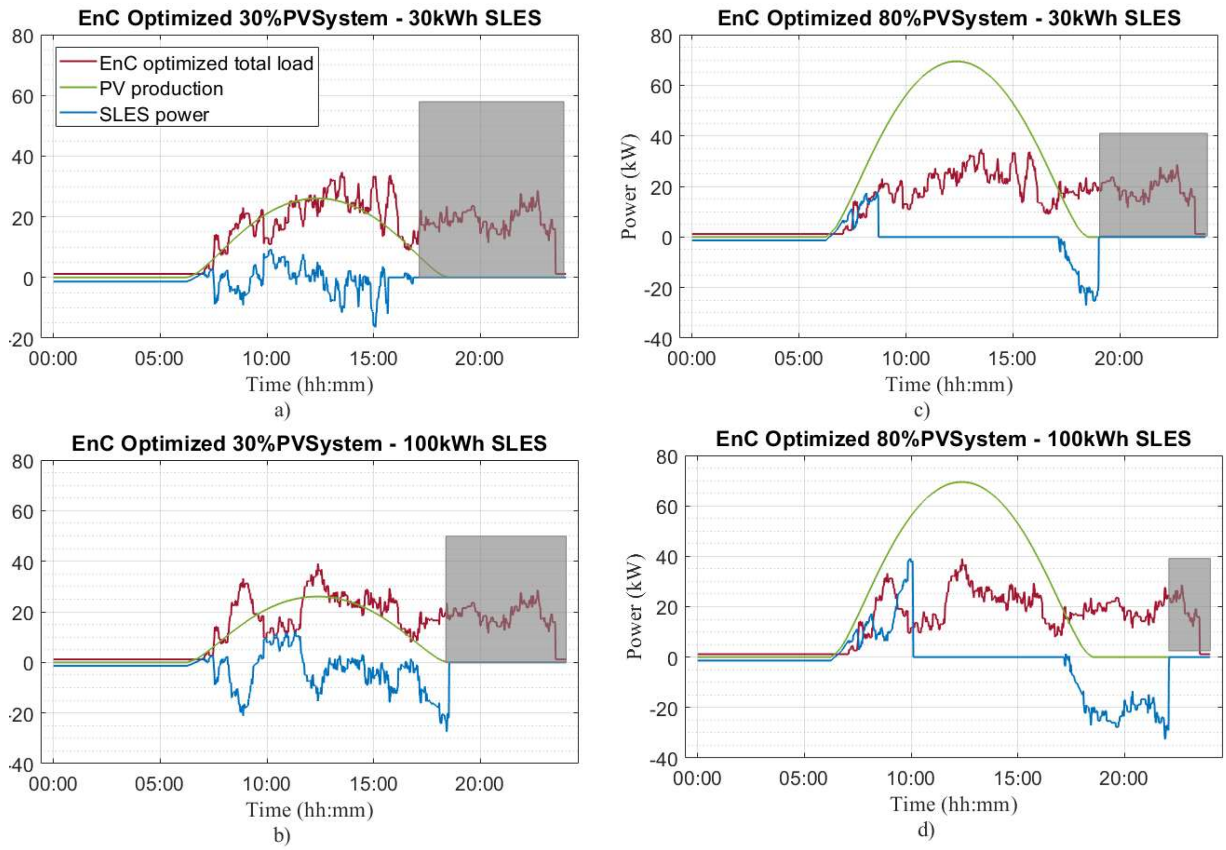


Figure 5.16 - Resilience framework results for each scenario with SLES power for use case #1, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

Subsequently, an analysis was performed to assess the results obtained for the different scenarios. Comprehensive examination of graphical data in Figure 5.15 and tabular data in ANEX 1 reveals complete alignment of controllable load scheduling within the solar window. Contrariwise, non-controllable loads demonstrate substantial energy consumption beyond the solar window, requiring the usage of surplus energy stored during daylight hours. In this specific use case, of a complete disconnection between the EnC and the EPG, the SLES will solely accumulate surplus photovoltaic energy during daylight hours. If this stored energy proves insufficient to meet the EnC's nighttime demands, the SLES will be unable to recharge for the subsequent day.

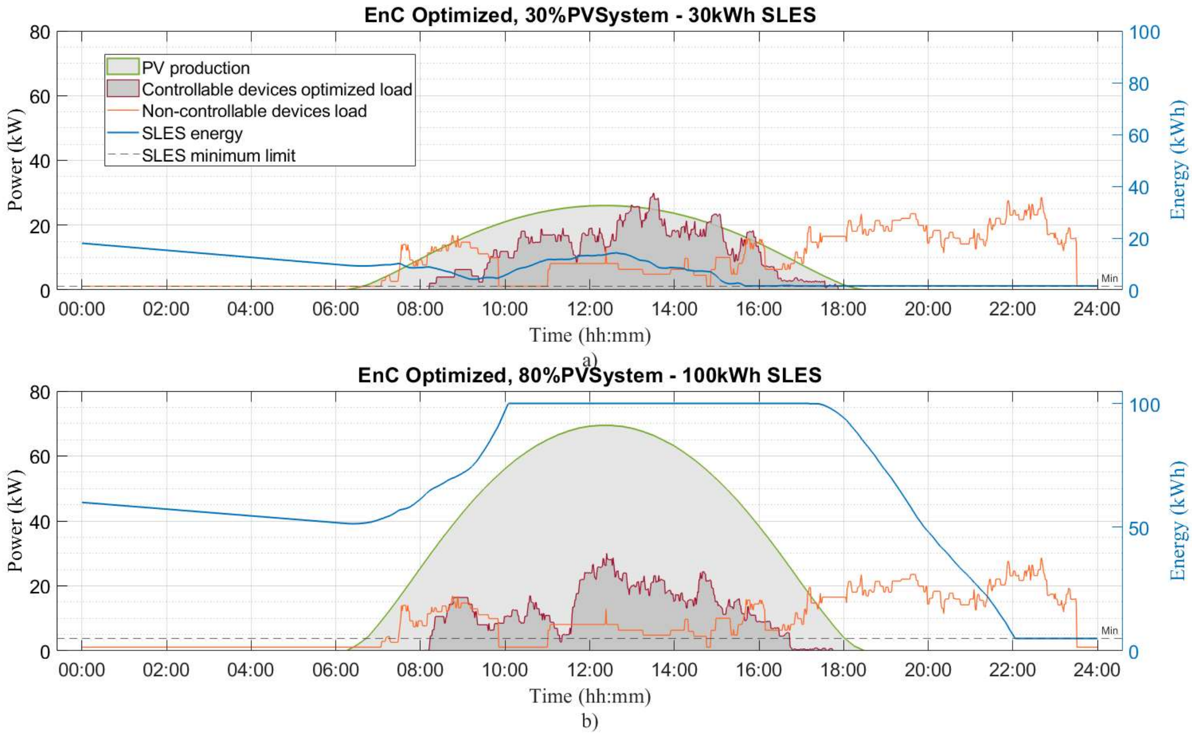


Figure 5.17 - Use case #1 opposite situations, a) Scenario #1, b) Scenario #4.

As depicted in Figure 5.17 the two most divergent scenarios involve a community with 30% of EnC's houses with PVsystem and 30 kWh SLES, and conversely, a community with 80% of EnC's houses with PVsystem and 100 kWh SLES. In the scenario with lower PVsystem installed and lower storage, even with optimal load management strategies, the available power is insufficient to fully charge the SLES, rendering it incapable of providing enough energy during periods of low or no solar generation.

An analysis of the baseline load diagram, Figure 5.7 and Figure 5.8, and the optimized load diagrams Figure 5.15 and Figure 5.16, based on 24-hour energy consumption, demonstrates that although it doesn't meet 100% of the EnC's needs, there has been a significative improvement both in the consumption met by optimizing loads and in the PV production wasted.

It is also noted that despite the comprehensiveness of the EnC's photovoltaic system, covering 24 out of 30 houses for scenarios 3 and 4, there is no SLES capable of storing the produced energy, for the capacities chosen for this work to be tested, resulting in a surplus of generated energy for both scenarios, contrary to scenarios 1 and 2 where there is no energy waste.

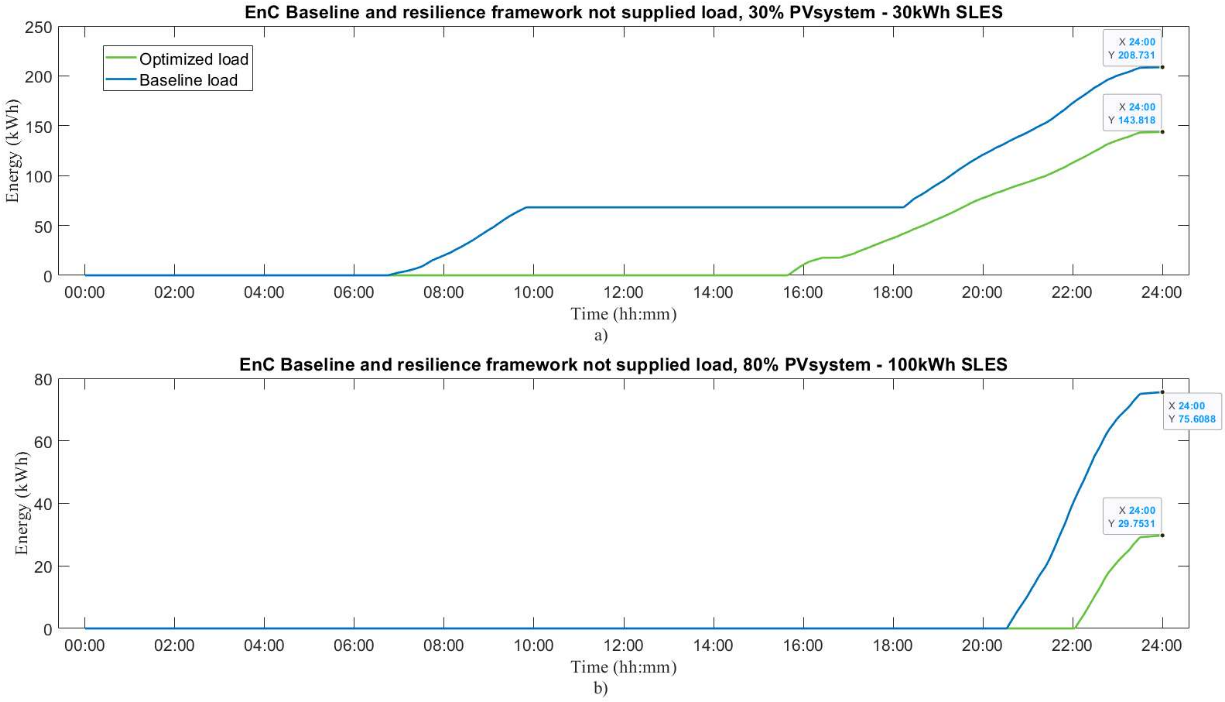


Figure 5.18 - Baseline and resilience framework not supplied load for two different scenarios of use case. #1, a) Scenario #1, b) Scenario #4.

In contrast to scenario 1, with 30% PV penetration and 30 kWh of SLES capacity, the EnC with 80% PV and 100 kWh SLES, as illustrated in Figure 5.17, experiences a curtailment of the of PV energy production. However, even with the SLES reaching its maximum storage capacity, a portion of the non-controllable load, particularly between 22h00 and midnight, remains unsatisfied.

Given the EnC's complete isolation from the EPG, this unmet load of 29.75 kWh, as depicted in Figure 5.18, represents a 9% mismatch from the EnC's total demand. Analyzing the baseline and the resilience framework based operation for both extreme scenarios:

- <u>Scenario 1, 30%PVsystem - 30kWs SLES</u>: In Figure 5.18a), The baseline load of EnC (blue line) has 208,73 kWh energy not supplied and after the resilience framework usage (green line) 64,92 kWh are successfully supplied. This means that, although 141,81 kWh of unsupplied load inside the EnC, the developed framework improves the EnC capacity to work disconnected from the EPG;

- <u>Scenario 4, 80%PVsystem - 100kWh SLES</u>: In Figure 5.18b), The baseline load of EnC (blue line) has 75,60 kWh energy not supplied and after the resilience framework usage (green line) an 29,75 kWh that was not supplied.

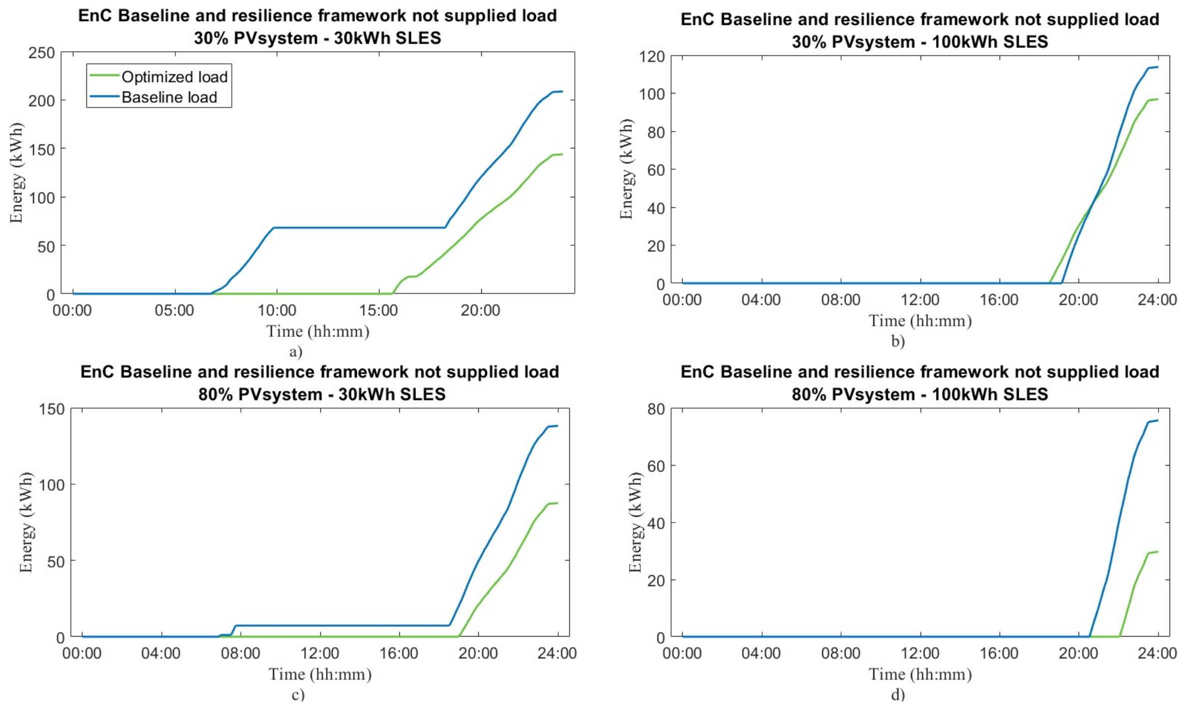


Figure 5.19 - Baseline and resilience framework not supplied load for use case #1, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

Table 5.8 – Values of baseline and resilience framework not supplied load for use case #1

	Scenario 1 Figure 5.19 a)	Scenario 2 Figure 5.19 b)	Scenario 3 Figure 5.19 c)	Scenario 4 Figure 5.19 d)
Baseline	208,73 kWh	113,82 kWh	138,19 kWh	75,61 kWh
Resilience frame-work	143,81 kWh	96,86 kWh	87,56 kWh	29,75 kWh

Inspecting through the above presented figures (from Figure 5.15 to Figure 5.19) and analyzing the metrics considered for this work and their results regarding use case #1, presented in Table 5.9, it is observed that:

- Metric 1 and Metric 6: In the specific case of this work, the solar time window it is from 8h to 17h. All controllable loads were shifted towards the solar time window in the four scenarios, resulting in 145,69kWh of consumed energy inside the solar window. This demonstrates that the optimization algorithm successfully maximized the use of energy from photovoltaic production for these loads;

- **Metric 2**: Regarding community unsupplied load, it is evident that the lower the SLES capacity and the number of houses with PV systems, the higher the unsupplied load. This occurs because the community is operating completely disconnected from EPG, so the lower the available power and storage within the community, the greater the unsupplied load;
- **Metric 3**: Observing the SLES capacity at EoD, it is observed that in all situations, it reaches its minimum capacity limit (5% of the maximum capacity). This shows that in none of the scenarios the needs of the EnC are fully met, which is also observed in Figure 5.19;
- **Metric 4 & 5**: As seen in Table 5.9, metric 4 shows an increasing value with both the increase in the number of houses with PV systems and the increase of the SLES capacity. This occurs because, in the initial scenarios, there is a lack of energy surplus from photovoltaic production, preventing the batteries from recharging after depleting their stored energy. On the other hand, in scenarios with higher photovoltaic production capacity, there is a greater ability to recharge, and the usage of the SLES outside sunlight hours is higher, reaching 66,8% in the last scenario. However, analysis of metric 5 indicates that more storage capacity is still needed. In none of the scenarios, the community's needs are entirely satisfied.

Table 5.9 - Metrics for use case #1, baseline vs resilience framework.

Scenario PV [%] / SLES [kWh]	**Metric 1** Number of appliances working on solar time	**Metric 2** Unsupplied Community load (%)	**Metric 3** Battery capacity in EoD (%)	**Metric 4** Average daily value of battery capacity (%)	**Metric 5** Surplus Energy in EoD (kWh)	**Metric 6** Consumed Energy inside solar window (kWh)
Baseline 30 / 30	34 of 73	62,96	5,00	41,75	36,85	50,11
30 / 30	73 of 73	43,63	5,00	25,14	0,00	145,69
Baseline 30 / 100	34 of 73	34,65	5,00	35,30	0,00	50,11
30 / 100	73 of 73	29,40	5,00	36,00	0,00	145,69
Baseline 80 / 30	34 of 73	42,26	5,00	50,63	319,99	50,11
80 / 30	73 of 73	26,60	5,00	59,60	280,10	145,69
Baseline 80 / 100	34 of 73	22,83	5,00	60,18	281,41	50,11
80 / 100	73 of 73	9,00	5,00	66,80	244,90	145,69

In this way, for a smaller unsupplied load consumption, it is important to find a balance between photovoltaic production and SLES capacity installed in the EnC. Depending on the needs of the EnC and the scenario that is more relevant, both cases can prove effective. That is, if one desires a community that always has the maximum possible storage capacity for the produced energy, it requires the installation of an SLES with greater capacity. However, this involves substantial costs. On the other hand, if the goal is to have a community capable of using its surplus energy or selling it to the grid for other users or DSO to use, one may opt for a smaller SLES capacity.

On the next subchapters, a set of simulations related to use case #2 and #3 will be analyzed, allowing for the comparison of the results presented for use case #1, where the community is completely disconnected from EPG, with scenarios in which the community is connected to EPG.

5.3.2 Use Case #2

The integration of EnCs with the EPG introduces complexities and opportunities in managing short-term faults. EnCs, equipped with decentralized energy resources and storage systems, offer enhanced resilience compared to conventional grid-dependent setups. Renewable energy sources and energy storage within EnCs enable sustained power supply during grid disruptions, potentially functioning as localized microgrids.

In this instance, as outlined in subsection 5.2.2, aside from SLES storing energy from the EPG for later use, the EnC consistently prioritizes energy consumption from renewable energy production over the EPG. Between 7h00 and 12h00, a total unforeseen disconnection from the EPG occurs, forcing the EnC's consumption to be supported by the SLES and photovoltaic production, if existent. In this situation, the resilience framework re-locates the loads from the moment the fault occurred, as depicted on graphics presented at Figure 5.20.

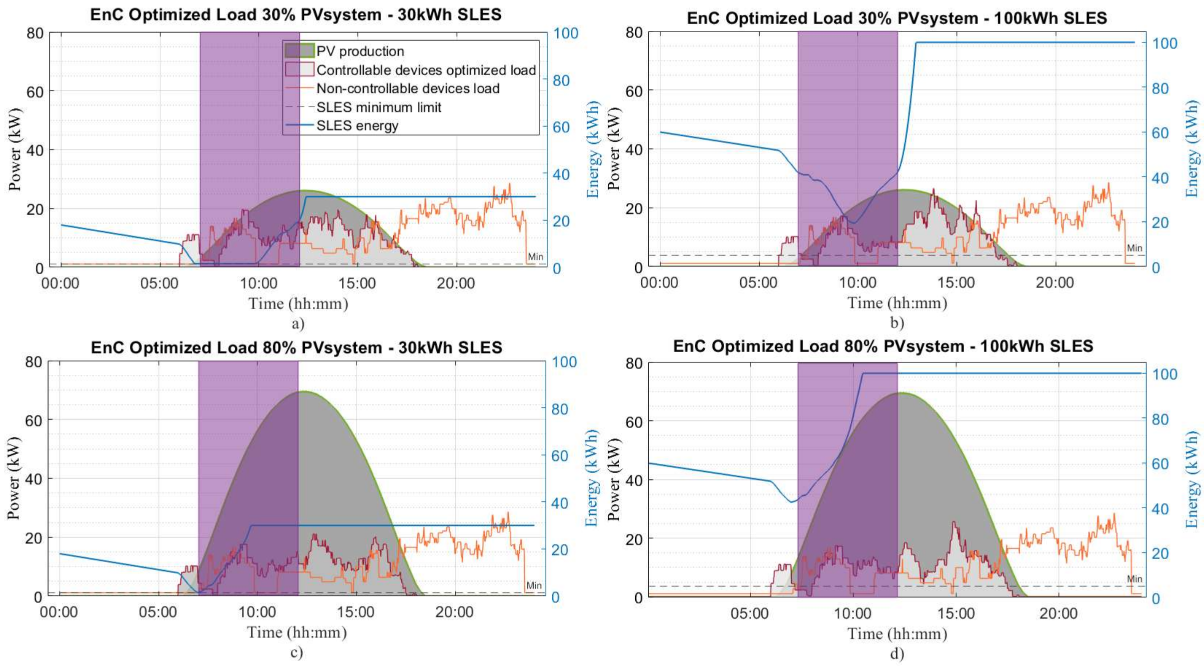


Figure 5.20 - Resilience framework results overview for use case #2 - Short-term Blackout, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

As depicted in Figure 5.20 a) and Figure 5.21a) , scenario #1 experienced a 23,24 kWh of unsupplied load consumption during the initial hours following the fault, resulting in a 7,02% unsupplied community load, also presented in Table 5.11. This occurred due to insufficient combined capacity from the SLES and PV production. However, after 10h00, the PV system's production was sufficient to maintain user comfort until the fault was resolved and the EPG connection restored.

In contrast, scenarios #2, #3, and #4, as illustrated in Figure 5.20b), Figure 5.20c) and Figure 5.20d), respectively, demonstrated the optimization algorithm of the resilience framework within the solar generation window effectively meets the EnC's energy needs and ensures a fully charged SLES, mitigating the risk of a second fault.

This is also possible to analyze in Figure 5.22 a), b) and c) that illustrate the unsupplied energy consumption for scenarios #1, #2, and #3 in both the baseline cases without optimization and the optimized cases. While scenario #4 achieved complete suppression of consumption in its baseline state, as presented in Table 5.10. Although in the baseline scenario EnC's needs are completely suppressed, resilience framework was still implemented to reduce surplus production by strategically scheduling appliances within the solar generation window.

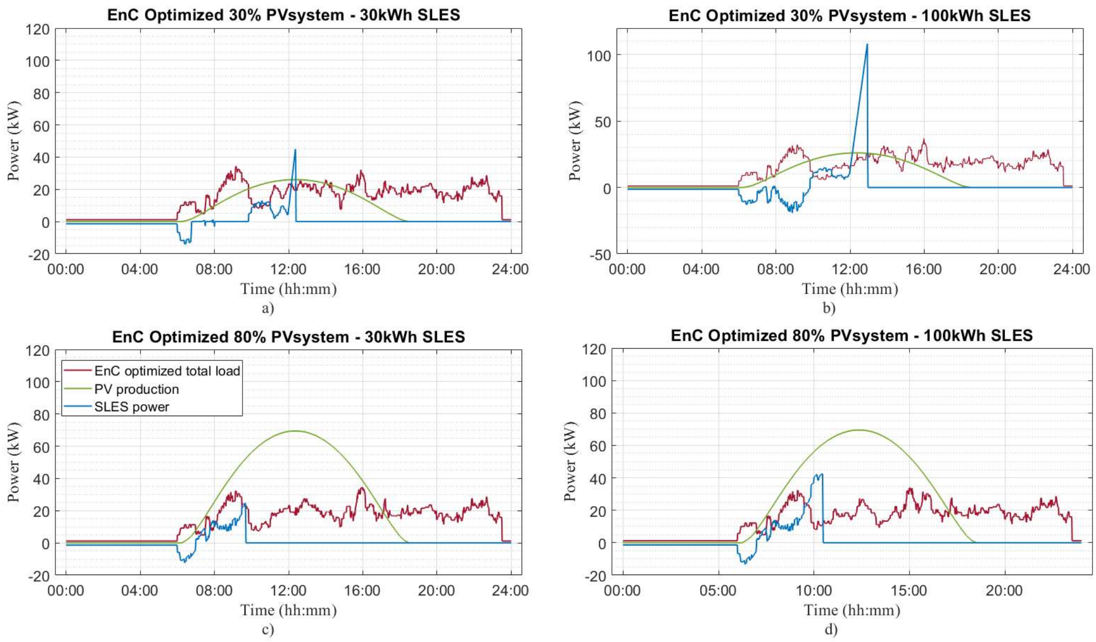


Figure 5.21 - Resilience framework results for each scenario with SLES power for use case #2, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

Table 5.10 – Values of baseline and resilience framework not supplied load for use case #2

	Scenario 1 Figure 5.22 a)	Scenario 2 Figure 5.22 b)	Scenario 3 Figure 5.22 c)	Scenario 4
Baseline	32,74 kWh	0,35 kWh	2,09 kWh	0 kWh
Resilience Frame-work	23,24 kWh	0 kWh	0 kWh	0 kWh

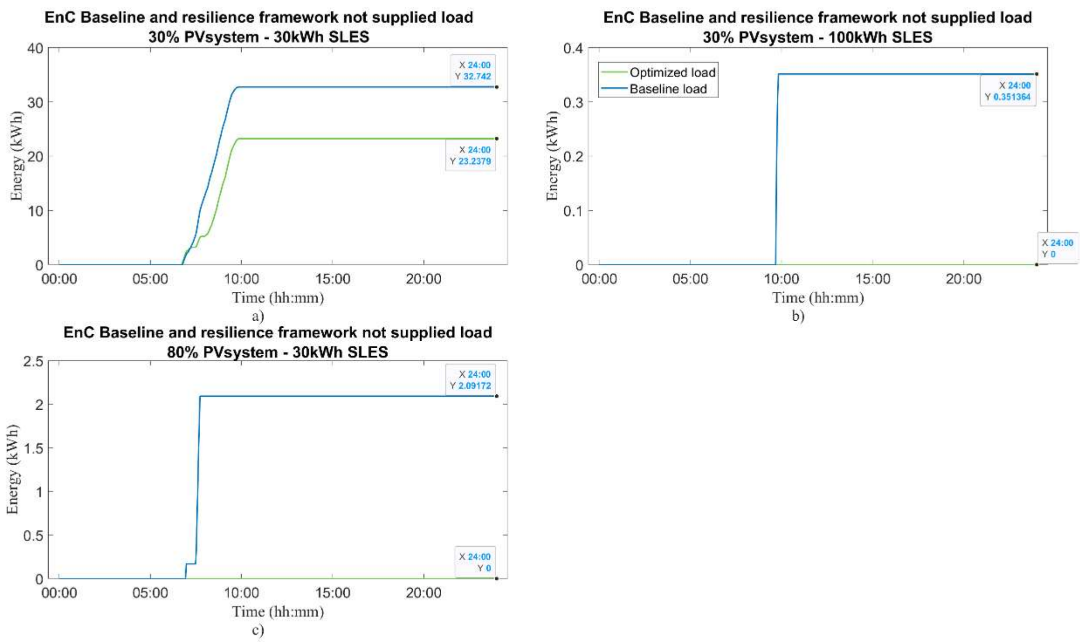


Figure 5.22 - Baseline and resilience framework not supplied load for use case #2, a) Scenario #1, b) Scenario #2, c) Scenario #3.

Looking through Table 5.11, it is possible to conclude that regarding surplus energy, despite prioritizing the use of PV production after the SLES reaches maximum capacity, there is still significant surplus production, mainly for the scenarios with 80% of houses with PVsystem.

Table 5.11 - Metrics for scenario #2 – EPG blackout, baseline vs resilience framework.

Scenario PV %_SLES kWh	**Metric 1** Number of appliances working on Solar time	**Metric 2** Unsupplied Community load (%)	**Metric 3** Battery capacity in EoD (%)	**Metric 4** Average daily value of battery capacity (%)	**Metric 5** Surplus Energy in EoD (kWh)	**Metric 6** Consumed Energy inside solar window (kWh)
Baseline 30 / 30	34 of 73	20,55	100	66,96	44,09	50,11
30 / 30	66 of 73	7,02	100	65,87	10,45	101,24
Baseline 30 / 100	34 of 73	0,77	100	69,60	40,92	50,11
30 / 100	66 of 73	0	100	71,19	39,71	101,24
Baseline 80 / 30	34 of 73	1,79	100	74,21	320,89	50,11
80 / 30	66 of 73	0	100	76,62	276,99	101,24
Baseline 80 / 100	34 of 73	0	100	79,80	282,48	50,11
80 / 100	66 of 73	0	100	81,05	243,66	101,24

5.3.3 Use Case #3

Energy Communities contribute to the DSO by providing localized energy resources and fostering a more distributed energy landscape. By generating and supplying energy within the community, EnCs can alleviate strain on the EPG during peak demand periods. This collaboration enhances grid resilience and reduces the need for centralized energy production. Additionally, EnCs, with their renewable energy sources and energy storage capabilities, offer the DSO flexibility in managing fluctuations in demand and supply. The symbiotic relationship between Energy Communities and DSOs exemplifies a sustainable approach to energy distribution, promoting efficiency and reliability in the broader energy infrastructure.

As mentioned in use case #3 EnC has available from EPG 250kW of power that due to DSO constrains decreases to 10kW. This happens from 14h00 to 20h00, represented in Figure 5.13 by the yellow rectangle.

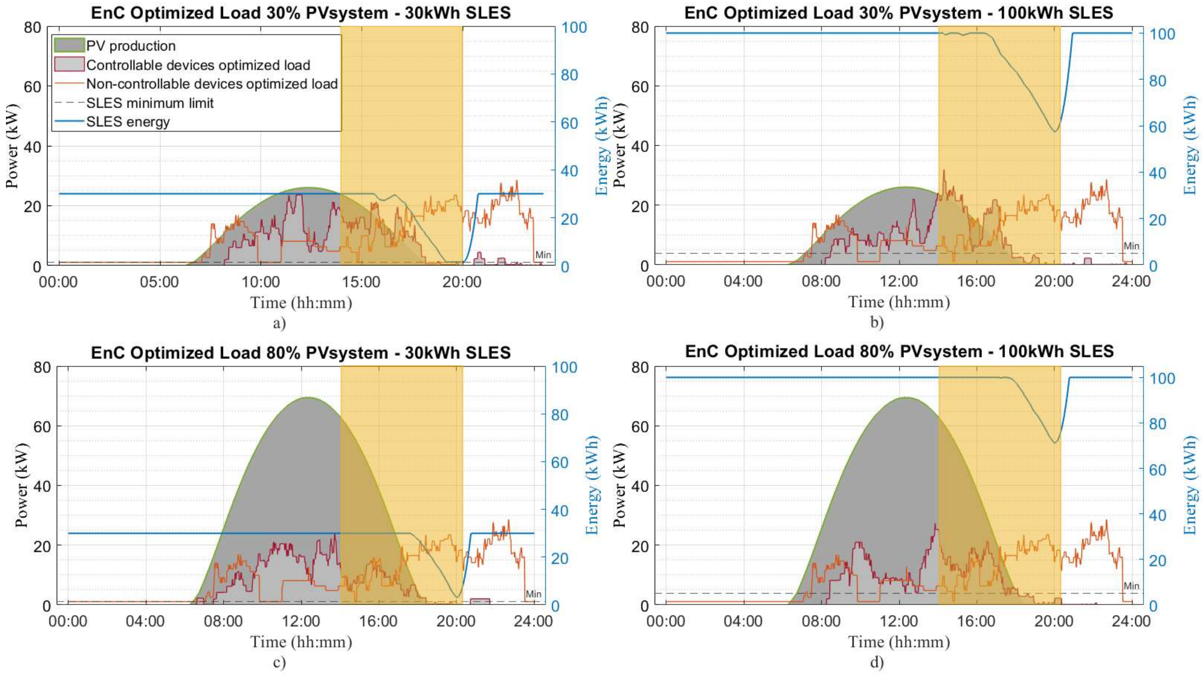


Figure 5.23 Resilience framework results overview for use case #3 - DSO necessities, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

Given the awareness of this reduction by the resilience framework orchestrator, the EnC undertakes a strategic load reconfiguration and initiates the energy storage process from the early hours of the day. This proactive measure is implemented in anticipation of the forthcoming timeframe characterized by the power reduction from the EPG. Also, as seen in Figure 5.24, outside of the fault period, the EnC consumption that is not satisfied by PV production is satisfied by the EPG connection.

The outcomes derived from this use case, as depicted in Figure 5.23 and Figure 5.25 alongside the presented metrics in Table 5.13, demonstrate a notable distance from scenario #1. Unlike the case wherein the EnC operates fully disconnected from the EPG, the current use case reveals the EnC's adeptness in strategically reconfiguring its appliances. This adeptness enables the community to effectively meet users' energy comfort requirements by solely leveraging the SLES capacity in response to a reduction in power from the EPG regarding DSO needs.

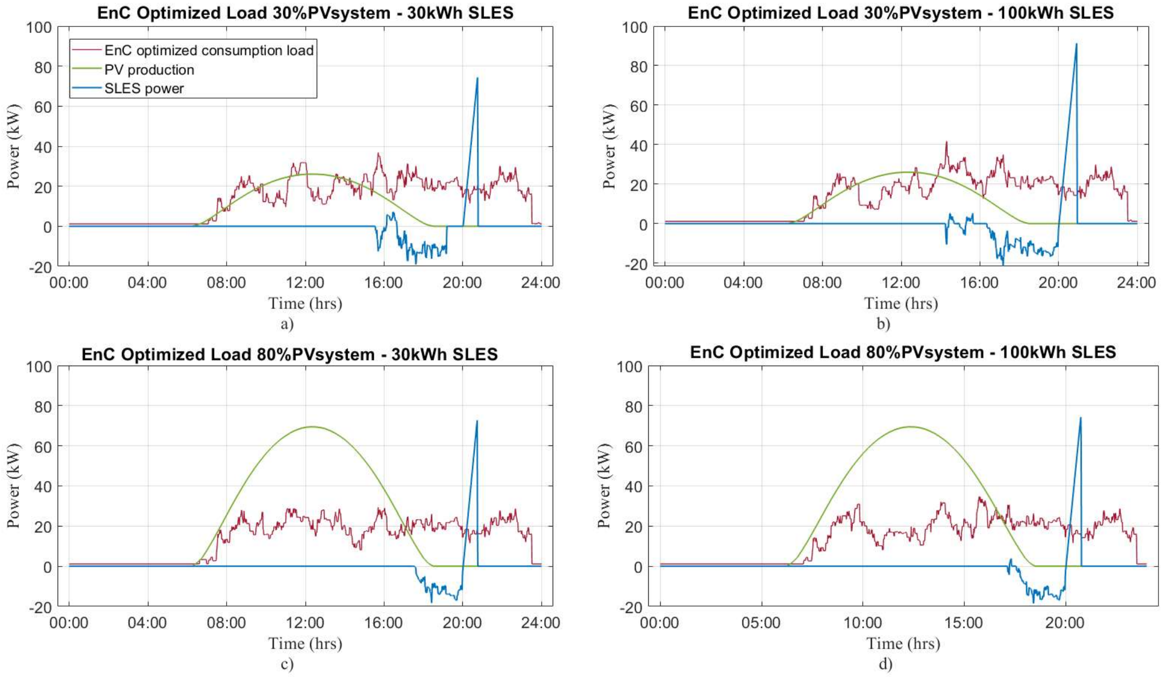


Figure 5.24 - Resilience framework results for each scenario with SLES power for use case #3, a) Scenario #1, b) Scenario #2, c) Scenario #3, d) Scenario #4.

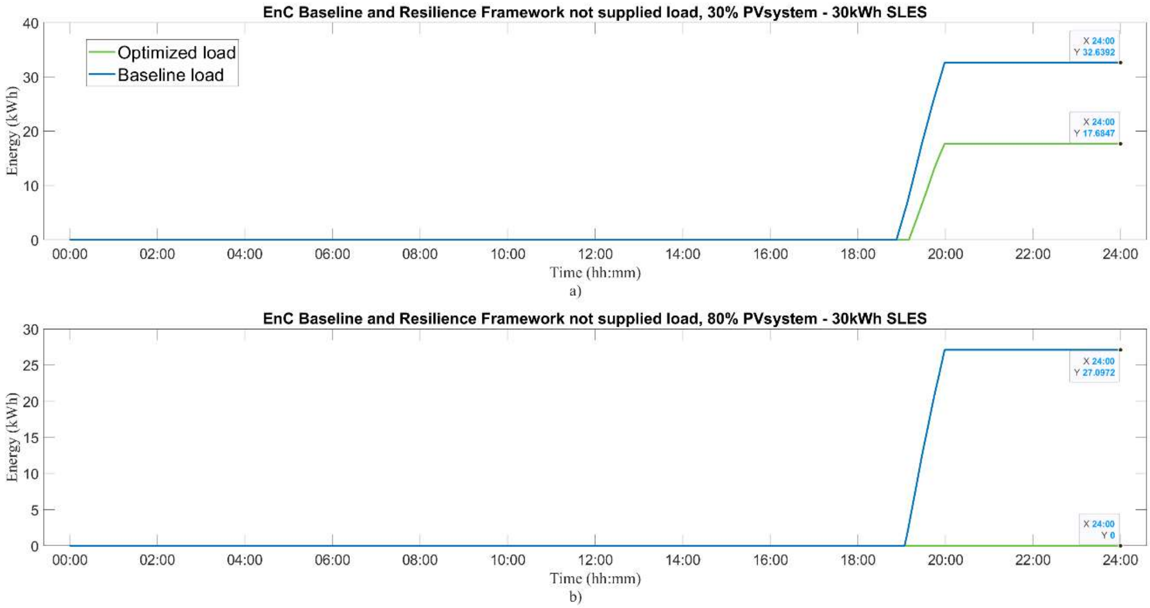


Figure 5.25 - Baseline and resilience framework not supplied load for use case #3, a) Scenario #1, b) Scenario #3.

As depicted in Figure 5.13, only scenarios 1 and 3 exhibited not supplied energy consumption in their baseline. A comparative analysis of Figure 5.25 and Table 5.12 reveals that scenario 1 achieved 50% reduction in not supplied EnC consumption following resilience framework optimization procedures, while scenario 3 successfully eliminated all not supplied energy consumption.

Table 5.12 - Values of baseline and resilience framework not supplied load for use case #3.

	Scenario 1 Figure 5.19 a)	Scenario 3 Figure 5.19 c)
Baseline	32,64 kWh	27,10 kWh
Resilience Framework	17,68 kWh	0,00 kWh

Analyzing the metrics, presented in Table 5.13, it is observed that in this use case, not all appliances were adjusted to operate within the solar window. However, given the intermittent grid connection and the rechargeable nature of the SLES, this proves to be a minor concern in the majority of scenarios. Only in scenario 1, where 30% of houses have PVsystem, and the SLES has 30 kWh, does it briefly reach minimum capacity. Nevertheless, in this instance, only 5,37% is noted as unsupplied load. In all other scenarios, user needs are completely satisfied, and battery usage ranges are around 90%.

Table 5.13 - Metrics for scenario #3 – DSO necessities, baseline vs resilience framework.

Scenario PV %_SLES kWh	Metric 1 Number of appliances working on Solar time	Metric 2 Unsupplied Community load (%)	Metric 3 Battery capacity in EoD (%)	Metric 4 Average daily value of battery capacity (%)	Metric 5 Surplus Energy in EoD (kWh)	Metric 6 Consumed Energy inside solar window (kWh)
Baseline 30 / 30	34 of 73	9,58	100	92,89	74,72	50,11
30 / 30	67 of 73	5,37	100	91,38	31,50	114,79
Baseline 30 / 100	34 of 73	0	100	96,89	75,05	50,11
30 / 100	69 of 73	0	100	96,68	36,24	114,64
Baseline 80 / 30	34 of 73	8,18	100	93,61	356,24	50,11
80 / 30	66 of 73	0	100	95,76	308,65	110,63
Baseline 80 / 100	34 of 73	0	100	97,38	354,85	50,11
80 / 100	68 of 73	0	100	98,46	310,20	115,66

In this specific use case, emphasis is placed not on utilization of renewable energy, but rather on the reorganization of loads and SLES charging to ensure community readiness for a foreseen power curtailment. Analysis via metric 5 reveals the presence of energy surplus relative to the PV production. This phenomenon is particularly pronounced in scenarios where 80% of households possess PVsystem, aligning with anticipated outcomes. Regarding metrics 1 and

6 it is possible to understand that, when comparing to the baseline cases, all scenarios have improved regarding solar window load shifting and increase PV production consumption. Unlike use cases #1 and #2, not all appliances were successfully rescheduled within the solar generation window. This is primarily attributed to the foreseen nature of the fault in this use case, which occurred during the solar time window. Consequently, some appliances were required to operate outside of this window to meet critical needs.

5.4 Hypothesis Assessment

Hypothesis - " EnC’s resilience is improved if the use of EnC’s energy flexibility allows to maintain the EnC users’ comfort level in case of a fault or a DSO power curtailment event.", can be assessed by comparing the metrics presented for scenario #1 with the baseline values. Recalling that user's comfort is the ability to maintain users’ wellbeing related to energy usage, which is instantiated by maintaining the maximum appliances turned on at the time specified by the user (baseline). Analyzing the initial values in which 39 of 73 appliances were operating outside the solar window (8h00 - 17h00), and therefore turned off, it is possible to verify by the metrics presented in Table 5.9, Table 5.11 and Table 5.13 that in every use cases, with EnC totally disconnected form EPG or with a short-term fault and DSO curtailment, the resilience metrics showed that improvements were done, thus the resilience of the EnC was improved.

For use case #1, it is possible to verify that all appliances start time were successfully shifted within the solar generation window, and non-controllable loads were supported by the SLES, albeit not entirely in some scenarios. Nevertheless, a notable improvement was observed compared to the baseline scenario, benefiting users and reducing not supplied energy consumption. This enhancement contributes to the EnC's overall resilience, particularly in the event of complete disconnection from the EPG.

Use cases #2 and #3, addressed the improvement of benefits offered to EnC users and DSO if resilience is implemented in a cooperative EnC level. In contrast to scenario #1, these scenarios demonstrated a reduction in unsupplied community load, facilitated by the interconnected relationship between the EnC and EPG, thereby enhancing user energy comfort. Additionally, unlike scenario #1, the SLES consistently maintained a full charge by the EoD. This strategic advantage is particularly valuable during periods without solar generation, ensuring that the SLES remains fully prepared to mitigate any unforeseen events.

Therefore, the collaborative relationship between the EnC and the EPG benefits not only the LV grid and the DSO but also the community users, as evidenced by the achieved outcomes. However, it is crucial to recognize that even with a resilience framework in place, the EnC may face limitations in mitigating the effects of prolonged and unforeseen faults depending on Its characteristics of generation and storage systems.

6

CONCLUSIONS

The final chapter of this thesis serves as a conclusion. Subchapter 6.1 offers an overview of the undertaken work, while subchapter 6.2 describes the main findings and contributions resulting from the research. Additionally, Section 6.3 outlines a set of future research directions that remain open as a result of this work.

6.1 Research Work Overview

This work addressed the lack of literature on Energy Community (EnC) resilience. Its primary focus was to enhance EnC LV grid resilience during faults, considering its energy flexibility, being enlarged to clarify the concept of EnC resilience. Key aspects were studied, defined and developed, including EnC resilience and respective measurement metrics, storage devices usage, resilience framework for effective management, and resilience framework optimization algorithms for load management during faulty events. The research contributed to both theoretical understanding and practical methodologies for bolstering the resilience of Energy Communities.

Three distinct use cases were considered for different scenarios of SLES and PV system capacities within a 30-household EnC, aiming to understand how the energy flexibility of each household within the community can enhance the resilience in cases of failure, restrictions or disconnection from the EPG.

By applying genetic based optimization algorithms for load management and considering a set of defined metrics for the analysis of EnC resilience, it was found that, by understanding the consumption profile of the community and its production profile, it is possible to make the energy community self-sustainable or capable of operating disconnected from the grid when necessary—either due to DSO requirements or as a response to an energy blackout.

These results showed that energy communities operating independently from EPG are vital for promoting energy resilience and sustainability, pointing out numerous benefits namely enhanced resilience, decentralized energy generation, environmental sustainability, community empowerment, flexibility, and economic benefits. These benefits even extend to the EPG itself, also enhancing its own resilience.

By operating autonomously, EnCs can maintain functionality during grid disruptions, improving resilience to power outages and unforeseen events. Decentralized energy generation, such as solar panels, reduces dependency on centralized grids, minimizing transmission losses and improving energy efficiency. Prioritizing renewable energy sources contributes to reduced carbon emissions and environmental sustainability, playing a crucial role in mitigating climate change. Empowering community members to actively participate in energy decision-making fosters a sense of ownership and responsibility, reinforcing their role as stakeholders in their local energy infrastructure. Engaging users and the DSO at the community level enhances user awareness of the role of EnC flexibility in addressing critical situations and empowers them to make informed decisions about their appliance usage and energy consumption.

Tailoring energy solutions to local needs and conditions enables more efficient resource utilization and the integration of solutions that may be challenging within a centralized grid. As demonstrated in the results, various scenarios can be considered to accommodate the specific needs of the community, including adjusting production capacity or storage capacity based on expected energy consumption.

EnCs also offer economic benefits, such as reduced transmission and distribution costs, job creation, and increased economic resilience within the community.

This research provides valuable insights for policymakers and investors, supporting more informed and comprehensive investments in the creation and implementation of energy communities. By addressing climate change and offering users and key stakeholders a more sustainable and efficient energy solution, EnCs can contribute to a more resilient and equitable energy future.

6.2 Main Findings and Contributions

The main contributions of this research work to scientific knowledge can be separated into two major points, as follows:

- **EnC Resilience Concept and Resilience Metrics**: A significant gap identified in the existing literature is the lack of a specific definition for EnC resilience and a corresponding set of metrics to quantify and evaluate its improvement. To address this gap, this research proposes a comprehensive definition and a group of six metrics, as outlined below:
    - **EnC's resilience** - Energy community resilience refers to the ability of a community to withstand, recover from, and adapt to disruptions or challenges related to its energy infrastructure. This definition encompasses the community's capacity to maintain essential energy services, such as electricity, or heating, in the face of various stressors just like in EPG's resilience definition. Specifically in this work, the definition of EnC's resilience means the ability of a community to maintain users' comfort;
    - **EnC resilience metrics -** A comprehensive set of metrics is proposed to evaluate the performance and resilience of an EnC. These metrics assess solar energy utilization, unmet energy demand, SLES capacity adequacy and utilization efficiency, surplus energy management, and power consumption optimization. By analyzing these metrics, the resilience framework's ability to optimize renewable production usage, manage energy storage, and enhance user comfort during faulty events can be evaluated, enabling informed decision-making for future improvements and sustainable energy practices;
- **Resilience Framework**: The framework quantifies the energy flexibility of the EnC under investigation. These calculations are subsequently employed to assess resilience metrics and verify the effectiveness of the proposed resilience enhancement

methodologies. The framework provides a holistic overview of the EnC, considering user devices, energy generation, storage capacity and power demand.

During the research work several scientific papers were published, which are listed below.

Journal Papers:

- Mar, A.; Pereira, P.; F. Martins, J. A Survey on Power Grid Faults and Their Origins: A Contribution to Improving Power Grid Resilience. Energies 2019, 12, 4667;
- Mar, A.; Pereira, P.; Martins, J. Energy Community Flexibility Solutions to Improve Users' Wellbeing. Energies 2021, 14, 3403. https://doi.org/10.3390/en14123403;
- Mar, A., Pereira, P. & Martins, J.F. Energy Community Resilience Improvement Through a Storage System. *SN COMPUT. SCI.* 5, 794 (2024). https://doi.org/10.1007/s42979-024-03149-w;

Conference Proceedings:

- Mar, A., Pereira, P., Martins, J. (2023). Storage System for Energy Communities. In: Camarinha-Matos, L.M., Ferrada, F. (eds) Technological Innovation for Connected Cyber Physical Spaces. DoCEIS 2023. IFIP Advances in Information and Communication Technology, vol 678. Springer, Cham. https://doi.org/10.1007/978-3-031-36007-7_3;
- A. Mar, P. Pereira and J. F. Martins, "Resilience Metrics applied to Renewable Energy Communities," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Tallinn, Estonia, 2023, pp. 1-5, doi: 10.1109/CPE-POWERENG58103.2023.10227398.

6.3 Future Work

This thesis explores deeper into the examination of risks to the electrical grid and the potential repercussions they may imply. More precisely, the research concentrates on exploring strategies to improve power interruptions in the event of blackouts or power cuts necessity by DSO requirements within an energy community. Additionally, the study places emphasis on comprehending how the implementation of cooperative flexibility can improve energy communities' resilience, a quality becoming more crucial in light of the unpredictability of various events like natural disasters, extreme weather conditions or unexpected faulty events.

For the future, this work can be extended by carrying out research activities on different directions, namely:

- The integration of V2X to the ecosystem of the energy community being part of the resilience framework, both as consumer and as a "storage device" that can supply energy to the community if necessary. This will allow to use the flexibility of the vehicle and have another element to supply energy if necessary, during nighttime, for example;
- As resilience of the network is a relatively recent subject, it is important to continue the study, particularly in developing new metrics that enable a more comprehensive analysis of the concept;
- Another important point, focusing on the optimization of electrical usage, is the comparative study with other optimization algorithms in order to understand if the results can be improved;
- Considering that solar radiation it is not aways on 100%, and clouds can appear, or dust can be at the panels, the use of Photovoltaic prediction algorithms can be an improvement to this work as future work;
- Regarding the users' comfort, a interesting point as future work is the study of what means comfort for different users;
- Another point that is considerable for future work is sizing an optimal storage system taking into account the community's consumption and production characteristics;
- Finaly, it is desirable that, the algorithms and metrics considered for the work of this thesis should be applied to a real-life case.

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A

ALGORITHM OPTIMIZATION RESULTS

This appendix delineates the tables containing outcomes resulting from the modification of the optimization algorithm's initial time across all simulations conducted in the course of this study.

A.1 Use Case #1

In appendix A1, from Table 7.1 to Table 7.4, there are the simulations results for use case #1 and the 4 scenarios PV30%_SLES30kWh, PV30%_SLES100kWh, PV80%_ SLES30kWh, and PV80%_ SLES100kWh respectively.

Table 7.1 – Use case#1 PV 30% _ SLES 30kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	15h34	X	10h23
House #2	8h30	10h30	14h00
	15h31	14h37	11h18
House #3	15h15	X	22h00
	14h14	X	9h53
House #4	15h45	17h30	18h00
	14h38	11h49	15h27
House #5	18h00	20h00	21h30
	9h36	12h39	14h09
House #6	7h00	X	21h30
	12h15	X	14h16
House #7	6h30	X	14h30
	12h43	X	9h31
House #8	19h00	12h00	X
	10h43	12h43	X
House #9	9h00	21h00	21h00
	12h05	11h47	8h13
House #10	18h00	11h30	13h30
	14h45	12h30	13h15
House #11	8h15	8h00	17h30
	13h38	8h49	14h24
House #12	8h45	8h30	20h00
	15h35	12h14	9h35

House #13	15h00	15h00	X
	13h18	10h18	X
House #14	15h00	15h30	X
	11h39	13h30	X
House #15	18h30	18h00	12h30
	14h09	9h29	12h38
House #16	7h15	7h00	21h30
	11h51	14h29	14h25
House #17	6h00	6h00	7h30
	14h37	12h11	10h31
House #18	X	19h00	6h00
	X	11h22	10h51
House #19	9h00	9h00	19h00
	12h51	10h35	9h39
House #20	X	18h30	9h30
	X	13h19	16h34
House #21	7h30	X	7h15
	13h49	X	10h37
House #22	6h15	12h30	6h45
	11h12	12h39	12h32
House #23	19h45	21h00	X
	15h24	10h19	X
House #24	9h00	11h30	9h00
	10h05	14h10	13h30
House #25	18h00	8h00	X
	15h27	12h48	X
House #26	8h30	10h30	7h20
	11h43	8h23	14h41
House #27	8h15	X	6h10
	11h35	X	15h22
House #28	X	17h30	19h00
	X	15h34	13h21
House #29	X	20h15	9h15
	X	12h49	13h25
House #30	X	X	8h45
	X	X	11h15

* X means that the house #n does not have that appliance.

Table 7.2 – Use case #1 PV 30% _ SLES100kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	15h17	X	13h07
House #2	8h30	10h30	14h00
	15h27	15h44	15h17
House #3	15h15	X	22h00
	11h37	X	13h17
House #4	15h45	17h30	18h00
	10h35	8h20	12h38
House #5	18h00	20h00	21h30
	12h16	12h47	13h31
House #6	7h00	X	21h30
	13h18	X	14h35
House #7	6h30	X	14h30

	14h29	X	11h21
House #8	19h00	12h00	X
	10h20	14h02	X
House #9	9h00	21h00	21h00
	11h56	8h14	12h39
House #10	18h00	11h30	13h30
	10h46	11h41	11h39
House #11	8h15	8h00	17h30
	11h38	11h34	12h11
House #12	8h45	8h30	20h00
	10h24	14h19	8h17
House #13	15h00	15h00	X
	13h30	14h33	X
House #14	15h00	15h30	X
	12h49	13h12	X
House #15	18h30	18h00	12h30
	8h39	9h41	11h32
House #16	7h15	7h00	21h30
	13h05	12h19	10h10
House #17	6h00	6h00	7h30
	14h27	12h45	15h44
House #18	X	19h00	6h00
	X	12h24	9h37
House #19	9h00	9h00	19h00
	8h05	9h18	11h53
House #20	X	18h30	9h30
	X	8h38	8h21
House #21	7h30	X	7h15
	9h51	X	14h40
House #22	6h15	12h30	6h45
	14h24	12h10	13h38
House #23	19h45	21h00	X
	10h49	15h29	X
House #24	9h00	11h30	9h00
	11h27	13h45	8h36
House #25	18h00	8h00	X
	15h06	11h56	X
House #26	8h30	10h30	7h20
	10h27	10h33	11h36
House #27	8h15	X	6h10
	12h25	X	14h29
House #28	X	17h30	19h00
	X	14h09	13h27
House #29	X	20h15	9h15
	X	8h41	11h35
House #30	X	X	8h45
	X	X	9h45

* X means that the house #n does not have that appliance.

Table 7.3 – Use case #1 PV 80% _ SLES 30kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	15h34	X	10h23

House #2	8h30	10h30	14h00
	15h31	14h37	11h18
House #3	15h15	X	22h00
	14h14	X	9h53
House #4	15h45	17h30	18h00
	14h38	11h49	15h27
House #5	18h00	20h00	21h30
	9h36	12h39	14h09
House #6	7h00	X	21h30
	12h15	X	14h16
House #7	6h30	X	14h30
	12h43	X	9h31
House #8	19h00	12h00	X
	10h43	12h43	X
House #9	9h00	21h00	21h00
	12h05	11h47	8h13
House #10	18h00	11h30	13h30
	14h45	12h30	13h15
House #11	8h15	8h00	17h30
	13h38	8h49	14h24
House #12	8h45	8h30	20h00
	15h35	12h14	9h35
House #13	15h00	15h00	X
	13h18	10h18	X
House #14	15h00	15h30	X
	11h39	13h30	X
House #15	18h30	18h00	12h30
	14h09	9h29	12h38
House #16	7h15	7h00	21h30
	11h51	14h29	14h25
House #17	6h00	6h00	7h30
	14h37	12h11	10h31
House #18	X	19h00	6h00
	X	11h22	10h51
House #19	9h00	9h00	19h00
	12h51	10h35	9h39
House #20	X	18h30	9h30
	X	13h19	16h34
House #21	7h30	X	7h15
	13h49	X	10h37
House #22	6h15	12h30	6h45
	11h12	12h39	12h32
House #23	19h45	21h00	X
	15h24	10h19	X
House #24	9h00	11h30	9h00
	10h05	14h10	13h30
House #25	18h00	8h00	X
	15h27	12h48	X
House #26	8h30	10h30	7h20
	11h43	8h23	14h41
House #27	8h15	X	6h10
	11h35	X	15h22
House #28	X	17h30	19h00

	X	15h34	13h21
House #29	X	20h15	9h15
	X	12h49	13h25
House #30	X	X	8h45
	X	X	11h15

* X means that the house #n does not have that appliance.

Table 7.4 – Use case#1 PV 80% _ SLES 100kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	15h17	X	13h07
House #2	8h30	10h30	14h00
	15h27	15h44	15h17
House #3	15h15	X	22h00
	11h37	X	13h17
House #4	15h45	17h30	18h00
	10h35	8h20	12h38
House #5	18h00	20h00	21h30
	12h16	12h47	13h31
House #6	7h00	X	21h30
	13h18	X	14h35
House #7	6h30	X	14h30
	14h29	X	11h21
House #8	19h00	12h00	X
	10h20	14h02	X
House #9	9h00	21h00	21h00
	11h56	8h14	12h39
House #10	18h00	11h30	13h30
	10h46	11h41	11h39
House #11	8h15	8h00	17h30
	11h38	11h34	12h11
House #12	8h45	8h30	20h00
	10h24	14h19	8h17
House #13	15h00	15h00	X
	13h30	14h33	X
House #14	15h00	15h30	X
	12h49	13h12	X
House #15	18h30	18h00	12h30
	8h39	9h41	11h32
House #16	7h15	7h00	21h30
	13h05	12h19	10h10
House #17	6h00	6h00	7h30
	14h27	12h45	15h44
House #18	X	19h00	6h00
	X	12h24	9h37
House #19	9h00	9h00	19h00
	8h05	9h18	11h53
House #20	X	18h30	9h30
	X	8h38	8h21
House #21	7h30	X	7h15
	9h51	X	14h40
House #22	6h15	12h30	6h45
	14h24	12h10	13h38

House #23	19h45	21h00	X
	10h49	15h29	X
House #24	9h00	11h30	9h00
	11h27	13h45	8h36
House #25	18h00	8h00	X
	15h06	11h56	X
House #26	8h30	10h30	7h20
	10h27	10h33	11h36
House #27	8h15	X	6h10
	12h25	X	14h29
House #28	X	17h30	19h00
	X	14h09	13h27
House #29	X	20h15	9h15
	X	8h41	11h35
House #30	X	X	8h45
	X	X	9h45

* X means that the house #n does not have that appliance.

A.2 Use Case #2 - Short-Term Blackout

In appendix A2, from Table 7.5 to Table 7.8, there are the simulations results for use case #2 and the 4 scenarios PV30%_ SLES 30kWh, PV30%_ SLES 100kWh, PV80%_ SLES 30kWh, and PV80%_ SLES 100kWh respectively.

Table 7.5 – Use Case#2 PV 30% _ SLES 30kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	8h00	X	9h30
House #2	8h30	10h30	14h00
	8h30	10h30	14h00
House #3	15h15	X	22h00
	15h15	X	16h11
House #4	15h45	17h30	18h00
	15h45	13h12	16h44
House #5	18h00	20h00	21h30
	12h42	10h35	13h20
House #6	7h00	X	21h30
	13h30	X	12h37
House #7	6h30	X	14h30
	6h30	X	14h30
House #8	19h00	12h00	X
	11h47	12h00	X
House #9	9h00	21h00	21h00
	9h00	13h04	13h47
House #10	18h00	11h30	13h30
	15h18	11h30	13h30
House #11	8h15	8h00	17h30
	8h15	8h00	12h28
House #12	8h45	8h30	20h00

	8h45	8h30	15h54
House #13	15h00	15h00	X
	15h00	15h00	X
House #14	15h00	15h30	X
	15h00	15h30	X
House #15	18h30	18h00	12h30
	11h04	15h04	12h30
House #16	7h15	7h00	21h30
	15h42	13h46	15h51
House #17	6h00	6h00	7h30
	6h00	6h00	12h31
House #18	X	19h00	6h00
	X	13h32	6h00
House #19	9h00	9h00	19h00
	9h00	9h00	11h45
House #20	X	18h30	9h30
	X	11h08	9h30
House #21	7h30	X	7h15
	14h26	X	10h27
House #22	6h15	12h30	6h45
	6h15	12h30	6h45
House #23	19h45	21h00	X
	11h43	13h44	X
House #24	9h00	11h30	9h00
	9h00	11h30	9h00
House #25	18h00	8h00	X
	10h02	8h00	X
House #26	8h30	10h30	7h20
	8h30	10h30	9h09
House #27	8h15	X	6h10
	8h15	X	6h10
House #28	X	17h30	19h00
	X	14h55	16h49
House #29	X	20h15	9h15
	X	12h10	9h15
House #30	X	X	8h45
	X	X	8h45

* X means that the house #n does not have that appliance.

Table 7.6 - Use Case#2 PV 30% _ SLES 100kWh.

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	8h00	X	9h30
House #2	8h30	10h30	14h00
	8h30	10h30	14h00
House #3	15h15	X	22h00
	15h15	X	12h52
House #4	15h45	17h30	18h00
	15h45	15h43	12h27
House #5	18h00	20h00	21h30
	15h41	13h05	15h00
House #6	7h00	X	21h30
	12h54	X	12h52

House #7	6h30	X	14h30
	6h30	X	14h30
House #8	19h00	12h00	X
	13h24	12h00	X
House #9	9h00	21h00	21h00
	9h00	19h49	16h34
House #10	18h00	11h30	13h30
	13h46	11h30	13h30
House #11	8h15	8h00	17h30
	8h15	8h00	10h43
House #12	8h45	8h30	20h00
	8h45	8h30	15h57
House #13	15h00	15h00	X
	15h00	15h00	X
House #14	15h00	15h30	X
	15h00	15h00	X
House #15	18h30	18h00	12h30
	13h34	15h52	12h30
House #16	7h15	7h00	21h30
	15h42	13h28	12h02
House #17	6h00	6h00	7h30
	6h00	6h00	13h49
House #18	X	19h00	6h00
	X	13h31	6h00
House #19	9h00	9h00	19h00
	9h00	9h00	13h49
House #20	X	18h30	9h30
	X	12h19	9h30
House #21	7h30	X	7h15
	14h47	X	14h32
House #22	6h15	12h30	6h45
	6h15	12h30	6h45
House #23	19h45	21h00	X
	11h31	13h21	X
House #24	9h00	11h30	9h00
	9h00	11h30	9h00
House #25	18h00	8h00	X
	11h26	8h00	X
House #26	8h30	10h30	7h20
	8h30	10h30	13h38
House #27	8h15	X	6h10
	8h15	X	6h10
House #28	X	17h30	19h00
	X	15h59	12h15
House #29	X	20h15	9h15
	X	14h20	9h15
House #30	X	X	8h45
	X	X	8h45

* X means that the house #n does not have that appliance.

Table 7.7 - Use Case#2 PV 80% _ SLES 30kWh.

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30

	8h30	X	9h30
House #2	8h30	10h30	14h00
	8h30	10h30	14h00
House #3	15h15	X	22h00
	15h15	X	12h48
House #4	15h45	17h30	18h00
	15h45	14h34	13h18
House #5	18h00	20h00	21h30
	12h25	16h15	10h10
House #6	7h00	X	21h30
	13h25	X	16h30
House #7	6h30	X	14h30
	6h30	X	14h30
House #8	19h00	12h00	X
	11h35	12h00	X
House #9	9h00	21h00	21h00
	9h00	16h22	11h31
House #10	18h00	11h30	13h30
	13h45	11h30	13h30
House #11	8h15	8h00	17h30
	8h15	8h00	11h21
House #12	8h45	8h30	20h00
	8h45	8h30	15h44
House #13	15h00	15h00	X
	15h00	15h00	X
House #14	15h00	15h30	X
	15h00	15h30	X
House #15	18h30	18h00	12h30
	15h39	15h36	12h30
House #16	7h15	7h00	21h30
	12h50	12h36	13h25
House #17	6h00	6h00	7h30
	6h00	6h00	13h45
House #18	X	19h00	6h00
	X	12h27	6h00
House #19	9h00	9h00	19h00
	9h00	9h00	15h32
House #20	X	18h30	9h30
	X	15h44	9h30
House #21	7h30	X	7h15
	12h19	X	10h33
House #22	6h15	12h30	6h45
	6h15	12h30	6h45
House #23	19h45	21h00	X
	10h25	12h49	X
House #24	9h00	11h30	9h00
	9h00	11h30	9h00
House #25	18h00	8h00	X
	12h35	8h00	X
House #26	8h30	10h30	7h20
	8h30	10h30	11h05
House #27	8h15	X	6h10
	8h15	X	6h10

House #28	X	17h30	19h00
	X	12h44	15h35
House #29	X	20h15	9h15
	X	14h20	9h15
House #30	X	X	8h45
	X	X	8h45

* X means that the house #n does not have that appliance.

Table 7.8 – Use Case#2 PV 80% _ SLES 100kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	8h00	X	9h30
House #2	8h30	10h30	14h00
	8h30	10h30	14h00
House #3	15h15	X	22h00
	15h15	X	12h16
House #4	15h45	17h30	18h00
	15h45	16h44	14h28
House #5	18h00	20h00	21h30
	14h25	13h28	12h12
House #6	7h00	X	21h30
	14h42	X	10h55
House #7	6h30	X	14h30
	6h30	X	14h30
House #8	19h00	12h00	X
	14h42	12h00	X
House #9	9h00	21h00	21h00
	9h00	14h07	10h10
House #10	18h00	11h30	13h30
	14h28	11h30	13h30
House #11	8h15	8h00	17h30
	8h15	8h00	15h34
House #12	8h45	8h30	20h00
	8h45	8h30	15h42
House #13	15h00	15h00	X
	15h00	15h00	X
House #14	15h00	15h30	X
	15h00	15h30	X
House #15	18h30	18h00	12h30
	14h46	15h41	12h30
House #16	7h15	7h00	21h30
	11h20	10h29	15h26
House #17	6h00	6h00	7h30
	6h00	6h00	13h26
House #18	X	19h00	6h00
	X	13h36	6h00
House #19	9h00	9h00	19h00
	9h00	9h00	14h42
House #20	X	18h30	9h30
	X	12h15	9h30
House #21	7h30	X	7h15
	14h35	X	14h33
House #22	6h15	12h30	6h45

	6h15	12h30	6h45
House #23	19h45	21h00	X
	12h21	11h37	X
House #24	9h00	11h30	9h00
	9h00	11h30	9h00
House #25	18h00	8h00	X
	14h40	8h00	X
House #26	8h30	10h30	7h20
	8h30	10h30	10h12
House #27	8h15	X	6h10
	8h15	X	6h10
House #28	X	17h30	19h00
	X	16h29	12h25
House #29	X	20h15	9h15
	X	16h23	9h15
House #30	X	X	8h45
	X	X	8h45

* X means that the house #n does not have that appliance.

A.3 Use Case #3 - DSO constrains

In appendix A3, from Table 7.9 to Table 7.12, there are the simulations results for use case #3 and the 4 scenarios PV30%_ SLES 30kWh, PV30%_ SLES 100kWh, PV80%_ SLES 30kWh, and PV80%_ SLES 100kWh respectively.

Table 7.9 – Use Case #3 PV 30% _ SLES 30kWh

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	14h18	X	11h23
House #2	8h30	10h30	14h00
	12h22	13h28	9h04
House #3	15h15	X	22h00
	11h37	X	10h30
House #4	15h45	17h30	18h00
	10h25	14h08	10h25
House #5	18h00	20h00	21h30
	10h32	12h39	13h26
House #6	7h00	X	21h30
	15h20	X	16h40
House #7	6h30	X	14h30
	20h26	X	11h41
House #8	19h00	12h00	X
	15h26	13h17	X
House #9	9h00	21h00	21h00
	11h05	15h27	15h48
House #10	18h00	11h30	13h30
	8h17	11h06	13h08
House #11	8h15	8h00	17h30
	17h29	10h41	14h22

House #12	8h45	8h30	20h00
	15h21	13h33	14h54
House #13	15h00	15h00	X
	14h41	11h06	X
House #14	15h00	15h30	X
	20h37	16h18	X
House #15	18h30	18h00	12h30
	13h14	17h10	14h38
House #16	7h15	7h00	21h30
	11h35	14h29	12h37
House #17	6h00	6h00	7h30
	16h37	11h03	13h26
House #18	X	19h00	6h00
	X	9h08	10h00
House #19	9h00	9h00	19h00
	9h53	15h49	8h38
House #20	X	18h30	9h30
	X	16h39	13h05
House #21	7h30	X	7h15
	15h31	X	9h35
House #22	6h15	12h30	6h45
	17h28	16h32	9h42
House #23	19h45	21h00	X
	21h37	8h25	X
House #24	9h00	11h30	9h00
	16h33	8h12	14h44
House #25	18h00	8h00	X
	15h20	15h27	X
House #26	8h30	10h30	7h20
	16h29	14h30	11h18
House #27	8h15	X	6h10
	13h30	X	13h45
House #28	X	17h30	19h00
	X	11h07	11h18
House #29	X	20h15	9h15
	X	9h43	15h24
House #30	X	X	8h45
	X	X	11h40

* X means that the house #n does not have that appliance.

Table 7.10 - Use Case #3 PV 30% _ SLES 100kWh.

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	12h19	X	11h23
House #2	8h30	10h30	14h00
	12h25	14h16	8h39
House #3	15h15	X	22h00
	11h45	X	13h39
House #4	15h45	17h30	18h00
	16h34	13h25	11h33
House #5	18h00	20h00	21h30
	10h44	9h17	13h49
House #6	7h00	X	21h30

	13h51	X	9h24
House #7	6h30	X	14h30
	18h44	X	14h37
House #8	19h00	12h00	X
	16h40	8h12	X
House #9	9h00	21h00	21h00
	17h18	14h38	14h33
House #10	18h00	11h30	13h30
	12h35	12h38	8h32
House #11	8h15	8h00	17h30
	16h14	12h32	16h18
House #12	8h45	8h30	20h00
	11h31	16h12	14h31
House #13	15h00	15h00	X
	8h20	13h33	X
House #14	15h00	15h30	X
	12h25	16h19	X
House #15	18h30	18h00	12h30
	16h43	14h46	17h25
House #16	7h15	7h00	21h30
	15h07	9h33	11h32
House #17	6h00	6h00	7h30
	13h36	15h10	10h28
House #18	X	19h00	6h00
	X	13h25	11h29
House #19	9h00	9h00	19h00
	12h22	14h16	15h51
House #20	X	18h30	9h30
	X	14h39	16h21
House #21	7h30	X	7h15
	14h09	X	16h49
House #22	6h15	12h30	6h45
	9h24	16h09	9h27
House #23	19h45	21h00	X
	12h35	13h28	X
House #24	9h00	11h30	9h00
	15h13	10h20	14h18
House #25	18h00	8h00	X
	12h21	16h31	X
House #26	8h30	10h30	7h20
	8h45	13h35	13h54
House #27	8h15	X	6h10
	21h25	X	14h12
House #28	X	17h30	19h00
	X	12h25	15h37
House #29	X	20h15	9h15
	X	13h20	10h24
House #30	X	X	8h45
	X	X	10h54

* X means that the house #n does not have that appliance.

Table 7.11 - Use Case #3 PV 80% _ SLES 30kWh.

	Washing Machine	Dryer Washer	Dish Washer

House #1	8h00	X	9h30
	14h34	X	15h54
House #2	8h30	10h30	14h00
	9h40	12h40	12h49
House #3	15h15	X	22h00
	13h22	X	14h31
House #4	15h45	17h30	18h00
	11h17	11h30	10h29
House #5	18h00	20h00	21h30
	14h29	15h03	7h39
House #6	7h00	X	21h30
	10h46	X	10h14
House #7	6h30	X	14h30
	13h35	X	8h36
House #8	19h00	12h00	X
	15h14	10h33	X
House #9	9h00	21h00	21h00
	6h30	11h21	12h33
House #10	18h00	11h30	13h30
	11h45	9h37	12h48
House #11	8h15	8h00	17h30
	8h27	10h20	8h10
House #12	8h45	8h30	20h00
	15h47	15h35	13h42
House #13	15h00	15h00	X
	10h40	12h19	X
House #14	15h00	15h30	X
	8h32	13h24	X
House #15	18h30	18h00	12h30
	13h32	12h36	15h20
House #16	7h15	7h00	21h30
	17h30	9h32	9h30
House #17	6h00	6h00	7h30
	12h29	8h53	9h42
House #18	X	19h00	6h00
	X	16h31	12h45
House #19	9h00	9h00	19h00
	13h33	10h31	13h32
House #20	X	18h30	9h30
	X	10h34	11h11
House #21	7h30	X	7h15
	16h39	X	11h31
House #22	6h15	12h30	6h45
	12h29	9h29	17h26
House #23	19h45	21h00	X
	8h19	10h38	X
House #24	9h00	11h30	9h00
	13h21	9h47	12h23
House #25	18h00	8h00	X
	15h06	10h24	X
House #26	8h30	10h30	7h20
	13h54	15h31	16h17
House #27	8h15	X	6h10

	17h25	X	11h23
House #28	X	17h30	19h00
	X	14h53	11h17
House #29	X	20h15	9h15
	X	11h38	20h43
House #30	X	X	8h45
	X	X	7h29

* X means that the house #n does not have that appliance.

Table 7.12 - Use Case #3 PV 80% _ SLES 100kWh.

	Washing Machine	Dryer Washer	Dish Washer
House #1	8h00	X	9h30
	12h21	X	15h37
House #2	8h30	10h30	14h00
	9h51	16h17	16h21
House #3	15h15	X	22h00
	14h34	X	9h13
House #4	15h45	17h30	18h00
	10h17	8h26	14h22
House #5	18h00	20h00	21h30
	15h02	9h28	13h39
House #6	7h00	X	21h30
	16h20	X	8h16
House #7	6h30	X	14h30
	19h53	X	13h39
House #8	19h00	12h00	X
	15h20	15h28	X
House #9	9h00	21h00	21h00
	15h41	14h46	13h01
House #10	18h00	11h30	13h30
	15h35	14h12	13h45
House #11	8h15	8h00	17h30
	16h23	16h15	10h20
House #12	8h45	8h30	20h00
	12h52	10h42	11h42
House #13	15h00	15h00	X
	8h51	8h02	X
House #14	15h00	15h30	X
	10h29	9h34	X
House #15	18h30	18h00	12h30
	10h10	9h12	16h27
House #16	7h15	7h00	21h30
	17h12	9h19	11h11
House #17	6h00	6h00	7h30
	13h43	9h35	11h01
House #18	X	19h00	6h00
	X	15h36	13h50
House #19	9h00	9h00	19h00
	9h36	12h21	8h26
House #20	X	18h30	9h30
	X	16h21	13h16
House #21	7h30	X	7h15
	13h14	X	15h47

House #22	6h15	12h30	6h45
	15h53	13h02	17h56
House #23	19h45	21h00	X
	16h41	14h29	X
House #24	9h00	11h30	9h00
	13h23	9h37	15h19
House #25	18h00	8h00	X
	17h38	10h32	X
House #26	8h30	10h30	7h20
	9h28	9h29	13h02
House #27	8h15	X	6h10
	17h27	X	13h05
House #28	X	17h30	19h00
	X	13h04	14h54
House #29	X	20h15	9h15
	X	13h04	11h34
House #30	X	X	8h45
	X	X	12h30

* X means that the house #n does not have that appliance.

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THE USE OF COOPERATIVE FLEXIBILITY TO IMPROVE THE ENERGY COMMUNITIES' RESILIENCE