Grid and System-Oriented Use of Flexibility Provided by Energy Communities

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2025

Renata Rodrigues Lautert

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Grid and System-Oriented Use of Flexibility Provided by Energy Communities

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I Abstract

In the current energy transition scenario, the power system has been incorporating actions aimed at decentralizing energy generation, digitalizing the system, decarbonizing, deregulating and democratizing access to electricity. The concept of an energy community (EC) matches these aspects, promoting sustainability and increasing flexibility.

The aim of this dissertation is to develop a control model for an EC that encompasses three different levels of flexibility and incentives for the use of flexibility. The simulated EC operates exclusively with renewable energy sources, uses a battery energy storage system (BESS) and integrates an electric vehicle (EV). Power dispatch was implemented using rule-based and optimization methods based on mixed-integer linear programming. The EC is inserted into the energy market, allowing transactions with the grid using a real-time tariff. Economic viability was assessed by calculating the daily operating cost. The main objective of the optimization was to minimize costs while prioritizing the use of available renewable resources. The analysis was conducted considering four days representative of the seasons. Scenarios of excess generation and low demand, along with low generation and high demand, were simulated to validate the proposed methodology. The three levels of flexibility were configured using adjustable parameters, including the initial and final state of charge of the BESS, the weighting coefficients for charging and discharging the BESS and the EV. These levels range from F1, the most flexible, to F3, the most conservative. Incentives in the form of rewards were introduced in accordance with the EC use of flexibility. In addition, an analysis of the voltage levels on the EC buses was performed, verifying compliance with the normative standards.

The results demonstrated that the optimization model was more efficient in managing energy, guaranteeing that loads were met throughout the period analyzed. The EC's revenue increased by 30% in the worst-case scenario and exceeded three times the revenue, in the most beneficial scenario when using the optimized method. The behavior of BESS and EV was crucial both technically and economically, as the strategy of charging in times of surplus or low tariffs and discharging in times of deficit or high prices increased flexibility and reduced costs. In all scenarios, voltages remained within regulatory limits, even under extreme conditions. The proposed model has been shown to promote flexibility and efficiency, ensuring safe operation in alignment with sustainability objectives.

Keywords: Distributed generation. Energy community. Flexibility. Optimization. Power system. Storage systems.

II Kurzzusammenfassung

Im aktuellen Szenario der Energiewende umfasst das Stromsystem Maßnahmen zur Dezentralisierung der Energieerzeugung, zur Digitalisierung des Systems, zur Dekarbonisierung, zur Deregulierung und zur Demokratisierung des Zugangs zu Strom. Das Konzept einer Energiegemeinschaft (EC) entspricht diesen Aspekten, fördert die Nachhaltigkeit und erhöht die Flexibilität.

Das Ziel dieser Dissertation ist die Entwicklung eines Steuerungsmodells für eine EC mit drei Flexibilitätsebenen und Anreizen für die Nutzung der Flexibilität. Die simulierte EC nutzt ausschließlich erneuerbare Energiequellen, ein Batteriespeichersystem (BESS) und ein Elektrofahrzeug (EV). Der Energieeinsatz wurde regelbasiert implementiert und mit gemischt-ganzzahliger linearer Programmierung optimiert. Die EC ist in den Energiemarkt eingebunden, ermöglicht Netztransaktionen zu Echtzeittarifen und bewertet die Wirtschaftlichkeit anhand der täglichen Betriebskosten. Ziel der Optimierung war es, Kosten zu minimieren und die Nutzung erneuerbarer Ressourcen zu maximieren. Die Analyse umfasste vier repräsentative Tage der Jahreszeiten. Szenarien mit überschüssiger Erzeugung bei geringer Nachfrage sowie mit niedriger Erzeugung bei hoher Nachfrage wurden simuliert. Drei Flexibilitätsebenen (F1 bis F3) wurden anhand einstellbarer Parameter definiert, darunter der Ladezustand des BESS und Gewichtungskoeffizienten für Lade- und Entladeprozesse. F1 ist die flexibelste, F3 die konservativste Stufe. Anreize in Form von Belohnungen wurden in Übereinstimmung mit der EC-Flexibilitätsregelung eingeführt. Zusätzlich wurde eine Spannungsanalyse durchgeführt, um die regulatorischen Vorgaben einzuhalten. Die Ergebnisse zeigen, dass die Optimierung effizient war, erneuerbare Ressourcen priorisierte, Kosten senkte und die Spannungsniveaus innerhalb der Grenzwerte blieben, selbst unter extremen Bedingungen.

Die Ergebnisse zeigten, dass das Optimierungsmodell ein effizientes Energiemanagement ermöglichte und garantierte, dass die Lasten während des gesamten analysierten Zeitraums gedeckt wurden. Die Einnahmen der EC stiegen bereits im ungünstigsten Fall um 30 % und überstiegen im günstigsten Fall das Dreifache, wenn die optimierte Methode angewendet wurde. Das Verhalten von BESS und EV war sowohl technisch als auch wirtschaftlich von entscheidender Bedeutung, da die Strategie des Ladens in Zeiten mit Überschuss oder niedrigen Tarifen und des Entladens in Zeiten mit Defizit oder hohen Preisen die Flexibilität erhöhte und die Kosten reduzierte. In allen Szenarien blieben die Spannungen selbst unter extremen Bedingungen innerhalb der gesetzlichen Grenzen. Es hat sich gezeigt, dass das vorgeschlagene Modell Flexibilität und Effizienz fördert und einen sicheren Betrieb im Einklang mit den Nachhaltigkeitszielen gewährleistet.

Schlagwörter: Dezentrale Erzeugung. Energiegemeinschaft. Flexibilität. Optimierung. Speichersysteme. Stromnetz.

III Resumo

No cenário atual de transição energética, o sistema de potência vem incorporando ações visando descentralizar a geração de energia, digitalizar o sistema, descarbonizar, desregular e democratizar o acesso à eletricidade. O conceito de comunidade energética (EC) se encaixa com esses fatores, promovendo a sustentabilidade e elevando a flexibilidade.

O objetivo desta dissertação é desenvolver um modelo de controle para uma EC que abrange três níveis distintos de flexibilidade e incentivos para o uso da flexibilidade. A EC simulada opera exclusivamente com fontes renováveis de energia, utiliza um sistema de armazenamento de energia em baterias (BESS) e integra um veículo elétrico (EV). O despacho de potência foi implementado por meio do método baseado em regras e de um método de otimização fundamentado em programação linear inteira mista. A EC está inserida no mercado de energia, permitindo transações com a rede utilizando uma tarifa de tempo real. A viabilidade econômica foi avaliada, calculando o custo diário de operação. O objetivo principal da otimização foi minimizar os custos enquanto priorizava o uso de recursos renováveis disponíveis. A análise foi realizada considerando quatro dias representativos das estações do ano. Foram simulados cenários de excesso de geração e baixa demanda, bem como de pouca geração com alta demanda, para validar a metodologia proposta. Os três níveis de flexibilidade foram configurados através de parâmetros ajustáveis, sendo eles o estado de carga inicial e final do BESS, coeficientes de ponderação para carga e descarga do BESS e do EV. Esses níveis variam de F1, mais flexível, a F3, mais conservador. Incentivos na forma de recompensas foram introduzidos de acordo com o uso da flexibilidade pela EC. Além disso, foi realizada uma análise dos níveis de tensão nas barras da EC, verificando a conformidade com os padrões normativos.

Os resultados mostraram que o modelo de otimização foi mais eficiente no gerenciamento da energia, garantindo o atendimento às cargas durante todo o período analisado. A receita da EC aumentou 30% no pior cenário e atingiu um valor superior a três vezes a receita no cenário mais favorável, utilizando o método com otimização. O comportamento do BESS e do EV foi crucial tanto técnica quanto economicamente, pois a estratégia de carga em momentos de excedente ou tarifas baixas e descarga em períodos de déficit ou preços elevados aumentou a flexibilidade e reduziu os custos. Em todos os cenários, as tensões permaneceram dentro dos limites regulamentares, mesmo em condições extremas. O modelo proposto demonstrou promover flexibilidade e eficiência, assegurando uma operação segura e alinhada aos objetivos de sustentabilidade.

Palavras-chave: Comunidade energética. Flexibilidade. Geração distribuída. Otimização. Sistema de potência.

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VIII List of Symbols

Greek symbols

α	binary indicator for BESS	δ	weighting coefficient
β	binary variable	θ	binary indicator for EV
γ	binary variable (market)	η	efficiency

Variables

Bal	power balance	kW	P	power	kW
b	coefficient	-	SOC	state of charge	%
C	cost	€	t	time	h
E	energy	kWh	T	tariff	€/kWh
H	step function	-	U	voltage	p.u.
n	set of n	-			

Indexes

Bal	balance	load	load
BESS	battery energy storage system	max	maximum
Ch	charging	min	minimum
deg	degradation	n	line segments
Dis	discharging	N	nominal
EV	electric vehicle	op	operational
fi	final	purch	purchase
gen	generation	sale	sales
grid	grid	tot	total
in	initial	V2G	V2G

IX List of Abbreviations

ANEEL	National Electric Energy Agency
BESS	battery energy storage system
BG	biogas
CAPEX	capital expenditure
DA	day-ahead
DER	distributed energy resources
DG	distributed generation
DSO	Distribution System Operator
EC	energy community
EEG	Renewable Energy Act
EH	energy hub
EMS	energy management system
EN	European Norm
EnWG	Energy Industry Act
EPS	electrical power system
ESS	energy storage systems
EU	European Union
EV	electric vehicle
F1	flexibility model 1
F2	flexibility model 2
F3	flexibility model 3
FACTS	flexible alternating current transmission systems
HVDC	high voltage direct current
MG	microgrid
MILP	mixed-integer linear programming
NR	normative resolution

OF	objective function
OPEX	operating expenditure
P2P	peer-to-peer
PV	photovoltaic
RES	renewable energy sources
SC	smart contracts
SOC	state of charge
TE	transactive energy
V2G	vehicle-to-grid
WT	wind turbine

1 Introduction

The dynamics of systems and processes have led to the definition of new concepts and forms of organization, requiring more frequent updating at this time of transition. The ideals of sustainability have permeated various branches of world society in recent years, including the electricity sector, which has expanded and improved the use of renewable energies. The installed capacity of renewable energy generation sources has been increasing worldwide. The population in general and the governments of various countries have supported renewable energies due to their multiple benefits, stipulating transition plans and targets with greater participation of these systems in the electricity matrix [1].

There has been significant growth in wind and solar generation, as illustrated in Figure 1.1, mainly in the form of distributed generation (DG) for solar. These systems demonstrate intermittent generation behavior, varying according to the availability of the primary energy source. In this way, the balance between generation and demand becomes a more challenging issue. A common practice adopted globally is to reduce renewable energy generation, i.e., the plant generates less than its potential capacity in order to maintain the system's balance or prevent congestions. This action is called curtailment and is based on sustainability principles, it needs to be reduced and even avoided, as the use of energy from renewable sources should be maximized [2], [3].

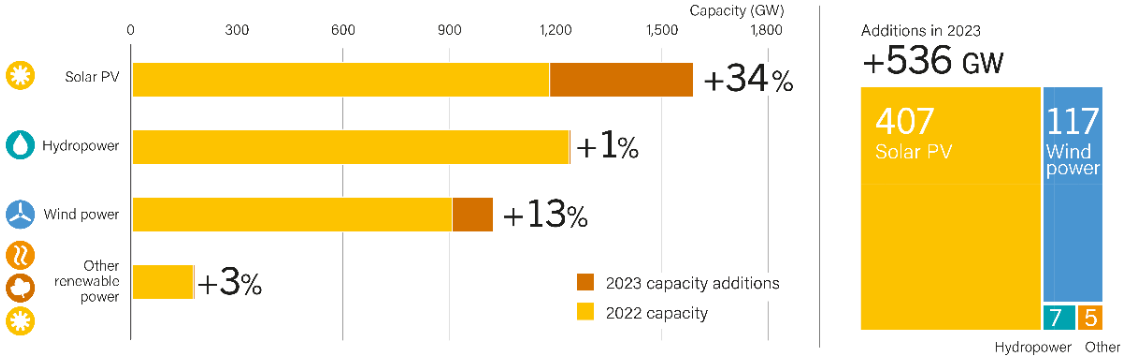

Figure 1.1: Additions of renewable generation capacity in 2023 worldwide according to [4].

In the context of power systems, flexibility consists of the capability to effectively adapt electricity supply and consumption to achieve specific economic or technical objectives. This concept can be defined as the capacity of power system operations, generators, loads, and assets to alter or adjust their operating patterns within a designated time frame while responding to external service requests. Moreover, these adjustments must occur without leading to unplanned disruptions or outages [5].

Numerous changes have been taking place in the electric power system (EPS), both in the generation and distribution of energy. The rise in the number of prosumers has contributed to the increase in distributed generation. In addition, there is a growing digitalization of the system, favoring monitoring and data collection [6].

Among these transformations, the configuration of the system in the form of energy communities has increased and has become the focus of research worldwide. Energy communities (ECs) represent a configuration that prioritizes renewable sources, serving a neighborhood, with the possibility of trading energy and offering benefits to the parties involved. ECs have several advantages over centralized systems. Energy transactions within a given neighborhood reduce electricity losses, while at the same time diminishing the load on lines and transformers. This is due to the fact that energy generation is located close to consumption, and there is a balance between generation and demand at distribution level.

Microgrids (MGs) have a similar concept of EC. They comprise distributed generation, primarily from renewable energy sources (RES), along with loads, energy storage systems (ESS), and an advanced control system. They have clearly defined electrical boundaries and coordinated control of their own distributed energy resources (DERs). MGs can operate either connected to the main grid or in islanded mode [7]. They can have different ownerships, such as the system operator, aggregators, prosumers and consumers. The resources do not necessarily belong to a single stakeholder. There can therefore be different interests and objectives. An MG can be associated with one or more consumers, unlike an EC, which represents a community.

On the other hand, ECs usually operate continuously connected to the main grid. They take the form of an association, cooperative, partnership, non-profit organization or other legal entity that is governed by local members or shareholders. These entities are dedicated to distributed generation and perform the functions of distribution network operator, supplier or aggregator at a local level, and can cross borders. Their assets are usually shared among the members [8].

The economic aspect is also related to the EC. Energy transactions with the grid or other entities (such as an MG or another EC) are a defining characteristic of the EC, allowing peer-to-peer (P2P) transactions to increase respective profits and facilitating interactions. The development of a local energy market also helps to reduce investment in traditional grid infrastructure, especially transmission systems. In this way, ECs can provide flexibility for the grid and the system. Demand response, energy storage and load shifting are examples of actions that increase flexibility. With advances in technology, legislation, dynamic pricing and some incentives to implement renewable energy systems and ESS, the number of ECs has increased significantly in Europe [6], [9], [10].

Conversely, energy transactions between prosumers, consumers and producers will affect the flow of power and therefore technical aspects, including voltage, protection, fault recovery and network reliability must be considered. This makes it necessary to model and simulate the system in order to assess the possible impacts and define actions to ensure safe operation [6].

The implementation of an optimal system for power dispatch for ECs, encompassing the priorities and objectives of those affected, is essential. Profit is another important factor associated with optimization modeling, as it must be economically viable to implement and operate. Thus, the analysis of the operation of ECs is relevant in the current context. The flexibility it can offer in various aspects can be exploited and benefit the system and the grid.

1.1 Motivation

Power systems are undergoing transformations, driven not only by changes in technology, but also by economic, social, geographical and political factors. These shifts have fueled the ongoing energy transition, which promotes several trends, including decarbonization, digitalization, decentralization, deregulation and democratization. They represent the 5Ds of the energy transition (Figure 1.2), fostering renewable energies, increased efficiency, local energy production, market competitiveness and equitable access to energy [11], [12].

The 5Ds principles have supported scenarios of greater sustainability and empowerment in the energy sector. Decarbonization focuses on lowering greenhouse gas emissions through the adoption of renewable energy sources such as solar, wind, hydropower and biogas. It represents a major challenge in tackling climate change, permeating multiple scales of governance.

Digitalization involves advanced digital tools and software in the grid, integrating artificial intelligence and real-time monitoring. It enables process optimization and smarter operations, contributing to energy management and energy efficiency. Decentralization, in this context, refers to the switch from the traditional centralized system to smaller, distributed ones. Distributed generation represents a tendency in this process, which is present in energy communities and microgrids [12].

Figure 1.2 The 5Ds of energy transition.

Deregulation consists of reducing or removing government control of the energy market, promoting private sector participation and competitiveness. It can dismantle monopolies, allowing other players to enter. Prosumers have the alternative of becoming active participants in the energy market. In the short term, it can cause fluctuations in the price of electricity until it reaches stability [11]. Democratization guarantees equal and secure energy access for all communities. Energy democracy encompasses factors related to popular sovereignty, participatory management and civic involvement, and is implemented through locally relevant indicators. It enables the involvement of citizens, who generally prioritize choices with a sustainable bias [13], [14].

These elements provide a positive response to the social scene, encouraging energy efficiency, autonomy and caring about environmental values. The EPS can apply these concepts and adopt approaches that follow the same path. Energy communities represent one possibility for incorporating 5Ds, providing advantages and flexibility for the grid and the system, in an affordable secure and resilient way [15].

Flexibility in the EPS can be defined as the possibility for consumers and/or prosumers to affect power dispatch in both directions: consumer-grid and grid-consumer. In certain energy markets, the consumer (or prosumer) can actively participate, including by selling energy to the grid or neighborhood. This participation is based on the strategy adopted, according to market rules and stipulated objectives [16].

Flexibility can be used in different contexts, and various entities can benefit from it. Grid-oriented flexibility consists of the operator taking advantage of this mechanism to influence the state of the grid. Relieving grid congestion and maintaining voltage levels are examples of the benefits provided by this flexibility. System-oriented use encompasses all forms of usage that serve the operation of the system and, consequently, guarantee the balance of active power. Flexibility in this category benefits from controlling the injection and absorption of power from the grid, encompassing the energy market [17].

There are several options for providing flexibility, which can include photovoltaics, wind power, biogas generation, community storage and electric mobility, including the possibility of injecting battery power into the grid, referred to as vehicle-to-grid (V2G) technology. All of them offer benefits at the most diverse levels for system and grid-oriented use, especially at the distribution level [17].

Besides the advantages, there can also be negative impacts from distributed generation. Among them are fluctuations in voltage levels [18]. Thus, it is essential to have optimized management of power dispatch, ensuring that the technical parameters remain within the values stipulated in the standards.

Given the aforementioned motivations, this dissertation will address the flexibility provided by energy communities. The approach selected corroborates the reasons outlined and will provide a constructive discussion on the subject.

1.2 Use of flexibility in power systems

A wide range of publications provide applications for the use of flexibility in the power system and optimization methods employed in it. The research of [19] proposed BESS's active demand-side flexibility management for flexible local markets. The method was effective and enabled the available flexibility of the system to be represented, based on power, energy and duration of demand response.

Energy communities are considered flexible tools in the optimal balancing of the network, according to [20]. The strategies adopted reduced load fluctuations and increased self-consumption of renewable energy; however, technical aspects of the network were not examined. The research of [10] designed an energy management solution for a local EC with community energy storage. The study compared various scenarios with a centralized approach and promoted self-consumption. The results proved that the strategies adopted were consistent and effective, providing financial benefits.

Reinforcement learning was the technique selected by [21] to offer flexibility services in a local EC. The model introduced a scenario with DER and storage system, enabling optimized energy transactions, reducing operating costs. In [22], a heuristic method was employed to verify the potential of residential photovoltaic (PV) and battery energy storage system (BESS) to provide EC flexibility services by checking the PV overgeneration and BESS state of charge (SOC) of some residences. The model was effective and increased flexibility, making a certain energy capacity available to the grid.

Network-aware compensation algorithms were used to coordinate the flexible resources of ECs in [23]. The method can respond to internal or external signals in order to increase flexibility. The results showed that the algorithm was efficient in providing flexibility.

The study of [24] simulated an EC and its energy transactions between consumers and electric vehicles. The model employed mixed-integer linear programming (MILP), with the aim of minimizing costs. The results showed a reduction of between 1.6% and 3.5% in the energy costs of the EC evaluated. The power dispatch of an EC was optimized using MILP in the research of [25]. Energy transactions between the grid and other prosumers were scheduled by developing a P2P energy management system (EMS). Finally, the EC reduced its energy dependence on the grid and its operating costs by up to 18.8%.

Another energy management model for an EC was developed by [16]. The method used was MILP, and a real case study was compared with a centralized model. The results were satisfactory within the restricted scenario analyzed. A renewable EC was studied by [26] in Austria. The authors developed an optimization solution based on MILP to minimize costs and carbon dioxide emissions. The EC had nine members from one municipality, with PV, BESS and different tariff scenarios. In all scenarios, the participants obtained economic and environmental benefits, demonstrating the efficacy of the proposed method.

Research and analysis in the field of biogas has been growing recently. The management of a biogas power plant was analyzed by [27] in the context of transactive energy. There was a biogas storage system and various simulations were conducted in order to drive the system's primary machine, generating energy at strategic times. In this way, the flexibility and reliability of the system was increased by enabling the generation and transaction of energy, benefiting both the prosumer and the distribution system.

An Energy Hub (EH) was studied in Finland, based on biogas power generation from biomass. The research proposed a linear optimization framework for optimal scheduling of a biogas-based EH for participation in the day-ahead (DA) electricity and thermal energy market. The EH comprises, in addition to the biogas system with storage, a PV power plant, electricity storage, electric heating, biogas heating, a boiler and electrical and thermal loads. Uncertainties related to solar radiation and the DA price were modeled to generate random scenarios using the Monte Carlo method. The results indicated the optimal performance of the EH, in which there is the possibility of participating in the electricity and thermal markets through the biogas produced. In addition, comparative results demonstrated that eliminating the biogas plant and using natural gas significantly increases the expected costs of EH [28].

The research by [29] carried out an analysis in a German case study for an EC. The achievements showed that the EC promoted an increase in energy neutrality and grid reliability. In a simulated scenario with high DER penetration, there was an 80% reduction in voltage level violations. In addition, local energy consumption was prioritized, reducing energy imports from the grid.

The research in [30] proposes a system of rewards and penalties based on the carbon trading mechanism and user satisfaction. The study analyzes energy usage within the community and applies rewards according to carbon emissions. Additionally, [31] proposes the concept of a zero-carbon community, implementing a reward-and-punishment system tied to carbon emissions.

Table 1.1 compares various publications with the topics covered in the methodology proposed in this dissertation, demonstrating the broad coverage of this approach.

Table 1.1 Comparison of other publications and this dissertation

Reference	RES	Storage	EV	EC	Transactive energy	Flexibility model	Voltage analysis
[19]	✓	✓	✓	-	-	✓	-
[20]	✓	✓	✓	✓	-	-	-
[10]	✓	✓	-	✓	✓	✓	-
[21]	✓	✓	-	✓	✓	✓	-
[22]	✓	✓	-	✓	-	✓	-
[23]	✓	✓	-	✓	✓	✓	-
[24]	✓	✓	✓	✓	✓	-	-
[25]	✓	✓	-	✓	✓	-	-
[16]	✓	✓	✓	✓	✓	-	-

Reference	**RES**	**Storage**	**EV**	**EC**	**Transactive energy**	**Flexibility model**	**Voltage analysis**
[26]	✓	✓	-	✓	✓	-	-
[27]	✓	✓	-	-	✓	✓	-
[28]	✓	✓	-	-	-	-	✓
[29]	✓	✓	✓	✓	-	-	✓
[30]	✓	✓	✓	✓	-	-	-
[31]	✓	✓	-	✓	✓	-	-
Proposed method	✓	✓	✓	✓	✓	✓	✓

1.3 Research objective and contribution of the work

As mentioned, the power system is facing a number of challenges in the current energy transition [6]. Energy communities and the possibility of aggregating flexibility initiatives and incorporating the concepts contained in the 5Ds represent a set of elements capable of bringing advantages to those involved and to society. In this context, the general objective of this dissertation is to develop a power dispatch model in which energy communities increase the use of flexibility for both the grid and the system.

The specific objectives of this research are:

- Scale energy community with DER to enhance their overall efficiency and sustainability.
- Maximize the utilization of the power generation resources available within ECs, prioritizing renewable sources to promote greener and more sustainable energy consumption.
- Optimize the processes of energy transactions and power dispatch, both within the EC and in interactions with the external grid.
- Develop and implement a model that enhances the flexibility of the EC by leveraging the capabilities of BESS, ensuring more adaptive and efficient energy management strategies.

- Evaluate energy trading, minimize operating costs and define the conditions under which energy will be sold or purchased.
- Perform technical analysis encompassing voltage stability, analyzing the voltage on the buses and active power losses within the EC.

By developing this work and addressing various aspects pertinent to the topic, its contributions include:

- Development of a methodology to optimize energy management in ECs, involving real-time pricing, DER, BESS and electric vehicle (V2G), keeping the voltage within the values stipulated by the standards.
- Developing a method in which ECs provide flexibility for the grid and the system, where the energy storage system plays a crucial role in this operation.
- Creating levels of flexibility for the EC by assigning parameters to the energy storage system, including initial and final daily SOC and a weighting coefficient.
- Implementation of incentives for community-friendly behavior through rewards, based on storage system activity and energy sales.

1.4 Structure of the work

The structure of this dissertation consists of an introduction to the subject in Chapter 1, covering the motivation that led to its development and the objectives and contributions.

Chapter 2 discusses the concept of flexibility, defining its characteristics and presenting the primary sources and potential solutions to enhance flexibility.

Chapter 3 explains the concept of an energy community, exploring its fundamental components. This chapter also examines the relevant regulatory frameworks and provides an overview of the energy market in which energy communities operate.

The methodology used in power dispatch is described in detail in Chapter 4, involving energy management through rule-based approach and the optimization method chosen to be implemented. The strategies adopted for economic and technical analysis are also presented, including voltage stability.

Chapter 5 describes the proposed flexibility model at three different levels and the incentive model for the EC through rewards.

Detailed case studies are presented and thoroughly discussed in Chapter 6 to serve as evidence and provide validation for the proposed approach.

Chapter 7 presents the results of the simulation from the proposed model in its distinct scenarios and discusses their implications. The behavior of the storage system was assessed, along with an economic evaluation for the simulated days. Voltage levels are also presented in this section.

Finally, Chapter 8 draws conclusions from the method proposed and implemented, pointing to suggestions for future work which could give continuity to research in this area of study.

There are some important topics related to this dissertation proposal, however they will not be covered, which are:

- Demand response, despite the arbitrariness of reducing loads.
- Frequency control and synchronization of generators.
- Implementation of smart contracts on the blockchain network.
- Maintenance, additional costs and capabilities of the main grid to meet EC demands.

2 Flexibility in Electric Systems

The term flexibility has a broad concept that varies depending on the context and area of applicability. It is important as it helps grid operators to maintain their system stable and reliable. In the power system, flexibility is related to the ability to appropriately adjust electricity generation and consumption according to reach economic or technical goals [5], [18].

It is essential in power system operation, accelerating the current transition in which more renewable energies are gradually being introduced to the grid. Some of the advantages of a flexible grid are cost savings, since it reduces the need to construct new power plants and transmission lines, as distributed energy resources have been incorporated into the grid increasingly; and increased efficiency, by reducing losses and making operation more efficient [18], [32].

The definition of flexibility requires addressing the following criteria: type of flexibility resource (consumer or grid side), duration of flexibility activation (from seconds to years) and incentive for flexibility provision coming from an external stimulus, as illustrated in Figure 2.1 [5], [33]. Flexibility has a wide concept and can be formulated as the ability of power system operation, generators, loads and assets to change or modify their operating routines for a given time interval, and to respond to external service request signals without causing non-planned outages. Therefore, flexibility may involve load variation, generation variability, or even a combination of both [5].

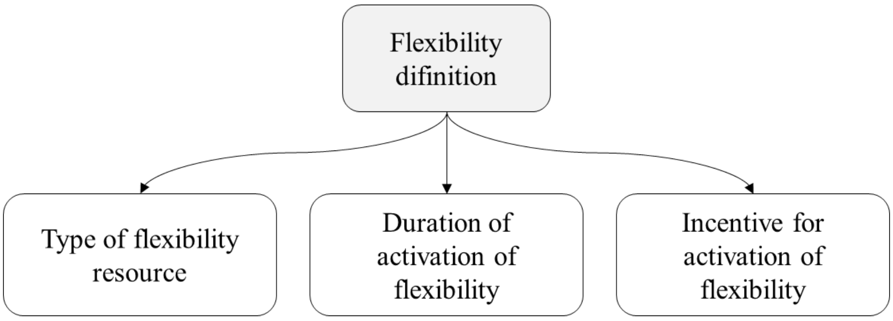

Figure 2.1 Criteria for flexibility definition according to [5].

Characterizing flexibility resources is fundamental to developing a flexibility model. The characteristics include the ability of the elements to respond to requests inherent in availability, time, volume and cost. They are divided into two main sectors: technical and economic. The technical aspect can be classified as quantitative (power capacity, service duration), qualitative (availability, location) and controllability (direct or indirect control). The economic aspect embraces capital expenditure (CAPEX), comprising investment costs to enable flexibility; and operating expenditure (OPEX), covering short-term and routine costs [5]. Figure 2.2 depicts this classification.

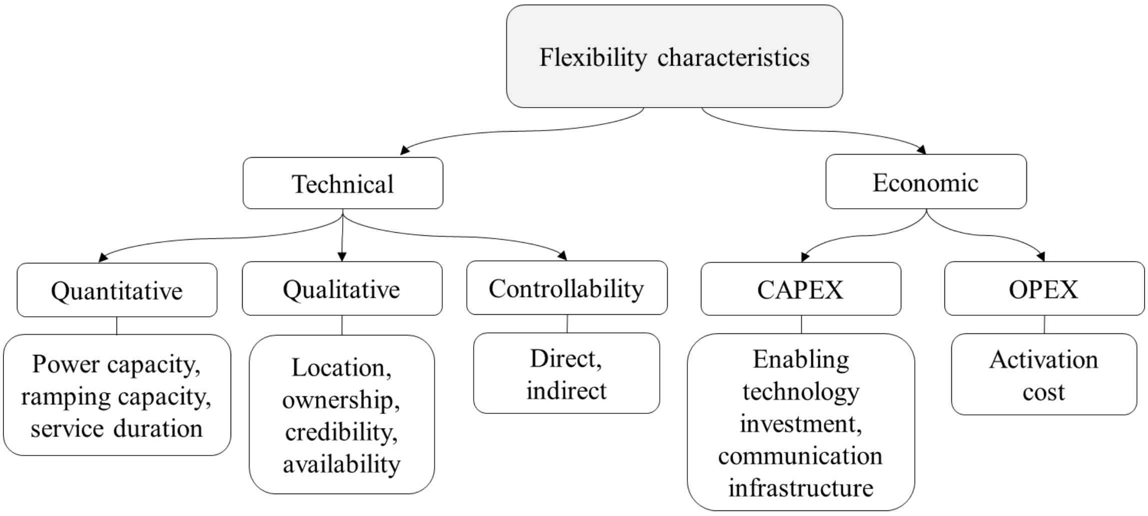

Figure 2.2 Classification of characteristics of flexibility resources according to [5].

2.1 Sources of flexibility

Various elements may offer flexibility in a variety of solutions. Their classification is shown in Figure 2.3, dividing them into sources of flexibility and enablers. The first branch is separated into flexibility assets and operational flexibility. Energy storage, demand and supply represent the assets. While grid reconfiguration, innovative operating techniques and dynamic line rating are part of operational flexibility, where voltage or current can be adjusted in real time. The enablers branch is divided into grid interconnection, grid hardware (such as FACTS, HVDC converters), regulation (standardization and incentives) and the market, where stakeholders can come together to facilitate the exchange of goods and services [5], [34], [35].

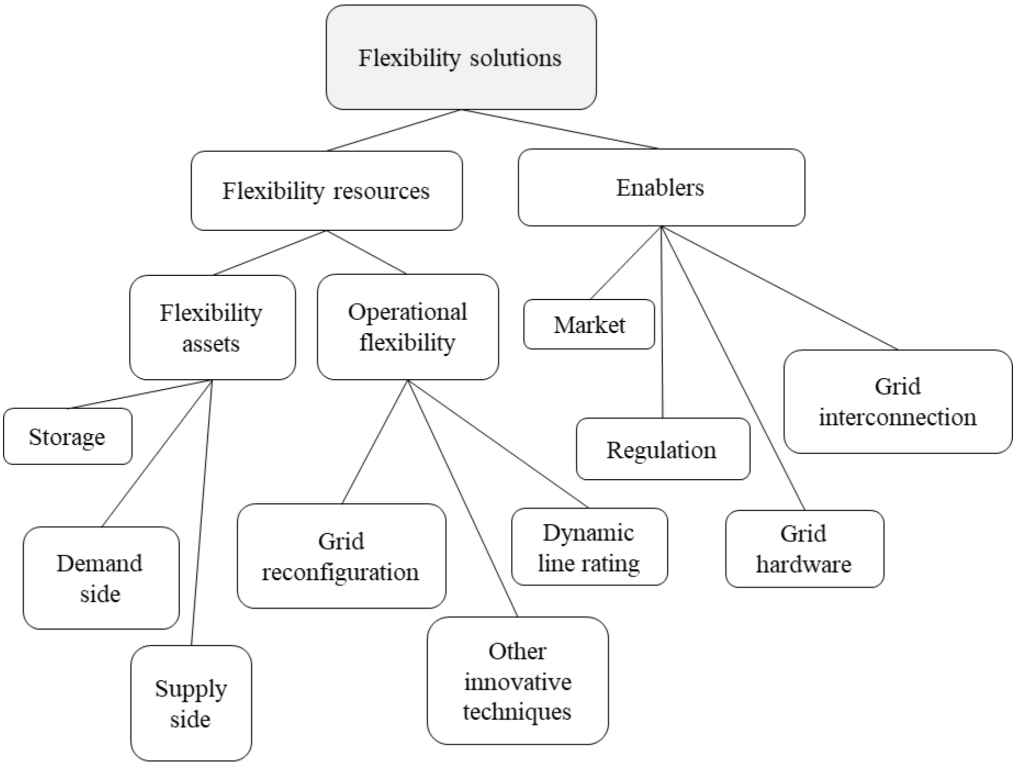

Figure 2.3 Classification of flexibility resources and their enablers according to [5].

Since flexibility solves the problem of variability and uncertainty, and these occur on different time scales, the solution chosen must match the temporal framework. For example, demand-side management, modulation of generated power, grid settings and batteries are all real-time flexibility solutions. On the other hand, modifications to the tariff structure, investments in generation, storage and the grid are long-term solutions [33].

Regarding the use of flexibility, several entities can take advantage of it. Own use flexibility is applied by prosumers and consists of optimizing individual consumption of the energy produced [17].

Grid-oriented flexibility refers to alleviating the grid in times of congestion. Actions within this scope aim to maintain or adjust voltage levels and other technical parameters, guaranteeing safe operation. Transmission and distribution operators have various devices for this purpose and can benefit from flexibility on both the supply and demand side [17].

Flexibility on the supply side is achieved through the coordinated operation of generation assets. Their optimized management benefits the transmission and distribution systems. Demand-side flexibility provides for changes in the pattern of energy consumption. There can be shifting of controllable loads, such as electric vehicle (EV) charging [34].

The system-oriented use of flexibility includes applications with the goal of keeping the system balanced. The injection and absorption of power, including energy transactions through markets and their conceivable products are part of this use of flexibility [17].

3 Energy Communities

Energy communities are formed by power system customers, especially those who own distributed energy resources, and act as a single entity, like an association, a cooperative, or a partnership. In general, they include renewable and intermittent energy sources, pushed mainly by energy-efficiency initiatives and economic incentives. One of their objectives is energy self-sufficiency. In addition, they can improve grid reliability by reducing or avoiding congestion and instability caused by the mismatch between supply and demand. Municipalities have a key role to play in encouraging citizens to become part of an EC. Incentives can come in the form of funding, regulation, and even the provision of space for installation [29], [36], [37], [38]. An illustration of an energy community can be seen in the Figure 3.1.

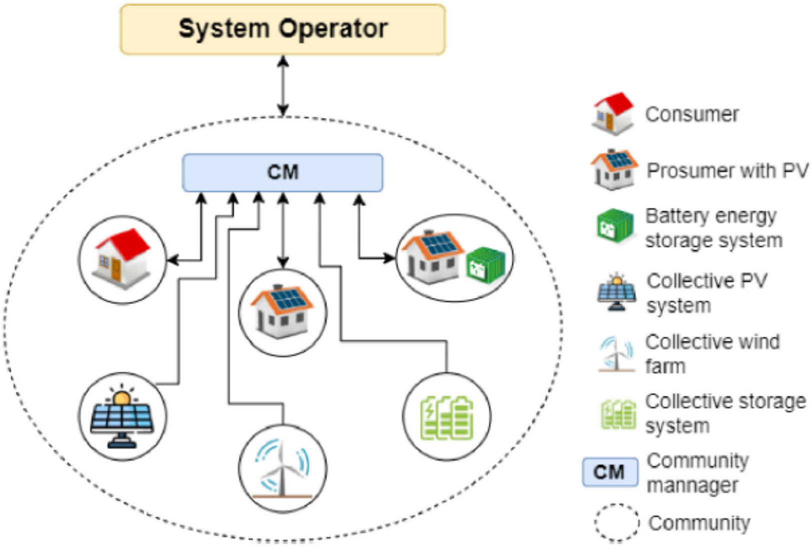

Figure 3.1 Representation of an energy community according to **[39]**.

ECs have several advantages over centralized systems, such as reducing electricity losses and transmission investments. The concept of an energy community is relevant in developing countries, where the connection to the main grid may be limited or non-existent, depending on the location. Thus, investments in projects in this field provide a viable alternative for access to electricity in certain regions [40]. On the other hand, energy transactions between prosumers and consumers will affect the flow of power and, consequently, technical aspects of the network need to be considered. Solid regulation is therefore needed to take these aspects into account in order to guarantee secure operation [41].

The digitalization and automation of distribution grid components, together with the rapid integration of intermittent DERs into the grid, are giving rise to new grid topologies and creating economic opportunities. In order to incorporate smart and flexible loads and DERs, as well as achieving scalable grid control, transactive energy (TE) is emerging as a method for coordinating the operation of the different agents in power systems. Therefore, this structure of ECs allows the participation in the promising P2P energy market and potentially obtain profits [42], [43], [44].

Transactive energy can be facilitated between microgrids through the use of smart contracts (SC). These contracts establish specific operating conditions, including viable tariffs and guaranteed energy supply. Blockchain protocols can be employed in these transactions, promoting the decentralization of the energy sector [42].

3.1 Assets

The assets of ECs are owned by certain prosumers or acquired by the EC itself, such as energy generation units, like biogas (BG), photovoltaic and wind turbines (WT), as well as energy storage systems, represented by batteries and even electric vehicles [40].

In the scenario where the assets are owned by the EC, there may be a greater economic benefit due to the fact that they have been specially designed for it. Managing the operation of these assets is a duty that needs to be well planned and analyzed, from both a technical and economic point of view. The sizing of generation and storage systems, along with the constraints applied to their operation, reflect technical aspects that need to be considered. In addition, the economic factor is indispensable and resources must be managed in a balanced way in order to minimize operating costs [40]. The parameters defined for EC operation in the proposed model will be presented and discussed in Chapter 4.

3.1.1Photovoltaic systems

Energy from the sun is the most abundant and inexhaustible source on the Earth's time scale, both as a source of heat and light. It can therefore be exploited in a variety of ways.

A photovoltaic system is a set of elements that generate and supply electricity by converting solar energy [45], [46].

Over the years, the efficiency of PV cells has increased significantly, and the cost of the PV panel has decreased. This has made it possible to extract more power from these systems, which have shown rapid growth in installed capacity worldwide. In addition, the publication of standards, regulations and government incentives have contributed to the spread of PV systems [1], [47].

In addition to the environmental benefits, PV systems can have an influence on the grid and their increased penetration can leads to voltage fluctuations. The intermittent behavior of PV systems over time can be seen in Figure 3.2, with data from eight days of operation [48]. The variation in energy is significant throughout the day, causing considerable variations in voltage and current. A research study carried out in Australia indicated that the increased penetration of PV systems reduced undervoltage events in that location. On the other hand, overvoltage events increased significantly, causing inverters shutdown when the voltage exceeded the nominal value [49].

Integrating BESS into PV systems increases the self-sufficiency, self-consumption and profitability of the installation. In this way, it is possible to store energy produced during the day for use at night or at cloudy times, reducing energy imports from the grid [50]. Commercial and utility-scale PV+BESS systems in Germany account for up to 20% of total installations in 2023. Conversely, in residential rooftops systems, the share commissioned has grown from almost 20% in 2014 to nearly 80% in 2023 [51]. This progression is shown in the Figure 3.3.

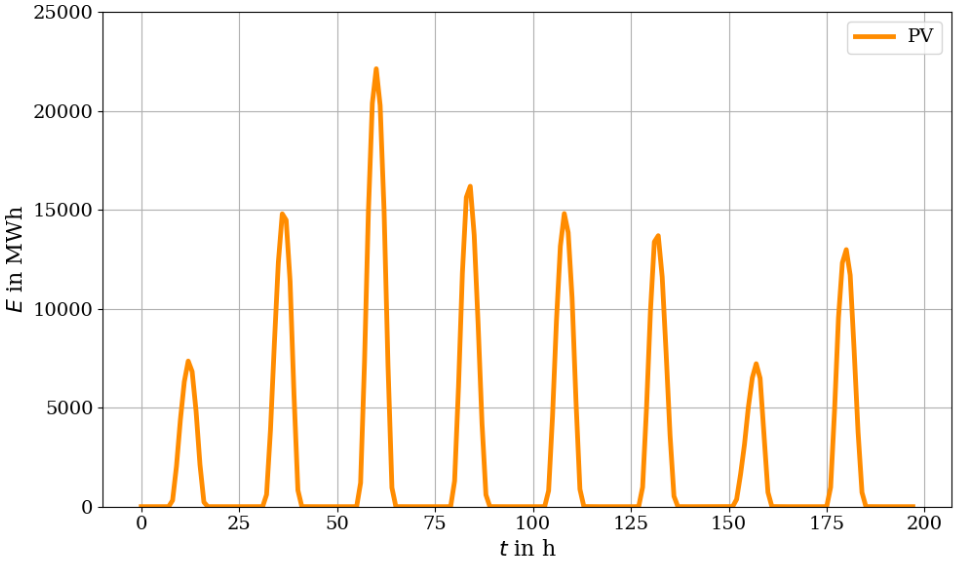

Figure 3.2 PV generation over eight days [48].

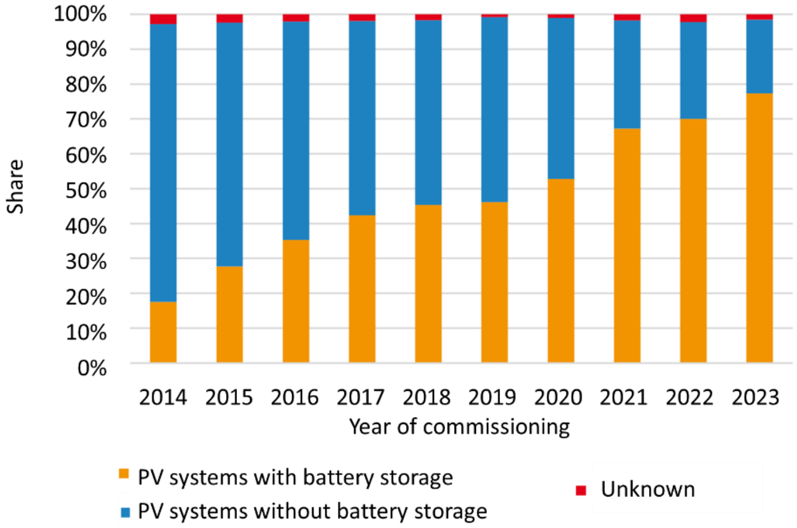

Figure 3.3 Share of PV-Installations with BESS according to [51].

3.1.2Wind generation

The movement of air masses in the atmosphere gives origin to winds, which vary according to altitude, temperature difference and pressure. Wind generators have been adding capacity every year around the globe for the last ten years, both in onshore and offshore plants. In 2023, the annual increase in wind generation increased by more than 50% compared to the previous year in various regions of the world [52], [4].

Similarly to PV systems, wind generators have variable generation depending on the wind speed at the installation location, posing challenges for balancing generation and demand. This dynamic performance can be visualized in Figure 3.4.

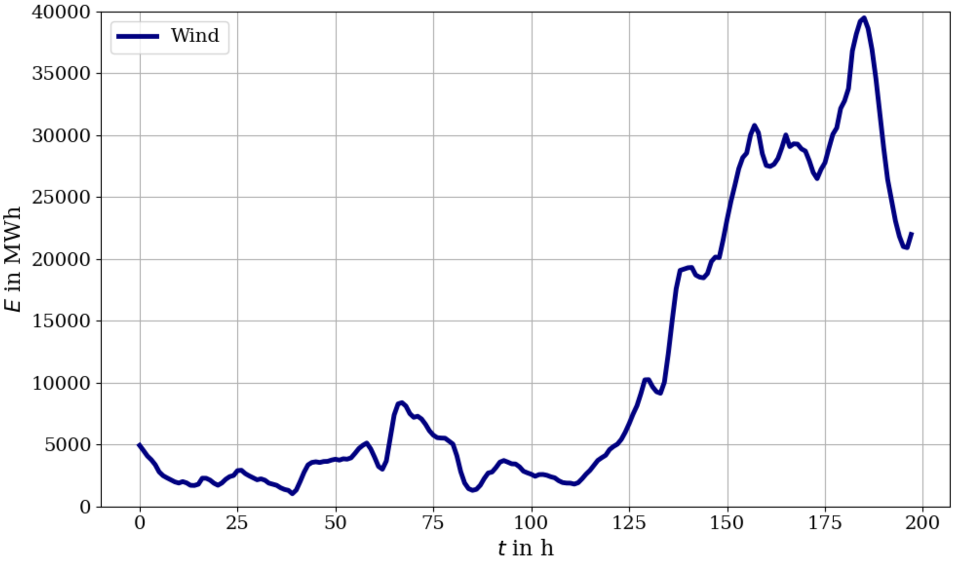

Figure 3.4 Wind generation over eight days [48].

Several countries have drawn up challenging targets to achieve certain power and wind generation capacities. These actions have been driven by diverse motivations, such as climate change, energy security, economic growth goals and the cost competitiveness of wind energy [4].

3.1.3Biogas Generation

Biogas is a biofuel made up of different gases, with methane gas being the only combustible element present in it. Biogas production provides energy recovery from organic waste (biomass) and avoids greenhouse gas emissions. Biogas production in rural areas makes it possible to improve infrastructure and diversify new sources of income for rural producers. It represents a firm and dispatchable source of generation, without intermittency [53]. Biogas power plants allow greater flexibility in the storage and use of electricity. Interest in research into generating electricity from biogas plants has been growing recently. One of the reasons is that biogas supports the development of sustainable energy and is environmentally friendly. Instead of burning biomass waste, the use of these plants reduces waste treatment costs and pollutant emissions [54]. As mentioned, wind and photovoltaic generators have intermittent behavior, so combining them with biogas systems promotes greater stability and versatility in operation. Figure 3.5 provides an example of biomass generation (which presents similar pattern), where power generation is less variable and more controllable.

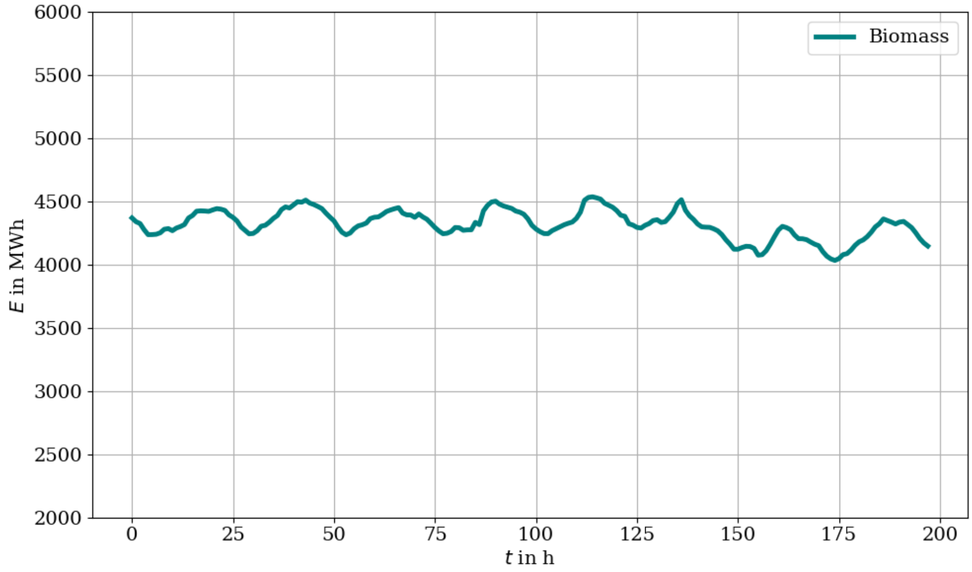

Figure 3.5 Biomass generation over eight days [48].

The integrated development of renewable sources and energy storage is one of the factors that will be required to achieve the specific objectives of reducing global greenhouse gas emissions. This type of approach is fundamental to accelerating decarbonization in energy generation processes, where zero-carbon energy systems play an important role in this transition and provide environmental and economic advantages [55], [56].

3.1.4Battery energy storage system

Battery energy storage systems have proven to have potential in reducing voltage rise problems in distribution networks. In addition, BESS can store surplus generation to maximize self-consumption at peak times or, in case of need, inject energy back into the grid [57].

The flexibility of storage systems can serve as a tool to guide the management of energy and power reserves during operation. This can be applied to energy and capacity reserve transactions to guarantee internal self-sufficiency or resolve operational uncertainties, achieved through the effective management of control parameters. Elements such as storage systems increase operational flexibility, as initiatives in this direction guarantee the effective management of energy resources and increase the efficient use of renewable energies [19].

BESS, primarily comprising lithium batteries, are the most common ESS utilized in microgrids, offering different options available in the market [7]. Among battery technologies, Li-ion holds the largest market share. This is attributed to its high efficiency, longer lifecycle, and high energy and power density. However, its high cost remains the primary challenge for commercial-scale use [58]. Projections, however, indicate a reduction in Li-ion battery costs due to several factors expected to drive market expansion, such as the supply of raw materials and improved charging and discharging strategies. Figure 3.6 presents forecasts for battery prices in $/kWh up to the year 2030, with the price expected to reach $80 per kWh. A significant milestone in this trajectory for the battery market is around 2025, when the price is anticipated to drop below $100 [59].

Figure 3.6 Expected price per kWh of batteries by 2030 according to [59].

3.1.5 Electric vehicles

The possibility of EVs acting both as a load and as an energy supplier to the grid has been increasingly explored. As with microgrids, EVs can participate in demand response programs, charging according to established strategies. Vehicle-to-grid battery power injection technology can contribute to the management of generation and demand. This integration assists in relieving peak demand by shifting the load, minimizing costs and reducing dependence on the main grid [60], [61], [62].

The integration of EVs as part of the energy management solution in ECs contributes to the reliability of the system. The EV's battery can act as a backup power source, supporting the grid during periods of low energy production or high demand. This configuration not only extends the discharge period of the main energy storage system, in accordance with established limits and restrictions, but also ensures that critical loads are met, even in challenging conditions [24].

In addition, the combination of optimization methods for load dispatch in an EC that incorporates electric vehicles has been shown to effectively integrate EVs into its operation. This integration takes advantage of vehicle battery storage to increase grid stability and reduce operating costs. Exploring these approaches is essential to enable more strategic energy use and cost-effective management within the EC, especially in scenarios with high EV penetration [24], [63].

3.2 Energy market

The energy market adapts to the influence of various elements, such as the addition of new components to the system, new regulations and incentives. The local energy market is designed to manage the purchase and sale of energy in a given region, usually with a high penetration of DERs. The problems caused by the high installed capacity of DERs, such as congestion and voltage variations, can be overcome in this sort of market [34] [29].

There are currently a number of business models in the energy market and new opportunities are arising in this niche. One emerging model in this scenario is the P2P relationship, in which energy is exchanged between prosumers and consumers. The figure of the aggregator or operator of the EC represents another business format, in which there is a coalition and these agents become responsible for managing the energy and revenue of the EC, distributing it to all its participants. The three main processes in this market are contracting and bidding, activation and settlement [34].

The EC Ecovillage implemented in Scotland represents a successful example of this approach. One of the challenges it encountered was the fair distribution of benefits and income among participants [40].

3.2.1Transactive energy

Transactive energy consists of a reliable, accessible, and sustainable system that seeks to maximize the benefits for all agents involved in the process [64], [65]. According to [66], it comprises a system of economic and control mechanisms that enables the dynamic balance of supply and demand throughout the entire electrical infrastructure, using value as a key operational parameter.

TE has been adopted in microgrids in some countries, expanding business markets in the energy sector. In this context, the spread of blockchain and the potential implementation of smart contracts to transact energy provide a new way to operate this market. Decentralization represents another important characteristic of this proposal, as it reduces the need for measurement and data storage infrastructure. In addition to economic evaluation, technical analyses are crucial for the safe operation of these transactions and must also be considered [64], [67].

The concept of transactive energy, involving the trading of surplus energy generated, has been studied globally. It enables autonomous operation within the electricity market. Its feasibility and effectiveness have been analyzed, and it could be introduced into research at the national level, leading to grid flexibilization. The combination of these elements enables the creation of sustainably favorable scenarios, which can be optimized and implemented, promoting the development of new business models [68], [69].

3.2.2Blockchain and smart contracts

The specifications of these conditions can be established through smart contracts between the involved parties, benefiting both sides. Since a flexible contract establishes a lower tariff and an amount of future demand in advance [70]. Additionally, smart contracts offer versatility by establishing a quantity of energy to be sold or bought within a minimum and maximum limit, and blockchain can enable these transactions [71]. Thus, in this context of evidence of growth in DG investments and electricity usage, the analysis and study of energy generation and its management, reducing curtailment, prove relevant in the current scenario.

The possibility of including TE in the system enables an attractive proposition for the agent, allowing them to generate energy, reduce costs, transact energy with the grid, and remain in the market. Smart contracts provide greater operational flexibility to the involved parties, representing a right that can be exercised as agreed upon between the parties [72]. As an effective risk management tool, smart contracts provide participants with profit opportunities when electricity prices fluctuate favorably, while protecting against risks caused by adverse tariff changes [73].

Blockchain is a chain of transaction blocks recorded sequentially, overseen by multiple administrators who manage the operation of client/server systems. It consists of a P2P network where all users have equal control over the network's direction and operation. Numerous computers, or nodes, are interconnected to form this network, and once a transaction is verified by the nodes and uploaded, it cannot be undone. Consequently, the data stored on the blockchain cannot be altered. This technology can facilitate transactions without a central authority, as it is a decentralized and secure system, proving to be a disruptive and highly promising tool [74].

Energy communities in a given neighborhood can be linked via the blockchain system. Without compromising data quality or transparency, this network aims to enhance the security and confidentiality of operations. Blockchain-based renewable ECs offer numerous benefits but face significant challenges. These include technological, financial, societal, environmental, political, and institutional constraints, as well as rules and regulations, social norms, and end-to-end privacy and security issues. Key elements such as privacy, resource management, constraints, and pricing remain difficult to reconcile practically and effectively. Evaluating and deciding on the best algorithm or procedures to use, the most appropriate technology, the most suitable investor, and a highly skilled workforce are essential [74].

In a blockchain network, SC are computer programs that execute and regulate transactions between distributed nodes. They can be triggered when certain conditions are met and can automatically execute and control energy trading events [64].

Generally, the operation of SC begins with the initialization of the contract, which triggers the command to read the power and price offered by generators. It is assumed that forecasting, estimation, and price selection are performed at the generator's end. The offer is then communicated to buyers (consumers), and the bidding procedure begins. There are various techniques for price settlement, with the most commonly used being the double auction, which ranks bids and offers in ascending and descending order to determine a settlement price. The next step is to assess the physical feasibility of allocations by inspecting the network's energy flows. Subsequently, the smart contract is updated with the results, and the energy transaction is verified using the generator's smart meter recording. Once verified, the total units and generation duration are checked, and any necessary escalations and penalties are applied. Finally, the payment to generators is authorized, and the transaction is recorded [64]. The operation of smart contracts within the blockchain is shown in the Figure 3.7.

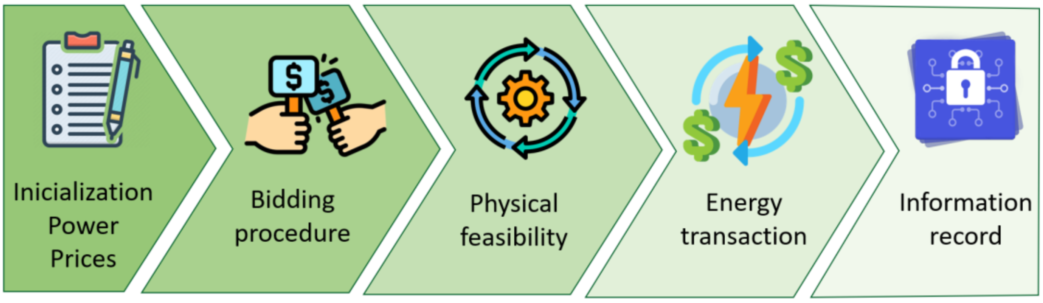

Figure 3.7 Smart contract operation in blockchain.

3.3 Regulation for energy communities

Regulation is essential for the implementation and operation of ECs. With consolidated regulation, it is easier to contribute to the energy transition, promoting the construction of a more sustainable future. In addition to valuing socio-economic items, technical requirements are maintained when they are included in a regulatory framework, guaranteeing a safe supply of electricity [75].

The adoption of regulations facilitates the implementation of ECs, and for this to occur, the involvement of citizens and public entities is necessary. The participation of local authorities is also important and encourages the implementation of ECs [38]. This is a complex process and involves a certain part of society, therefore it can take time to plan and manage the regulation until it is published and comes into force [75].

3.3.1Brazil

In Brazil, the National Electric Energy Agency (*Agência Nacional de Energia Elétrica* – ANEEL) published in 2012 the ANEEL Normative Resolution (*Resolução Normativa* – NR) 482, making DG and electricity compensation possible in Brazil. This resolution defines shared generation, which is characterized by the gathering of consumers within the same concession area, making it possible to compensate the surplus energy from DG between them [76]. In 2015, ANEEL NR 687 came into force, which updated and expanded the previous resolution [77]. At present, under Brazilian law, DG is divided into micro-generation and mini-generation. Distributed micro-generation includes alternating current electricity generating plants of up to 75 kW. Distributed mini-generation includes generating plants between 75 kW and 5 MW for dispatchable sources and up to 3 MW for non-dispatchable sources [78].

According to [78], shared generation is characterized by the gathering of consumers, by means of a consortium, cooperative, voluntary civil or building condominium or any other form of civil association, constituted for this purpose, made up of individuals or legal entities that have a consumer unit with distributed micro-generation or mini-generation, with all consumer units being served by the same distributor [79]. It can therefore be seen that the concept of shared generation is similar to the concept of an energy community, but the sale of surplus energy still needs regulatory and normative support.

Currently, according to ANEEL NR 1.059 (2023), the Brazilian scenario prohibits the sale of energy credits and surpluses from micro-generation or mini-generation, as well as obtaining any benefit from the allocation of energy credits and surpluses to other holders [79]. However, Article 24 of Law No. 14.300/2022 indicates the possibility of trading surplus energy generation from distributed micro-generation and mini-generation plants in their concession areas. These transactions will be feasible after accreditation of interested parties in public calls promoted by the concessionaire, under ANEEL regulations [78]. Regulatory improvements covering energy communities are essential in the current scenario of the power system and energy trading, which should encourage technical and socio-economic benefits in the regions where they are located.

3.3.2Europe

In Europe, the energy market is advancing faster than in Brazil. In 2003, Directive 2003/54/EC came into force, establishing rules for the internal electricity market [80]. In 2009, it was repealed, giving way to Directive 2009/72/EC, which laid down rules for the cross-border market at European Union (EU) level [81]. At the end of 2018, the promotion of the use of energy from renewable sources was reformulated through Directive 2018/2001, defining EC [82].

Each country has its own regulations for renewable energies and the energy market. In Germany, for instance, these laws are found in the Renewable Energy Act (EEG) [83] and Energy Industry Act (EnWG) [84]. One of its principles is to make supply and demand more flexible, through energy efficiency and energy storage. In EU, the renewable energy community is based on open and voluntary participation, is autonomous and effectively controlled by shareholders or members who are located in the vicinity of the renewable energy projects owned and developed by that legal entity. The shareholders or members are individuals, small and medium-sized enterprises or local authorities, including municipalities. The main objective of the EC is to provide its shareholders or members or the localities where it operates with environmental, economic and social benefits rather than financial gains [82].

Renewable energy trading occurs between market participants through a contract with pre-determined conditions governing the automated execution and settlement of the transaction directly between the market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to trade between peers is without prejudice to the rights and obligations of the parties involved as final consumers, producers, suppliers or aggregators [82].

Article 22 of Directive 2018/2001 establishes that Member States must ensure that consumers, especially private individuals, can participate in renewable energy communities without discrimination or unfair conditions, as long as they do not use this participation as their main activity. These communities have the right to produce, consume, store and sell renewable energy, share energy internally and access energy markets without discrimination [82].

States must assess obstacles to the development of these communities, create favorable conditions to promote them, eliminate unjustified barriers, guarantee transparent and fair procedures, facilitate access to financing and ensure the inclusion of vulnerable consumers. The support scheme should be incorporated into national energy and climate plans, allowing communities to compete fairly in the market. In addition, cross-border participation can be planned and the specific characteristics of communities can be taken into account when designing support policies [82].The solid regulations established lead to a supportive environment for the implementation of ECs. Since the publication of the EC Directive, the number of ECs has grown steadily in several European countries [85].

4 Power Dispatch

Power dispatch is the planning and management of generation plants. Meeting loads with the available supply is determined according to defined criteria. Normally, dispatch is performed with the aim of minimizing costs and increasing the efficiency of the system. Therefore, prices and tariffs are considered, as well as technical parameters in order to guarantee the reliability and safe operation of the grid.

Renewable energy sources present a particular challenge when it comes to power dispatch. This is due to the characteristic of intermittency. Uncertainty on the generation and demand side drives the advancement of data forecasting to increase operational assertiveness. There are a variety of energy management methods that can be employed to optimize power dispatch [86].

4.1 Energy management

An optimal EMS is necessary to ensure power supply, encompassing the priorities of each system regarding power dispatch and demand response. Profit represents an important factor associated with optimization modeling, as there needs to be economic feasibility for its implementation and operation [87].

Energy management becomes a viable solution to minimize curtailment. Additionally, there is a way to monetize energy in this operation. In this context, advantageous situations in various aspects may emerge for both system operators and end customers, mitigated by the implementation of energy management mechanisms and controlled energy trading among different prosumers. Environmentally, this approach promotes the increased use of RES in power generation, leading to reduced greenhouse gas emissions. Technically and economically, local generation and consumption reduce energy losses and postpone or eliminate the need for investments in transmission and distribution infrastructure [57].

The EMS can be classified into three types: centralized, decentralized and distributed [87]. The representation of them is shown in Figure 4.1.

- Centralized: Each unit is equipped with its own local controller that operates independently. Instead of sharing all data with other local controllers, it exchanges global information to facilitate decision-making for the entire system.

- Decentralized: Independent control provides data from other local controllers. The information shared among local controllers is asynchronous and can be accessed by a central controller.
- Distributed: Each local controller unit utilizes information such as voltage and frequency from neighboring units. This data exchange through a two-way communication link helps the central controller derive a global solution.

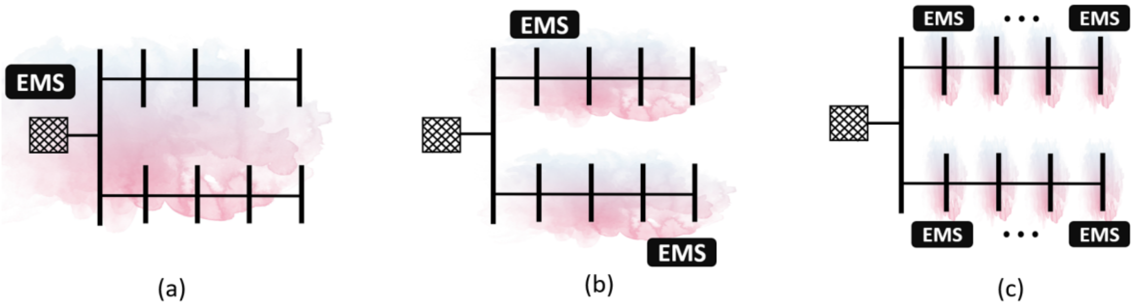

Figure 4.1 EMS classification: (a) centralized, (b) decentralized and (c) distributed.

Recently, there has been a transition of the EMS from a centralized to a decentralized, and ultimately to a distributed configuration. This evolution is driven by the introduction of new elements and topologies within the grid [88].

Various EMS techniques are distinguished based on the numerical methods employed for managing the energy management system. These methods are generally divided into three categories [87]:

- Classical methods: Mathematical programming methods that select specific variables to optimize an objective function within a group of constraints. The branch and bound technique is a classic component used to solve this approach iteratively, seeking the optimal solution without integer constraints. These classical methods employ both linear and nonlinear optimization models and are categorized into certainty and uncertainty-constrained problems, such as MILP and mixed-integer non-linear programming.
- Metaheuristic methods: They are a subset of random search and generation algorithms. This iterative method is unlikely to guarantee a global optimum solution due to its convergence properties. However, this limitation can be mitigated by averaging the solutions. Particle swarm optimization, genetic algorithm and crow search algorithm are examples of metaheuristic methods.

- Intelligent methods: Artificial intelligence is utilized to solve these problems. They have the capability to utilize a variety of tools, from small software applications to large hardware systems. Fuzzy control, neural networks, game theory and deep learning represent some examples of this method.

This dissertation adopts the classic MILP method for managing EC power dispatch, given its widespread application and proven effectiveness in addressing similar problems. The analysis will focus on power balance, tariffs, and the status of the BESS to support optimal decision-making for power dispatch between the EC and the grid. This analysis will also identify favorable periods for charging and discharging the BESS.

In addition, power dispatch will be performed using a non-optimized, rule-based method. This alternative approach is implemented to enable a comparative analysis between the two methods. By examining and analyzing the results from both approaches, it will be possible to provide a deeper understanding of their distinct behaviors and operational characteristics.

4.2 Optimization method

Mixed-integer programming has emerged as a highly effective tool for modeling and solving real-world planning and scheduling problems, with a seemingly limitless range of applications. A MILP involves an optimization problem characterized by a linear objective function and will be adopted in this research. The problem is subject to linear constraints and bounds but does not include any nonlinear constraints. Additionally, some components are required to take integer values [89], [90].

The optimization of power dispatch in the EC will be performed over an interval of one day and can later be expanded to a longer period of time. The DERs present in the CE and considered in the development of this method consist of BESS, EV, and distributed generation. The objective function (OF), together with the limits and constraints, have been defined according to the operation goal. The optimization process was developed in *Matlab*, while data pre-processing was conducted in *Python*. This section has been partly published in [90].

4.2.1Objective function

The EMS is responsible for optimizing power dispatch to minimize operational costs. The EC can sell surplus energy, store it, or use it to charge EVs. Conversely, when there is an energy deficit, power to supply the loads can be sourced from the BESS, EVs, or purchased from the grid. The EMS ensures power balance within the EC to maintain safe operation of the power system. The simulation will span 24-hour, analyzing the operation over the course of one day.

In order to achieve this goal, the objective function is defined as:

$$\begin{aligned} OF = \sum_{i=1}^{24} \{ & E_{\mathrm{purch},i} \cdot T_{\mathrm{purch},i} + E_{\mathrm{sale},i} \cdot T_{\mathrm{sale},i} \\ & + b_{\mathrm{deg},i} \cdot \left[(\delta_{\mathrm{BESS,Ch}} \cdot E_{\mathrm{BESS,Ch},i} + \delta_{\mathrm{EV,Ch}} \cdot E_{\mathrm{EV,Ch},i}) \right. \\ & \left. - (\delta_{\mathrm{BESS,Dis}} \cdot E_{\mathrm{BESS,Dis},i} + \delta_{\mathrm{EV,Dis}} \cdot E_{\mathrm{EV,Dis},i}) \right] \} \end{aligned} \tag{4.1}$$

where the goal is to reduce operational costs hourly. Therefore, energy transactions involving energy purchase and sale (E_{purch}, E_{sale}) will preferentially occur during periods of low tariff (T_{purch}, T_{sale}). BESS and EV operations ($E_{\mathrm{BESS,Ch}}$, $E_{\mathrm{BESS,Dis}}$, $E_{\mathrm{EV,Ch}}$, $E_{\mathrm{EV,Dis}}$) are also considered, which are associated with a degradation coefficient (b_{deg}). Besides, the *OF* also considers weighting coefficient for BESS charging ($\delta_{\mathrm{BESS,Ch}}$), discharging ($\delta_{\mathrm{BESS,Dis}}$), for EV charging ($\delta_{\mathrm{EV,Ch}}$) and discharging ($\delta_{\mathrm{EV,Dis}}$). These weighting coefficients are defined in section 5. This constitutes a minimization problem as defined by:

$$\min \, OF \tag{4.2}$$

It is known that the battery degradation process is non-linearly related to its lifespan and mode of operation. To incorporate the degradation cost practically, the linearized model is derived from its non-linear form, utilizing piecewise linear segments from the Special Ordered Set of Type 2 [91]. The degradation coefficient consists of the sum of the product between the charge or discharge weighting coefficient (β_n) of the BESS or EV and the step function (H_n) encompassing a set N of n line segments, given by:

$$b_{\mathrm{deg},i} = \sum_{n \in N} \beta_{n,i} \cdot H_{n,i} \tag{4.3}$$

The details of the degradation cost modeling can be obtained at [92].

4.2.2 Battery energy storage system

The energy level of the BESS (E_{BESS}) at time t+1 is calculated by subtracting the discharged energy ($E_{\mathrm{BESS,Dis}}$) and adding the received energy during charging ($E_{\mathrm{BESS,Ch}}$) to the energy level at time t, as shown in the equation:

$$E_{\mathrm{BESS},t+1} = E_{\mathrm{BESS},t} - \eta_{\mathrm{Dis}} . E_{\mathrm{BESS,Dis},t} + \eta_{\mathrm{Ch}} . E_{\mathrm{BESS,Ch},t} \tag{4.4}$$

The charge and discharge efficiency of the BESS (η_{Ch}, η_{Dis}) is set at 90 % [93]. The energy for the BESS will maintain a range between minimum and maximum value ($E_{\mathrm{BESS,min}}$, $E_{\mathrm{BESS,max}}$), according to the constraint:

$$E_{\mathrm{BESS,min}} \leq E_{\mathrm{BESS},i} \leq E_{\mathrm{BESS,max}} \tag{4.5}$$

The minimum and maximum power limits ($P_{\mathrm{BESS,min}}$, $P_{\mathrm{BESS,max}}$) for the BESS charge and discharge ($P_{\mathrm{Ch,BESS}}$, $P_{\mathrm{Dis,BESS}}$) are expressed in:

$$P_{\mathrm{BESS,min}}\,(1 - \alpha_i) \leq P_{\mathrm{BESS,Ch},i} \leq 0 \tag{4.6}$$

$$0 \leq P_{\mathrm{BESS,Dis},i} \leq P_{\mathrm{BESS,max}}\ \alpha_i \tag{4.7}$$

where α is a binary indicator that ensures the BESS will not be charged and discharged simultaneously.

The SOC of the BESS will be represented as a percentage, indicating the current charging level of the battery. It is defined as the ratio of the instantaneous energy stored ($E_{\mathrm{BESS},i}$) to the total energy capacity of the battery ($E_{\mathrm{BESS,tot}}$), according to:

$$SOC_i = \frac{E_{\mathrm{BESS},i}}{E_{\mathrm{BESS},tot}} \tag{4.8}$$

The SOC for lithium batteries should be maintained within a specified range of 20 % to 90 % [94], as indicated by the following constraint:

$$20\ \% \leq SOC_i \leq 90\ \% \tag{4.9}$$

The initial and final daily SOC (SOC_{in}, SOC_{fi}) are equal, based on:

$$SOC_{\mathrm{in}} = SOC_{\mathrm{fi}} \tag{4.10}$$

They were stipulated differently according to the flexibility levels modeled in section 5.

4.2.3 Electric vehicle

Analogously to the BESS, constraints governing the EV battery were established according to:

$$E_{\mathrm{EV},t+1} = E_{\mathrm{EV},t} - \eta_{\mathrm{Dis}} \cdot E_{\mathrm{EV,Dis},t} + \eta_{\mathrm{Ch}} \cdot E_{\mathrm{EV,Ch},t} \tag{4.11}$$

$$E_{\mathrm{EV,min}} \leq E_{\mathrm{EV},i} \leq E_{\mathrm{EV,max}} \tag{4.12}$$

where E_{EV} represents the actual energy from the EV, $E_{\mathrm{EV,Dis}}$ the discharged energy from EV; $E_{\mathrm{EV,Ch}}$ the energy charged from EV. Besides, the minimum and maximum power limits ($P_{\mathrm{EV,min}}$, $P_{\mathrm{EV,max}}$) for the EV charge and discharge ($P_{\mathrm{Ch,EV}}$, $P_{\mathrm{Dis,EV}}$) are expressed in:

$$P_{\mathrm{EV,min}} . (1 - \theta_i) \leq P_{\mathrm{Ch,EV},i} \leq 0 \tag{4.13}$$

$$0 \leq P_{\mathrm{Dis,EV},i} \leq P_{\mathrm{EV,max}} . \theta_i \tag{4.14}$$

where θ is a binary indicator that ensures the EV will not be charged and discharged simultaneously.

The possibility of selling energy to the grid via V2G has advantages, but it is important to limit this transaction to possible use by the driver. The minimum SOC set for the EV was 30 % so that the user always has at least a certain amount in the battery. The maximum SOC is 90 %, therefore this constraint applies:

$$30\,\% \leq SOC_{\mathrm{EV},i} \leq 90\,\% \tag{4.15}$$

4.2.4 Power balance

Power balance is crucial for ensuring the safe operation of the system. It is essential that the total energy supply and demand are always in equilibrium. Thus, it is described as:

$$P_{\mathrm{purch},i} + P_{\mathrm{sale},i} + P_{\mathrm{gen},i} + P_{\mathrm{BESS,Ch},i} + P_{\mathrm{BESS,Dis},i} + P_{\mathrm{EV,Ch},i} + P_{\mathrm{EV,Disch},i} = P_{\mathrm{load},i} \tag{4.16}$$

Equation (4.16) ensures that the total of purchased power (P_{purch}), sold power (P_{sale}), generated power (P_{gen}), the power charged to and discharged from both the BESS ($P_{\mathrm{BESS,Ch}}$, $P_{\mathrm{BESS,Disch}}$) and EV ($P_{\mathrm{EV,Ch}}$, $P_{\mathrm{EV,Disch}}$) is equal to the power demand (P_{load}). The charging powers were assumed to be negative in magnitude.

4.2.5 Energy exchange

The energy exchange between the grid and the EC is restricted to a specific amount. The purchased power from the grid (P_{Purch}) and the sold power to the grid (P_{Sale}) are limited to minimum and maximum power values according to:

$$P_{\mathrm{sale,min}} \cdot (1 - \gamma_i) \leq P_{\mathrm{sale},i} \leq 0 \tag{4.17}$$

$$0 \leq P_{\mathrm{purch},i} \leq P_{\mathrm{purch,max}} \cdot \gamma_i \tag{4.18}$$

In Equations (4.17) and (4.18), the unidirectional energy exchange is ensured by the binary variables γ_i at all times. When the EC purchases energy, it will not be selling. These variables control the energy transaction such that positive values represent purchased energy, while negative values indicate energy sales.

4.3 Rule-based method

The rule-based method is used to manage energy in the EC and its interaction with the grid. This method presents simplicity and low computational effort. The data used was presented in section 6. The limits on the SOC, charging and discharging of the BESS and

EV follow the same limitations defined in sections 4.2.2 and 4.2.3, according to equations (4.9), (6.1), (6.2), (4.15), (6.3) and (6.4).

The algorithm starts by loading the generation and demand data. Subsequently, the BESS and EV parameters are defined, including installed capacity, stochastically generated idle periods and SOC limits. The power balance is checked; if it is positive, the batteries of the storage system and the EV will be charged and the remainder will be sold to the grid. Otherwise, the BESS will discharge, as will the EV, and the EC will purchase energy from the grid to maintain system stability, with a zero-power balance. Finally, the SOC is updated and the process is iterated until the daily data is finalized. The flowchart illustrating this method can be visualized in Figure 4.2.

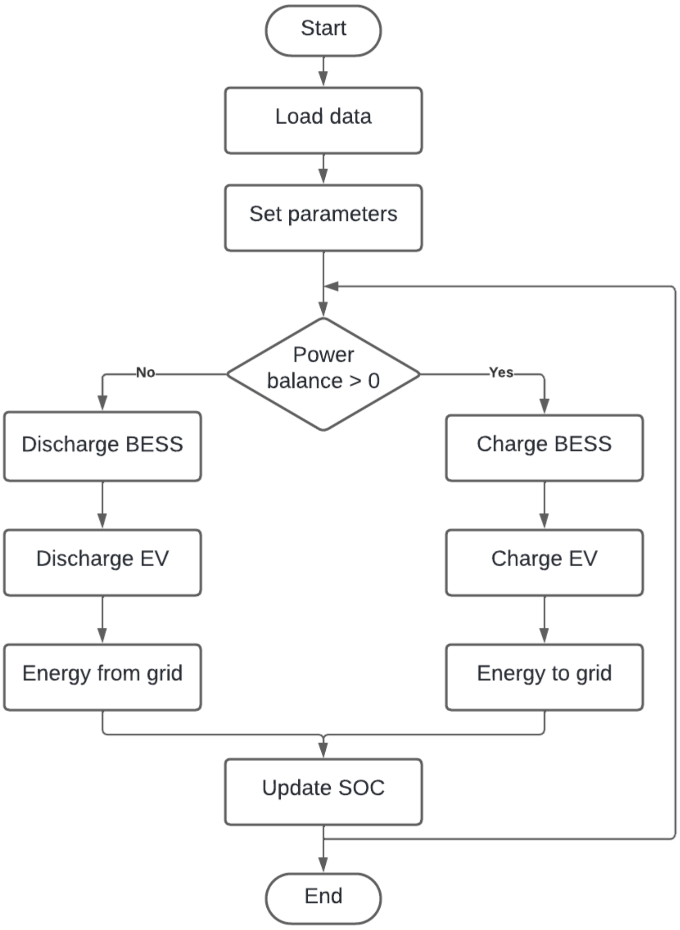

Figure 4.2 Flowchart of the rule-based method.

4.4 Economic analysis

The implementation of ECs has enabled the empowerment of users, promoting energy transactions within the market in their neighborhood. These factors contribute to a rise in efficiency and the local economy.

Real-time pricing, which presents a variable value at each moment, is also referred to as variable pricing. This tariff, currently adopted in some countries, offers advantages compared to other tariff models, increasing efficiency even in contexts where demand elasticity is low [95]. According to [96], this type of tariff is widely used in economic analyses. The variable tariff for energy pricing represents a flexible option in the energy market and is utilized in this modeling.

The economic assessment will be performed by determining the daily operating cost of the EC. The operational cost (C_{op}) for the simulated days was calculated by:

$$C_{\mathrm{op},i} = \sum_{i=1}^{24} E_{\mathrm{sale},i} . T_{\mathrm{sale},i} - E_{\mathrm{purch},i} . T_{\mathrm{purch},i} \tag{4.19}$$

where the sum of the purchased energy multiplied by its tariff is subtracted from the sum of sold energy multiplied by the sales tariff over the course of one day.

4.5 Voltage stability

The dynamic behavior of the power system, which increasingly includes intermittent energy sources and their converters, faces difficulties in maintaining stability. Stability is the ability of a system, given an initial operating condition, to restore equilibrium state after being subjected to a physical disturbance, maintaining the system undamaged [97].

Voltage stability is related to the system's ability to maintain steady voltages close to the nominal value on the buses after a perturbation. Coordinated power dispatch between generation and transmission directly affects this variable. The flow of active and/or reactive power in a set of buses influences this ability, as there is a limitation in the elements, interfering in the voltage level [97], [98].

Voltage instability can cause load shedding in a region or trigger protection devices, which may lead to cascading outages. In addition, interruptions or operation under field current limitation can result in the loss of synchronism of some generators [8].

According to European Norm (EN) 50160 [99], a standard which specifies the main characteristics of the voltage in the public network under normal operating conditions, the voltage range must not exceed ±10% of the nominal voltage (U_{N}), according to the constraint:

$$0.9U_{\mathrm{N}} \leq U_i \leq 1.1U_{\mathrm{N}} \tag{4.20}$$

5 Flexibility Model

The flexibility concept proposed in this model includes generating resources from renewable sources (PV, WT and BG), an electric vehicle and a battery energy storage system, the latter being the main flexibility resource. The duration of the flexibility activation can be up to hours, with the active operation of the BESS. The presence of the BESS and its configuration for the flexibility scenarios with different SOC and weighting coefficients can be considered an incentive element for activating flexibility.

The EC's quantitative technical flexibility characteristics refer to the installed capacity of each asset, as dimensioned in section 6.1. The qualitative features include the ownership of the assets which belongs to the entity itself, as well as their availability. Controllability is also integrated into this set, as it is decentralized. The economic flexibility characteristic considered in this modeling will be OPEX, involving variable purchase and sale tariffs.

Therefore, the flexibility solutions adopted in this model include DG, BESS and EV assets. The enablers of flexibility encompass the energy market, the existence of regulation for EC (as in the European case mentioned in section 3.3.2) and the connection to the grid, allowing energy transactions. A general representation of the proposed flexibility model is shown in the Figure 5.1.

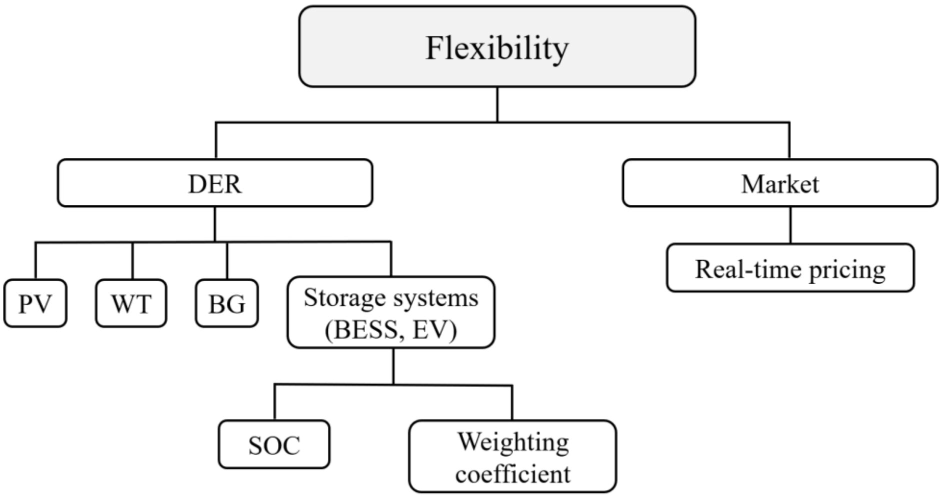

Figure 5.1 Representation of the proposed flexibility model.

5.1 Flexibility levels

This dissertation proposes three levels of flexibility involving batteries and the flexibility provided by these elements represented by BESS and EV in this approach. The parameters involved in these levels are:

SOC_{in}: BESS initial SOC.

SOC_{fi}: BESS final SOC.

$\delta_{\mathrm{BESS,Ch}}$: weighting coefficient for BESS charging.

$\delta_{\mathrm{BESS,Dis}}$: weighting coefficient for discharging the BESS.

$\delta_{\mathrm{EV,Ch}}$: EV charging weighting coefficient.

$\delta_{\mathrm{EV,Dis}}$: weighting coefficient for EV discharge.

The three levels of flexibility stipulated have the parameters defined in the Table 5.1. The model was exhaustively tested with various combinations of SOC and weighting coefficients, until it achieved satisfactory results with the defined values. Level 1 (F1) is the most flexible, with the highest SOC (80%) and the lowest weighting coefficients δ, promoting more charging and discharging and increasing the flexibility of the system's operation.

Table 5.1 Defined parameters for the stipulated levels of flexibility

Flexibility level	SOC_{in}	SOC_{fi}	$\delta_{\mathrm{BESS,Ch}}$	$\delta_{\mathrm{BESS,Dis}}$	$\delta_{\mathrm{EV,Ch}}$	$\delta_{\mathrm{EV,Dis}}$
F1	80%	80%	0.008	0.008	0.006	0.060
F2	50%	50%	0.020	0.020	0.010	0.090
F3	30%	30%	0.060	0.060	0.030	0.120

Flexibility level 2 (F2) is intermediary, with intermediate values for SOC (50%) and weighting coefficients for charging and discharging the BESS and EV. Finally, level 3 (F3) has less flexibility, with higher values for δ and lower final and initial SOC. Therefore, storage systems are expected to operate more conservatively. Figure 5.2 shows the representation of this three-level flexibility model with the variables involved.

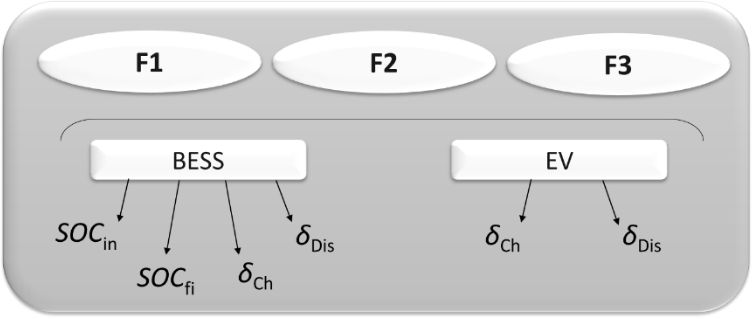

Figure 5.2 Variables of the proposed three-level flexibility model.

5.2 Incentive for flexibility

The energy market in which the EC operates includes various stakeholders. The citizens from the EC, the company that supplies energy, the distribution system operator (DSO), the aggregators and the regulator from the energy market represent examples of them.

A community-friendly behavior is appreciated due to the benefits it provides. The EC under study is considered environmentally friendly because its power generation relies on renewable sources. Furthermore, certain actions can benefit the participants of the EC, such as activities involving the storage system and obtaining profit from energy sales, contributing to enhance its flexibility [100].

Some established measures can act as incentives for the EC. Rewards stipulated by any stakeholder can represent a type of incentive. This dissertation proposes system-oriented use of flexibility through incentives provided by the DSO or aggregators to the EC in the form of rewards. A prize, as an amount of money established by the stakeholders, is the maximum possible value. The reward will correspond to a percentage of this maximum amount.

This reward will rely on different factors, determined by the specific actions taken by the EC. It is also based on predefined parameters set by the energy market. Both the flexibility and the reward will increase depending on BESS activity and V2G dispatch, besides the power balance and tariff applicable at different times of the day.

Since the reward varies with each value of the chosen variables, a method will be implemented to calculate these amounts for each case. Fuzzy logic will be employed to address this problem, as it can produce outputs in varying degrees – ranging from 0 to 1 – rather than in binary form. This approach allows for the inclusion of multiple inputs and outputs with different ranges of variation and weights. Ultimately, the result is presented clearly, based on the predefined rules [101], [102].

The reward for the simulated days, calculated hourly, was determined through fuzzy logic. The inputs of the model are the power of V2G (P_{V2G}), charging and discharging power from the battery (P_{BESS}), power balance (P_{Bal}), purchase and sales tariffs (T_{purch}, T_{sale}). The output is the reward. The minimum, maximum and step size for the inputs and output, known as membership functions, are presented in Table 5.2.

Table 5.2 Range for membership functions

Parameter	**Minimum**	**Maximum**	**Step size**
P_{V2G}	0	7	0.1
P_{BESS}	-5	5	0.1
P_{Bal}	-15	15	0.1
T_{purch}	0	0.2	0.01
T_{sale}	0	0.2	0.01
Reward	0	100	1

Fuzzification is the process of establishing the ranges and weights of the input and output variables. Various curves can be used to define the membership function, such as triangular, trapezoidal or Gaussian [103]. For each input and output, weight ranges were assigned and categorized into low, medium and high, with membership values varying between 0 and 1. The degree was considered to be increasing, as can be seen in Figure 5.3 for P_{V2G}, Figure 5.5 for P_{Bal}, Figure 5.6 for T_{purch} and T_{sale}, and Figure 5.7 for the reward output. The exception was P_{BESS}, which featured two high and medium ranges, illustrated in Figure 5.4. Negative values correspond to BESS discharge, and positive values represent charging. The reward was considered high during periods of significative BESS activity, both during discharging and charging. Accordingly, there were two high ranges—high 1 and high 2. Similarly, two ranges were established for medium charging and discharging values—medium 1 and medium 2.

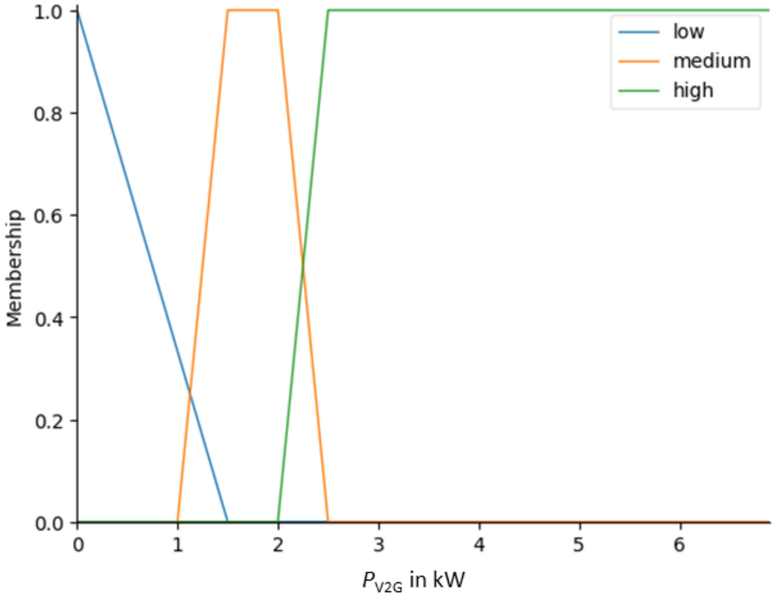

Figure 5.3 Range and weights for P_{V2G}.

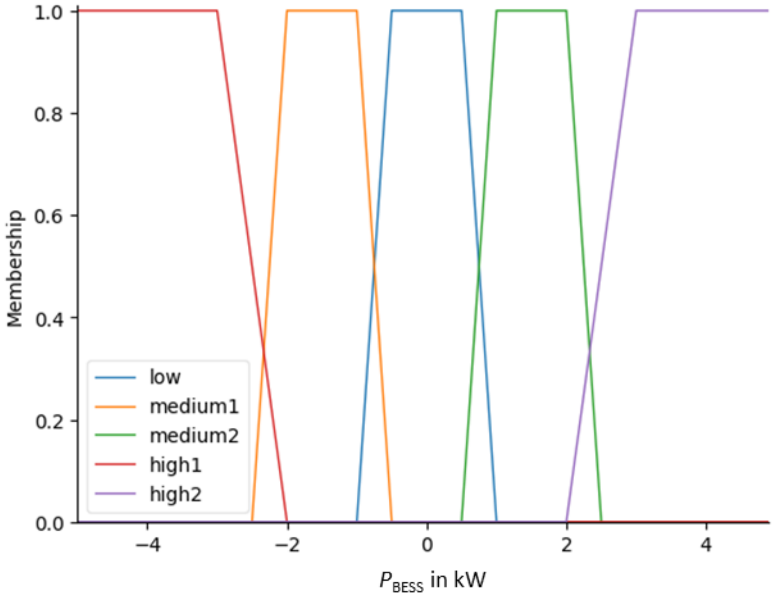

Figure 5.4 Range and weights for P_{BESS}.

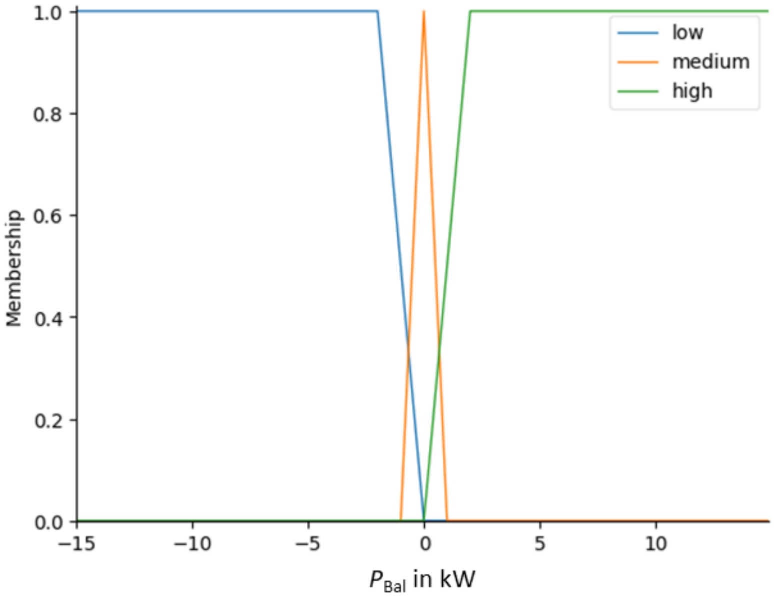

Figure 5.5 Range and weights for P_{Bal}.

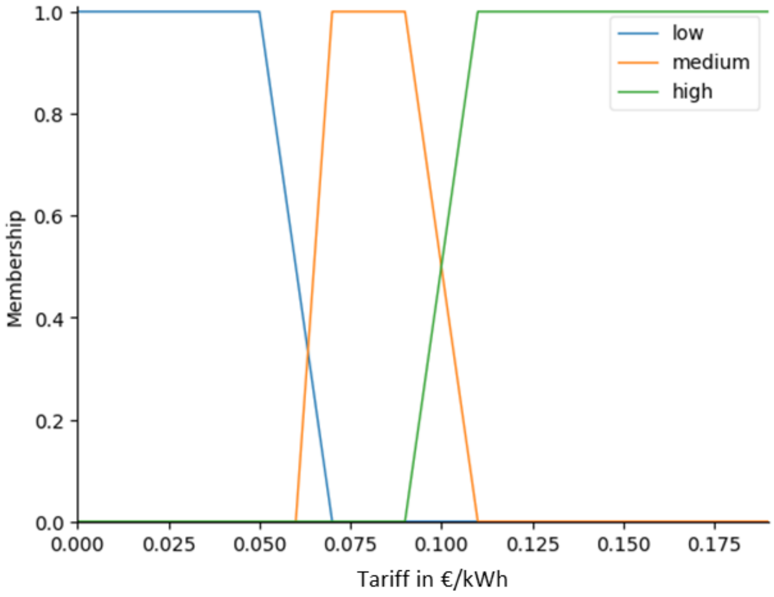

Figure 5.6 Range and weights for T_{purch} and T_{sale}.

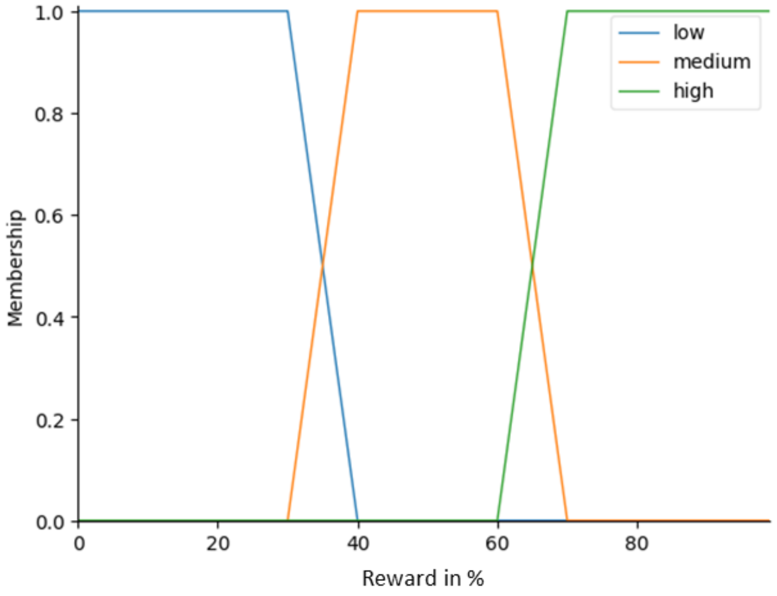

Figure 5.7 Range and weights for reward.

After defining the variables, their ranges, and weights (fuzzification), the rules describing how the inputs and outputs relate to each other must be established. For this dissertation, 40 rules were defined, assigning higher rewards to greater levels of charging and discharging of BESS and V2G systems. The power balance and tariffs were also incorporated into the rules. For example, if the P_{Bal} is low or high, but there is minimal activity in the BESS or V2G, combined with an average $T_{\mathrm{purch}}/T_{\mathrm{sale}}$, the reward is low. Table 5.3 presents the rules established for this model, setting weights for each combination of variables and their corresponding reward. The weights are categorized as low (L), medium (M), medium 1 (M1), medium 2 (M2), high 1 (H1), high 2 (H2). The fuzzification process and the defined rules were tested under different configurations and scenarios, with the results evaluated until the final rules were established.

Table 5.3 Fuzzy rules for the rewards

Rule	P_{V2G}	P_{BESS}	P_{Bal}	T_{purch}	T_{sale}	**Reward**
1	M	M1	H	M	M	M
2	L	L	L or H	M	M	L
3	M	M1 or M2	M	M	M	M
4	L	H1	L	H	H	M

Rule	P_{V2G}	P_{BESS}	P_{Bal}	T_{purch}	T_{sale}	**Reward**
5	L	H2	H	M	L	M
6	H	H1	H	L	M	H
7	H	H2	L	H	H	H
8	L	L	M	M	M	L
9	H	M1	H	H	M	M
10	H	M2	L	M	L	H
11	M	L	M	M	M	M
12	H	M2	M	L	H	H
13	H	M1	H	M	M	H
14	H	H2	H	L	H	H
15	H	H1	L	M	M	H
16	L	H2	L	H	M	H
17	L	M2	H	M	H	M
18	L	M1	L	H	M	M
19	L	L	H	L	H	L
20	L	H1	L	H	M	M
21	L	L	L	H	H	L
22	L	M2	M	H	M	M
23	L	H2	M or H	M	H	H
24	L	H1	H	H	M	H
25	L	H1	M	M	M	M
26	L	H2	H	M	M	M
27	L	H2	M	M	L	M
28	H	H1	M	M	M	M
29	H	H2	M	M	H	H
30	H	M1	L	H	L	M
31	H	M1	M	M	M	M
32	H	M2	H	M	H	H
33	H	L	L	M	L	M

Rule	P_{V2G}	P_{BESS}	P_{Bal}	T_{purch}	T_{sale}	Reward
34	H	L	M	M	M	M
35	H	L	H	L	H	H
36	M	H1 or H2	H	H	H	H
37	M	H1	L	M	M	M
38	M	H2	L	M	M	H
39	L	H2	M	H	H	H
40	L	M1	H	H	H	M

The inference process is based on the variables (fuzzification) and rules defined in the model. This process is followed by defuzzification, where the result is presented according to the values of the input variables. The proposed method using fuzzy logic to calculate rewards for EC is shown in Figure 5.8. The implementation was carried out in Python through the openly-source library scikit-fuzzy. The reward is calculated hourly, and the average of the 24-hour rewards represent the total daily reward earned by the EC on the specific days analyzed in the proposed case study, encompassing four seasons and three levels of flexibility.

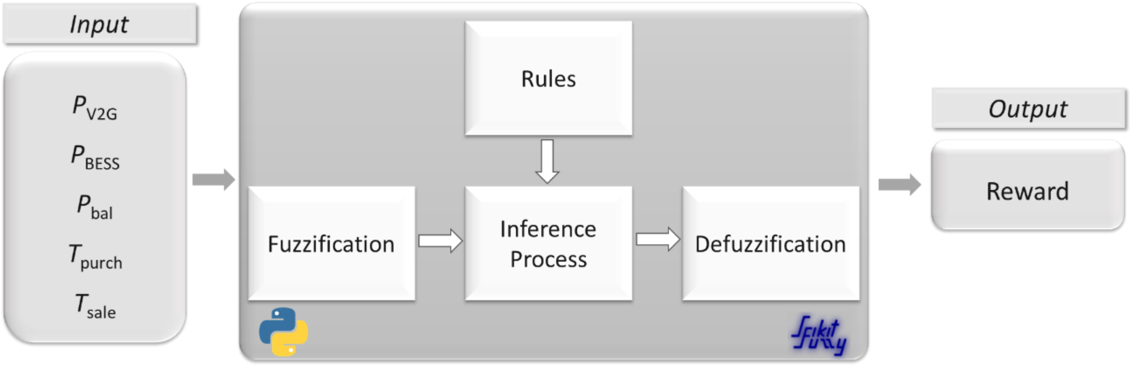

Figure 5.8 Proposed Fuzzy logic model.

5.3 Model overview

Development of the model began with data collection from SMARD [48] and MILP optimization for the simulations. The parameters and levels of flexibility were established and introduced into the optimization. The input data was generation, demand and tariffs, which were subject to the objective function, limits and constraints presented in section 4.2. The outputs are the power dispatch comprising the BESS, EV and grid powers (P_{BESS}, P_{EV}, P_{grid}). Subsequently, the economic assessment is carried out for the days analyzed, verifying the EC's revenue. The voltage levels are evaluated, checking whether the values in each bus are within the levels established by the standards, besides active power losses calculation. Finally, the rewards were computed and assessed. An overview of the modeling is illustrated in the Figure 5.9.

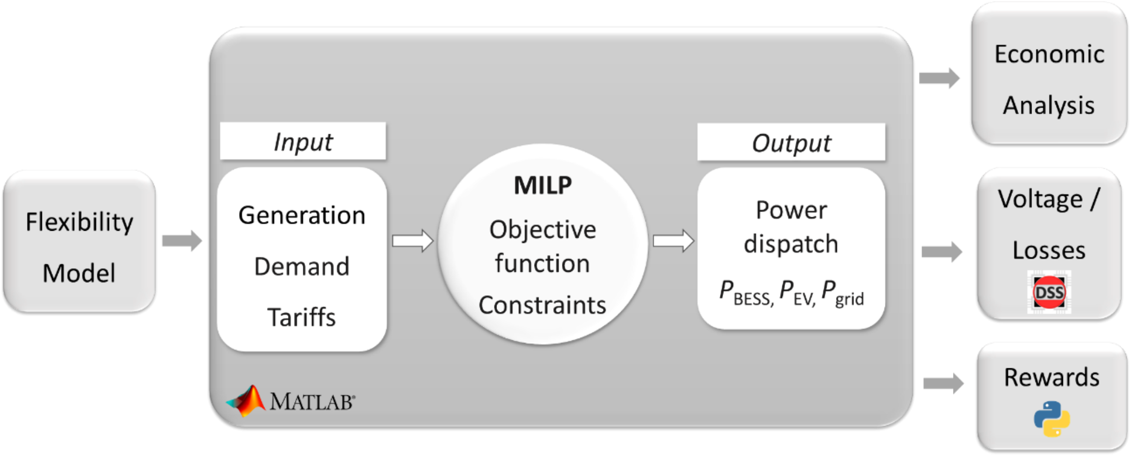

Figure 5.9 Overview of modeling and its stages.

6 Case Study

6.1 General description

The EC studied has three generators: photovoltaic, wind and biogas; a fixed load and a variable load; an EV and a BESS. The analysis of its operation will be conducted on four different days, covering the four seasons: summer, autumn, winter and spring. Although the analysis of a single day at the season does not necessarily reflect its behavior over three months, data was collected for each of the four cases analyzed, selecting representative days in different seasons.

The wind and PV systems display stochastic behavior, influenced by real-time meteorological conditions. Conversely, the BG system was programmed to generate a fixed amount of energy throughout the day. The loads are consistently met through energy generated, sourced from the BESS, purchased from the main grid, or from the EV's battery. Surplus energy can be stored in the BESS, sold to the grid, or sent to the EV. In the event of a negative power balance, the BESS will discharge to meet the demand, or the grid can supply energy, which will be considered as an infinite bus. These decisions will be based on the model formulation, objective function, and relevant constraints and limitations. It was assumed that the grid operates under normal conditions and that the generators will not be shut down.

The maximum power generation for each technology at the four days is shown in Table 6.1. The maximum capacity of the BESS is 48 kWh, while for the EV this amount reaches 40 kWh. The 24-hour generation and total demand profiles (P_{load}) for the summer day chosen, combined with the power balance, are shown in the Figure 6.1. The same data for the autumn day is presented in Figure 6.2, for winter in Figure 6.3 and for spring in Figure 6.4.

Table 6.1 Maximum generated power by technology and season, in kW

Power plant	Summer	Autumn	Winter	Spring
PV	18	7.4	6.5	13.1
WT	2.1	5.7	28.6	4.7
BG	18	12	10	12

The EC topology is shown in the Figure 6.5. There is a transformer (from 13.8 kV to 220 V) connected between buses 1 and 2, the wind generator is on bus 3, on bus 4 there is a fixed load of 2 kW in spring, while in the other seasons its value is 10 kW. An EV is on bus 5, a biogas generator on bus 6, a variable load on bus 7, the BESS on bus 8, and the PV system on bus 9.

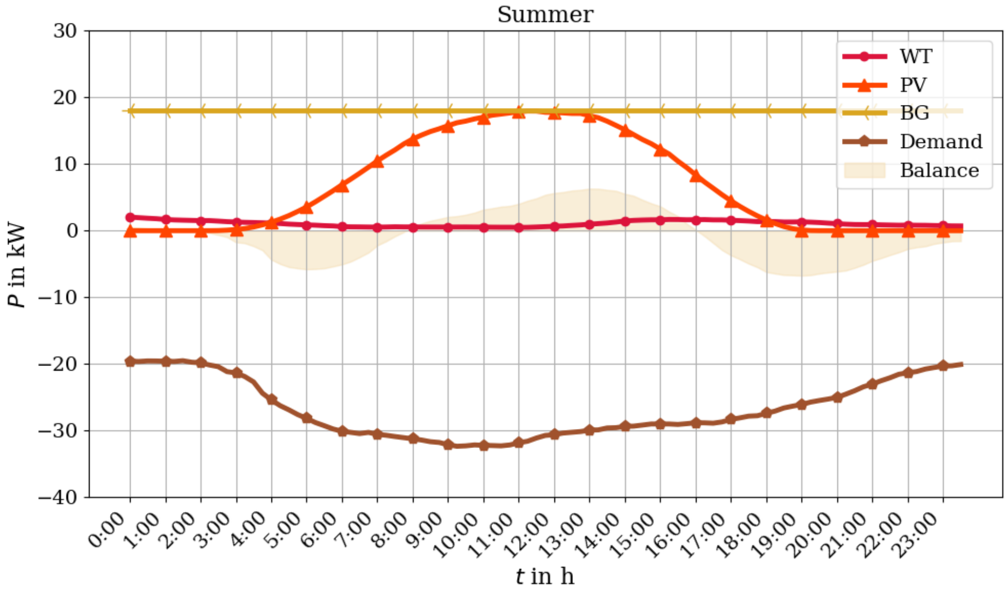

Figure 6.1 EC generation, demand and power balance for the day analyzed in summer.

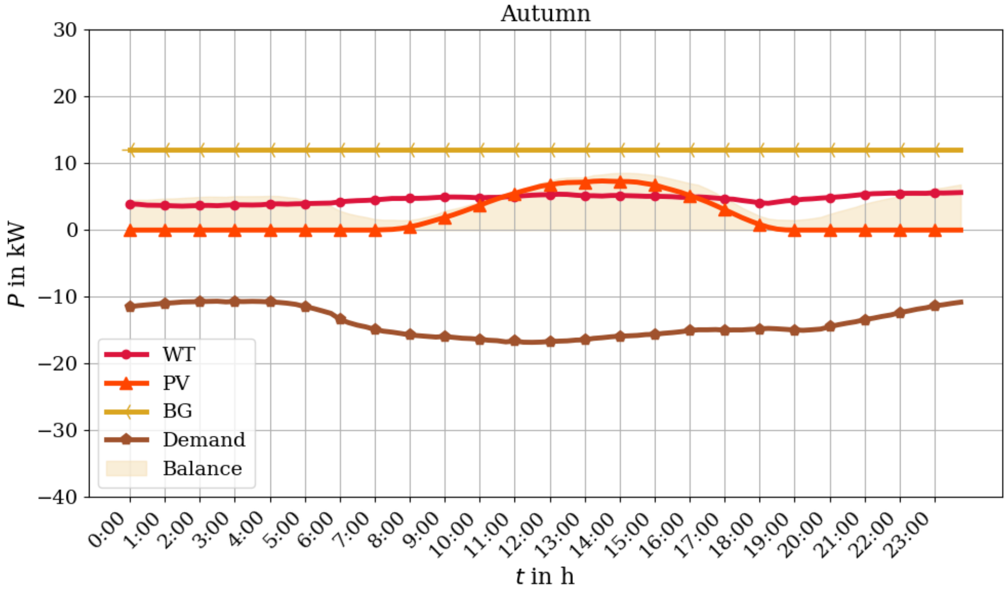

Figure 6.2 EC generation, demand and power balance for the day analyzed in autumn.

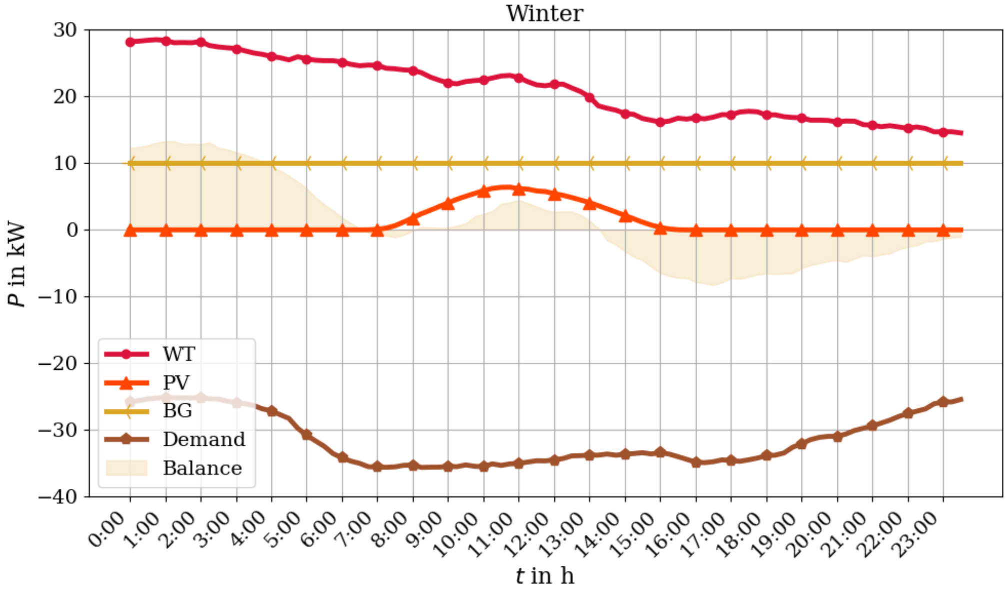

Figure 6.3 EC generation, demand and power balance for the day analyzed in winter.

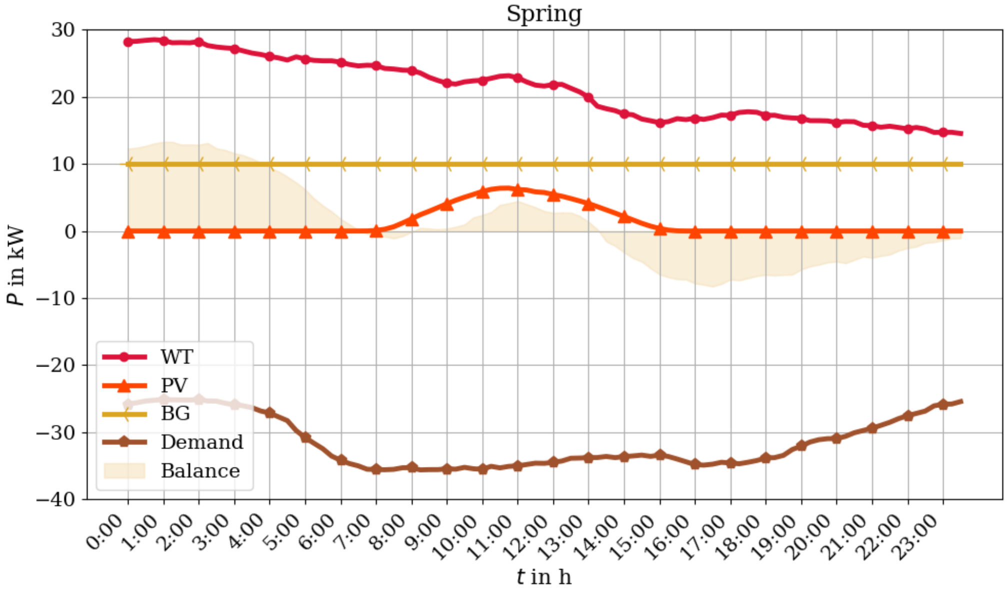

Figure 6.4 EC generation, demand and power balance for the day analyzed in spring.

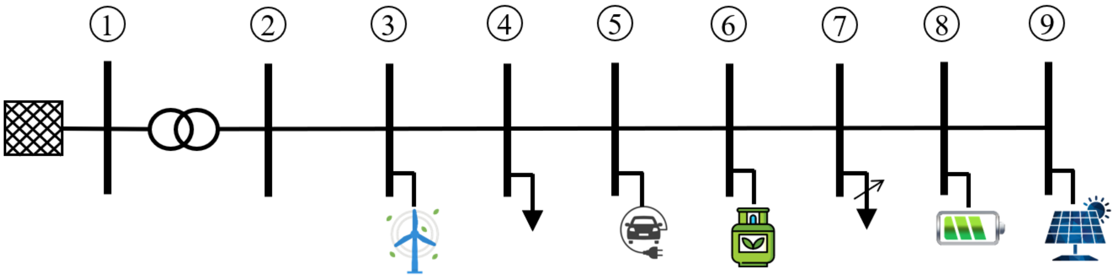

Figure 6.5 Energy community topology.

6.2 Limits and constraints

Limits and restrictions were established according to the methodology presented in section 4.2. Based on equations (4.6) and (4.7), the lower boundary for BESS charging was set at -5 kW, while an upper limit of 5 kW, represented the power discharge from the BESS, represented by:

$$-5 \leq P_{\mathrm{Ch,BESS},i} \leq 0 \tag{6.1}$$

$$0 \leq P_{\mathrm{Dis,BESS},i} \leq 5 \tag{6.2}$$

For EV, the daily initial SOC was set at 50 %. Furthermore, as denoted by equations (4.13) and (4.14), the lower limit for charging was established at -7 kW, with an upper limit of 7 kW (given the presence of significant chargers with this power capacity [104]) indicating the injection of power V2G:

$$-7 \leq P_{\mathrm{Ch,EV},i} \leq 0 \tag{6.3}$$

$$0 \leq P_{\mathrm{Dis,EV},i} \leq 7 \tag{6.4}$$

In energy transactions, equations (4.17) and (4.18), the amount of energy in these transactions is stipulated by the local energy market. For this case study, the minimum power sold to the grid is -36 kW, while the maximum power purchased is set at 36 kW, denotated by:

$$-36 \leq P_{\text{sale},i} \leq 0 \tag{6.5}$$

$$0 \leq P_{\text{purch},i} \leq 36 \tag{6.6}$$

In the power balance equation (4.16), data of P_{gen} and P_{load} were presented in this section for each case study. Total generation power is the sum of PV (P_{PV}), WT (P_{WT}) and BG (P_{BG}) powers, represented by:

$$P_{\text{gen},i} = P_{\text{PV},i} + P_{\text{WT},i} + P_{\text{BG},i} \tag{6.7}$$

6.3 Economic assessment

For the economic analysis, the energy tariffs were considered along with the energy exchange. Therefore, only energy transaction costs were analyzed. System acquisition and maintenance expenses were disregarded. The energy price curves utilized in equations (4.1) and (4.19), including both purchase and sales prices (T_{purch}, T_{sale}), are illustrated in Figure 6.6 for the day analyzed in summer, in Figure 6.7 for autumn, Figure 6.8 for winter and Figure 6.9 for spring.

6.4 Voltage and loss calculations

Given the critical importance of ensuring that voltage levels remain within the limits established by the relevant standards, the EC under analysis will be modeled and simulated using the *OpenDSS* software. This simulation will allow for the precise calculation of voltage levels across all buses within the system. In addition to evaluating voltage levels, the simulation will also compute the power losses occurring throughout the network. These calculations will be performed for every case study, covering all the different levels of flexibility proposed in the analysis. This approach ensures a comprehensive assessment of the EC’s performance under varying operational scenarios.

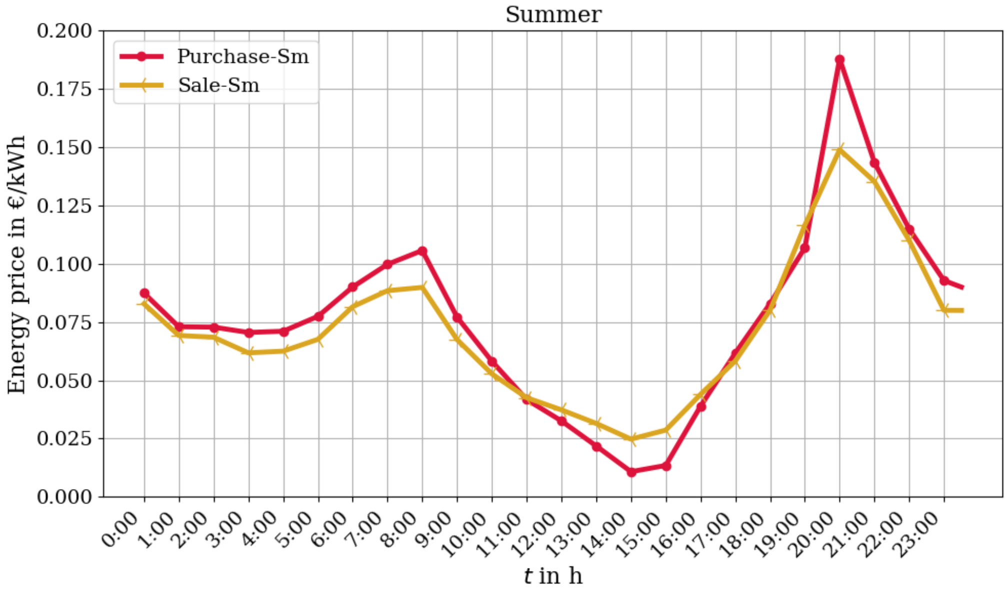

Figure 6.6 Energy prices (tariffs) for the day analyzed in summer.

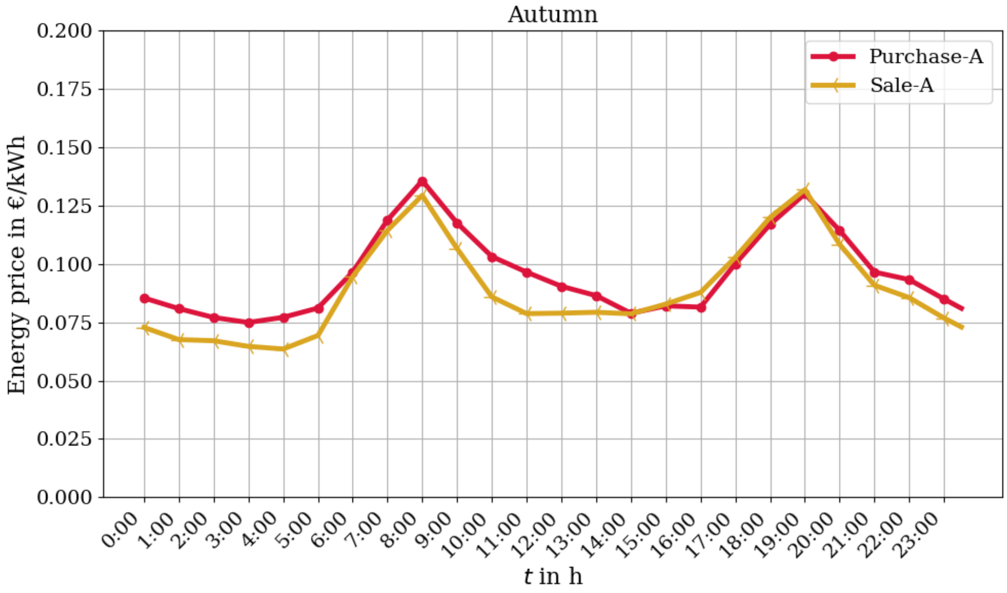

Figure 6.7 Energy prices (tariffs) for the day analyzed in autumn.

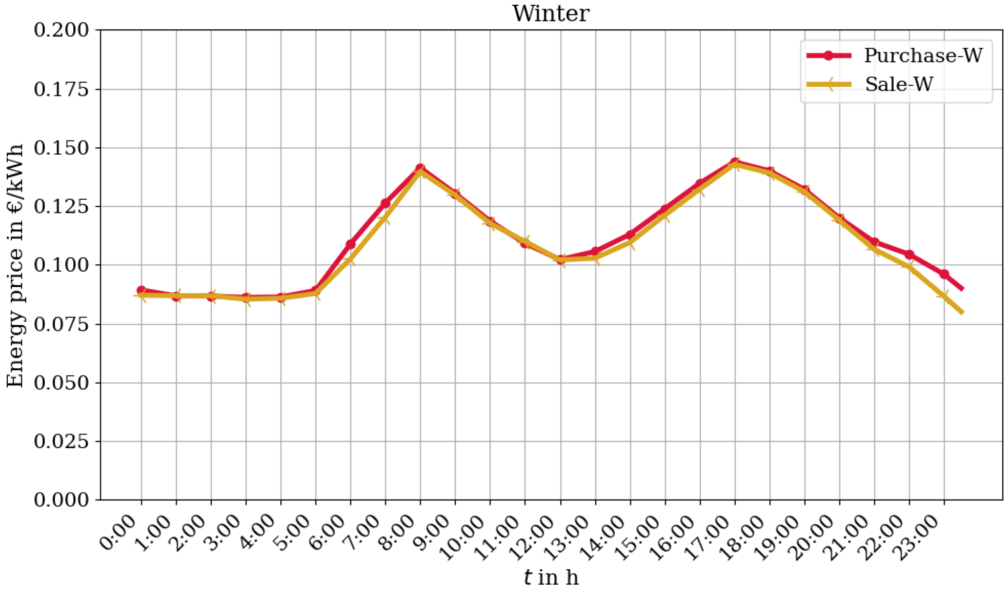

Figure 6.8 Energy prices (tariffs) for the day analyzed in winter.

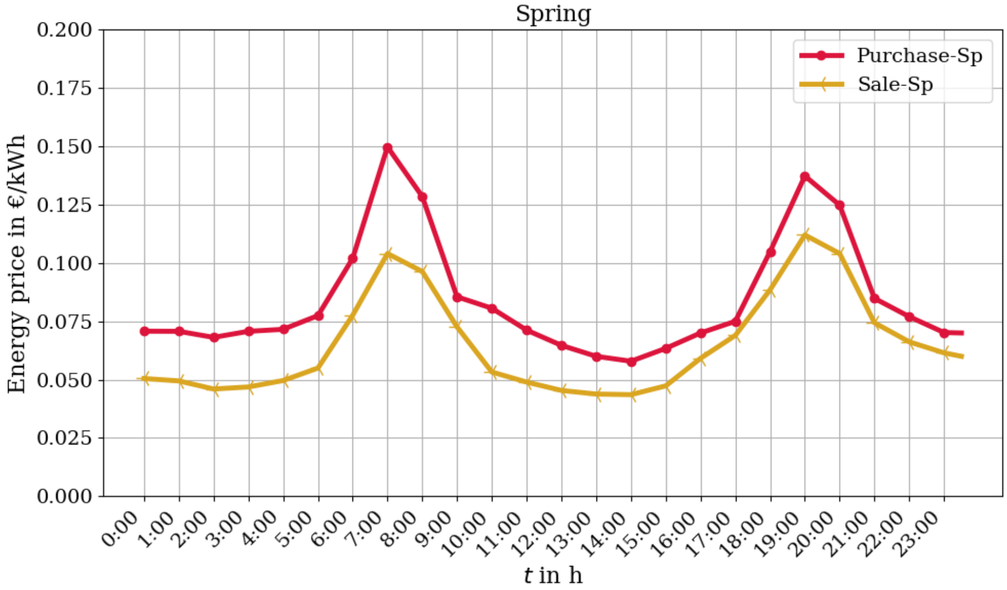

Figure 6.9 Energy prices (tariffs) for the day analyzed in spring.

7 Simulation and Results

The proposed flexibility model was designed and developed considering different levels of operation and was then subjected to detailed simulations to assess its performance. In this section, the results obtained from the power dispatch carried out in the modeled EC will be comprehensively presented, with an emphasis on its interaction with the electricity grid and the performance of the energy storage systems. Initially, the results will be presented based on the proposed level of flexibility. For the SOC, the results will also be displayed according to the specific day of the year chosen, in order to highlight the differences in each case. These results were analyzed in the context of critical variables, including the application of real-time tariffs, the impacts of intermittent energy generation and the specificities of the flexibility model developed for the investigation.

Additionally, there will be a detailed description and in-depth discussion of the results obtained in both the technical and economic analysis. The interaction between the different components of the EC energy system will be explored, with emphasis on the benefits and challenges presented by the proposed flexibility model. The impacts of storage and dispatch strategies on operational efficiency will also be discussed, as well as their contribution to economic optimization and adaptation to the context of real-time tariffs. Finally, the results presented will provide a complete overview of the performance of the flexibility model, highlighting its implications for EC operation and sustainability.

7.1 Flexibility level 1

As the simulation was conducted on four different days, representing each of the seasons, the presentation of the results will follow the same organized format, divided by season. This approach allows the data and conclusions to be presented in a systematic way, making it easier to interpret the particularities of each specific scenario.

The analysis will start with a detailed presentation of the results related to energy dispatch, including fundamental aspects such as the energy sold to the grid, the energy purchased from the grid and the charging and discharging operations of the BESS and EV. These elements are essential for understanding the operational and energy management strategies adopted in the simulation.

For flexibility level 1 (F1), the results are graphically represented in the figures corresponding to each season. Specifically, Figure 7.1 illustrates the results obtained for the simulated summer day, highlighting the interactions between generation, storage and the electricity grid. Next, Figure 7.2 presents the results of the simulated autumn day, capturing the variations and their impact on energy dispatch. Similarly, Figure 7.3 shows the results of the winter day, highlighting the specific challenges and strategies adopted. Finally, Figure 7.4 details the performance observed on the spring day.

In Figure 7.1, which shows the results for the summer day, it is clear that the BESS plays a key role in the operation of the EC. During periods when the power balance is negative, the BESS discharges its stored energy in order to supply local loads and reduce dependence on the grid. This strategy is observed during intervals when internal generation is not sufficient to meet the EC's energy demand.

The BESS is charged at strategic times throughout the day. For example, from 10am onwards, when there is a surplus of energy from local generation, the system takes the opportunity to store this energy. In addition, another significant charging period takes place from 22:30 onwards. In this case, the main objective is to ensure that the end-of-day state of charge is at adequate levels to meet future demands, keeping the system operational and efficient.

At times when the energy stored in the BESS is not sufficient to meet the EC's demand, it is necessary to purchase energy from the electricity grid. This purchase takes place on a complementary basis, ensuring that all loads are met. However, from 7pm onwards, there is a strategic behavior of both the BESS and the EVs. During this period, both start discharging and selling energy to the grid. In the case of EVs, this operation takes place through the V2G concept, which allows the energy stored in the vehicles to be exported to the system.

Although the EC's energy balance is negative after 7pm, the choice to sell energy to the grid is economically advantageous. This is because, at this time of day, energy tariffs reach high values, which allows the EC to generate a profit from the sale of energy. This strategy not only contributes to the EC's financial sustainability, but also demonstrates the importance of intelligent and flexible management of available energy resources, maximizing economic benefits even in situations of unfavorable energy balance.

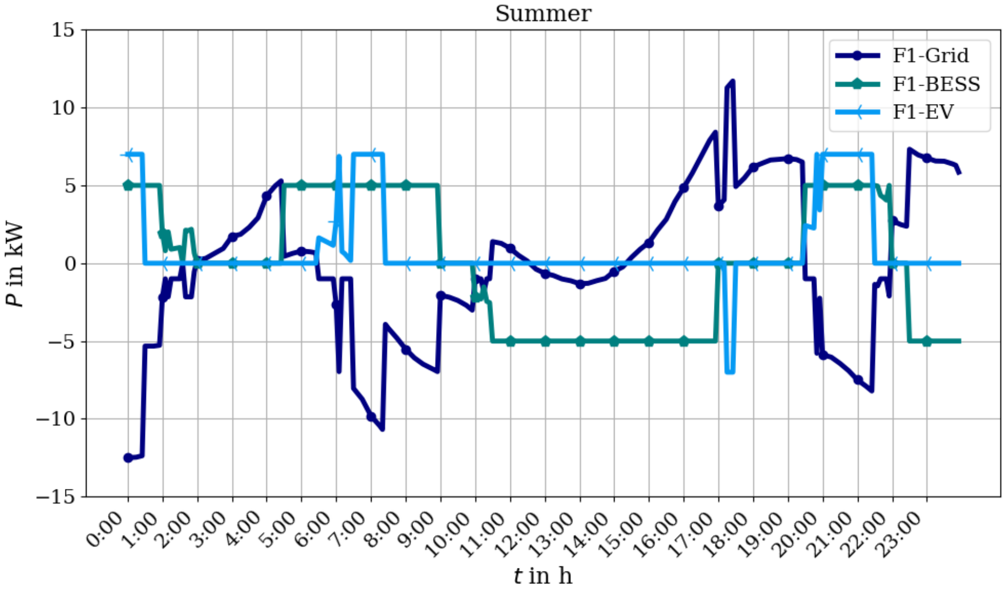

Figure 7.1 Power dispatch in Summer for F1 level.

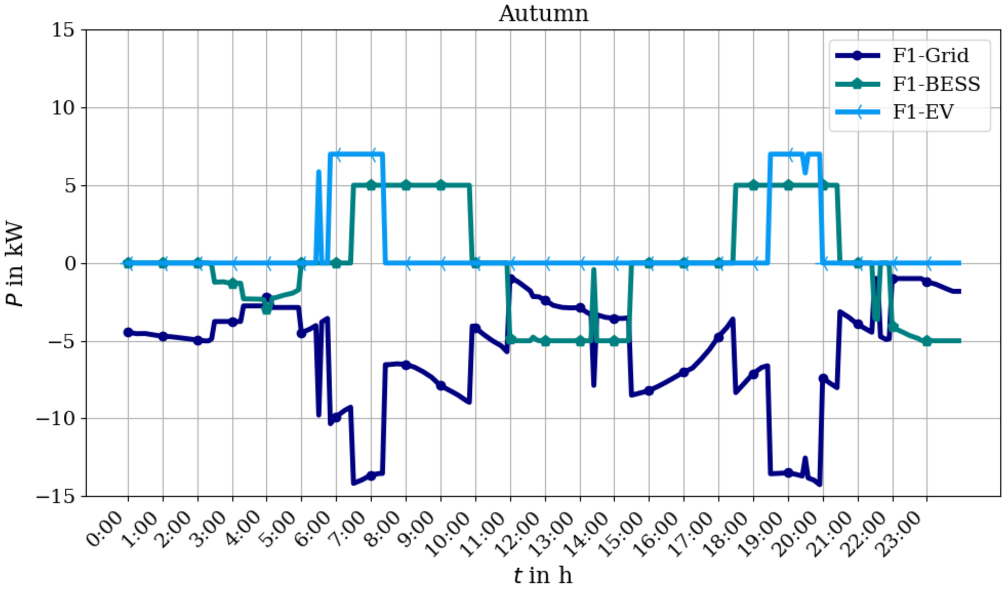

Figure 7.2 Power dispatch in Autumn for F1 level.

For the autumn day analyzed, the results of which are shown in Figure 7.2, it can be noted that the EC power balance remained positive throughout all 24 hours. This implies that local energy production was sufficient to fully meet the EC's internal demand at all times of the day. In addition, the surplus energy generated was consistently sold to the electricity grid, generating additional revenue and contributing to the operation's positive financial performance.

During this day in autumn, the BESS was discharged at strategic times, and the V2G concept was also activated at two specific times: around 7am and again at 7pm. These periods coincide with the times when energy tariffs are highest, as illustrated in Figure 6.7. This direct relationship between discharge times and higher prices reflects a deliberate strategy of economic optimization, maximizing the profits made by the EC by selling stored energy when it has the highest value on the market.

By discharging BESS and activating V2G at these peak tariff times, EC maximizes the use of available resources, balancing energy storage management with revenue generation opportunities. This strategy not only ensures the system's operational efficiency, but also contributes to significantly increasing the operation's profits on the autumn day.

The intelligent management of BESS and electric vehicles, aligned with the analysis of tariff conditions, demonstrates how operational flexibility can be used to maximize the EC's financial results in a favorable energy balance scenario.

In Figure 7.3, the power balance of the EC during the first half of the day is practically positive in all the periods analyzed. This means that, during this initial period, local energy production is sufficient to meet the EC's demand and still generates a surplus. As a result, this surplus energy is sold to the grid, which provides an additional source of income for EC. This behavior reflects the efficiency of energy management, when production conditions are most favorable.

In addition, around 8am, the energy stored in the EC's batteries is also sold to the electricity grid, taking advantage of the high energy tariffs at that time. This time is particularly advantageous as the price of energy is high, making the sale of stored energy a profitable strategy for the EC. By adopting this approach, the community maximizes its profits by taking benefit of the energy market conditions.

However, during the afternoon and evening, the situation changes. During these periods, the EC faces an energy deficit, as internal production is not enough to fully meet demand. As a result, the EC is forced to buy energy from the grid to supplement local production and ensure that consumption needs are met. This purchase of energy from the grid is necessary to balance the EC's energy balance, however it increases operating costs, as purchased energy generally has a higher cost.

Nevertheless, at around 6pm, an optimization strategy is observed: the energy stored in the batteries is sold back to the grid. This occurs due to the fact that, at this time, the price of energy once again reaches high levels, which makes it advantageous for the EC to export the stored energy and make an additional profit. This action of discharging the energy storage is a strategic measure to minimize the EC's overall costs, while taking advantage of favorable tariff conditions to generate revenue.

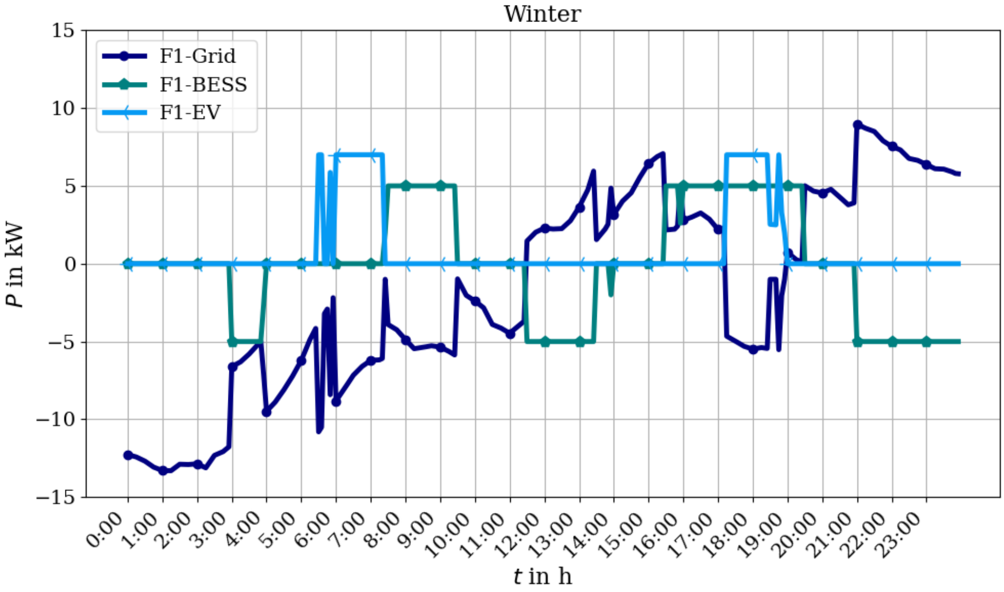

Figure 7.3 Power dispatch in Winter for F1 level.

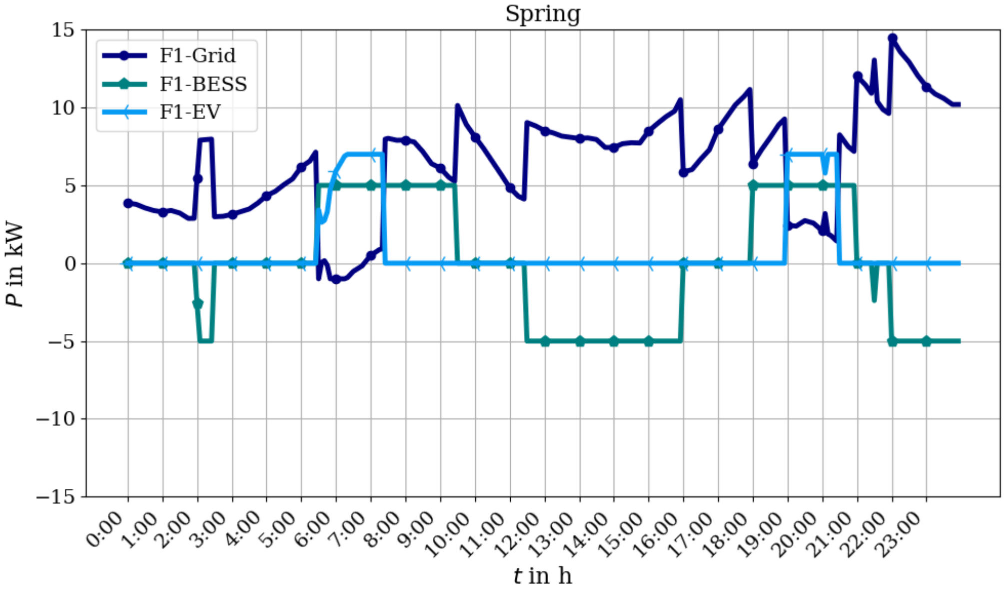

Figure 7.4 Power dispatch in Spring for F1 level.

On the spring day chosen for analysis, it can be observed that the grid supplies energy to the EC for practically the entire period analyzed. This characteristic can be clearly seen in Figure 7.4, which illustrates the behavior of the interaction between the EC and the grid throughout the day. The main reason for this constant dependence on the grid is the fact that the EC had a negative power balance at all times of the day, indicating that local generation was insufficient to meet the community's demand at every moment.

Despite the absence of internally generated surplus energy, it is possible to observe that there are periods throughout the day when the BESS is charged. This strategy is justified by the presence of lower energy tariffs, which makes it advantageous to purchase energy from the grid and store it for later use. In addition, both the BESS and the EVs are discharged at times of peak energy demand. The main aim of this strategic behavior is to reduce the costs associated with energy consumption at these critical times, as well as minimizing dependence on the electricity grid during periods when energy tariffs are higher. In summary, the analysis of the spring day reveals an operational pattern in which the EC adjusts its strategies to deal with the daily energy deficit, using the charging and discharging of energy stores as tools to optimize costs and improve efficiency.

7.2 Flexibility level 2

Flexibility model 2 (F2), which was developed with intermediate weighted indices, presents in this section the graphical results for power dispatch in the EC over the days analyzed. This model aims to optimize the interaction between the various elements of the system, such as the BESS, EVs and the electricity grid, in order to maximize the efficiency and profits of the operation. Figure 7.5 contains the results obtained from the optimization for power dispatch for the summer day chosen for analysis.

In addition, the results for the other days of the seasons are also presented, with Figure 7.6 showing the optimization results for autumn, Figure 7.7 representing the winter results, and Figure 7.8 displaying the power dispatch curves for spring. These graphs illustrate how the flexibility model 2 operates in different conditions, highlighting the adaptation of power dispatch strategies to the particularities of each season, considering the different patterns of generation, demand and energy tariffs.

In Figure 7.5, which shows the results for the summer day, it can be seen that the V2G strategy occurs, in addition to the BESS which also discharges energy. This behavior happens at times when the energy balance is negative, meaning that internal generation is not sufficient to meet demand, which coincides with periods when energy tariffs are at their highest. Therefore, the model's priority is to use storage systems, such as BESS and

V2G, to reduce dependence on the grid and maximize profits by selling surplus energy to the grid when tariffs are high.

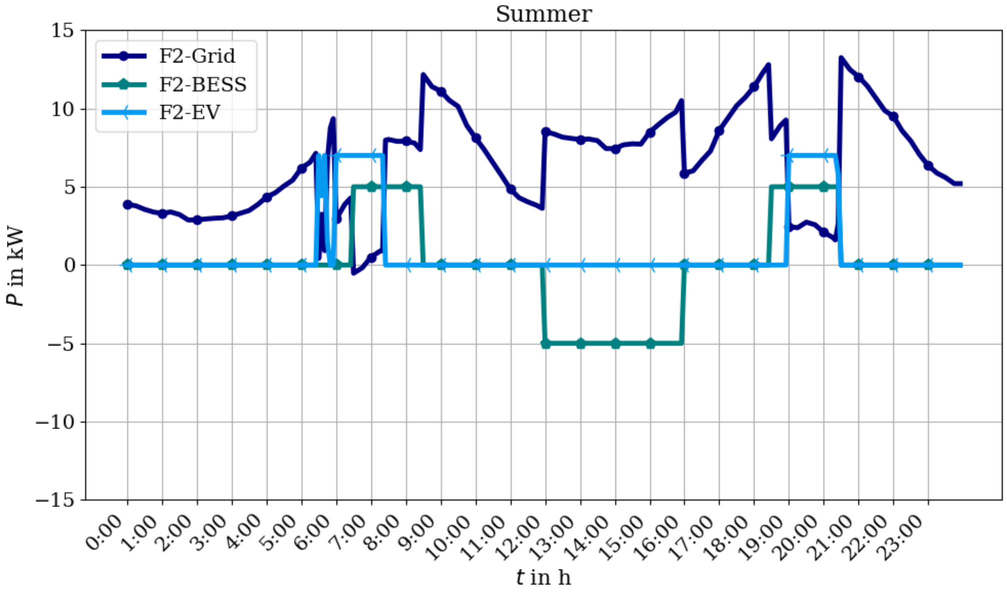

Figure 7.5 Power dispatch in Summer for F2 level.

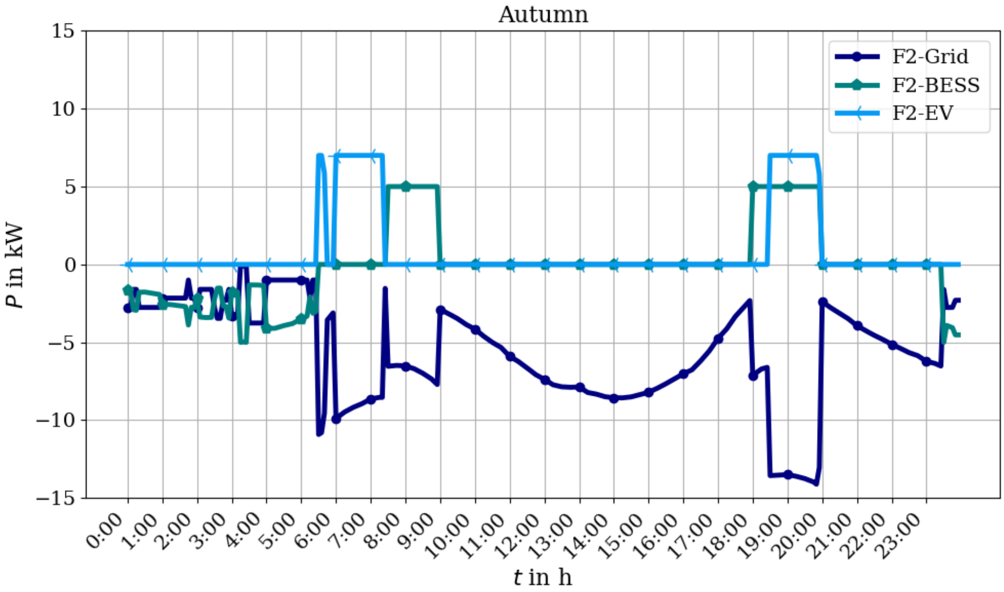

Figure 7.6 Power dispatch in Autumn for F2 level.

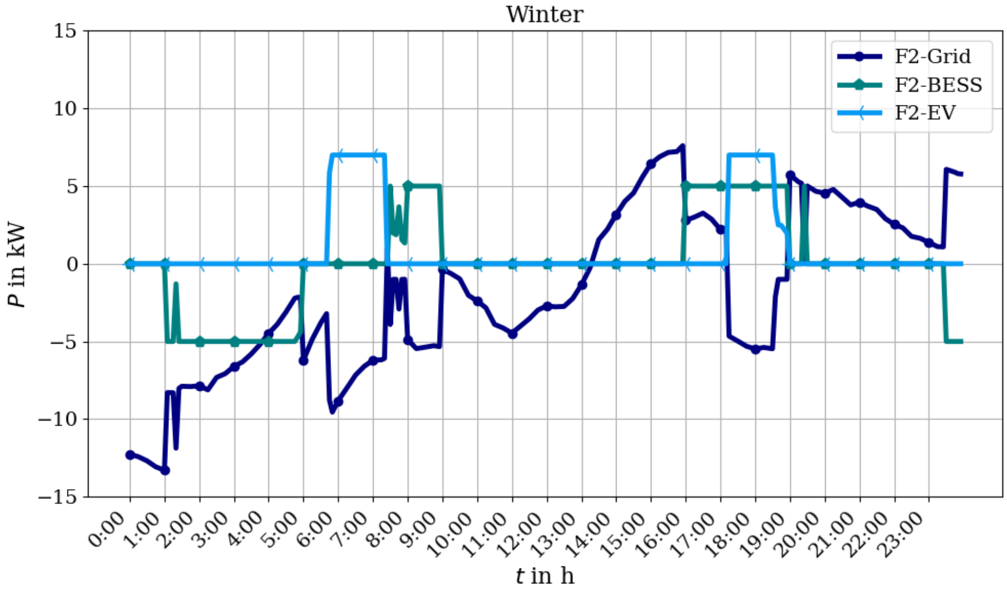

Figure 7.7 Power dispatch in Winter for F2 level.

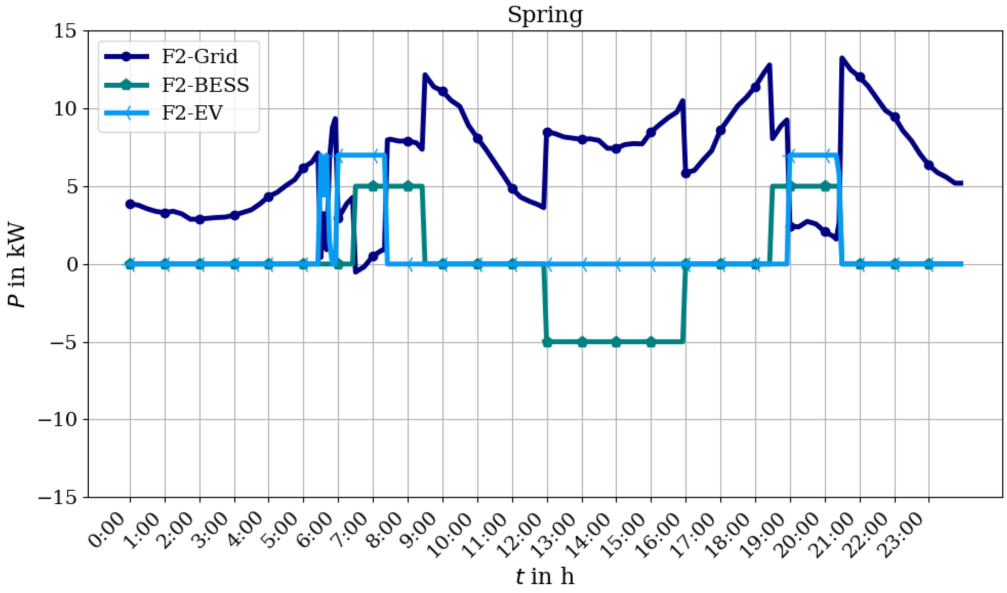

Figure 7.8 Power dispatch in Spring for F2 level.

In the case of autumn, the EC's power balance is positive throughout the day. The local energy production is sufficient to meet demand and still generates a surplus, part of this extra energy is sold to the grid 24 hours a day. This allows the EC to generate additional revenue by selling energy to the grid, taking advantage of favorable production conditions.

On the day analyzed in spring, the energy balance was negative throughout the day, indicating that local production was not enough to meet EC's internal demand. As a result, the EC had to buy energy from the grid throughout the period, which is reflected in Figure 7.8. This situation highlights EC's dependence on the grid when local generation is not sufficient, which implies higher costs for the community, since energy purchased from the grid has a higher cost, especially during periods of higher demand.

Therefore, the graphical figures and results presented in this section illustrate how the flexibility model 2 (F2) reacts adaptively to different seasonal scenarios, prioritizing the use of storage systems such as BESS and V2G to maximize the sale of energy during periods of high tariffs and minimize the purchase of energy from the grid when possible. The EC's behavior is adjusted according to the power balance of each season, which allows the community to optimize its operation and maximize profits depending on tariff and energy production conditions.

7.3 Flexibility level 3

The optimized results for the EC power dispatch were obtained according to flexibility model 3 (F3), and for the typical summer day under analysis, they are shown in detail in Figure 7.9. For the other seasons of the year, the results have also been organized and presented in separate figures: the data for autumn can be found in Figure 7.10, while the results for winter are shown in Figure 7.11. For spring, the results obtained have been depicted in Figure 7.12. A more careful analysis of the results generated by the F3 model reveals distinctive features, especially relating to the interaction with BESS and EV. With this model, which is characterized by having the least flexibility among those studied, there is a significant reduction in the number and intensity of interactions between the EC and these systems.

In general, the curves representing the EC's power balance are almost identical to the curves describing the power interacting with the electricity grid. This is because the reduced flexibility of the F3 model results in less frequent use of storage systems such as BESS, increasing reliance on the electricity grid to meet the community's needs. This reduced use of storage systems is especially noticeable in the case of spring, when the power balance is positive for practically the entire period under consideration. Even in these conditions, the BESS is only triggered to charge for short intervals of time, which reinforces the low use of this resource in the F3 model.

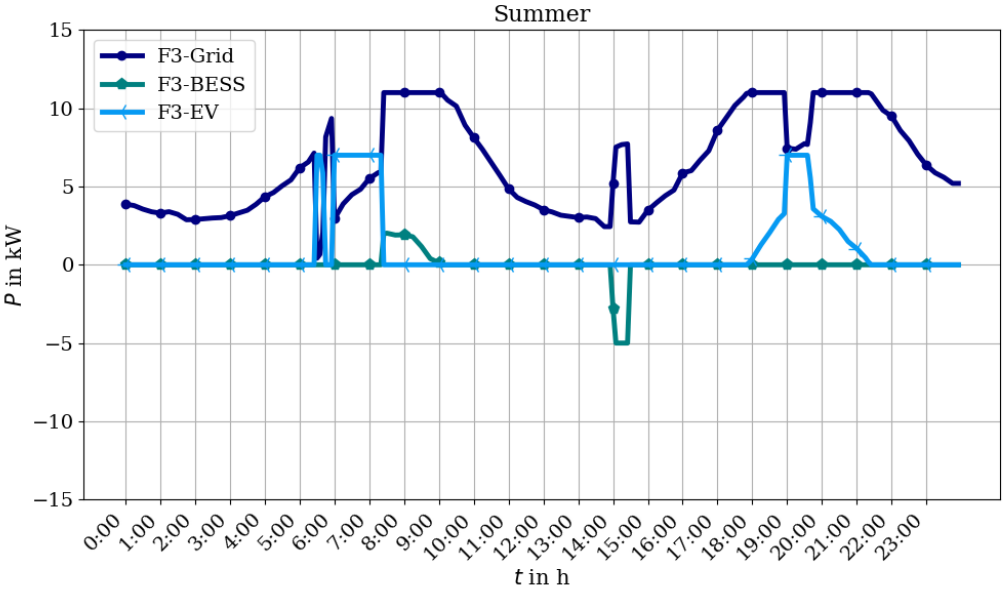

Figure 7.9 Power dispatch in Summer for F3 level.

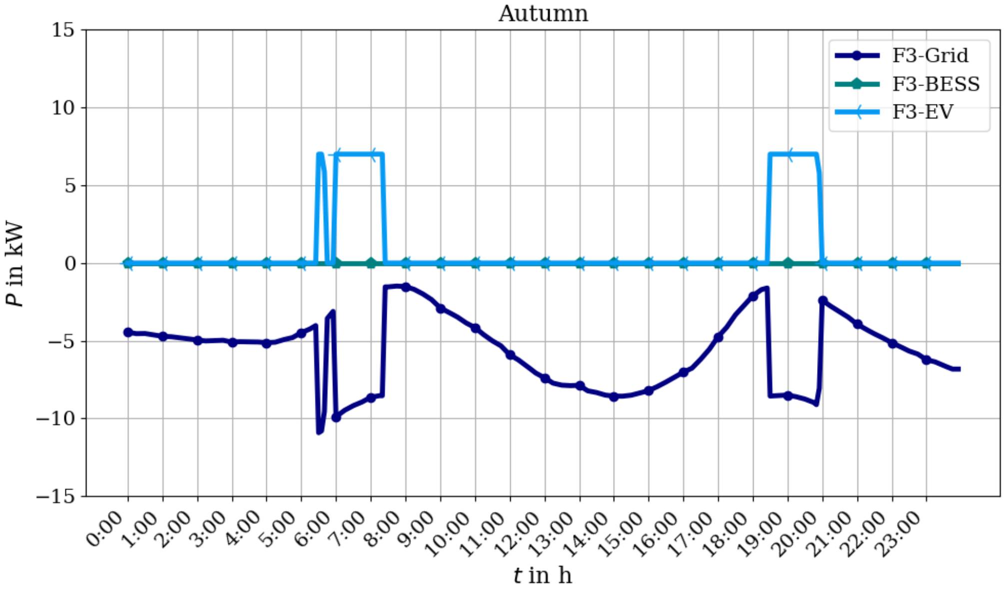

Figure 7.10 Power dispatch in Autumn for F3 level.

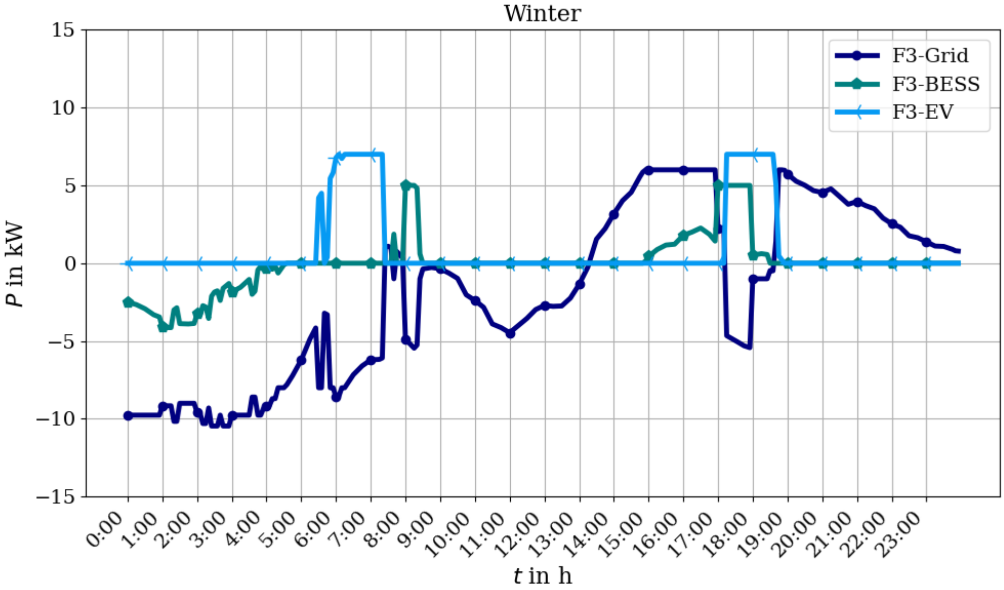

Figure 7.11 Power dispatch in Winter for F3 level.

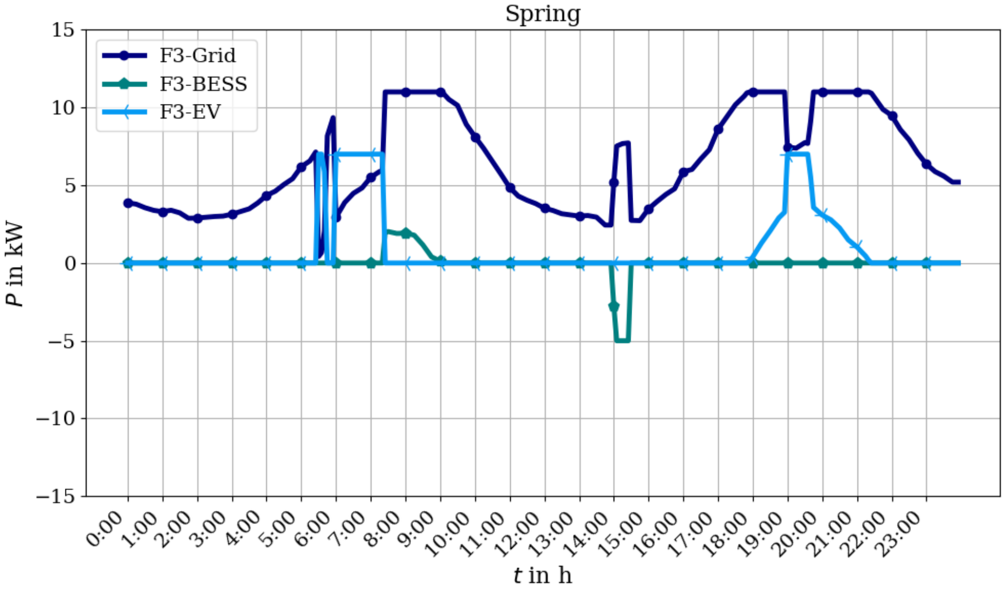

Figure 7.12 Power dispatch in Spring for F3 level.

Furthermore, in all four seasonal scenarios analyzed – summer, autumn, winter and spring – the V2G is strategically activated at times when electricity tariffs are at their highest. This practice is adopted to maximize the EC's financial gains, taking advantage of the possibility of selling stored energy at higher prices. Thus, even though the F3 model limits the EC's operational flexibility, the use of V2G during periods of high tariffs contributes to improving the profitability of the operation, even if the storage systems operate less intensively. This strategy is observed consistently in all seasons, highlighting the concern to align EC's operation with the best possible profitability scenarios within the limitations imposed by the model under analysis.

7.4 State of charge

The results related to the state of charge of the EC were analyzed separately for the representative days of each season, in order to study the behavior under different seasonal conditions. Figure 7.13 shows the SOC of the BESS for a typical summer day. Figure 7.14 refers to autumn, Figure 7.15 to winter and Figure 7.16 to spring. During the summer, as illustrated in Figure 7.13, the SOC reaches the minimum (20%) and maximum (90%) limits previously stipulated in equation (4.9). However, in the other seasons, only the upper limit of the SOC was reached.

In the autumn, represented by Figure 7.14 at flexibility level 3 (F3), the SOC remained constant. This behavior is a consequence of the fact that the F3 model was configured as the least flexible of the proposed levels, significantly limiting the action of the BESS on the day analyzed. Even though there was a surplus of energy available, the optimization revealed that, from an economic point of view, it was more advantageous to sell this surplus to the electricity grid than to store it in the BESS. This limitation reflects the conservative approach of the F3 model.

In general, in the summer the EC showed greater flexibility provided by the BESS, while in the autumn the opposite occurred, with less flexibility. The differences in the results between the seasons are attributed to the specific characteristics of each case, such as the power balance and the variations in the energy tariffs applied in the periods analyzed. In addition, the initial and final SOC values at each level coincided with the values established in the study criteria – 80% for F1, 50% in F2 and 30% in F3.

The SOC results for each proposed level of flexibility have been detailed. Figure 7.17 shows the data for flexibility level 1 (F1), while Figure 7.18 refers to level F2, and Figure 7.19 displays the results for level F3. Analyzing these results, it can be seen that only in model F1 (Figure 7.17) were the maximum (90%) and minimum (20%) SOC limits effectively reached. At levels F2 and F3, some values approached the lower limit of 20%, however did not reach it. This confirms that the BESS in the F1 model was significantly more active compared to the other levels.

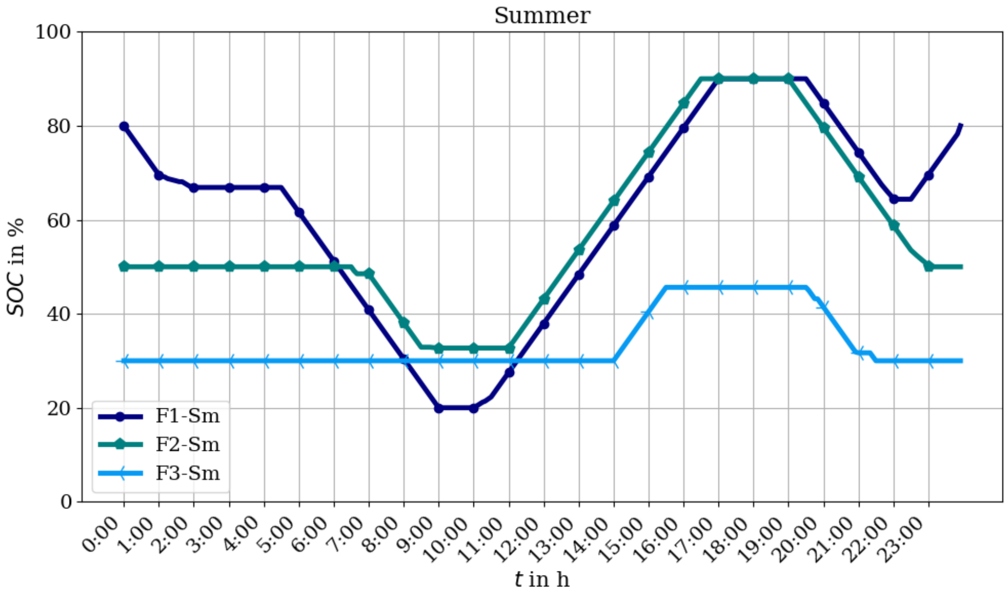

Figure 7.13 BESS SOC for summer.

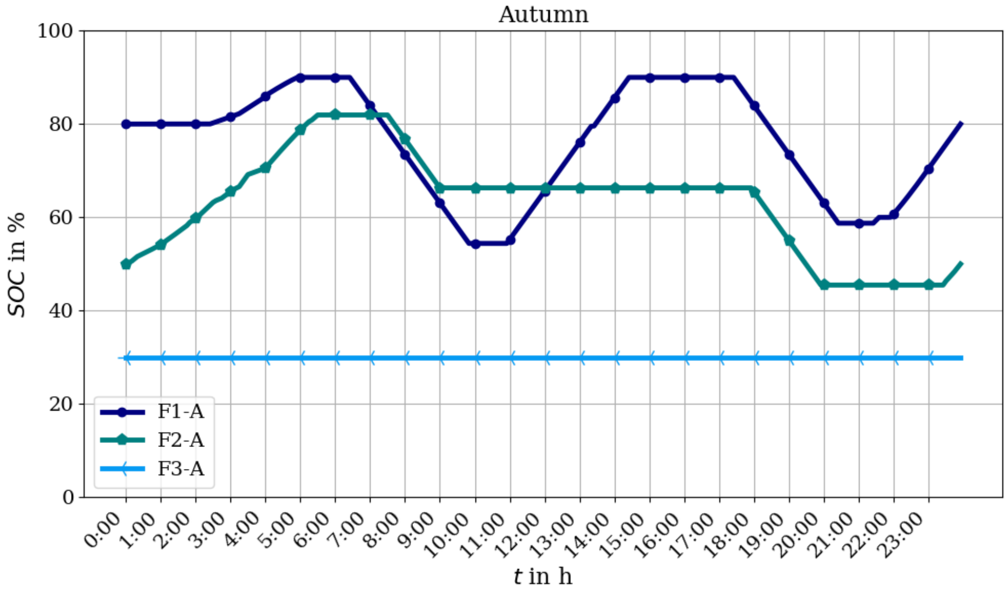

Figure 7.14 BESS SOC for autumn.

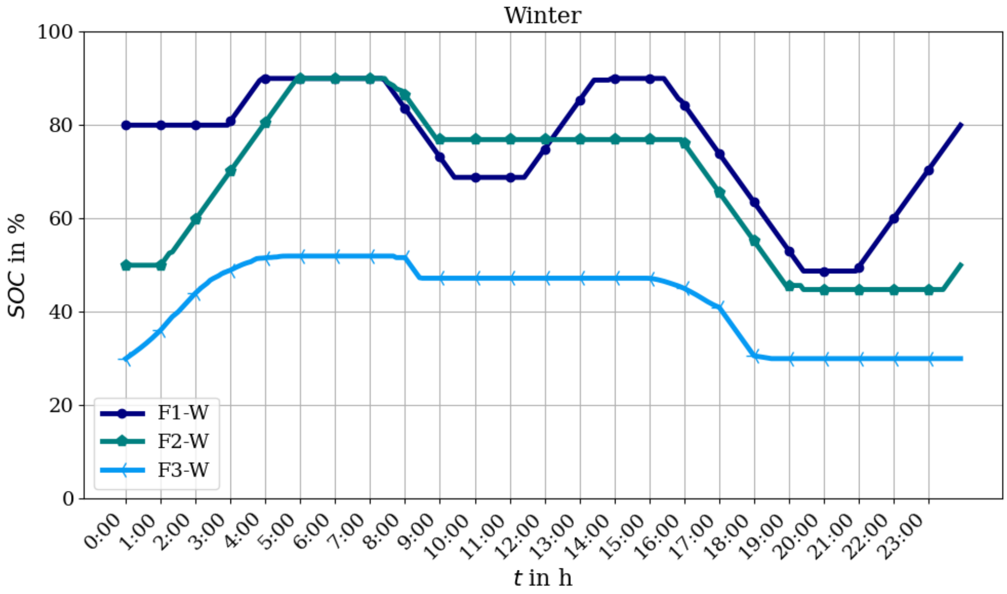

Figure 7.15 BESS SOC for winter.

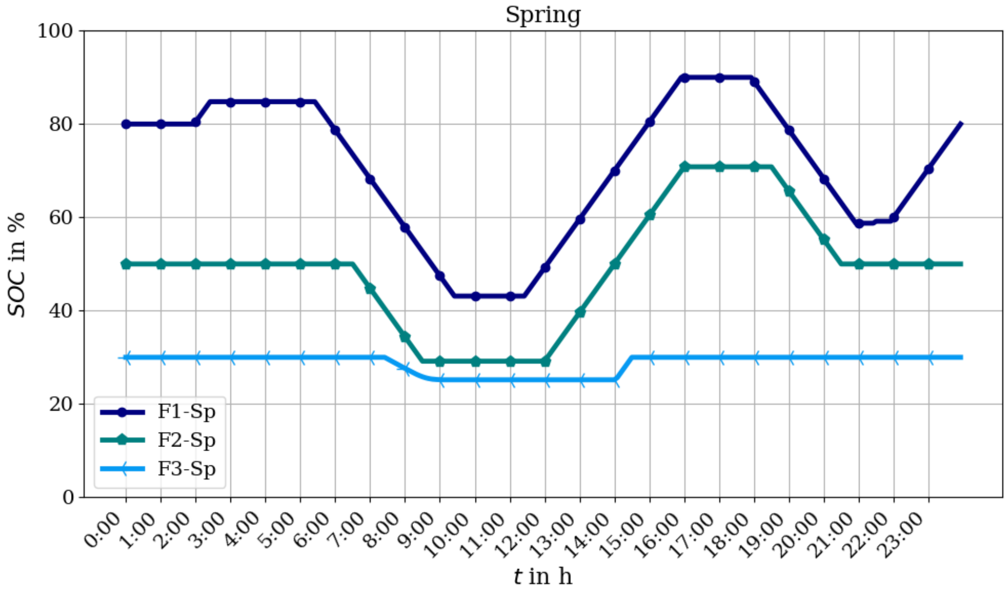

Figure 7.16 BESS SOC for spring.

Another behavior highlighted in the F1 model is that the BESS discharges its energy during peak tariff periods, while recharging at times of lower tariffs, demonstrating the optimal use of resources. F2 also presents this pattern, though to a slightly lower intensity.

The periods when energy prices reach high levels generally coincide with the hours of greatest demand on the electricity grid, known as peak hours. During these times, the BESS plays an essential role by discharging its stored energy to meet part of the EC load. This action has a significant impact, as it not only supplies local energy needs, but also reduces the amount of energy that needs to be drawn from the grid.

This BESS behavior brings benefits in multiple dimensions. For the EC, there is a direct decrease in operating costs during peak times, since the stored energy can be used instead of relying exclusively on the grid, which has higher tariffs at these times. For the distribution grid, the relief provided by BESS is equally valuable, as it reduces the overload on the power system during periods of greatest demand, helping to maintain the stability and reliability of the grid's operation.

By discharging energy during times of greatest need and relieving demand on the distribution infrastructure, BESS directly contributes to increasing the operational flexibility of both systems. This means that the EC and the grid can better adapt to fluctuations in energy demand and supply, optimizing the use of available resources and promoting a more balanced and sustainable system.

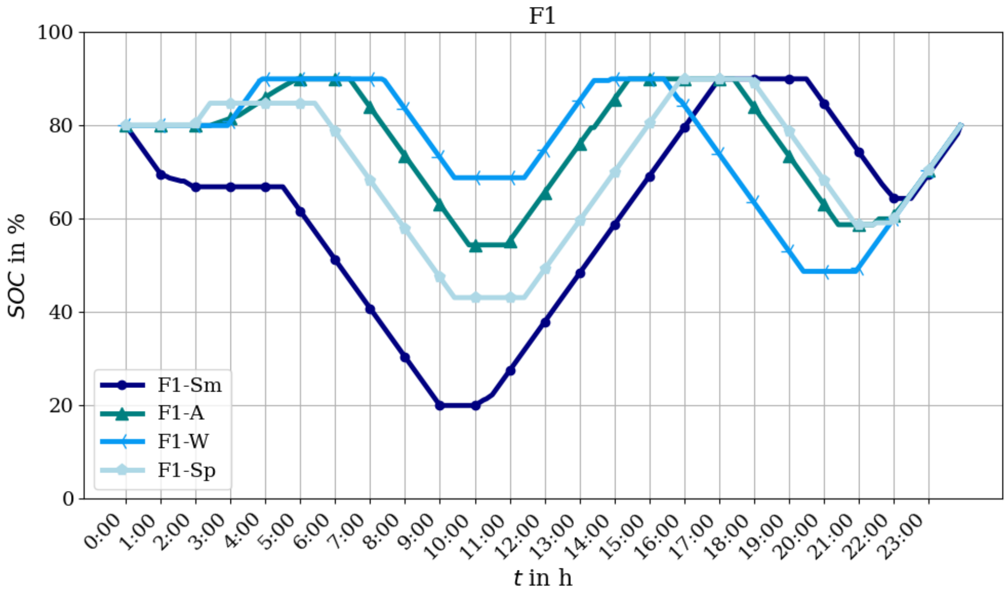

Figure 7.17 State of charge of the EC's BESS for flexibility model 1 – F1.

On the representative winter and autumn days analyzed, there was a surplus of generation at the start of the day, which led BESS to start charging at these times in the F2 model, which initial SOC was lower than in F1. This level of flexibility, with intermediate coefficients, was configured to maintain the initial and final SOC at 50%. The behavior of the SOC curves at the F2 level, as shown in Figure 7.18, is explained by these aspects.

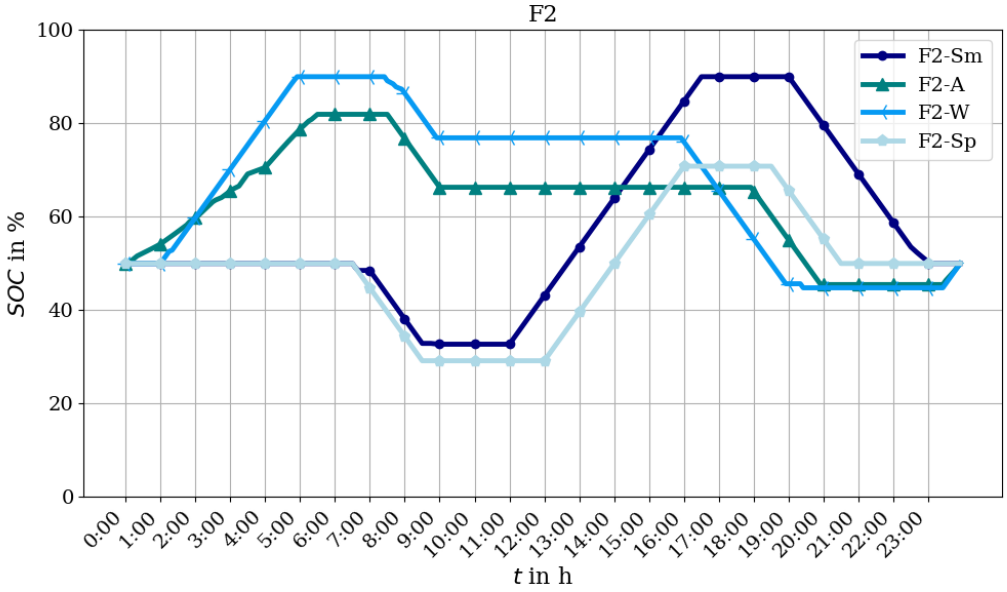

Figure 7.18 State of charge of the EC's BESS for flexibility model 2 – F2.

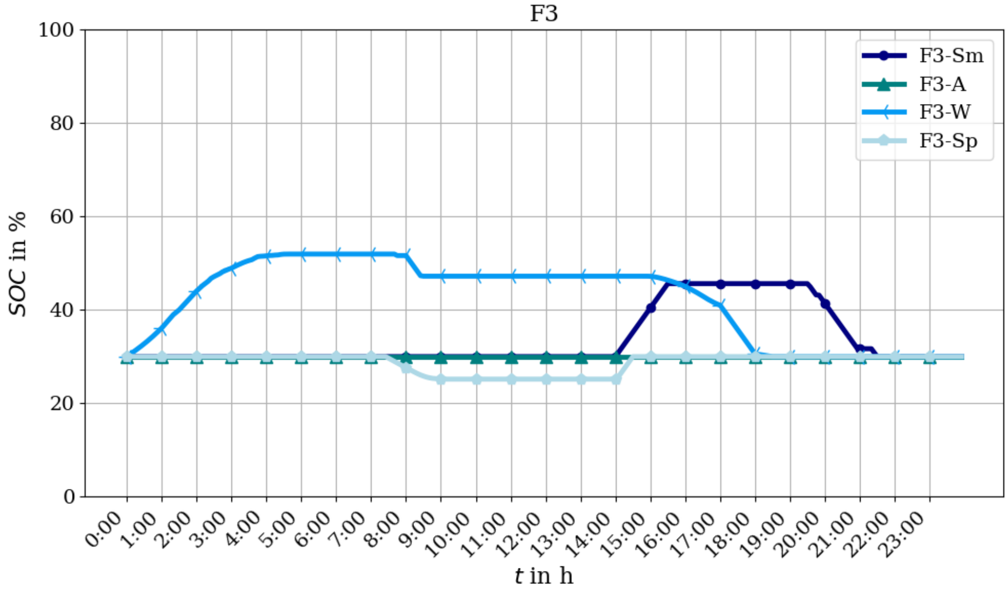

Figure 7.19 State of charge of the EC's BESS for flexibility model 3 – F3.

Moreover, the SOC curves for model F3, illustrated in Figure 7.19, confirm that this is the model with the least flexibility, since the BESS presented little activity compared to the other levels. Even in autumn, the SOC obtained a constant value of 30% on the simulated day.

The comparative graphical analysis between models F1, F2 and F3 clearly reveals the significant differences in the degree of operational flexibility proposed by each of them. These differences are particularly noticeable when observing how the operational flexibility of the EC decreases progressively from model F1 to model F3. This gradual reduction in flexibility is directly influenced by the increase in the weighting coefficients applied to the models, which implies greater control and restriction of operations.

Another determining factor for this reduction is the narrowing of the initial and final values stipulated for the SOC of the BESS at each level of flexibility. In the F1 model, these values are wider, allowing greater freedom for the BESS to act, while in the F3 model, these limits become more restrictive, considerably reducing the system's ability to adjust to operational demands and conditions. Thus, the combination of the increase in the weighting coefficients and the stricter limit for the SOC explains the different behavior observed between the three models.

7.5 Economic evaluation

The purpose of the economic analysis was to evaluate the operating costs of the EC for one day, considering the revenue obtained in the simulated scenarios over the periods studied. For each season, the results were presented in detail, considering the three levels of flexibility proposed (F1, F2 and F3). In the case of summer, the data is shown in Figure 7.20; for autumn, it is presented in Figure 7.21; the results for winter can be seen in Figure 7.22; and the results for spring are displayed in Figure 7.23.

The curves depicted in each figure provide relevant information on the hourly economic performance of the EC. Among them, the curve with the darkest color stands out, which was obtained by calculating the average of the three levels of flexibility – F1, F2 and F3. This approach allowed a more comprehensive and comparative analysis of the economic results obtained. When analyzing the curves presented, it can be observed that there was not a very significant variation in the economic results between the different levels of flexibility throughout the hours of the day, suggesting a relative uniformity in the operation.

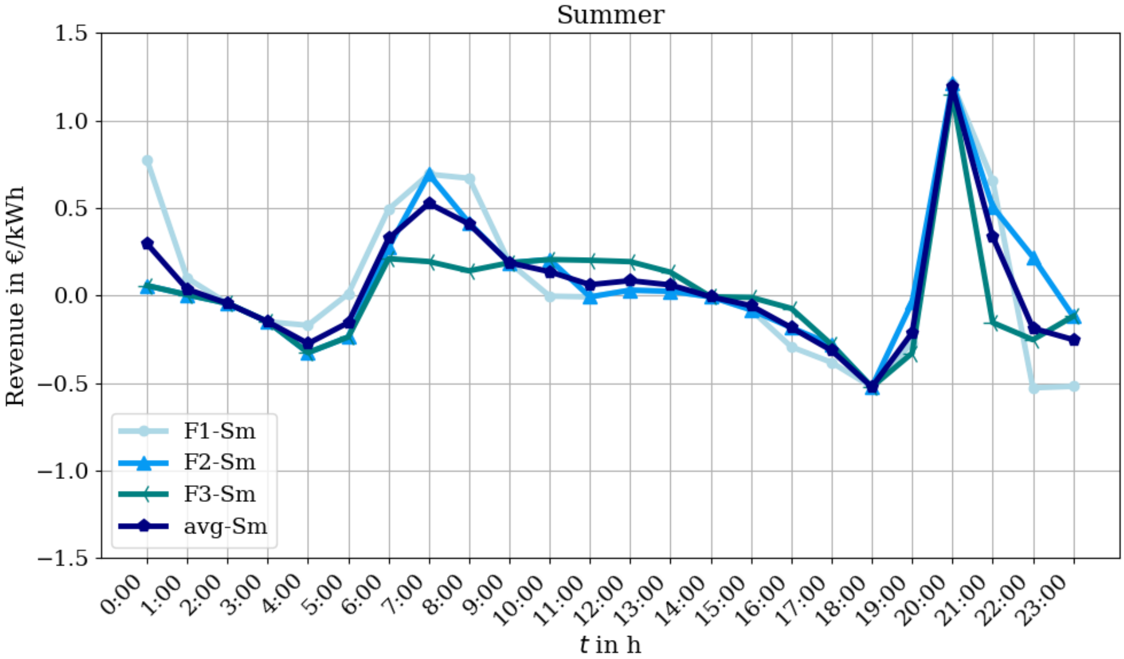

Figure 7.20 EC's revenue for the day simulated in summer.

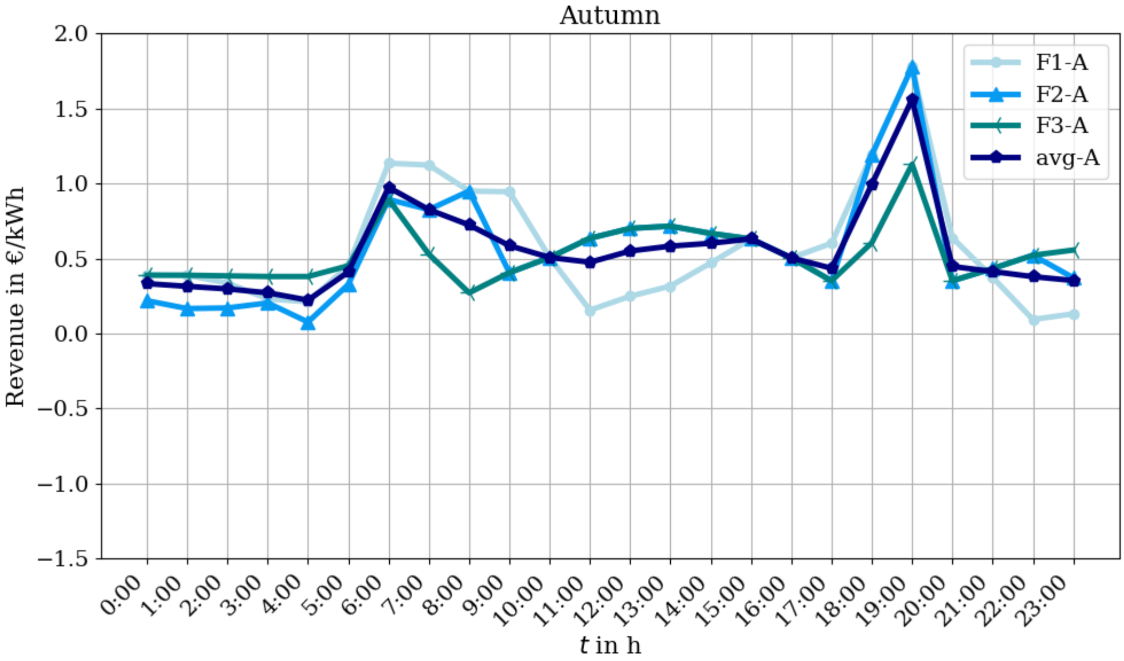

Figure 7.21 EC's revenue for the day simulated in autumn.

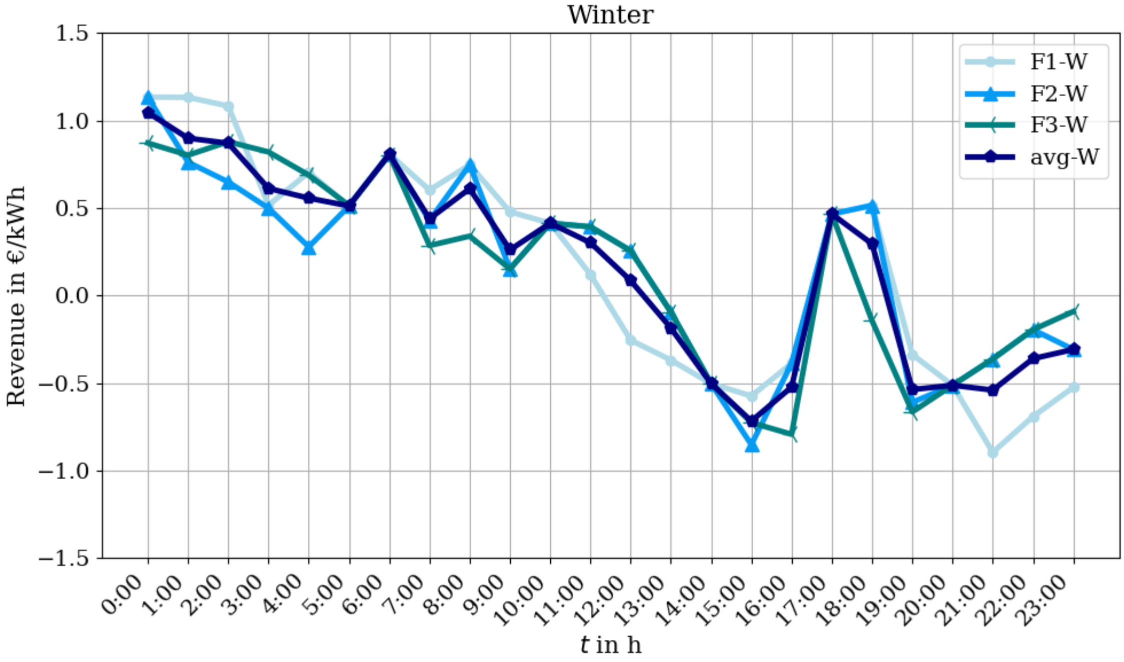

Figure 7.22 EC's revenue for the day simulated in winter.

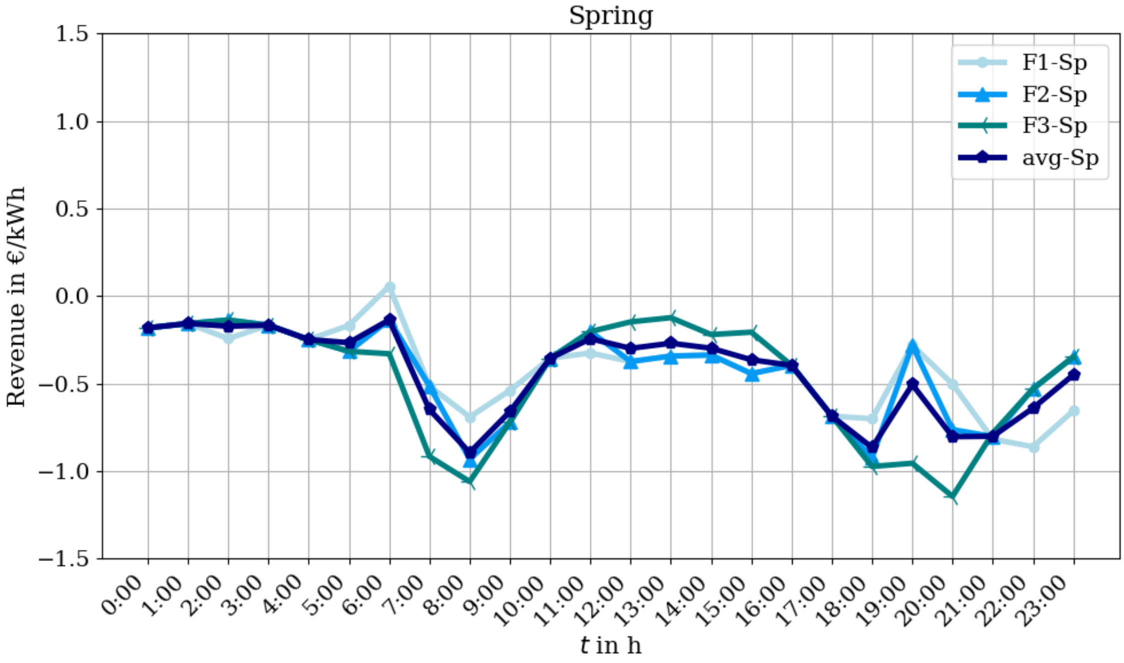

Figure 7.23 EC's revenue for the day simulated in spring.

However, some particularities are noticeable depending on the season analyzed. In the case of summer and autumn days, the corresponding figures (Figure 7.20 and Figure 7.21) show that profit was more significant at times when electricity tariffs were at their highest levels. This behavior is explained by the optimizing strategy which prioritizes the sale of energy at times of higher tariffs, thus maximizing EC's profitability.

On the winter day, as illustrated in Figure 7.22, a different characteristic can be observed. In this case, the EC started the day with a significant positive power balance, which resulted in times of high profitability in the very first hours of the period. In addition, another moment of high revenue was identified around 5pm, when the electricity tariff reached a high value. This combination of factors allowed CE to achieve such economic performance on the day analyzed.

In the spring, the results presented in Figure 7.23 indicate a different economic behavior compared to the other seasons. On this day, EC power generation was insufficient to fully meet demand, forcing the system to rely on the electricity grid to supply the loads. This dependency resulted in higher operating costs, especially at peak energy tariff times for this specific scenario. However, at around 7pm, the F1 and F2 flexibility models were able to be partially supplied by the BESS. This performance of the BESS contributed to a reduction in operating costs at this time, although to a limited amount, showing that higher levels of flexibility can provide some cost mitigation in situations of generation deficit.

Figure 7.24 details the average profits achieved in each of the scenarios considered during the analysis. In general terms, it can be seen that the scenario classified as more flexible, the F1 scenario, obtaining higher while F3-Sm stood out for having the lowest average profit levels compared to the other levels of flexibility analyzed in the summer. This was particularly due to the lower profit recorded at the start of the day, around 7am, and at the end of the day, around 9pm, observed in Figure 7.20. In these time slots, profit was significantly impacted by factors such as the energy transactions undertaken, the tariff values applied and the results obtained in the power dispatch determined by the optimization process. These elements contributed to the F3-Sm scenario performing less favorably than the others.

The average profits obtained in the simulated scenario for a typical spring day in the EC were the only negative at all the flexibility levels evaluated. This behavior was expected, considering that in all the periods analyzed there was a significant energy deficit, which made it necessary for the EC to purchase energy directly from the grid to meet the community's demand. This deficit occurred because local energy generation was insufficient to cover consumption, both at times of high and low demand, resulting in high costs due to the continuous purchase of energy. The constant need to fill this energy gap, coupled with the specific seasonal conditions of the simulated spring day, reinforced the negative financial impact, as the costs related to energy purchase transactions outweighed any possible revenue that could be generated by selling or optimizing in-place production. These factors contributed to the EC's economic performance being in deficit throughout the period analyzed, regardless of the level of flexibility adopted.

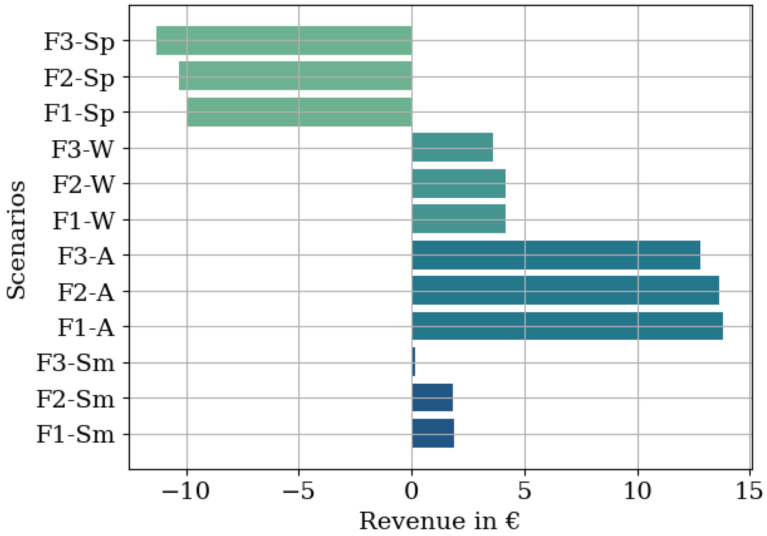

Figure 7.24 EC revenue by proposed scenarios.

During the autumn day analyzed in this dissertation, EC achieved a significant profit on its operations, marking a considerably higher financial performance when compared to the other scenarios evaluated. These positive results are attributable to the positive power balance recorded throughout the day, in which the amount of energy generated consistently exceeded the community's internal consumption. This condition allowed the EC to make the most of the surplus energy produced. Part of this excess was stored for later use, while the rest was commercialized, generating additional revenue from the sale of energy to the electricity grid. This efficient operating flow, combined with the optimized management of available energy resources, resulted in an economically advantageous operation for EC. Even in this energy surplus scenario, the algorithm was efficient in balancing generation, consumption and storage. In this manner, the operation proved to be economically advantageous given the specific characteristics of the day in question.

Finally, the only scenario in which the EC operation showed a daily economic deficit was on a typical spring day. In this specific case, the financial results were negative, reflecting an underperformance due to the unfavorable energy balance. In contrast, the autumn and winter scenarios showed positive daily operating profits, evidencing greater economic efficiency in their operations.

Among these profitable scenarios, the financial performance obtained on the typical summer day was the least significant, showing the lowest profit among the simulations with positive results. This limitation can be explained by the less favorable power balance recorded on this day, which resulted in a smaller amount of surplus energy available for sale to the grid. As the sales surpluses is an important source of revenue for CE, the reduction in the availability of exported energy had a direct impact on the economic gains obtained.

7.6 Rule-based approach

The results for power dispatch without optimization can be analyzed in this section. Figure 7.25 shows the power curves for the simulated summer day, while the results for autumn can be observed in Figure 7.26. Figure 7.27 shows the power dispatch for winter and finally, Figure 7.28 contains the results for spring.

On the simulated summer day, the EV presented little activity and there was minimal interaction with the grid. On the other hand, BESS was active at almost all times. In the autumn, the charging and discharging of the BESS was not significant throughout the day. However, the EV was very dynamic. On this day, the balance is always positive, so the EC sold energy to the grid significantly. On the day representing winter, there is initially a great interaction involving the storage systems and the grid, due to the surplus of energy during this period. Afterwards, there is no significant activity. In spring, the EC has a generation deficit throughout the day. This characteristic causes it to purchase energy from the grid for practically the entire period.

The data from the economic analysis for this modeling approach, which does not include optimization, can be examined in Figure 7.29. It displays the hourly results of the EC revenue over the four specific days analyzed. By summing up these individual hourly revenue values, it is possible to calculate and determine the EC's total daily revenue for each analyzed day. These aggregated daily revenue values are provided in Figure 7.30, where the overall outcomes for each season are clearly outlined. During the autumn season, the EC achieved its highest profit among all the analyzed cases. This favorable result occurred because the power balance remained consistently positive throughout the entire day, meaning that the EC generated more energy than it consumed, selling part of the surplus to the grid. Conversely, the spring season presented a contrasting scenario. During this period, the EC experienced a significantly lower revenue due to the power balance being negative. This situation indicates a greater reliance on energy supplied from the grid, which led to increased costs and reduced profitability. The comparison between these different cases highlights the important role of the power balance in determining the economic performance of the EC.

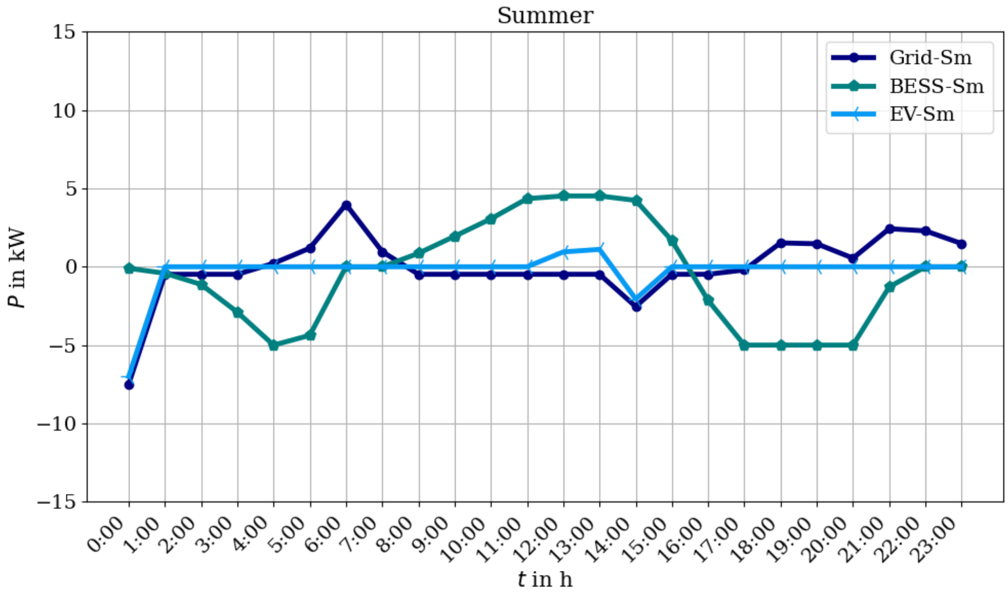

Figure 7.25 Power dispatch for the summer day.

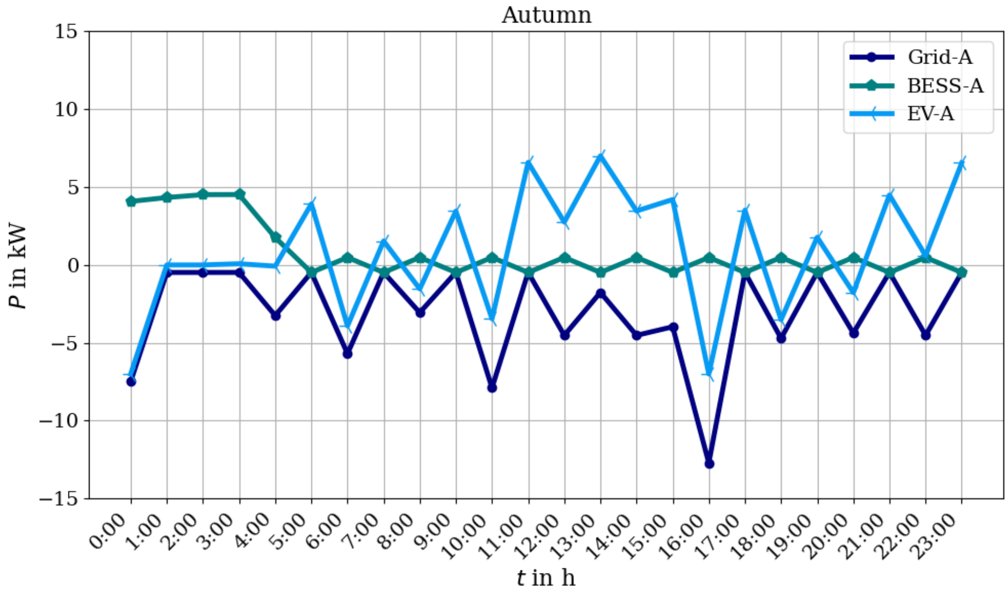

Figure 7.26 Power dispatch for the autumn day.

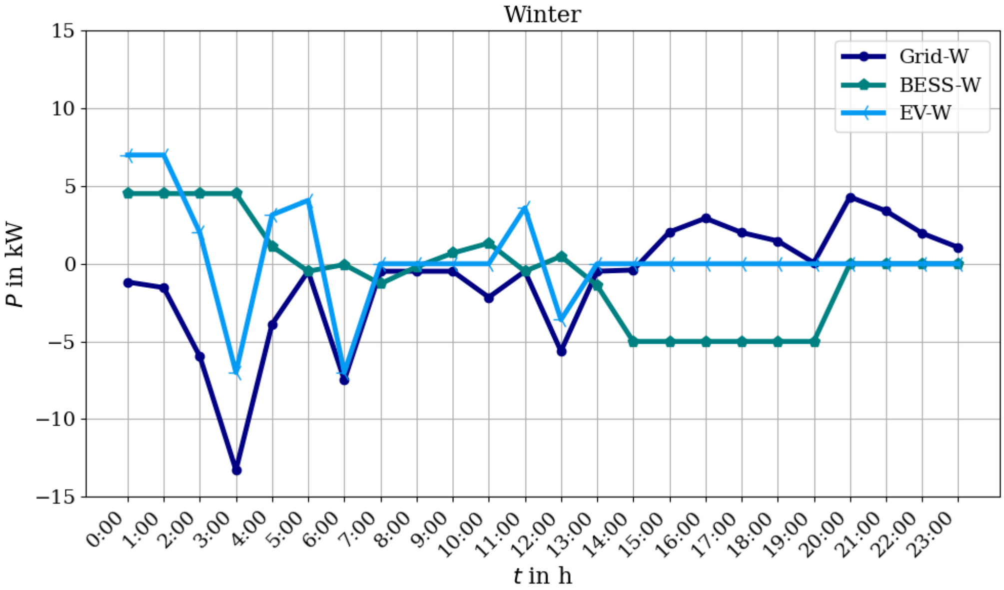

Figure 7.27 Power dispatch for the winter day.

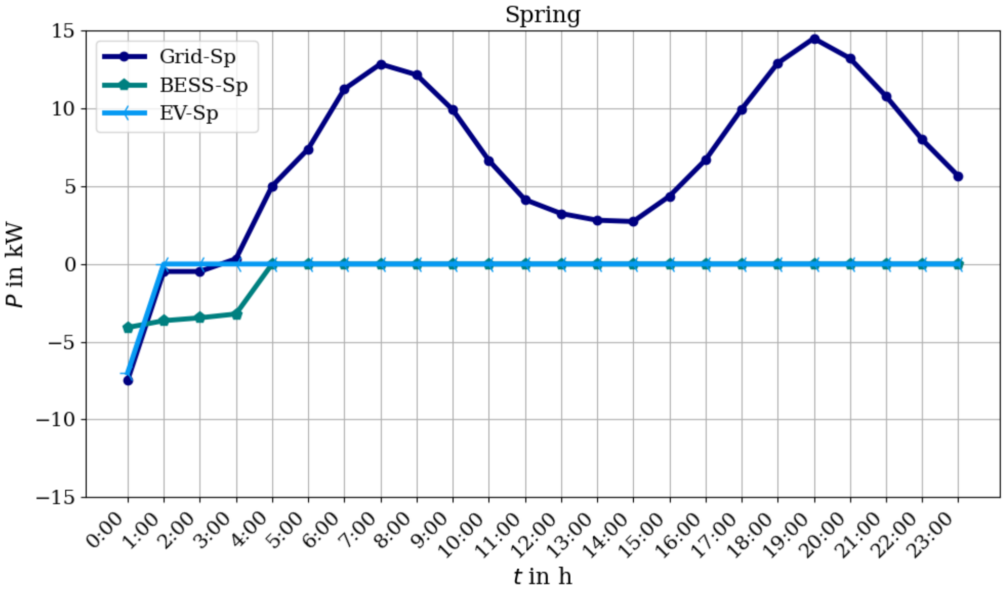

Figure 7.28 Power dispatch for the spring day.

When analyzing the revenues generated through this particular method, as illustrated in Figure 7.30, and comparing them to the revenues derived from the three distinct levels of flexibility that were suggested and implemented in the optimized model, as represented in Figure 7.24, it becomes evident that the case study utilizing the optimization approach yielded greater profits. This outcome highlights the effectiveness of the optimization method. To provide a clearer perspective, Figure 7.31 illustrates and contrasts these findings by displaying the percentage difference between the revenues generated by the two proposed methods. It is worth noting that, for the spring season, the observed values are negative. This result occurs because, on this particular day, the EC did not achieve any profit, however instead, incurred a cost.

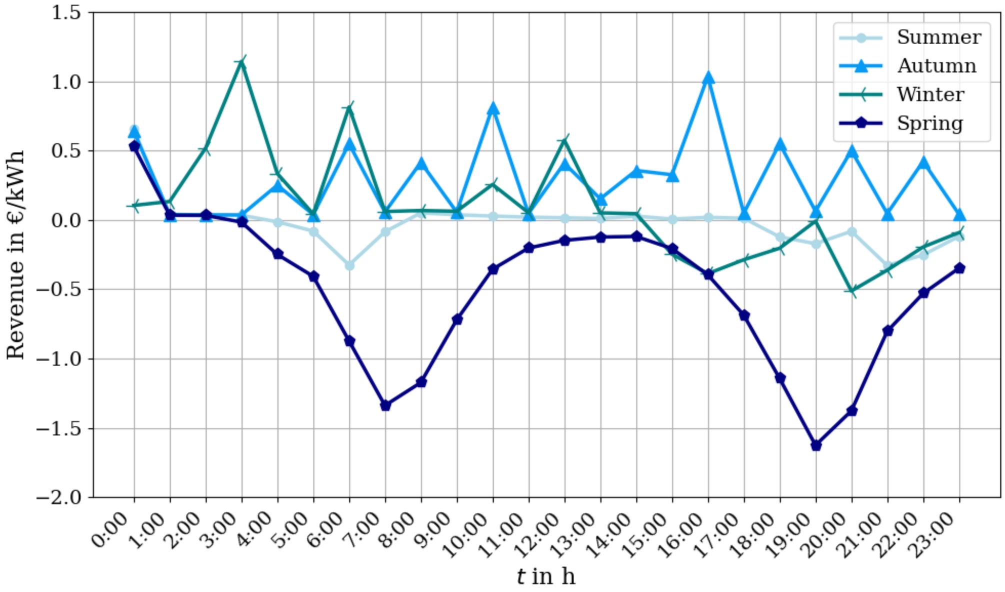

Figure 7.29 EC hourly revenue for each season.

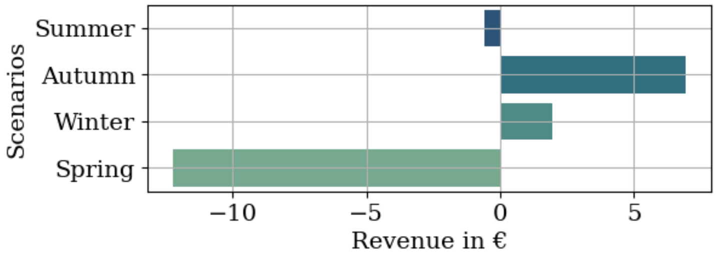

Figure 7.30 EC daily revenue for each season.

Nevertheless, across all the scenarios that were simulated during this study, the use of the optimization-based approach consistently led to either higher revenues or lower costs when compared to the alternative rule-based method. The increase in revenue ranged from 30% to 316%, with the latter representing the best performance during the summer in F1. A specific example can be observed in the autumn season at flexibility level F1. During this scenario, the optimized method managed to achieve 200% higher profit than what was obtained using the rule-based approach.

Furthermore, when evaluating the three levels of flexibility proposed in the model, it is apparent that the revenue progressively increased as the level of flexibility transitioned from F3 to F1. The most flexible level, F1, resulted in the highest revenue, highlighting the impact of flexibility on financial outcomes.

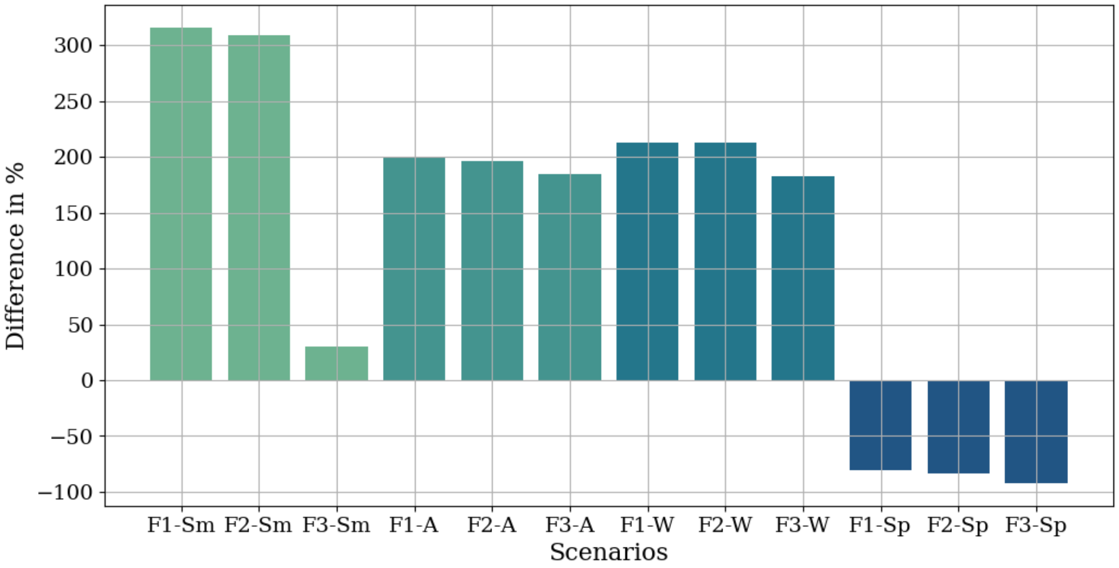

Figure 7.31 Revenue comparison between optimized and rule-based methods.

Although the MILP approach is inherently more complex and demands a greater amount of computational effort when compared to the simpler and less computationally intensive rule-based method, it offers economic advantages. While the increased complexity and computational requirements of MILP might initially appear to be a drawback, the resulting economic gains from its application justify these additional efforts.

7.7 Rewards

The hourly results calculated using fuzzy logic provide a detailed representation of the percentage of the reward allocated to the EC. These results determine the daily rewards for each season and for varying levels of proposed flexibility, which are comprehensively outlined in this section. Firstly, the calculation for a specific hour is presented as an illustrative example, aiming to effectively demonstrate the relationship between the input values and the resulting output.

In this particular instance, the input parameters included a power value of 7 kW for P_{V2G}, 5 kW for P_{BESS}, a balance power of -5.7 for P_{Bal}, 0.19 for T_{purch}, and 0.15 for T_{sale}. These specific values were derived from the simulated scenario of the summer case study, under conditions representing flexibility level 1, at 9pm. The parameters used, form the basis of the calculations, and are presented in Table 7.1, along with their corresponding weights as detailed in section 5.2 (Table 5.2).

Table 7.1 Values and weights for summer - F1 case study

Parameter	Value	Weight
P_{V2G}	7	High
P_{BESS}	5	High 2
P_{Bal}	-5.7	Low
T_{purch}	0.19	High
T_{sale}	0.15	High

Moreover, the graphical representation of these values, which are integral to the fuzzification process, is depicted in Figure 7.32, Figure 7.33, Figure 7.34, Figure 7.35 and Figure 7.36. This includes the membership functions and the ranges assigned to each variable, offering a visual understanding of how the system interprets the input values. Based on these computations, the calculated percentage reward for the EC amounted to 81.86%, illustrated in Figure 7.37.

When evaluating both the input parameters and the corresponding output, it is evident that the result adheres to the structure of rule 7, as outlined in Table 5.3. The reward was high as expected, due to the rule established with the respective input values, encouraging V2G and the functioning of BESS. This emphasizes the accuracy of the fuzzy logic method in accounting for dynamic input variables while maintaining alignment with predefined rules and weights in this simulation. The analysis highlights how the system achieves fair reward by consistently applying the rules within its framework.

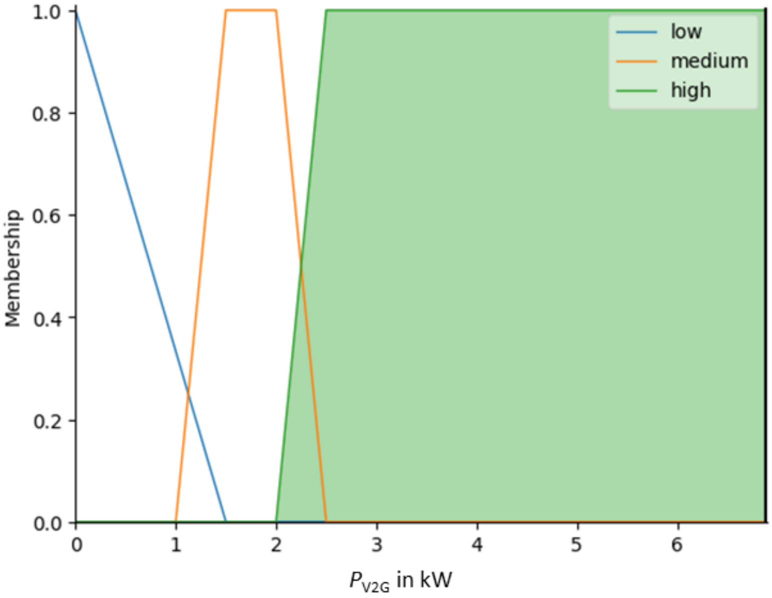

Figure 7.32 P_{V2G} input for summer – F1 (9pm).

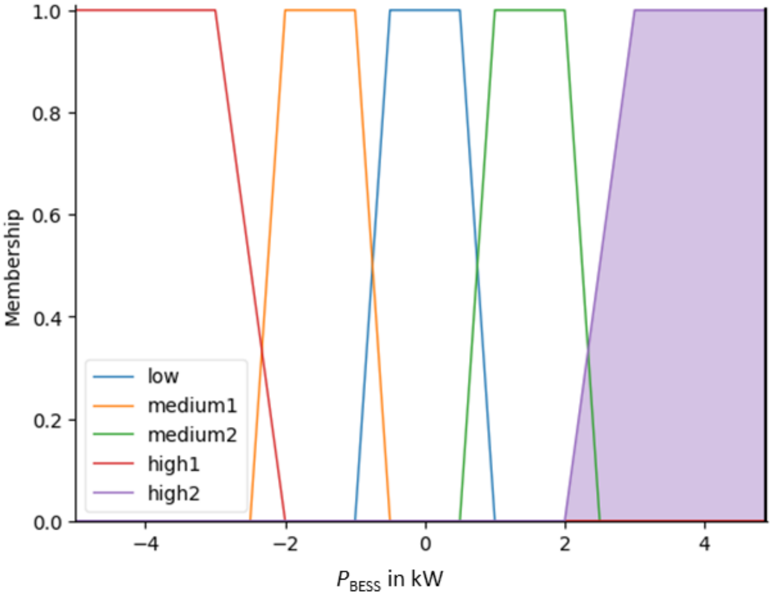

Figure 7.33 P_{BESS} input for summer – F1 (9pm).

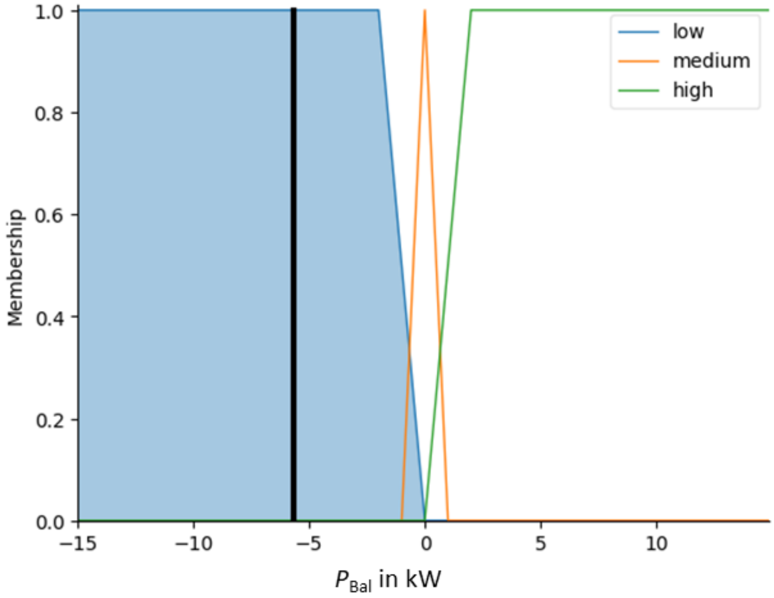

Figure 7.34 P_{Bal} input for summer – F1 (9pm).

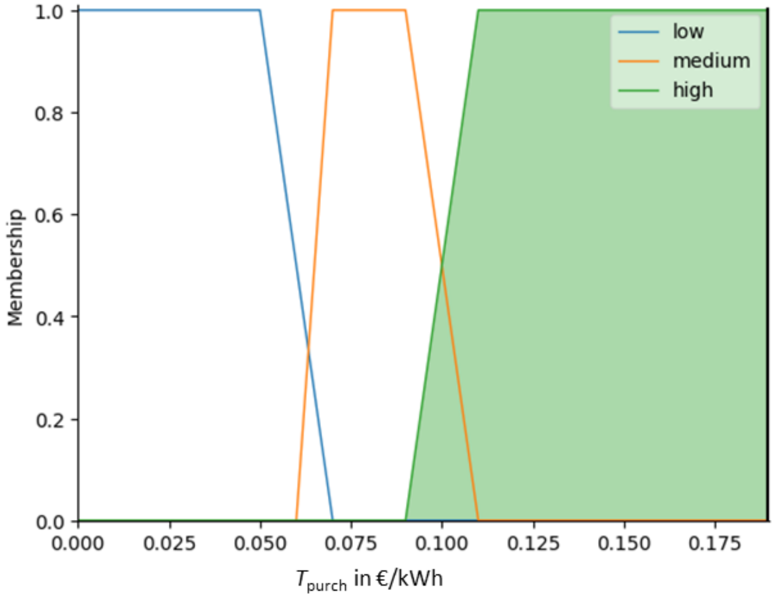

Figure 7.35 T_{purch} input for summer – F1 (9pm).

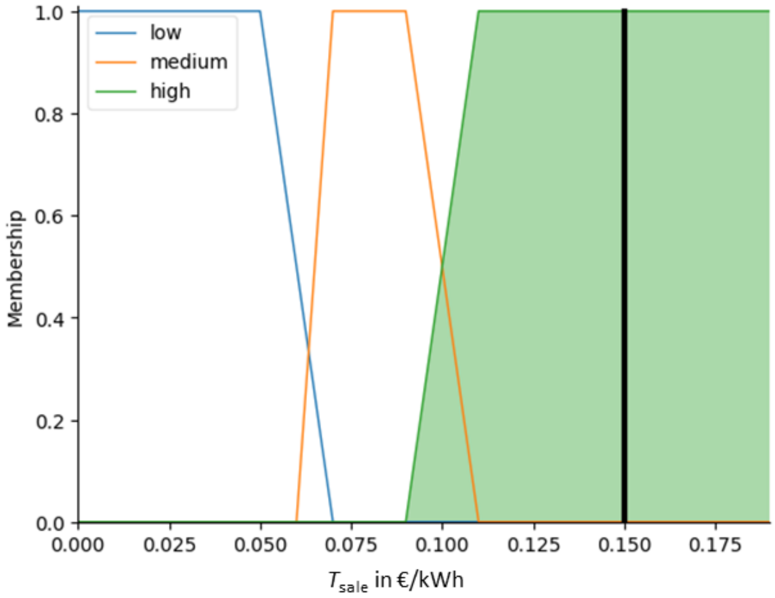

Figure 7.36 T_{sale} input for summer – F1 (9pm).

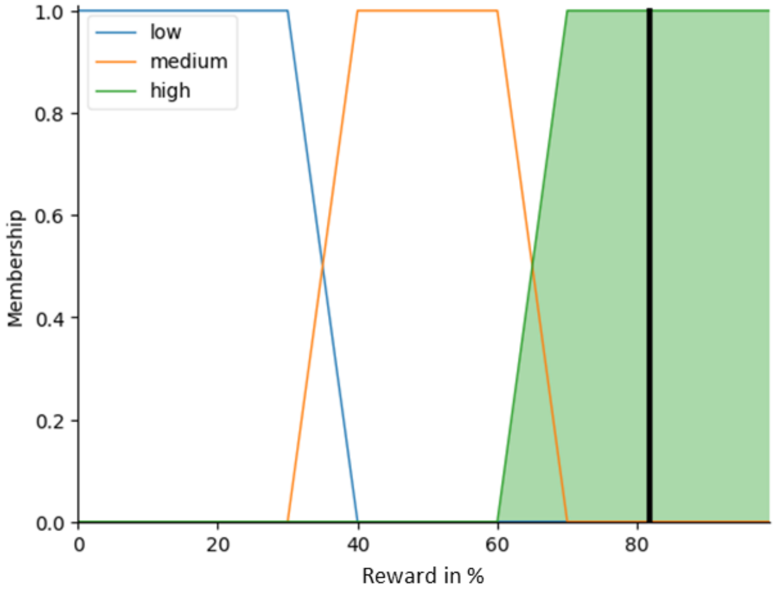

Figure 7.37 Reward output for summer – F1 (9pm).

When analyzing the daily results, Figure 7.38 provides an illustration of the average daily reward achieved for each scenario. The analysis includes comparisons across the four seasons of the year – spring, summer, autumn, and winter – and evaluates the results for all three defined levels of flexibility. A clear trend is observed, scenarios categorized under flexibility level 1 consistently demonstrate higher reward values compared to those under levels 2 and 3. When comparing the difference in rewards between levels F1 and F3 across all simulated days, it can be observed that the average reward for F1 is 40% higher than that for F3.

This phenomenon can be attributed to the fact that flexibility level 1 represents the most adaptable configuration. With greater flexibility, the energy storage system and V2G technologies, operate more actively and efficiently. This activity leads to higher reward percentages for the EC. In contrast, the scenarios associated with flexibility level 3, which is classified as the least flexible configuration, yielded the lowest reward percentages.

Moreover, within the scenarios, the winter day cases showed notably higher reward values compared to other seasons. This outcome is primarily linked to the increased relative activation and utilization of the BESS and V2G during winter days in this specific case study.

The hourly reward for one of these days is presented in Figure 7.39, focusing on a winter day scenario under flexibility level 1. The hourly analysis reveals significant variations throughout the day, with reward values peaking at certain times, reaching approximately 80% during some hours. These peak periods align with the charging and discharging cycles of the BESS and the active use of V2G technology. These events highlight the importance of flexibility and strategic energy management to maximize rewards, as systems respond dynamically to fluctuations in energy supply and demand.

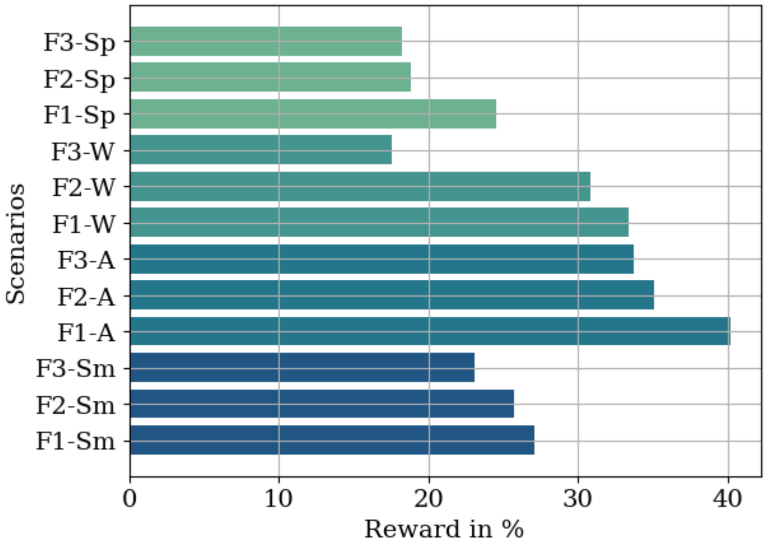

Figure 7.38 EC reward by proposed scenarios.

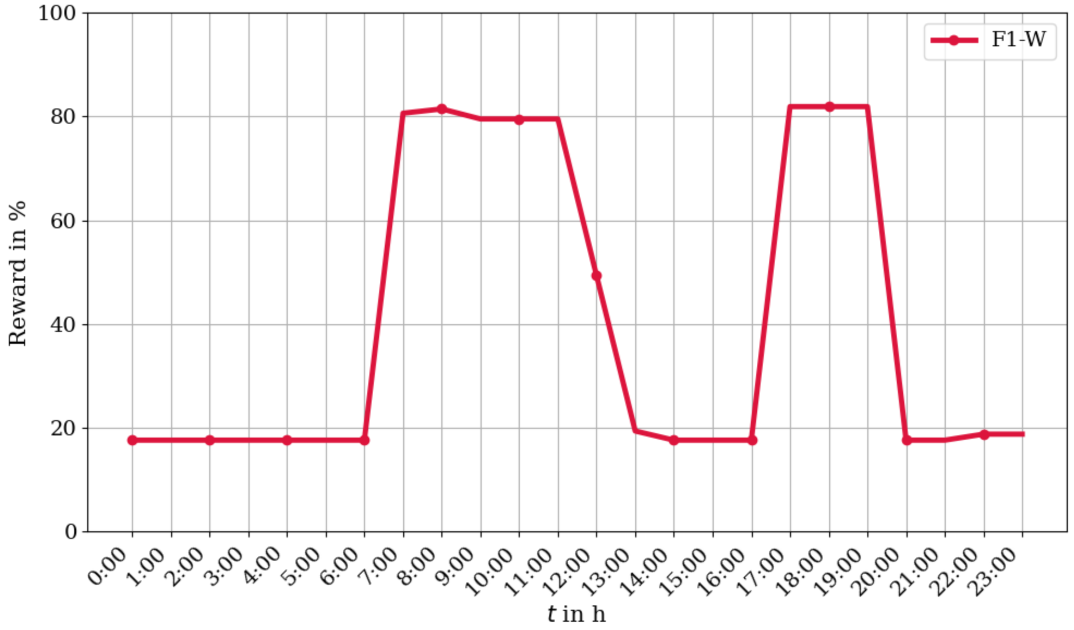

Figure 7.39 EC reward for winter in flexibility level 1.

7.8 Voltage level

During the analysis conducted over the simulated days in the EC, different power dispatch strategies were implemented, and the voltage levels in each bus of the system were calculated in detail for all the scenarios in flexibility model 1 (F1). This approach made it possible to evaluate the electrical behavior of the system under different seasonal and operational conditions. The results obtained, expressed in per unit (p.u.), were organized graphically to make them clearer. Annex A contains the tables with the data for the voltage results at the F1 level presented in this section.

On the summer day, the voltage values on each EC bus are detailed in Figure 7.40. For autumn, the results are presented in Figure 7.41, while the winter data has been summarized in Figure 7.42, and the results for spring are available in Figure 7.43. Each figure illustrates the characteristic behavior of the voltages on the buses during the different periods in F1, considering the impact of seasonal conditions and the power dispatch applied. The resulting voltages for flexibility level 2 (F2) on the four days studied can be observed in Figure 7.44, Figure 7.45, Figure 7.46 and Figure 7.47. For F3, the resulting values are presented in Figure 7.48, Figure 7.49, Figure 7.50 and Figure 7.51.

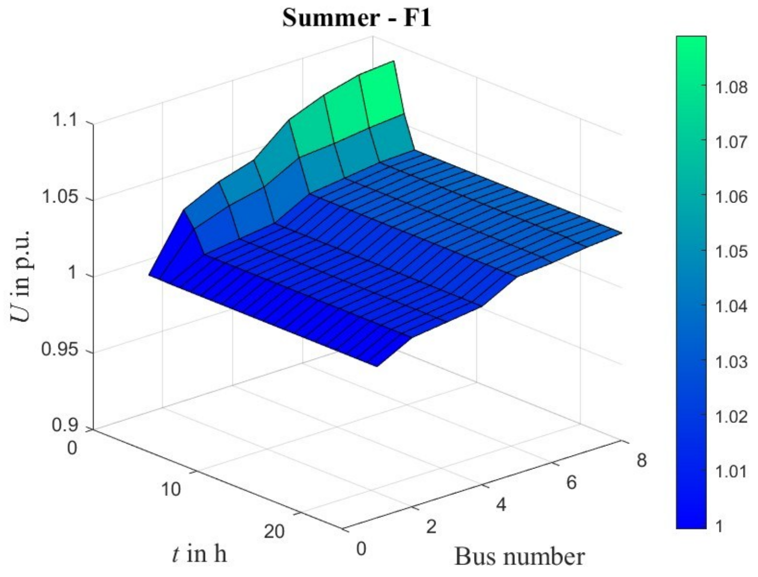

Figure 7.40 Voltage levels for the EC in summer – F1.

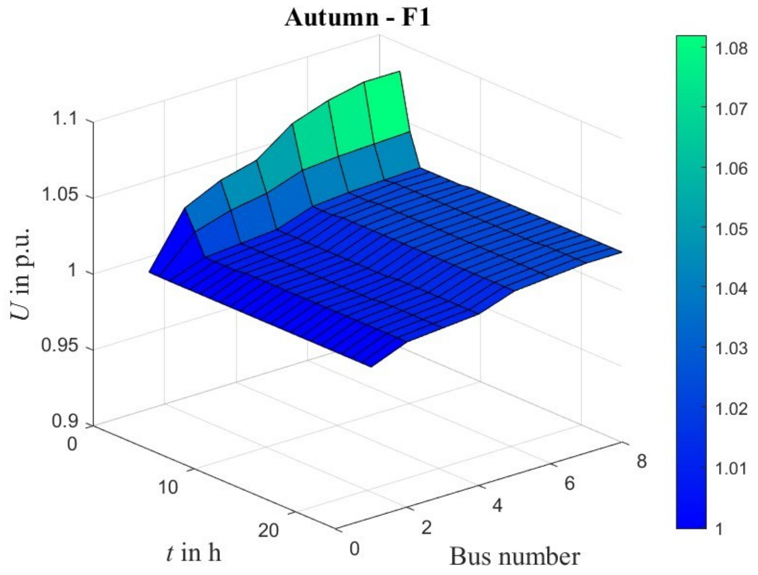

Figure 7.41 Voltage levels for the EC in autumn – F1.

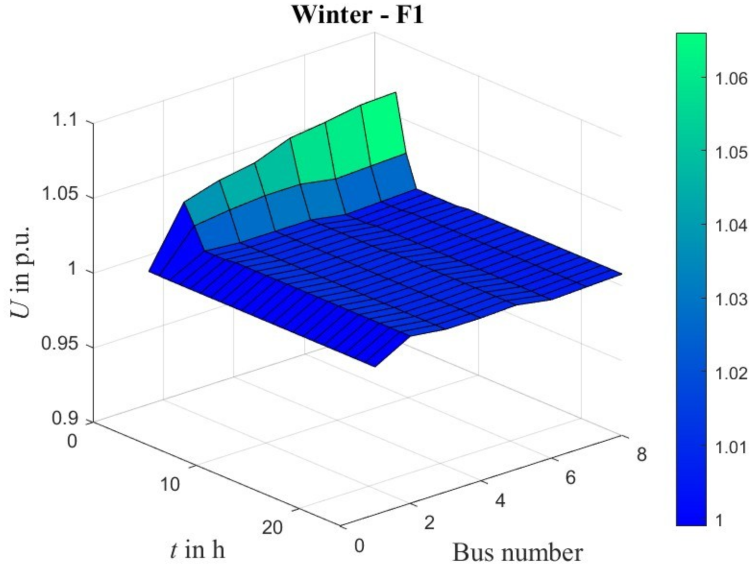

Figure 7.42 Voltage levels for the EC in winter – F1.

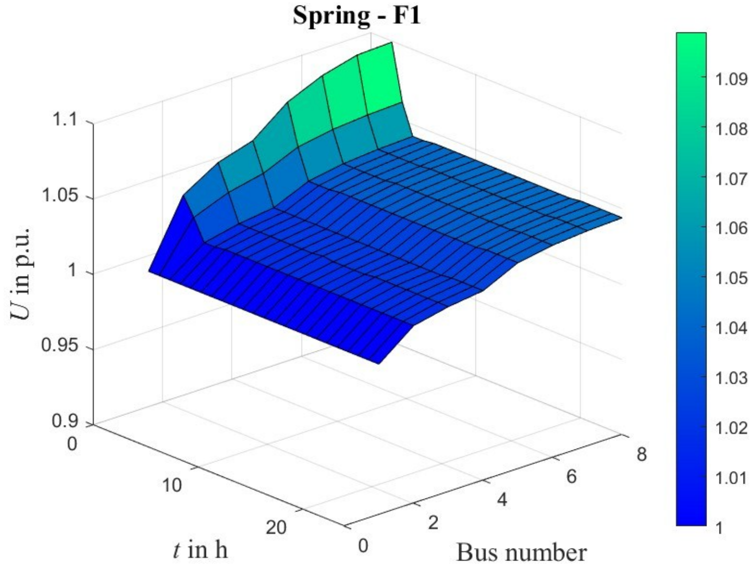

Figure 7.43 Voltage levels for the EC in spring – F1.

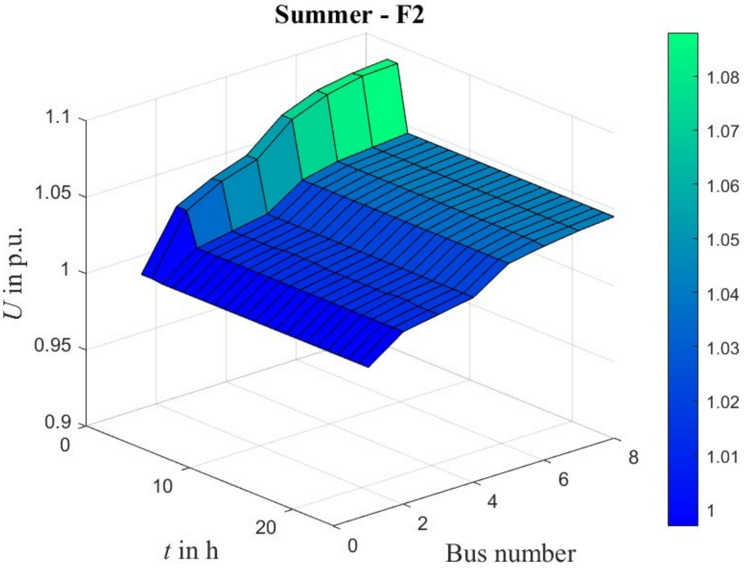

Figure 7.44 Voltage levels for the EC in summer – F2.

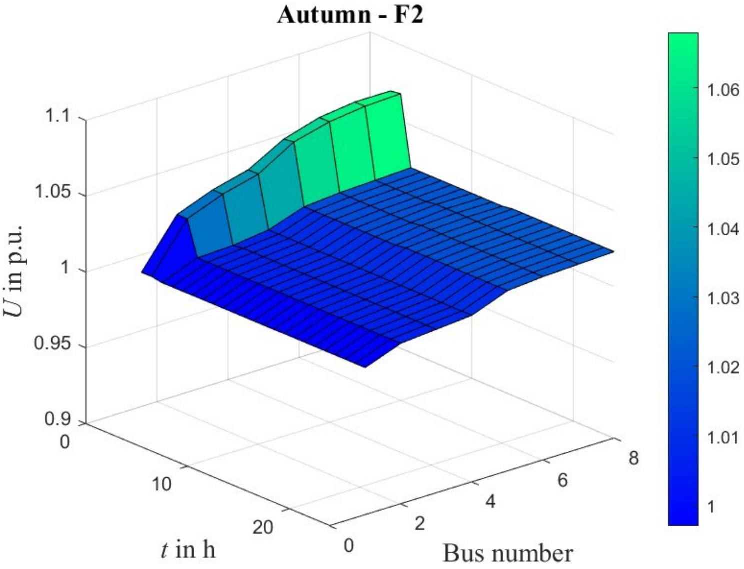

Figure 7.45 Voltage levels for the EC in autumn – F2.

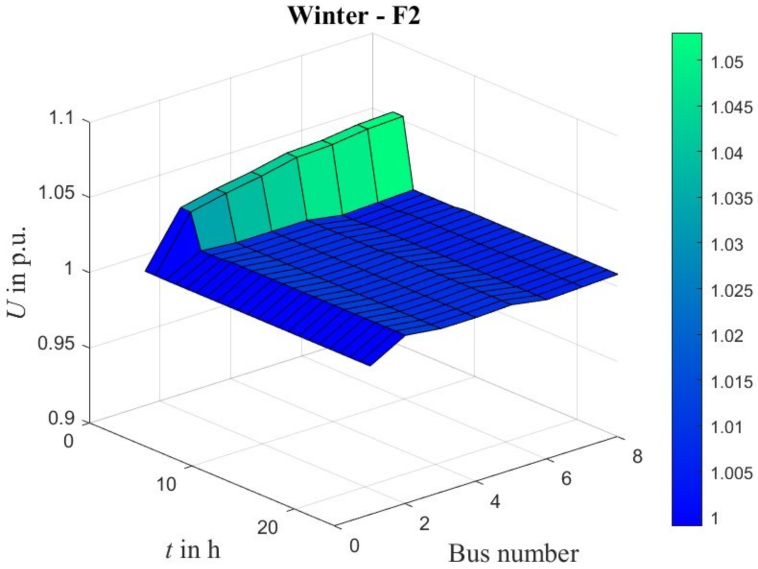

Figure 7.46 Voltage levels for the EC in winter – F2.

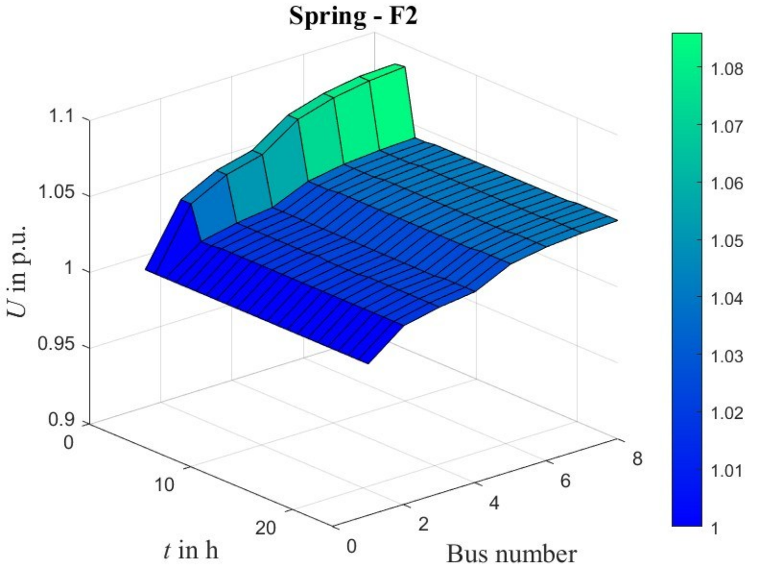

Figure 7.47 Voltage levels for the EC in spring – F2.

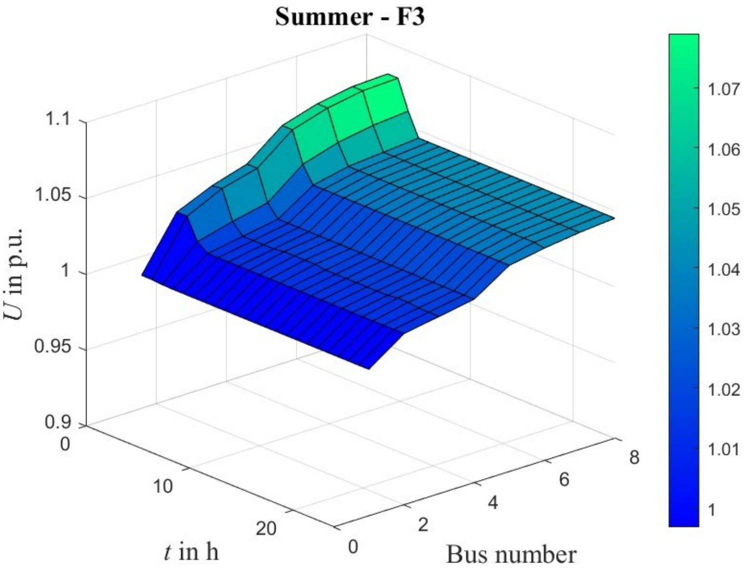

Figure 7.48 Voltage levels for the EC in summer – F3.

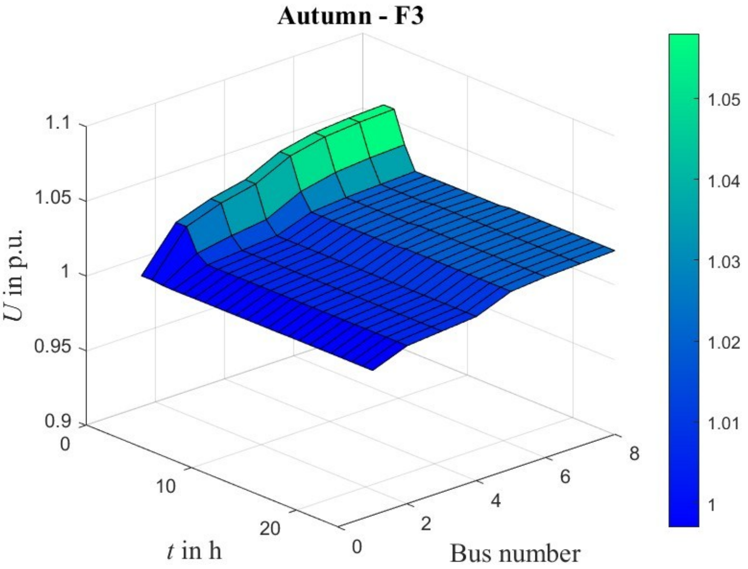

Figure 7.49 Voltage levels for the EC in autumn – F3.

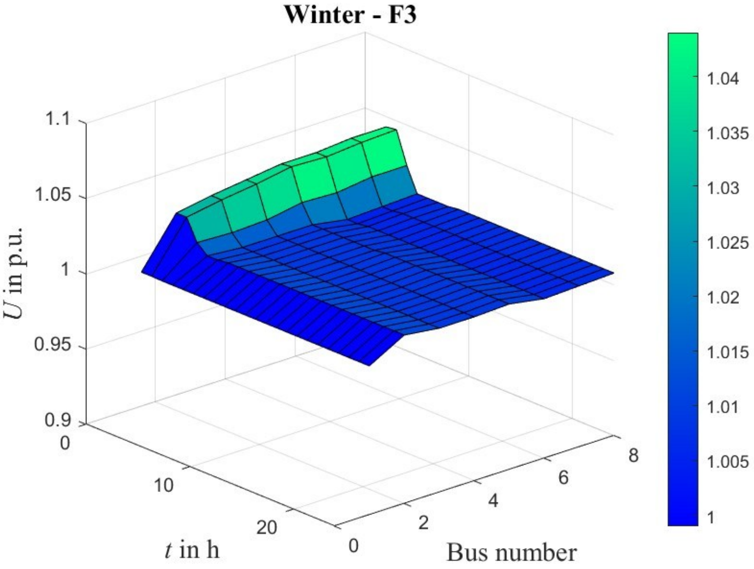

Figure 7.50 Voltage levels for the EC in winter – F3.

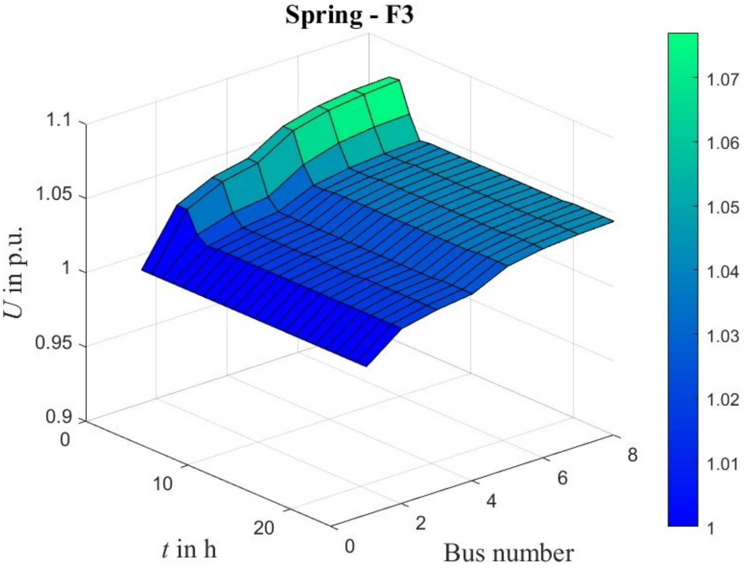

Figure 7.51 Voltage levels for the EC in spring – F3.

In addition, the reference bus maintained its value very close to 1 p.u. throughout the day, acting as a stable point in the system. The other buses that were further away from the transformer, on the other hand, started the day with values around 1.1 p.u. However, in the first few hours, there was a slight drop in voltages, which soon stabilized and remained practically constant until the end of the day, without major fluctuations in their magnitude.

In general, it was possible to identify a trend in the voltage levels of the buses according to their location. Voltages increased slightly as the buses moved further away from the transformer. This behavior was particularly evident in the representative summer, autumn and spring scenarios. In winter, however, voltages exhibited a more stable behavior, with less pronounced variations throughout the day.

When considering all the scenarios analyzed and the voltage results obtained in this dissertation, it is essential to highlight that the voltage levels at the buses remained consistently within the standards established by the applicable regulations. According to the regulations, these levels must be in the safe range between 0.9 and 1.1 p.u. [99], thus guaranteeing the stability and safety of the power system's operation.

At no time during the simulations conducted for the different seasonal scenarios – summer, autumn, winter and spring – were violations observed in the voltage levels stipulated by the standard. This is a clear indication that the system operated within the required technical parameters, demonstrating that the power dispatch strategies implemented were adequate to satisfy the requirements of the EC without compromising the quality of the electricity supply.

Maintaining voltage levels within normative limits also reflects the effectiveness of system planning and configuration. This stability is especially important to ensure the protection of equipment connected to the grid and the continuity of the energy supply, avoiding the risk of failures or damage caused by inadequate voltages.

In the same simulations, the average active power loss was calculated for the EC in every proposed scenario, as depicted in Figure 7.52 and Figure 7.53. The values exhibited minimal variation across the different levels of flexibility but showed more significant differences between the simulated days.

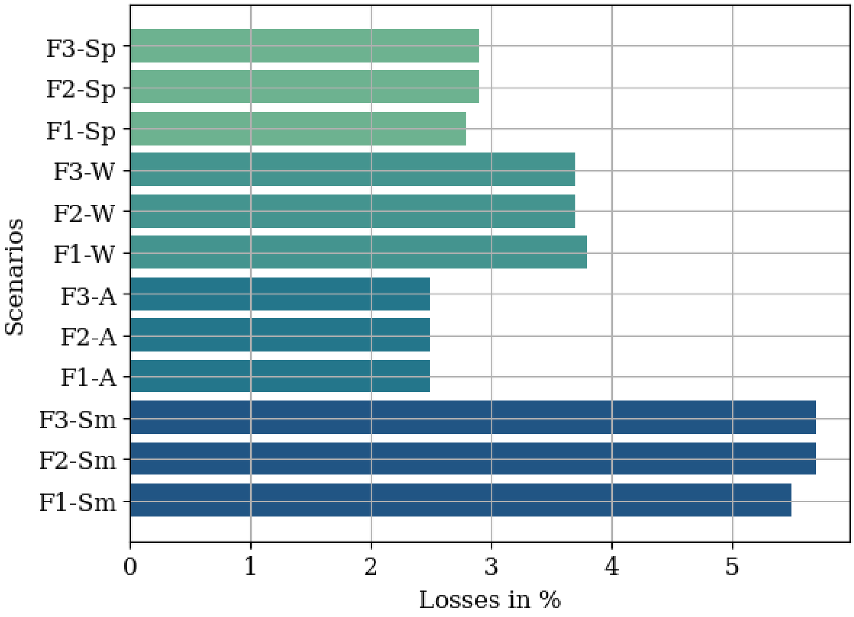

Figure 7.52 Power losses for every proposed scenario.

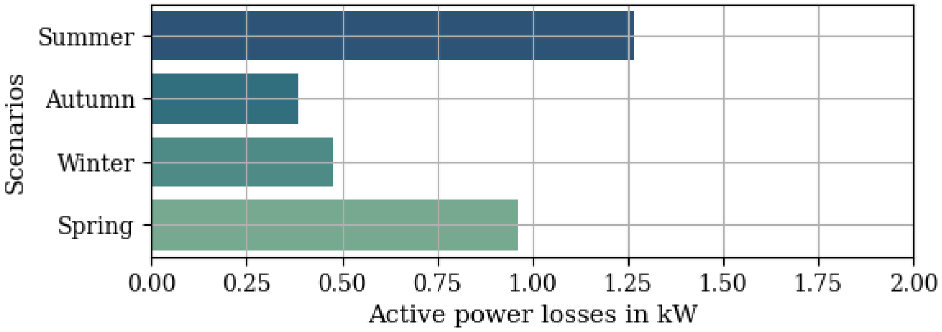

Figure 7.53 Active power losses.

In the summer case study, the average power loss was 5.6 %, while for autumn, it was approximately 3 %. During winter, the average loss decreased to 2.5 %, and for spring, it was 3.7 %. At the distribution level, this level of loss is considered acceptable within standard operational limits. The active power average losses fluctuated within a specific range, between 386 W during the autumn period and 1,267 W during the summer period. These variations in losses are clearly illustrated and depicted in Figure 7.53, providing a visual representation of the data over the different seasons.

8 Conclusion

Climate change is having an impact on various aspects of society, including the power system. Adapting to this new scenario requires structural and operational improvements in order to satisfy the requirements that are progressively being stipulated, as well as guaranteeing an operation that is simultaneously safe, efficient and sustainable. To achieve these objectives, it is essential to implement proposals that include flexible and innovative solutions.

The solutions can include energy storage systems, distributed renewable energy sources and energy markets, which represent important sources of flexibility. These elements contribute directly to the operation and optimization of the power distribution system. In this context, energy communities are a strategic opportunity. By integrating these components, ECs have the potential to become essential sources of flexibility for the power system, offering benefits to both consumers and the distribution grid.

However, in order to fully implement and operate these communities efficiently, it is essential to have clear and consistent regulations to guide their structuring and operation. These regulations must establish specific guidelines and rules for the proper functioning of these systems. As analyzed in Section 3.3 of this study, it was noted that Europe already has robust and well-structured regulations in this regard. However, in Brazil, it is still necessary to have an advance in order to achieve an equivalent level of regulation. This progress is necessary if the country is to take full advantage of the benefits provided by ECs.

After an extensive literature review, which included examining various concepts and consulting a range of scientific articles, it was possible to identify a gap in the existing research. Based on this analysis, the main contributions of this dissertation were defined. An EC was designed to operate at low voltage, integrating components such as a BESS, an EV, PV generation system, wind energy and biogas.

Power dispatch was identified as a fundamental stage in the efficient operation of the EC, and was therefore developed using the MILP optimization technique. This approach enabled the definition of an objective function, along with limits and constraints, with the aim of minimizing operating costs. In addition, priority was given to maximizing the use of available DER.

A three-level flexibility model was developed to allow adaptation to different operating conditions. This model incorporated the definition of initial and final daily SOC, along with weighting coefficients for the charging and discharging operations of the BESS and

EV, even including V2G operation. At the most flexible level, F1, the system has maximum adaptability. The intermediate level, F2, has moderate flexibility, while level F3 is the most conservative and restricted.

The optimization strategy allowed the EC to minimize its costs and maximize its profits, taking advantage of both the surplus energy generated during the day and the high price conditions on the energy market. The sale of energy from both surplus production and battery storage, combined with the purchase of energy from the grid only when necessary or economically advantageous, reflects efficient and economical management of available energy resources.

The comparative graphical analysis between models F1, F2 and F3 clearly highlights the difference in the degree of flexibility proposed. The operational flexibility in the EC progressively decreases from F1 to F3 as the weighting coefficients increase and the initial and final SOC values become more limited.

Therefore, BESS's ability to act at times of peak demand and tariffs demonstrates its strategic importance in the context of EC operation and grid support. It stands out as a vital element that provides flexibility for the system and the grid, improving the efficiency of the power system.

The economic analysis detailed the daily revenues obtained in each scenario, using a pricing system based on real-time tariffs. It was observed that, on the days analyzed, the spring operation presented negative revenue, due to a deficit power balance throughout the day. Despite this, on the other days, the system demonstrated its ability to generate daily profit, proving the economic viability of the proposal.

The results obtained confirm that the system not only fulfilled performance expectations, but also ensured conformity with regulatory requirements throughout all the scenarios analyzed. This consistent performance demonstrates that the operating conditions and management strategies implemented were effective in keeping the network within a safe and reliable operating regime, providing flexibility for those involved.

The four simulated scenarios, which included a representative day of each season, provided satisfactory technical and economic results. In the spring scenario, for example, a condition of high demand and low generation in the EC was simulated. In autumn, the opposite situation was considered, with excess generation and low demand. Even in these extreme conditions, the model was able to optimize power dispatch, ensuring that operating levels remained within the voltage limits set by the technical standards in force. The active power losses also presented acceptable values, not exceeding 6% in any of the scenarios.

When comparing the rule-based method with MILP approach, it becomes clear that each has its advantages. The first method stands out for its simplicity, making it easier to understand and implement. In addition, it requires less computational effort, which can be an advantage in scenarios where computational resources are limited or quick decisions need to be made. However, despite these benefits, the MILP approach has clear economic advantages that cannot be ignored. The difference in EC revenue between the two methods increased between 30 % and 316 % within the days analyzed. By reducing the overall costs associated with the EC, this method proves to be more advantageous in terms of financial results, especially when considering long-term operations.

Regarding incentives, the results clearly demonstrated a significant relationship between flexibility levels, system activity, and reward outcomes. Scenarios with higher levels of flexibility presented greater rewards, rising by an average of 40% from F3 to F1 level. This trend was attributed to the more intense and dynamic activities of the BESS and V2G technologies. Therefore, these results contribute to increased use of flexibility for the energy community.

Finally, the proposed model proved to be viable for implementation in the energy management control of ECs. Its application can make a significant contribution to system and grid flexibility. Depending on the specific objectives of the energy community, one of the three levels of flexibility can be chosen as the main strategy, maximizing the benefits for all those involved and ensuring a more efficient and sustainable operation.

8.1 Future work

As prospects and proposals for future work, there are several opportunities to expand and further develop the analysis conducted in this dissertation. One interesting possibility would be to develop and implement more intermediate levels of flexibility in the proposed model. These new levels could be evaluated in detail to verify their impact on the operational and economic results of the energy community, providing an even more comprehensive view of the system's behavior under different degrees of flexibility.

Another relevant area of study would be to investigate the optimal allocation of the BESS. This could be done by applying advanced optimization methods, considering aspects such as the ideal position of the BESS within the grid, energy efficiency and associated costs. Furthermore, it would be important to assess the impact of the chosen position for the BESS on the voltage levels of the energy community's buses. As the placement of the BESS is adjusted, variations in the voltage levels of the busbars can be significant, altering the operating conditions and efficiency of the system.

To complement the technical analysis, a broader and more in-depth economic assessment can be conducted. Such an analysis could include not only the costs associated with the daily operation of the system, but also the long-term implementation and maintenance costs. Such a study could cover a longer period, enabling a more realistic and detailed assessment of the system's economic viability. By considering costs and revenues over months or years, it would be possible to get a clearer picture of the return on investment and the financial sustainability of the energy community.

Additionally, the impact of different market conditions and incentive policies could be included in this economic analysis. For example, it would be interesting to assess how variations in energy tariffs, government subsidies or the introduction of new regulations would impact the operating costs and profitability of the system. It would allow strategies to be identified to maximize the financial and operational benefits of the EC, adapting the model to the dynamic conditions of the electricity sector.

Therefore, future work could explore both technical and economic analysis, contributing to a more complete understanding of how ECs work and how they can be optimized. These complementary investigations could broaden the scope of the research contributions, helping to turn energy community models into even more efficient, flexible and economically viable ones.

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A Voltage Analysis

The power flow was calculated for the EC considering the scenarios proposed in this dissertation. The results obtained for the voltages in F1 for each bus of the system have been presented graphically and are detailed in Section 7.8. This graphical approach allows a clear and comparative view of the behavior of the voltages over the different simulated conditions.

To complement the analysis, the numerical values corresponding to these voltages have been organized in specific tables for each season. In the case of the representative summer day, the numerical voltage data can be found in Table A.1, where the values recorded on each bus in the system are listed in detail. For autumn, the results obtained have been compiled in Table A.2, which follows the same format.

Similarly, the winter data is presented in full in Table A.3, allowing a specific analysis for this period. Finally, the values for a typical spring day are displayed in Table A.4, concluding the presentation of the results for all the seasons. This set of information provides a comprehensive and accurate view of the behavior of the voltages in the EC bars under the proposed conditions, offering subsidies for a detailed and comparative evaluation between the different scenarios and periods analyzed.

Table A.1 Voltage levels (in p.u.) in EC buses for simulated summer day in F1

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
00:00	1.000	0.999	1.035	1.046	1.053	1.072	1.081	1.087	1.089
01:00	1.000	0.999	1.025	1.033	1.038	1.050	1.052	1.055	1.057
02:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
03:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
04:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
05:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
06:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
07:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
08:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
09:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
10:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
11:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
12:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
13:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
14:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
15:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
16:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
17:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
18:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
19:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
20:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.035	1.036
21:00	1.000	0.999	1.011	1.014	1.017	1.029	1.032	1.034	1.036
22:00	1.000	0.999	1.011	1.014	1.017	1.029	1.031	1.034	1.036
23:00	1.000	0.999	1.011	1.014	1.017	1.029	1.031	1.034	1.036

Table A.2 Voltage levels (in p.u.) in EC buses for simulated autumn day in F1

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
00:00	1	0.9998	1.0350	1.0460	1.0520	1.0690	1.0770	1.0820	1.0820
01:00	1	0.9997	1.0220	1.0290	1.0330	1.0410	1.0430	1.0440	1.0450
02:00	1	0.9996	1.0080	1.0100	1.0120	1.0200	1.0220	1.0230	1.0240
03:00	1	0.9996	1.0080	1.0100	1.0120	1.0200	1.0220	1.0240	1.0240
04:00	1	0.9996	1.0080	1.0100	1.0120	1.0200	1.0220	1.0240	1.0240
05:00	1	0.9996	1.0080	1.0100	1.0120	1.0210	1.0230	1.0240	1.0240
06:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0240
07:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
08:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
09:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
10:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
11:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
12:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
13:00	1	0.9996	1.0090	1.0100	1.0120	1.0210	1.0230	1.0240	1.0250
14:00	1	0.9996	1.0090	1.0100	1.0130	1.0210	1.0230	1.0240	1.0250
15:00	1	0.9996	1.0090	1.0100	1.0130	1.0210	1.0230	1.0240	1.0250
16:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0240	1.0250
17:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0240	1.0250
18:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250
19:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250
20:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250
21:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250
22:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250
23:00	1	0.9996	1.0090	1.0110	1.0130	1.0210	1.0230	1.0250	1.0250

Table A.3 Voltage levels (in p.u.) in EC buses for simulated spring day in F1

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
00:00	1.000	1.000	1.043	1.057	1.064	1.082	1.092	1.098	1.099

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
01:00	1.000	1.000	1.031	1.040	1.045	1.055	1.059	1.061	1.062
02:00	1.000	1.000	1.017	1.022	1.025	1.035	1.039	1.041	1.042
03:00	1.000	1.000	1.017	1.022	1.025	1.035	1.039	1.041	1.042
04:00	1.000	1.000	1.018	1.022	1.025	1.035	1.039	1.041	1.043
05:00	1.000	1.000	1.018	1.022	1.025	1.036	1.039	1.041	1.043
06:00	1.000	1.000	1.018	1.022	1.025	1.036	1.039	1.041	1.043
07:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
08:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
09:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
10:00	1.000	1.000	1.018	1.023	1.025	1.036	1.040	1.042	1.043
11:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
12:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
13:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
14:00	1.000	1.000	1.018	1.022	1.025	1.036	1.040	1.042	1.043
15:00	1.000	1.000	1.018	1.023	1.025	1.036	1.040	1.042	1.043
16:00	1.000	1.000	1.018	1.023	1.025	1.036	1.040	1.042	1.043
17:00	1.000	1.000	1.018	1.023	1.025	1.036	1.040	1.042	1.043
18:00	1.000	1.000	1.018	1.023	1.025	1.036	1.040	1.042	1.044
19:00	1.000	1.000	1.018	1.023	1.026	1.037	1.041	1.043	1.044
20:00	1.000	1.000	1.018	1.023	1.026	1.037	1.041	1.043	1.044
21:00	1.000	1.000	1.018	1.023	1.026	1.037	1.041	1.043	1.044
22:00	1.000	1.000	1.018	1.023	1.026	1.037	1.041	1.043	1.044
23:00	1.000	1.000	1.018	1.023	1.026	1.036	1.041	1.043	1.044

Table A.4 Voltage levels (in p.u.) in EC buses for simulated winter day in F1

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
00:00	1.000	0.999	1.038	1.045	1.049	1.058	1.061	1.065	1.066
01:00	1.000	0.999	1.025	1.028	1.030	1.030	1.026	1.027	1.028
02:00	1.000	0.999	1.011	1.009	1.009	1.009	1.005	1.006	1.007
03:00	1.000	0.999	1.011	1.009	1.009	1.009	1.005	1.006	1.007
04:00	1.000	0.999	1.011	1.009	1.009	1.009	1.005	1.006	1.007
05:00	1.000	0.999	1.012	1.009	1.009	1.009	1.006	1.007	1.007
06:00	1.000	0.999	1.012	1.009	1.009	1.009	1.006	1.007	1.007
07:00	1.000	0.999	1.012	1.009	1.009	1.009	1.006	1.007	1.008
08:00	1.000	0.999	1.012	1.009	1.009	1.009	1.006	1.007	1.008
09:00	1.000	0.999	1.012	1.009	1.009	1.009	1.006	1.007	1.008
10:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
11:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
12:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
13:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
14:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008

Time	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*	*Bus 6*	*Bus 7*	*Bus 8*	*Bus 9*
15:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
16:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
17:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
18:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
19:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
20:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
21:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
22:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008
23:00	1.000	0.999	1.012	1.009	1.009	1.010	1.006	1.007	1.008

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