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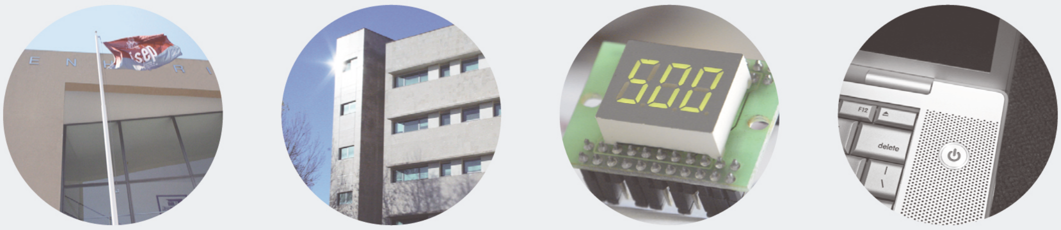

Modelação e Negociação de Flexibilidade em Comunidades de Energia Renovável

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Flexibility Modeling and Trading in Renewable Energy Communities

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“Success is not final, failure is not fatal: it is the courage to continue that counts”

(Winston Churchill)

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Abstract

The progressive replacement of traditional generation resources with intermittent resources has reduced the available supply-side flexibility and increased the need to unlock flexibility on the demand-side. At the same time, the rising electricity consumption in residential buildings requires an analysis of the potential flexibility of the loads within them to contribute to the operation needs of electrical grids. Lastly, regulations governing self-consumption have allowed end consumers to form energy communities based on local electricity markets. This is an additional incentive to define strategies for trading available flexibility at local level, in separate but simultaneously integrated structures within wholesale electricity markets.

The proposed dissertation work focuses on studying the flexibility of energy production and consumption by prosumers within a Renewable Energy Community (REC). The objective is to investigate how residential flexibility can be determined, modeled, and aggregated for trading in a local market created for this purpose. The work to be developed will present a two-stage model that determines residential technical flexibility and establishes a local market only for its transaction.

In the first stage, the optimal scheduling of domestic devices (flexible units or FUs) for each prosumer is determined, serving as a baseline for comparison, along with the technical limits of flexibility (maximum and minimum possible consumption profiles) for each FU.

In the second stage, a market model is established only for flexibility exchanges. The technical flexibility determined in the first stage is offered to the Community Manager (CM) as flexibility offer, with an associated price. This entity acts as an aggregator and simultaneously as the operator of the local market. At this level, the Distribution System Operator (DSO) submits its flexibility requirements for the next day to the CM, who is responsible for executing the clearing process. The pricing of the flexibility offered by prosumers in the market is based on the base energy tariff they are subject to, which corresponds to the cost of their optimal scheduling obtained in the first stage, without considering this flexibility. Therefore, offering flexibility becomes an incentive to reduce prosumers energy costs or increase their utility, complementing their mere participation in energy markets.

A case study based on a renewable energy community with a strong penetration of emerging technologies is used to validate and demonstrate the relevance of the proposed approach in terms of determining and activating residential FU flexibility. The obtained results show that participation in the local flexibility market leads to a reduction in prosumers energy costs, around 4.5%, in average. It can be an incentive for prosumers to join RECs that would not only have local energy trading structures but also mechanisms for negotiating and sharing flexibility. In addition, it was evidenced that the impact of electric vehicle chargers and battery energy storage systems on the total flexibility offered and accepted in the market is much greater than that the impact of other small loads studied. This not only constitutes an incentive for the study of the operational flexibility of these resources but also for investments in these emerging technologies.

Keywords

Local Flexibility Market, Available Flexibility Modelling, Prosumer Flexibility, Flexibility Community Market.

Resumo

A substituição progressiva dos recursos de geração tradicionais por recursos intermitentes tem reduzido a flexibilidade disponível do lado da oferta e aumentado a necessidade de desbloqueá-la do lado da procura. Ao mesmo tempo, o aumento do consumo de eletricidade nos edifícios residenciais obriga a que seja analisada a flexibilidade potencial das cargas que o constituem, de modo a contribuir para as necessidades de operação das redes elétricas. Por último, a regulamentação do autoconsumo, tem permitdo aos consumidores finais constituir comunidades energéticas beaseadas em mercados locais de eletricidade. Isto torna ainda mais importante a definição de estratégias para comercializar a flexibilidade disponível a esse nível, em estruturas de mercado local separadas, mas simultaneamente integradas nos mercados grossistas de eletricidade.

O trabalho proposto para dissertação assenta no estudo da flexibilidade da produção e consumo de energia por parte dos prosumidores de uma Comunidade de Energia Renovável. O objetivo é estudar como a flexibilidade residencial pode ser determinada, modelada e agregada de modo a ser transacionada num mercado local criado para esse fim. Assim, o trabalho a ser desenvolvido apresentará um modelo de dois estágios que determina a flexibilidade técnica residencial e cria um mercado local exclusivo para transaciona-la.

Numa primeira fase, determina-se o escalonamento óptimo dos dispositivos domésticos (unidades flexíveis ou UF) de cada prosumidor, o que constitui uma *baseline* de comparação, bem como os limites técnicos de flexibilidade (perfis de consumo máximos e mínimos possíveis) de cada UF.

Num segundo estágio, é estabelecido um modelo de mercado apenas para trocas de flexibilidade. A flexibilidade técnica determinada no primeiro estágio é disponibilizada ao Gestor de Comunidade (CM), enquanto oferta de flexibilidade, com um preço associado. Esta entidade desempenha as funções de agregador e simultaneamente de operador do mercado local. A este nível, o Operador do Sistema de Distribuição (ORD) submete os seus requisitos de flexibilidade, para o dia seguinte, ao CM, que é responsável pelo executar o *clearing*. A precificação da flexibilidade oferecida pelos prosumidores em mercado é feita com base no valor da tarifa base de energia a que estão sujeitos, que corresponde ao custo do seu escalonamento ótimo, obtido no primeiro estágio, que não considera essa mesma flexibilidade. Portanto, oferecer flexibilidade torna-se um incentivo para reduzir os custos energéticos dos prosumidores ou aumentar a sua utilidade, o que complementa a sua mera participação nos mercados de energia.

Um caso de estudo baseado numa comunidade de energia com forte penetração de tecnologias emergentes é utilizado e valida a metodologia desenvolvida. Para além disso é evidenciada a relevância da abordagem proposta em termos de determinação e ativação da flexibilidade de UFs residenciais os impactos das mesmas no fecho de mercado. Os resultados evidenciam que participação no mercado local de flexibilidade induz uma redução dos custos energéticos dos prosumidores, na casa 4.5%, em média. O impacto dos carregadores de veículos elétricos e dos sistemas de armazenamento de energia em baterias na flexibilidade total oferecida e aceite em mercado é muito superior ao de outras pequenas cargas estudadas. Tudo isto pode vir a resultar num incentivo ao investimento nos recursos referidos, bem como à associação de prosumidores em comunidades de energia renovável, onde para além de estruturas locais de comercialização de energia, existam outras que permitam a negociação e partilha de flexibilidade.

Palavras-Chave

Mercado Local de Flexibilidade, Modelação da Flexibilidade Disponível, Flexibilidade dos Prossumidores, Flexibilidade de uma Comunidade de Energia

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Acronyms

BESS – Battery Energy Storage System

BRP – Balance Responsible Party

CEC – Citizens Energy Community

CM – Community Manager

CSC – Collective/Community Self -Consumption

DER – Distributed Energy Resources

DSO – Distributor System Operator

EE – Energy Efficiency

EGAC – Entidade Gestora do Autoconsumo Coletivo

EU – European Union

EV – Electrical Vehicle

FU – Flexible Unit

GHG – Greenhouse gas

IEMD – European Directive on Common Rules for the Internal Market for Electricity

LEM – Local Energy Market

LFM – Local Flexibility Market

P2P – Peer to Peer

PHEV – Plug-In Hybrid Electric Vehicle

RDF – Redes de Distribuição Fechadas

RES – Renewable Energy Sources

REC – Renewable Energy Community

RED II – European Directive on Promoting the Use of Energy from Renewable Sources

SOC – State of charge

TE – Transactive Energy

VPP – Virtual Power Plant

Nomenclature

Notation		Description	[Unit]
T	–	Set of simulation periods (t).	-
C	–	Set of prosumers (c).	-
R	–	Set of flexibility requesters (r).	-
LSV	–	Set of load-shiftable-volume flexible units (lsv).	-
$W_{lsv,c}$	–	Set of periods in which a flexible unit (lsv) cannot activate flexibility.	-
$\lambda_{c,t}^{buy}$	–	Price of energy purchased by HEMS (local energy market price), for each prosumer (c), in period (t).	[€/kWh]
$\lambda_{c,t}^{sell}$	–	Price of energy sold by HEMS (feed-in tariff), for each prosumer (c), in period (t).	[€/kWh]
$E_{c,t}^{C}$	–	Forecast of prosumer (c) consumption profile, in period (t).	[kWh]
$E_{c,t}^{G}$	–	Forecast of prosumer (c) self-consumption profile, in period (t).	[kWh]
$E_{c}^{B,N}$	–	Nominal capacity of prosumer (c) BESS.	[kWh]
$E_{c}^{EV,N}$	–	Nominal capacity of prosumer (c) EV battery.	[kWh]
$SOC_{c}^{B\ min}$	–	Minimum state of charge of prosumer (c) BESS.	[%]
$SOC_{c}^{B\ max}$	–	Maximum state of charge of prosumer (c) BESS.	[%]
$SOC_{c}^{EV\ min}$	–	Minimum state of charge of prosumer (c) EV battery.	[%]
$SOC_{c}^{EV\ max}$	–	Maximum state of charge of prosumer (c) EV battery.	[%]
$\eta_{c}^{B\ Ch}$	–	Charging efficiency of prosumer (c) BESS.	[%]

$\eta_c^{B\ Dch}$	–	Efficiency of discharge of the prosumer's (c) BESS.	[%]
$\eta_c^{EV\ Ch}$	–	Efficiency of charging of the prosumer's (c) EV battery.	[%]
$EV_{c,t}^{trip}$	–	Energy requested by the prosumer's (c) EV user, in period (t).	[kWh]
$EV_{c,t}^{connection}$	–	Period of connection of the prosumer's (c) electric vehicle to the grid.	-
$P_c^{B\ Max}$	–	Maximum power of the BESS's inverter of the prosumer (c).	[kW]
$P_c^{EV\ Max}$	–	Maximum power of the prosumer's (c) EV inverter.	[kW]
$E_{c,t}^{SUP}$	–	Energy acquired from the grid, by the prosumer (c), in period (t).	[kWh]
$E_{c,t}^{SUR}$	–	Energy sold to the grid, by the prosumer (c), in period (t).	[kWh]
$E_{c,t}^{CMET}$	–	Energy consumed by the prosumer (c), in period (t).	[kWh]
$E_{c,t}^{B\ Ch}$	–	Energy charged by the prosumer's (c) BESS, in period (t).	[kWh]
$E_{c,t}^{B\ Dch}$	–	Energy discharged by the prosumer's (c) BESS, in period (t).	[kWh]
$E_{c,t}^{EV\ Ch}$	–	Energy charged by the prosumer's (c) EV battery, in period (t).	[kWh]
$E_{c,t}^{B}$	–	Energy stored in the prosumer's (c) BESS, in period (t).	-
$E_{c,t}^{EV}$	–	Energy stored in the prosumer's (c) EV battery, in period (t).	-
$\lambda_{lsv,c,t}^{UP}$	–	Market offer price for the flexibility UP of a flexible unit (lsv) at time (t), presented in the market by prosumer (c).	[€/kWh]
$\lambda_{lsv,c,t}^{DW}$	–	Market offer price for the flexibility DW of a flexible unit (lsv) at time (t), presented in the market by prosumer (c).	[€/kWh]
$F_{r,t}^{UP\ needs}$	–	Flexibility UP requirement presented in the market by the requester (r) at time (t).	[kWh]
$F_{r,t}^{DW\ needs}$	–	Flexibility DW requirement presented in the market by the requester (r) at time (t).	[kWh]

$H_{c,lsv}^{DW\,max}$	–	Maximum duration of a period of reduced consumption for one flexible unit (lsv) of the prosumer (c).	-
$H_{c,lsv}^{UP\,max}$	–	Maximum duration of a period of increased consumption for one flexible unit (lsv) of the prosumer (c).	-
$G_{c,lsv}^{DW\,max}$	–	Maximum number of periods of consumption reduction for one flexible unit (lsv) of the prosumer (c).	-
$G_{c,lsv}^{UP\,max}$	–	Maximum number of periods of increased consumption for one flexible unit (lsv) of the prosumer (c).	-
$H_{c,lsv}^{DW\,min}$	–	Minimum time interval between two periods of consumption reduction for the flexible unit (lsv) of the prosumer (c).	[h]
$H_{c,lsv}^{UP\,min}$	–	Minimum time interval between two periods of increased consumption for a load unit lsv, from the prosumer (c).	[h]
$E_{lsv,c,t}^{baseline}$	–	Baseline consumption for a flexible unit (lsv), from the prosumer (c), in period (t).	[kWh]
$F_{lsv,c,t}^{min}$	–	Minimum allowed consumption for the flexible unit (lsv), from the prosumer (c), in period (t).	[kWh]
$F_{lsv,c,t}^{max}$	–	Maximum allowed consumption for the flexible unit (lsv), from the prosumer (c), in period (t).	[kWh]
$F_{lsv,c,t}^{UP}$	–	Flexibility UP of flexible unit (lsv) from prosumer (c) activated by the market operator after market clearing at time (t).	[kWh]
$F_{lsv,c,t}^{DW}$	–	Flexibility UP of flexible unit (lsv) from prosumer (c) activated by the market operator after market clearing at time (t).	[kWh]
$\delta_{lsv,c,t}^{DW\,start}$	–	Binary variable -> 1 if the consumption reduction of a flexible unit (lsv) can starts in *t*, otherwise 0.	-
$\delta_{lsv,c,t}^{DW\,run}$	–	Binary variable -> 1 if the consumption reduction of a flexible unit (lsv) can be occurring in *t*, otherwise 0.	-
$\delta_{lsv,c,t}^{DW\,end}$	–	Binary variable -> 1, if the reduction of consumption a flexible unit (lsv) can end *t*, otherwise 0.	-

$\delta_{lsv,c,t}^{UP\ start}$	–	Binary variable -> 1, if the increase in consumption of a flexible unit (lsv) can begin in *t*, otherwise 0.	-
$\delta_{lsv,c,t}^{UP\ run}$	–	Binary variable -> 1, if the increase in consumption of a flexible unit (lsv) can be occurring in *t*, otherwise 0.	-
$\delta_{lsv,c,t}^{UP\ end}$	–	Binary variable -> 1, if the increase in consumption of a flexible unit (lsv) can end in *t*, otherwise 0.	-

1. INTRODUCTION

This chapter exposes the motivation and objectives of the work developed in the scope of this dissertation. More precisely, at first, the context in which this work is done and the motivation to develop it are exposed. The study focuses on determining the flexibility of a residential prosumer and its negotiation strategies in a Renewable Energy Community (REC) environment. Subsequently, the primary goals of this project are detailed, followed by a mention of other related projects and publications. At last, the structure and organization of this document are detailed.

1.1. CONTEXT AND MOTIVATION

For many years, the electrical grid had a structure that favored the centralization of production, on a large scale, far from the consumption centers [1]. The lack of storage solutions has always forced the maintenance of a balance between production and consumption. Consequently, operational reserves were used to cover any difference between generated and consumed energy [2].

In recent times, the appearance of new generation technologies, of an intermittent nature, has reduced the percentage of energy, coming from dispatchable sources, present in the energy mixes of the most developed countries [1]. This implies a growing need to carry out a "dynamic balancing" of the load, both on the supply side and on the demand side.

However, the International Energy Agency (IEA) argues that demand-side activities should always be the first choice in all energy policy decisions [3].

On the demand side, residential consumption (in buildings and houses) constitutes a large percentage of the energy currently demanded. In Portugal, this type of consumption represents about 46.4% of the total energy consumed [4] and in the United States, this value varies between 30 and 40% [2]. Some Demand Response (DR) programs have already been applied to this significant part of energy consumption [5]. These programs are characterized by the manipulation of the energy consumption of different resources, always maintaining the user's comfort. However, the emergence and proliferation of distributed energy resources (DER) (solar photovoltaic (PV), Electric Vehicles (EV), Battery Energy Storage Systems (BESS), Combined Heat and Power systems (CHP), etc.) combined with the rescheduling of the traditional white goods appliances (e.g., washing machine, dishwasher and dryer machine), allow a reduction of consumption and, at the same time, an grid capacity increase and some ancillary services satisfaction. Therefore, exploring the use of these devices' flexibility is a cheaper alternative to increasing the generation capacity and the size of the electrical grid to respond to those new paradigms [6].

Currently, the management of residential flexibility, as a form of DR, is facilitated through advances in automation, namely with the emergence of communication modules embedded in different appliances [7], [8]. Automatic programming of loads and user engagement can be performed by a centralized resource management system, such as Home Energy Management Systems (HEMS). This automation can also allow the implementation of effective and acceptable dynamic prices in the real-time electricity markets [9]. This would be difficult to execute manually. In addition, a considerable growth of DER, at the residential level, as predicted in [10], will boost the emergence of markets in which the commodity transacted will be the flexibility of these resources [11].

These flexibility markets fall within the provisions of Article 16th of the European Union Directive 2019/944 of 5 June 2019 [12], which defines common rules for electricity markets. In this article, the concept of Citizen Energy Communities (CEC) is defined. Point 3 of the article argues that all citizens should have free access to electricity markets and be able to participate in them as buyers or sellers of energy, directly to or through aggregators. Therefore, the significant presence of DER and appliances equipped with automation devices at the local level facilitates the exploration of flexibility in these communities.

There are already several projects of market structures in the literature for the local trade of energy and system services that even address flexibility. According to [13], they can be divided into two large groups:

(i) The implicit flexibility in energy commercialization in distribution networks based on Peer-to-Peer (P2P) trading schemes: models that use decentralized optimization to maximize the welfare of prosumers that share information between themselves and the market operator [14], [15]; models that organize prosumers according to their social class [16]; two-stage models that allow prosumers to participate in day-ahead and real-time market structures [17], [18]; models that predict bilateral contracts at the margin of the local market [19]; and other models.

(ii) Flexibility is traded within a dedicated market structure as a service provided to grids, large consumers, and communities. Models are developed where the Distribution System Operator (DSO) can request the flexibility it anticipates to mitigate overvoltage in the bus and overloads in the lines [20], and the Balance Responsible Party (BRP) acquires flexibility to balance energy production and consumption in its portfolios [21].

Both approaches aim to explore the main benefits of sharing energy flexibility among community members. Models based on (i) are the most found in the recent literature. A large part of the published works secondarily addresses flexibility exchanges and only see them as a benefit of decentralized production and local energy market models. Moreover, the term flexibility is treated too abstractly in literature: its definition is ambiguous, and despite the existence of metrics that allow for its quantification at the residential level, they are often disconnected from the proposed local market models.

1.2. OBJECTIVES

The decarbonization of the energy system cannot be performed without the use of the inherent flexibility of residential consumers and prosumers. Energy communities will play a significant role in this context, allowing a more active role of consumers and prosumers in the energy system. However, the definition, determination, and negotiation of such flexibility is still an object of study for several reasons. Thus, the following research challenges can be stressed:

- The flexibility concepts and definitions related to residential DER and appliances have been ambiguously defined in the literature. The different characteristics of DER and appliances are related to different types of flexibility making it difficult to have straightforward definitions to support all aspects;

- The way this flexibility can be determined and used through HEMS, considering the different characteristics while ensuring interoperability between the models;

- How flexibility, once quantified, can be applied in a local market as a service provided to that market and the upstream distribution grids.

In this context, this dissertation offers a humble contribution to the definition, determination, and negotiation of prosumer flexibility in energy communities and market environments. More precisely, the specific objectives defined for this dissertation were the following:

- Identify the key aspects of residential prosumer's flexibility for their integration into local flexibility markets;

- Research, design and development of a model for technically quantifying the available flexibility at the residential (prosumer point of view) level, accounting for the different DER and appliance characteristics;

- Design and development of negotiation strategies and models for the available flexibility at the prosumer and energy community level. Such models must be able to consider the social welfare of the community as well as the individual prosumer’s energy costs;

1.3. Related Projects and Publications

The work developed in the scope of this dissertation partially concerns the objectives and results of three research projects, namely:

- BATERIAS2030 – As baterias como elemento central para a sustentabilidade urbana (POCI-01-0247-FEDER-046109);

- DECARBONIZE – Development of strategies and policies based on energy and non-energy applications towards CARBON-neutral cities via digitalization for citizens and society (NORTE-01-0145-FEDER-000065);
- DECMERGE – Decentralized decision-making for multi-energy distribution grid management (2021.01353.CEECIND);

The developed work has resulted in the writing of a scientific paper, namely:

- João C. Agrela, Igor Rezende, Tiago Soares, Clara Gouveia, Ricardo Silva, José Villar, "Flexibility modeling and trading in renewable energy communities", 19th International Conference on the European Energy Market (EEM), Lappeenranta, Finland, 6-8 June, 2023. DOI: 10.1109/EEM58374.2023.10161931

1.4. Structure of the Dissertation

This thesis is organized into five chapters, whose content is summarized next.

Chapter 2 reviews the state of the art related to energy communities, their regulation, classification, and organization, existing electricity market models, metrics for quantifying residential flexibility found in the literature, and already formulated models for negotiating energy flexibility at a local level.

Chapter 3 presents the problem to be solved and defines the methodology to be followed for its resolution. At the same time, the mathematical formulation used for modeling the solution is described.

Chapter 4 comprises the validation of the developed models. It begins with an illustrative example in which the main metrics are described in detail and ends with a case study in which a REC with a high penetration of emerging resources is examined.

Finally, Chapter 5 is devoted to presenting the main conclusions of the work, followed by the possibilities that can be addressed in related future work.

2. STATE OF ART

The state of the art in energy flexibility on the demand side revolves around energy communities and local electricity markets. These groups of consumers collectively manage energy consumption and production, while local electricity markets allow for electricity exchange between producers and consumers. Energy communities and local markets are key to enhancing energy flexibility and enabling consumers to benefit from reduced costs while improving grid stability and renewable energy integration. Ongoing research is developing new models for understanding and implementing these concepts.

This chapter aims to provide a thorough review of the state of the art of the main topics related to this dissertation. Firstly, energy communities are discussed, namely their legal aspects and the different ways they can be classified. Next, the main local electricity market models are reviewed and some of their unique features are defined. Finally, demand-side flexibility is addressed, including the existing metrics for quantifying it and local market models for its exchange.

2.1. ENERGY COMMUNITIES

The energy sector is permanently undergoing upheaval due to climate change and the pursuit of carbon neutrality [22]. One of the changes that can be made is to integrate DER into consumer facilities, enabling them to self-consume the energy they produce and even inject their surplus into the grid. In this way, they become known as prosumers [23] and have access to several benefits, including a real decrease in their energy costs. It is reasonable to anticipate that consumers will become more integrated into Energy Communities, which have a variety of players and a high level of technical sophistication, in the not-too-distant future [24].

This section addresses, in a generic way, the concept of energy community. Firstly, the legal framework that communities have in the European Union and under Portuguese law is described. Subsequently, a characterization of the main aspects related to the structure of energy communities is made: the actors who participate in them are presented and the communities are classified according to their purpose, their organizational structure and the activities they carry out.

2.1.1. LEGAL FRAMEWORK

The European Union (EU) enacted legislation to provide a legal framework for the promotion and acceptance of Renewable Energy Sources (RES) within the community, as well as to structure an internal electricity market geared toward future challenges.

In July 2018, the European Directive on Promoting the Use of Energy from Renewable Sources (RED II) underwent reformulation, creating a unified framework for the promotion of these resources. In addition to other financial and environmental considerations, this agreement sets as the target a share of energy from RES to be attained by the year 2030 [25]. The June 2019 Directive on Common Rules for the Internal Market for Electricity (IEMD) establishes rules to be applied at various stages of the electricity system to create a truly integrated, competitive, and transparent electricity market that is focused on the consumer and as flexible as possible [26].

The concepts of "community" and "energy share" are mentioned and defined in both documents. Even though RED II and IEMD use the words "Communities of Renewable Energy Community" (REC) and " Citizen Energy Community " (CEC), respectively, they exhibit some agreement in their respective definitions in practice. The diagram in Figure 1 allows for the comparison of the key topics covered in both documents, as well as the creation of a link between the ideas raised.

Both RED II and IEMD define an energy community as a legal entity that seeks to benefit its members and the places in which they operate, both economically and socially. It is formed and must be effectively controlled by its members, who can be natural persons, small companies, or local entities such as municipalities.

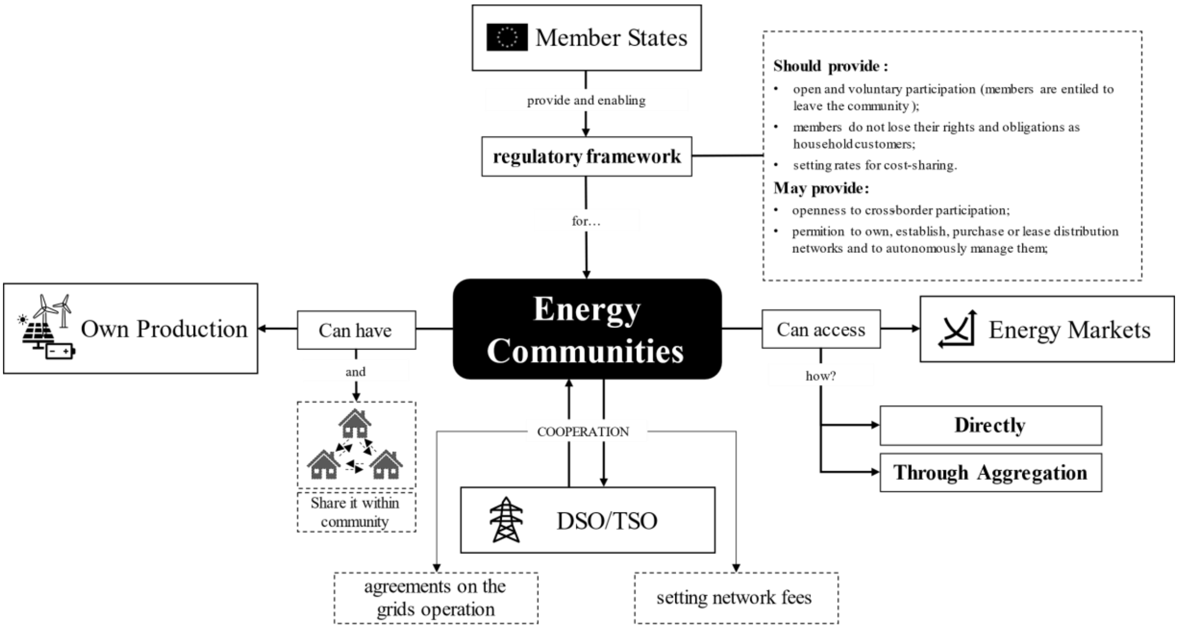

Figure 1. Legal framework for energy communities based on the European RED II [25] and IEMD [26] directives.

The relationships depicted in Figure 1 are based on community members' voluntary participation and the markets' and network operators' non-discriminatory stance. Participation in production activities is allowed, and production using RES is even encouraged. It is also feasible to take part in additional operations including the distribution, commercialization, aggregation, and storage of energy.

Despite all, some distinctions between CER and CEC must be considered, which are compiled in Table 1 [29], [30].

June 2021 has been set as the deadline for Member States to incorporate RED II's provisions into their domestic legislation, according to [23]. The IEMD, on the other hand, is silent on transposition deadlines, which should, in general, not exceed two years [27]. However, under Decree-Legislation number 15/2022 of January 14th, which establishes the organization and operation of the National Energy System [28], Portugal has already transposed the text of both aforementioned directives, jointly.

Table 1. Distinction between “Renewable Energy Communities” and “Citizen Energy Communities” [29], [30].

	Renewable Energy Communities	**Citizens Energy Communities**
Geographic Location	Close to renewable projects	No physical limits
Developed Activities	Generation, commercialization, storage, and supply of energy from renewable sources	Generation, distribution, commercialization, consumption, aggregation, energy storage, electric vehicle (EV) charging, energy efficiency (EE), and others
Generation Technologies	Renewable technologies	All technologies
Members and shareholders	Small end energy users	Energy users and companies (non-energy related) of any size

The national decree-law upholds *ipsis verbis* the definitions of "Renewable Energy Communities" and "Citizens Energy Communities". Despite this, some peculiarities in the transposition deserve to be mentioned, such as:

- The RECs and CECs take on the role of Management Entity of Collective Self-Consumption (EGAC);

- Members of a community have access to energy markets (completely and without discrimination), as shown in the schematic in Figure 1, as well as the ability to make bilateral contracts directly or through an aggregator;

- The right for communities to be owners or tenants of Closed Distribution Networks (RDF) is provided.

- The community is responsible for paying the Grid Access Tariffs, which are set by the Entidade Reguladora dos Serviços Energéticos (ERSE) and are based on the voltage level of the connection.

2.1.2. ENERGY COMMUNITIES STRUCTURE

Regulatory changes have motivated existing energy communities to shift their focus toward the market. As a result, the different stakeholders often have conflicting goals, which can make it difficult to design and organize the community [31]. This tension often pits the community against energy providers, grid operators, or government bodies [32].

In the literature review, the individuals in an energy community are referred to as actors. An actor is defined as all entities that conform to the definition outlined in Table , under the section for members and stakeholders. The part these actors play depends on various factors, such as the community's purpose, its organizational structure, and the role of legal entities.

Table 2 categorizes the different actors into three main groups and summarizes the tasks performed by each. The interaction among actors is influenced by the features of the communities they are a part of [30]. Numerous authors have proposed various methods for categorizing energy communities based on various characteristics. In subtopics 2.1.3, 2.1.4 and 2.1.5, communities are classified considering the following aspects:

- Purpose (single or multi-purpose) and location (place-based or non-place-based);
- Organization (centralized, decentralized, or distributed);
- Activities (energy management, energy generation, or self-consumption).

Table 2. Description of the functions played by the various players in the energy sector (adapted from [30]).

Actor	Function
Consumer	• Beneficiary of a service (energy or otherwise) provided by one of the other actors. • It is not required to have its own generation.
Energy Service Provider	• Any entity that provides energy-related services (generation, distribution, storage, equipment maintenance, aggregation, …). • May own and use infrastructure related to energy generation, distribution, storage, and information and communication technologies (ICT). • When prosumers are net generators, they can be considered energy service providers. • Not to be confused with energy service providers, energy companies, or energy suppliers.
Initiator	• Actors who coordinate and organize a community project. • May not be a beneficiary of the community energy service. • Consumers and prosumers can act as initiators.

2.1.3. CLASSIFICATION BASED ON PURPOSE AND LOCATION

Several technical factors contribute to the categorization of energy communities. In [33], two sets of options are examined for this categorization, resulting in a 4-cell matrix shown in Figure 2. Legally, as explained in Table 1, one of the distinctions between Renewable Energy Communities (RECs) and Energy Communities of Consumers (CECs) is their geographical location. CECs have no specific geographical restrictions, unlike RECs.

Based on this, local and non-local communities can be differentiated. Local communities are limited to a specific geographic area, while non-local communities are not.

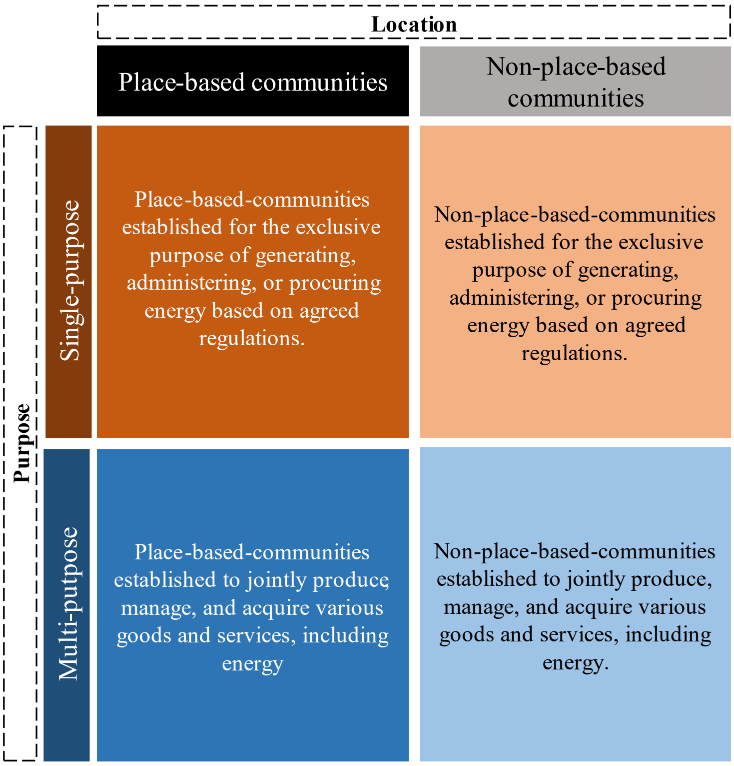

Figure 2. Categorization of energy communities based on their purpose and location (adapted from [33]).

Members in non-place-based energy communities have no physical connection, allowing for more diverse and flexible formats. In these communities, members don't have to own energy equipment and infrastructure [33]. Place-based communities, on the other hand, may be confined to condominiums, residential neighborhoods, or larger geographical areas where the community resides, obtains, transforms, and uses its energy resources [34]. In these communities, shared use of energy infrastructure and equipment is common and owned by the community. Members in non-place-based energy communities have no physical connection, allowing for more diverse and flexible formats. In these communities, members don't have to own energy equipment and infrastructure [33]. Place-based communities, on the other hand, may be confined to condominiums, residential neighborhoods, or larger geographical areas where the community resides, obtains, transforms, and uses its energy resources [34]. In these communities, shared use of energy infrastructure and equipment is common and owned by the community.

The authors in [33] also differentiate communities based on their purpose. Some communities are established solely for energy purposes, while others have a wider range of objectives. As a result, single-purpose and multi-purpose communities can be distinguished. Single-purpose communities are governed by rules exclusively designed for managing energy production, marketing, and consumption. On the other hand, multi-purpose communities allow for the sharing of other goods and services, which creates greater operational complexity [33].

2.1.4. CLASSIFICATION BASED ON THE ORGANIZATION

The authors in [35] provide a classification of energy communities based on their organizational structure. Hyytinen et al., 2015 [36] predict that energy services in the future will need a more prominent role from communities, cities, and municipalities, requiring a balance between centralized and distributed energy production. Figure 3 displays three different structures of energy communities: centralized, decentralized, and distributed. It illustrates the actual and virtual power flows among the different community types, as well as the relationship between various generation units (such as utility power plants, community power plants, virtual power plants, and self-generation) and local consumption units.

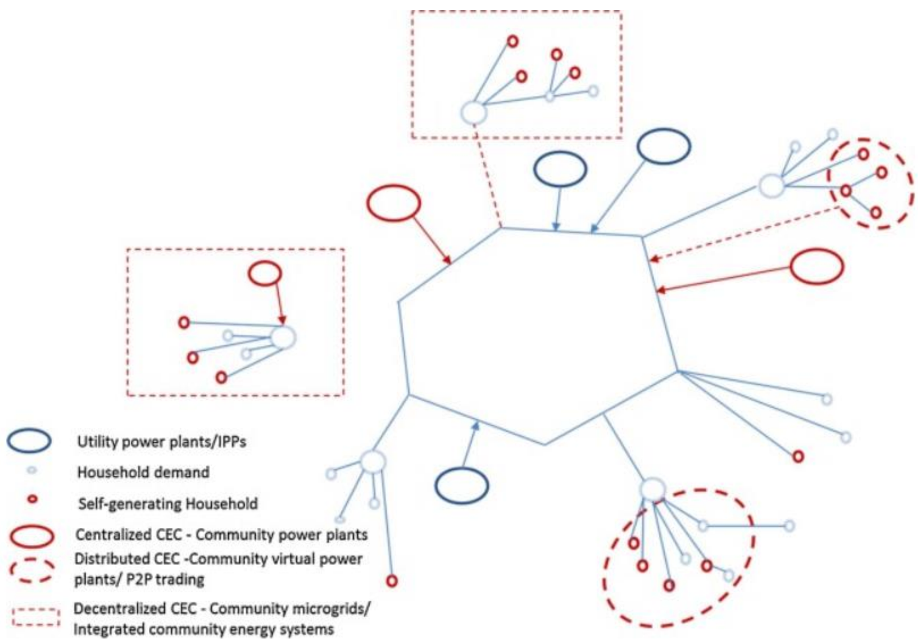

Figure 3. Energy community network typology – centralized, distributed, and decentralized [35].

In a centralized grid, a select group of actors holds power and control, regardless of their density [35]. Traditional centralized systems, such as large-scale energy production and national electrical grids, are dominated by dominant concessionaires [37]. A centralized energy community is distinct in that it can easily integrate with current centralized infrastructure schemes [35]. Its defining characteristics include:

- High level of cohesion;
- Direct connection among all members;
- Shared goals among all members;
- Centralized governance and decision-making structures;

Members' access and interaction with external entities are contingent upon central management bodies. Distributed power generation involves small-scale power generation located near the areas where it is used [16]. In a distributed energy community, members possess individualized distributed generation. According to [35], this definition encompasses communities whose members may not be geographically close. The main characteristics of a distributed energy community include:

- Presence of partially permeable and transitory borders linked by transversal connections;
- Utilization of intelligent technologies to overcome geographic limitations [38];
- Members make decisions individually based on their own preferences and goals, within a virtual community;
- Presence of a controlling or network management entity (an energy supplier or user) acting as an intermediary for internal and external communication;
- Structure based on hubs managed by a technology company that provides a platform and sets rules for services;
- Use of Virtual Power Plants (VPP) and P2P trading platforms;
- Possibility of utilizing open-source platforms such as blockchain instead of a broker to facilitate transactions.

Decentralized energy communities generate and consume energy locally for self-sufficiency, either connected or disconnected from the main grid [35]. These communities utilize distributed, small-scale energy production [39] and are crucial for a cleaner and lower-carbon energy system compared to centralized systems [40], [41]. The main features of these communities include [35]:

- Limited geographical membership;
- Ownership of energy resources and distribution infrastructure by members of the community as a group;
- Strong cohesion and a shared vision among members;
- The presence of new or reconfigured network infrastructure;
- Complex technological requirements, such as microgrids and smart meters;
- A governance model that involves key stakeholders, community members, and service providers.

The three energy community models have similarities, but also present distinct opportunities and challenges. At first glance, centralized communities may appear easier to establish within the current energy system structure, but they may be limited in terms of innovation. Distributed communities offer opportunities for entrepreneurs and their members to profit from the ability to transact assets. Decentralized communities are also attractive to entrepreneurs and allow for the integration of regional and national energy infrastructure planning, increasing efficiency. However, their high technical complexity, investment requirements, diverse stakeholder interests, and potential opposition from established operators may hinder their implementation.

In addition, the authors of [35] conducted a SWOT analysis of the three community models and summarizes the strengths and weaknesses of each model as derived from this analysis. This is shown in Table 3.

Table 3. The strengths and weaknesses of communities classified based on their organizational structure [35].

Community Classification	Strengths	Weaknesses
Centralized Energy Community	Ease of integration with the existing system. Widely studied by academia and better understood by the community and industry. Use of mature technologies. Low risk.	High level of cohesion. They are not a priority for existing system operators.
Distributed Energy Community	Individual investment and operating decisions are given priority over collective ones. Local operation and management create jobs. Stakeholder interests are clear and well defined. No need for a relationship between all community members.	Need to create new technological infrastructures. Need for specialized technological entities.
Decentralized Energy Community	Efficiency of the new infrastructures created. Local operation and management create jobs. The interests of stakeholders are clearly and distinctly defined.	High initial investment. Need to create new technological infrastructures. Need for specialized technology and service providers.

2.1.5. CLASSIFICATION BASED ON THE ACTIVITIES PERFORMED.

In addition to their purpose and internal organizational structure, energy communities can also be categorized based on the activities they conduct that influence energy production and utilization. In [42], energy consumption is considered an unseen result that depends on the actions performed in our daily lives. Nevertheless, in [43], the concept of "energetic practices" is introduced as the methods by which “energy is highlighted, made visible, problematized, managed, stored or discussed". This definition can then be utilized to mold domestic energy circumstances [44].

Energy practices also apply to activities carried out by energy communities. However, due to their collective nature, the activities of these communities are not just about domestic energy practices. Many of the projects developed there only effectively arise due to the joining of a certain number of members. In this way, the concept of collective energy practices also arises [44]. These practices explicitly aim to benefit the community, work towards common property energy resources, and ensure that community desires are represented in some way in local energy transition development.

In [44], three distinct collective energy practices applied to energy communities are distinguished: (i) promotion of individual energy practices by the collective, (ii) development of collective energy generation, and (iii) development of collective energy management. The scheme of Figure 4 presents the three types of activities performed and synthesizes the relationships between them using definitions and examples.

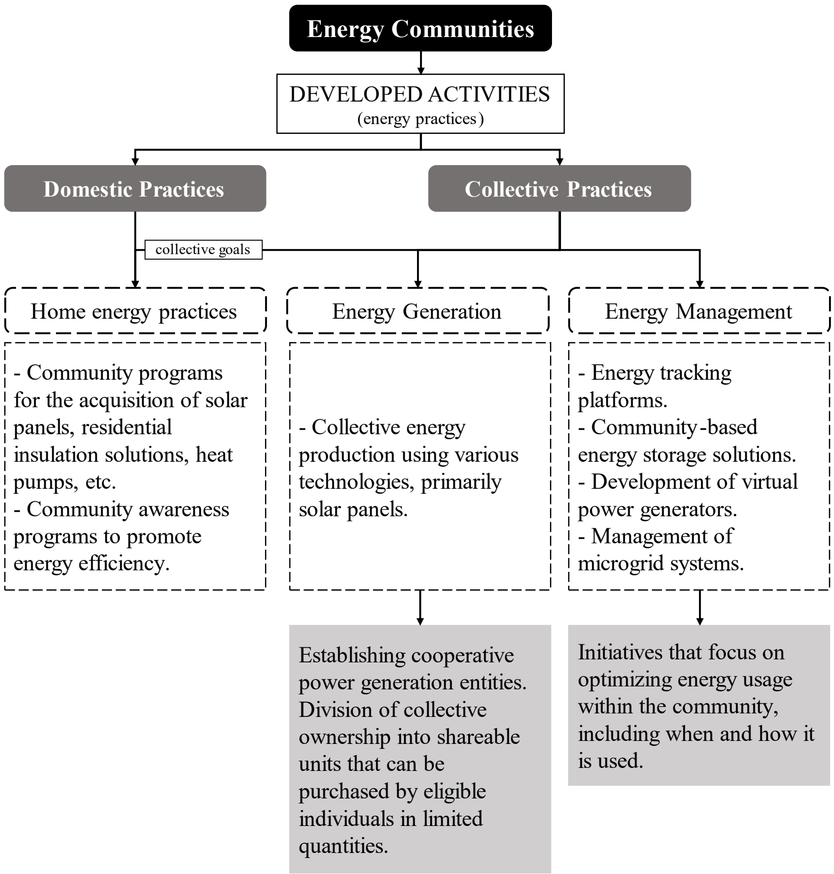

Figure 4. Energy practices implemented in energy communities (adapted from [44]).

2.2. Local Energy Markets

The development of distributed production has led to the adoption of smaller-scale production technologies. These small-scale generating units are usually in the possession of small owners, such as prosumers [45]. Currently, these actors are increasingly involved in the energy system [46]. However, in the past, they were denied access to the energy market and bidding processes due to legislative restrictions on the size of their generation units. Local energy markets can solve this problem by providing a platform for the transaction of energy assets for residential actors that integrate energy communities [47].

In this section, LEMs are addressed and some of their properties are reviewed. Initially, important concepts for the correct perception of the functioning models of local markets and their structure are defined, namely the players that participate in them and how they can relate and make offers. Later, different models of local energy markets are characterized: (i) the properties of these models are reviewed, (ii) the criteria for a model to be considered an LEM are outlined, (iii) the different designs of these models are analyzed in detail and (iv) the market clearing approaches are presented.

2.2.1. CONCEPTS

According to [48], a local market is a micro-market located in a residential area that integrates consumers, prosumers, and storage systems. An essential part of this market comes from energy exchanges between the actors in this same residential area. According to [49], local energy trading involves the transfer of energy from an element of the grid that has excess energy to another element that has a shortfall. As the viability of DER and BESS investment projects continues to increase [50], local energy trading is becoming an increasingly profitable option for end-users. In [48], local energy trading is categorized into three major groups:

(i) P2P trading energy;

(ii) Energy trading through a mediator;

(iii) Directly or through a mediator energy trading (combination).

If we classify (i) as a full P2P market, the players in the local market interact with each other directly without the need for mediators. In (ii), there is a mediator entity that acts as a representative for both sellers and buyers, determining the flow of traded energy and the energy prices in the market. Lastly, (iii) encompasses a combination of the models presented in (i) and (ii).

Figure 5 illustrates each of the three categories based on the financial, data, and power flows between the different actors in a local market.

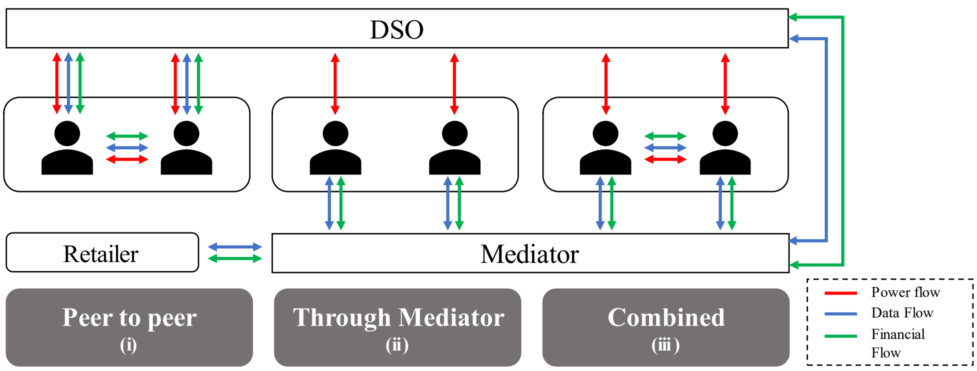

Figure 5. Market organization for local energy trading (adapted from [48]).

Alongside that way of grouping markets, other categories of LEMs are frequently presented in the literature. In a [49], the following types of markets are characterized based on the activities performed by participants and their objectives:

(i) Community or Collective Self-Consumption (CSC).

(ii) Transactive Energy (TE) markets.

The acronym CSC (i) arises in the regulatory context that focuses on empowering energy users [25]. A community-based self-consumption market involves excess energy generated commercialization between co-located prosumers. According to [51], the expression CSC designates a set of participants’ activities and not an organizational market structure.

The TE markets (ii) aim to balance supply and demand in electrical systems through decentralized coordination. In these markets, decentralized resources are managed autonomously, and price signals are used to provide stability to the system [52]. According to [53], different types of transactions are allowed between prosumers and consumers, with prosumers playing the role of sellers and retailers playing the role of buyers and vice versa.

In LEMs, as in any other market, the players and their goals have a significant impact on the market’s behavior. It is crucial to identify these players and clearly outline their roles. Table 4 categorizes these players into three main groups based on the definitions outlined in [48]. The most crucial aspects of each group are emphasized.

Table 4. Characterization of the players involved in local energy markets (adapted from [48]).

Market Player	Main references
Sellers	Any player capable of generating or storing energy. **Examples:** DERs, BESSs, EVs, PHEVs, energy cells, smart homes, flexible loads
Buyers	Players that demand energy from local generation. **Examples:** Consumers, prosumers, BESSs, EVs, PHEVs, energy cells, smart homes, flexible loads
Mediators	All players that are neither sellers nor buyers. However, some sellers/buyers may act as intermediaries. **Examples:** Aggregator, smart energy service provider (SESP), LEM operator, distributor, auctioneer and local price regulators

In terms of mediators, the literature provides various definitions for entities that aim to aggregate information from multiple players to facilitate market operations, optimize energy transactions, reduce costs for various actors, and reduce the burdens associated with a prosumer participating in a full P2P market on their own [54]. Table 5 presents a collection of the main types of mediators that can be found in the literature and their corresponding characterization.

Table 5. Characterization of different mediators in local energy markets [48].

Type of mediator	Reference	Characterization
Aggregator	[55]	Independent agent that groups two or more consumers into a single unit for energy buying or selling.
SESP	[56]	Aggregator with the ability to program flexible energy resources in a high DER penetration LEM.
LEM operator	[57]	Collects supply and demand bids (prices and values) from various actors to maximize community social welfare.
Distributor	[58], [59]	Collects surplus energy from producers and distributes it to consumers.
Auctioner	[60], [61], [62]	It’s not a physical entity. It’s just a collection of automated rules that enable the correct execution of local auctions.
Local Price Regulator	[63]	Regulates prices in a local market by monitoring a player’s generation and consumption and exchanging information with neighboring market regulators.

The way prices are set in LEMs can vary, as seen in different local market models present in academic literature. The review carried out by [64] grouped the price mechanisms, found in 53 publications, into five different categories. These mechanisms relate to the communication, which may or may not occur, between agents. Examples of this are messages related to price formation including buyer requirements and seller orders, which are defined as an offer of energy to be bought or sold, along with an associated monetary value, referred to as an offer price [65]. The identified mechanisms were:

- **Single Auction**: Only agents on one side of the market exchange messages. This is the most common mechanism in models where only one agent exists on one side of the market. Examples of this are the auctions in which consumers submit bids that are approved or rejected by market operators.
- **Double Auction**: Both buyers and sellers have the capability to transmit messages. This is the most prevalent mechanism in the P2P, CSC, and TE

markets. Sellers make an offer to sell energy in the market, while buyers indicate the maximum amount they are willing to pay. The challenge of this mechanism is ensuring that the agreed-upon price accurately reflects the cost of energy provided by the sellers.

- **System-determined mechanisms:** These mechanisms do not rely on market bids and offers. Prices are set by the operator through pre-agreements between parties.

- **Negotiation-based mechanisms:** There is no central market platform for buyers and sellers to participate in. These mechanisms are based on bilateral negotiations and are related to decentralized approaches like P2P.

- **Equilibrium-based mechanisms:** Prices are formed as a result of the interaction, with a game-theoretic solution concept used to establish an equilibrium.

2.2.2. LEMs Properties

For LEMs and future distribution grids to be established, solutions must be found for the implementation of significant amounts of DERs. According to [66], four properties must be included in these future distribution grids. They are:

- **Transitivity:** adjusting load profiles or bids considering current electricity prices and expected prices. In this way, players make their offers and receive, as feedback, the price of admitted offers. From then on, it should be possible for players to change their production and consumption (shifting it in time or changing its nominal values) in response to the same price signals.

- **Inclusivity:** all LEM participants, including small-scale end users, should participate in the markets regardless of the amount of flexible energy available.

- **Congestion management:** to prevent power flows from exceeding the nominal capacities of lines and preventing overloading and overvoltage in components.

- **Network balancing:** using DERs to solve frequency changes caused by sudden changes in production and consumption.

The authors in [66] state that an LEM is a market that meets at least one of these four requirements. There are already many ideas, plans, and possible ways to make LEMs in literature, but the authors only use some of these requirements to develop their market structures, and not all of them. This makes it hard to achieve one complete definition of what an LEM is. Different studies have different ideas, making it tough to bring them all together. However, these distinct ideas offer opportunities for improvement in specific market capabilities. In addition to the four requirements listed earlier, bidding horizons are another important part of local market models to consider [66]. These horizons are:

- **Hourly**: offers are made every hour. It coincides with the time base of day-ahead markets.

- **Short-term**: offers made in intervals of less than an hour. It coincides with the time base of intraday markets.

- **Real-time:** offers made in an undefined time interval but must be executed at most two minutes after the auction. It's the time base for ancillary services.

The scheme in Figure 6 summarizes everything previously stated regarding the classification of LEMs. The combination of one or more overarching properties with a time base is a mandatory requirement for the establishment of a local energy market.

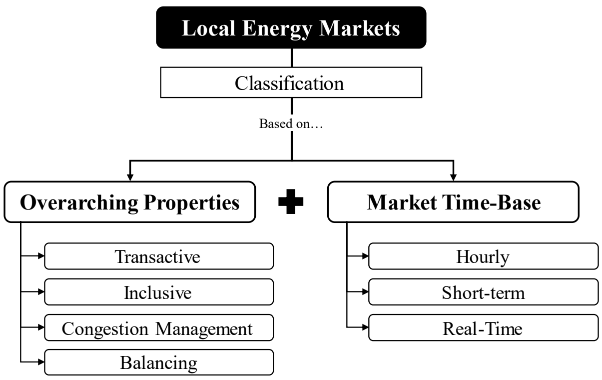

Figure 6. LEMs classification based on overarching properties and time-base (adapted from [66]).

2.2.3. LEMS DESIGNS

The literature review in [64] identified six distinct market designs. As stated by the authors, market design pertains to the interconnection of different price-forming mechanisms to form a complex market. The six structures identified were: (i) future market, (ii) real-time market, (iii) mixed future/real-time market, (iv) mixed decentralized/centralized market, (v) multi-layer market and (vi) settled after-the-fact market.

The main characteristics of future markets are:

- All trades occur before the settlement period and during the settlement period, participants aim to stay as close as possible to their negotiated positions;
- Any energy imbalances resulting from a deviation from the negotiated position are resolved during settlement.
- All trades occur before the settlement period and during the settlement period, participants aim to stay as close as possible to their negotiated positions;

The most relevant aspects of real-time markets are:

- All trades are made at the time of settlement and participants update their market positions throughout the settlement period based on actual energy demand;
- Greater tendency for participants to end the settlement period with a balanced offer/bid;
- If the total supply and demand in the market are not matched, imbalances may exist.

Mixed future/real-time markets combine aspects of the previous two designs:

- There are two trades: the first one is based on supply and demand forecasts, and the second one is to correct any forecast error during the settlement period.

The mixed decentralized/centralized markets feature a design that incorporates aspects of centralized markets (with the advantages of long-standing market models) and decentralized markets (adapted to the concepts of energy community and distributed production). The main characteristics of these markets are:

- There is a first stage of bilateral negotiation without the intervention of a market operator;
- In the second stage, a centralized auction is conducted, responsible by the market operator, in which the residual of bilateral negotiations is cleared.

The multi-layer markets are characterized as follows:

- There are multiple auctions at various levels (layers);
- At a lower level there are different internally balanced markets;

At each lower level, there is an aggregator that represents that in a higher-level market, aiming to eliminate supply and demand imbalances at these lower levels. The last design found in the literature is settled after-the-fact markets. These markets are governed by the following:

- Participants are paid or charged for the energy supplied or demanded after the settlement period;
- A price formation mechanism determined by the system is used;
- No negotiation is made before the settlement period.

The diagram of Figure 7 shows a framework for all market designs previously exposed. It describes the main events of each of the six designs, with temporal reference being the settlement period.

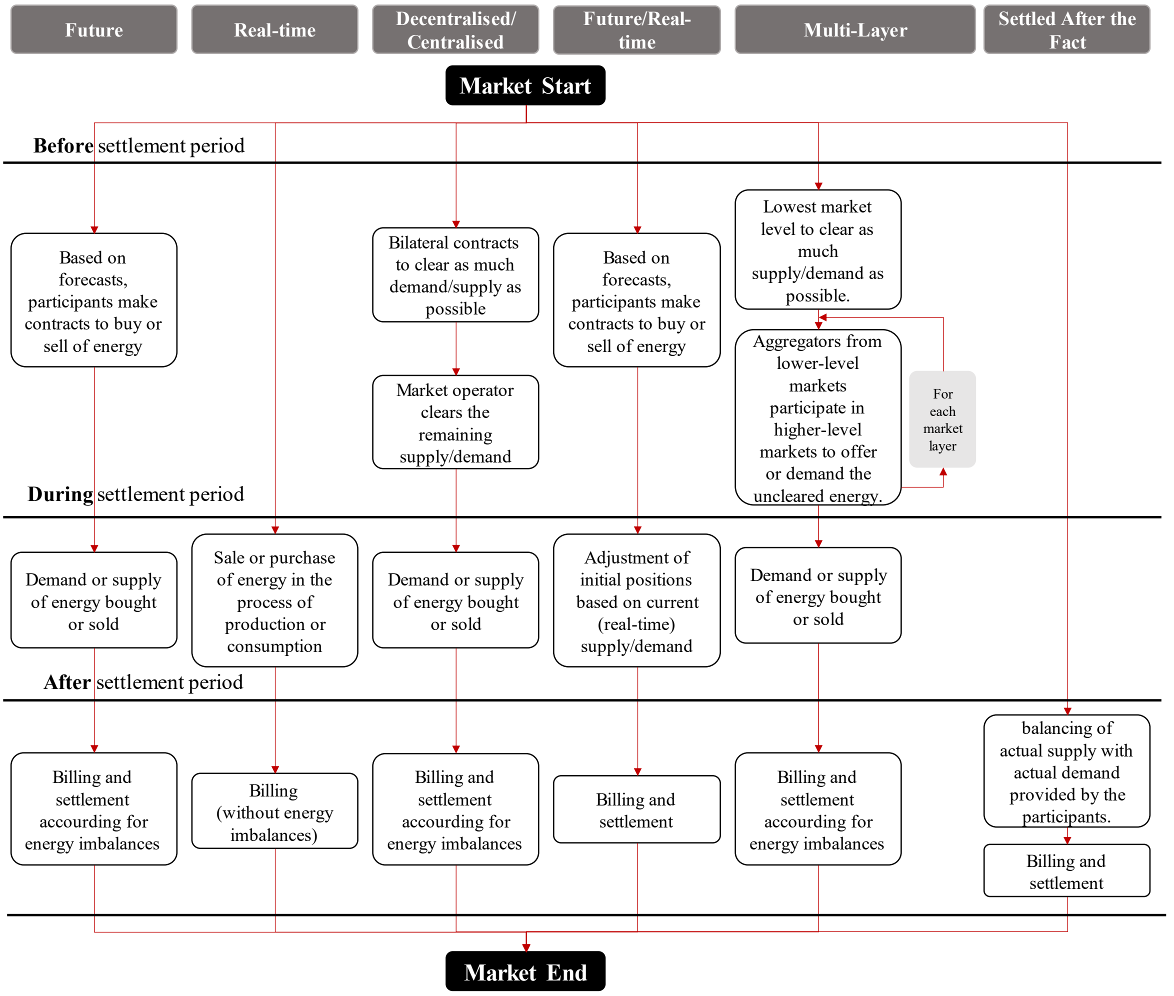

Figure 7. Local electricity market models framework (adapted from [64]).

In future markets, both single auction and double auction price formation mechanisms and bilateral negotiations are used. This market design is innovative and similar to the United Kingdom energy market model [67]. In real-time markets, the same market price formation mechanisms can be used, however, this design is generally linked to large, traditional power systems that act as an infinite bus and ensure the balance between supply and demand [64]. The mixed centralized/decentralized markets use bilateral negotiations in their decentralized parts and simple or double auctions in their centralized parts. The future/real-time markets and multi-layer markets also allow these two types of price formation mechanisms, while settled after-the-fact markets have their own price formation mechanism [64].

2.2.4. LOCAL MARKETS CLEARING APPROACHES.

Various clearing approaches are often found in the literature. These methodologies depend on the market structures, market rules, and market designs. There is a trend towards the use of distributed optimization algorithms in the decision-making processes associated with the proposed LEM models. Optimization problems mathematically define a market, and its constraints serve to represent the rules to which the players are subject. The objective functions define the purpose of the problem. According to [48], the two most common objective functions in the literature are:

(i) Social welfare maximization;

(ii) Operating cost minimization.

In economics, social welfare is defined as the sum of consumer and producer surpluses. The existence of this surplus allows for greater comfort for users of a given market and lower costs for the companies associated with them [68], [69]. The objective functions of typology (i) rely on maximizing the profit of each electricity market participant, individually, in order to promote the social welfare of all players. About LEM, it is common to be a mathematical expression where the sum of the cost of all sellers is subtracted from the sum of the utility of all buyers [48]. In (ii), minimizing operating costs is the goal of optimization problems. In practice, this cost reflects the cost of traded energy and market and system operators. The objective function represents the sum of each player's costs, individually, and the constraints are related to energy balance [48]. Still, in [48], distributed optimization methods can be divided into five groups. Table 6 presents the main characteristics of each of them.

Table 6. Market clearing approaches definition according to [48].

Clearing Mechanism	**Main references**
Decomposition methods	Dividing a complex optimization problem into several easier-to-solve subproblems.
Networked optimization	A decomposition technique is used in problems that should be decomposed based on the structure of the original problem.
Game theory-based methods	Game theory is used to neutralize these selfish behaviors. It allows various players with conflicting objectives to cooperate in decision-making.
Agent based methods	Each participant is considered an agent and can take on various forms within the problem: it can be a simple decision variable or even an intelligent object with an infinite number of actions and decisions.
Multi-level optimization	The optimization at higher levels depends on the results of lower levels, and the lower-level context is defined by the variables of the higher level.

The distributed methods are very useful for large-scale problems, but they require a coordinator to ensure the convergence of all individual decisions. In network optimization, the coordinating entity is no longer necessary as each decision maker can only coordinate their actions with their immediate neighbors. In game theory, coordination between players is not desired as it would be very complex to coordinate individual, often conflicting, objectives. Finally, agent-based methods are useful for large-scale problems as they allow the formation of many agents with various types of interaction.

2.3. Modeling and Trading Community Flexibility

Modeling and negotiating flexibility in local energy markets is crucial for the transformation of the energy sector. This section discusses flexibility in residential demand-side energy, classifying the most used energy resources in homes according to their flexibility. It covers automated energy management in homes, flexibility markets, and their correlation with energy markets. Finally, gaps in the literature are identified, which serve as the inspiration for this dissertation.

2.3.1. FLEXIBILITY AT DEMAND-SIDE

Modeling a robust local flexibility market requires the quantification of flexibility available in a community. For that, it is necessary to use modeling strategies that comprise different approaches, depending on the characteristics of each prosumer's devices.

2.3.1.1. CONCEPT

To understand the flexibility concept at the residential level, it is necessary to find a general definition for demand-side flexibility. According to [70], flexibility is the ability of an energy consumer to change the use of electricity. The Council of European Energy Regulators (CEER) mentions that this ability to change can be used in response to control signals, coming from the grid operators, or done voluntarily, in response to financial incentives.

Regarding residences, the definition of flexibility has some unanimity. Authors from [71] and [72] define it as the capacity of a building to adjust its energy demand and generation to meet the requirements of the electrical grid according to the local environmental conditions, without affecting the needs of its occupants. According to [2] it is understood by environmental conditions, for example, climate and occupant issues, thermal comfort, and productivity.

2.3.1.2. HOME DEVICES FLEXIBILITY CLASSIFICATION

The adoption of RD actions and the promotion of energy efficiency make it possible to change the normal operation of a building. In this way, [2] cites the technical reports of the United States Department of Energy [73] to name five DR strategies that promote the interaction of buildings with networks, namely: efficiency, load shedding, displacement of load, modulation, and generation.

In the literature, some works fit the strategies presented by [73] to the different devices existing in a house. In [74], the residence loads are grouped into three components: (i) “must-run” loads, (ii) adjustable loads (whose total value must be met over the scheduling horizon) and (iii) load that can be reduced (within a range that includes user satisfaction).

In [75] and [76], the concept of deferrable loads is presented, which are characterized by maximum and minimum load levels, by the total load and by the time limits for the beginning and end of use. The combination of all these concepts [77] results in individual residential loads cataloging equally into 3 types: (i) non-shiftable loads, (ii) shiftable loads, and (iii) controllable loads. It is also possible to consider loads without flexibility as a fourth type of load: those whose profile cannot be changed, or which cannot be interrupted after its initialization [78]. Table 7 presents a summary of the exposed concepts and makes different devices correspond to them.

Table 7. Typical residential devices and resources according to their flexibility type.

Flexibility Unit Type		**Main References**	**Examples**
Shiftable load units	**Shiftable profile**	Can be moved in time, but their energy profile cannot be changed	Dishwasher machines, washing machines, and other white goods
	Shiftable volume	Load profile can change (within certain limits), but the total volume, for a given time period, must be met.	Electric vehicles (when there is a charge set point, defined by the user, and which must be met at the end of the charging period)
Curtailable load units	**Reducible**	Load profile can be reduced to a certain limit, without being disconnected	Dimmable lamps
	Disconnectable	The load unit is turned off	Synchronous or induction industrial machines
Extendable Load Units		Load profile can be increased up to a certain limit	Thermal loads (where there is a minimum temperature set-point defined for user comfort)
Non-flexible load units		Load profile cannot be changed and/or the load cannot be stopped once initialized	Televisions, computers, domestic ovens

2.3.1.3. HOME ENERGY MANAGEMENT SYSTEMS

A HEMS provides efficient management and monitoring services for energy generation, consumption, conservation, and storage in a home [79]. They also allow the statistical collection of energy usage for different residents and can coordinate the operation of various intelligent home devices, as well as DERs [80].

According to [81] based on literature analysis, the functionalities of a HEMS can be divided into five modules:

- **Monitoring:** provides access to real-time information on energy usage and equipment usage patterns.
- **Logging:** allows for the collection and storage of information related to energy consumed by devices and generated by DERs, enabling real-time demand response.
- **Control:** devices and DERs can be directly controlled from the devices themselves or remotely from apps provided by the management system.
- **Management:** optimizes the efficiency of the device and DER usage.
- **Alarm:** identifies and informs the user of faults in their home electrical system.

According to [82], a HEMS intelligently monitors and adjusts the energy usage in a home using devices such as smart meters and plugs. The system has sensors within home devices that share information from an internal network. Figure 8 represents the architecture of a traditional HEMS and expresses the relationship between different components of the system.

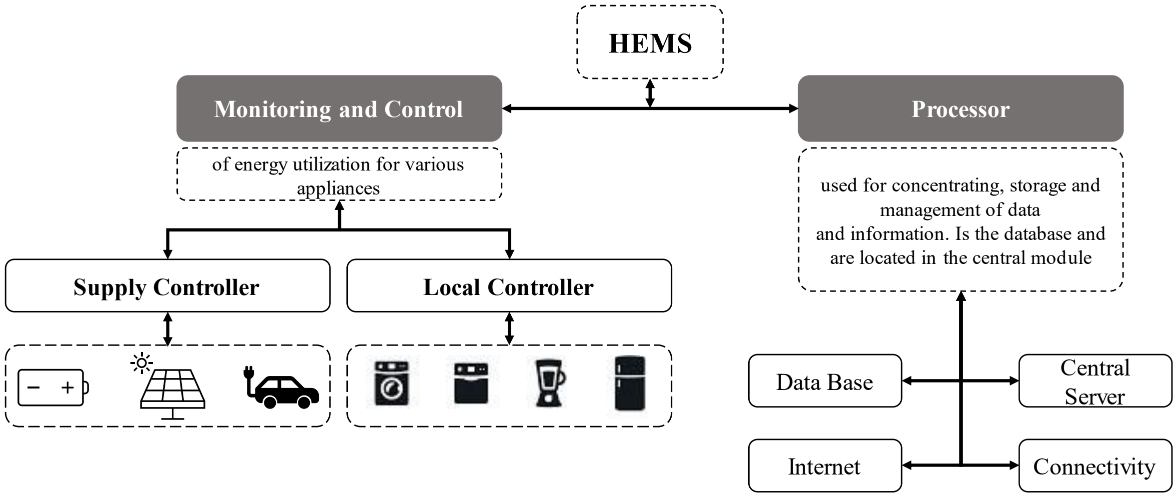

Figure 8. Typical architecture of a HEMS (adapted from [81]).

According to [83], it is common to have a gateway that enables the connection between HEMS and the outside world for easy internet access.

HEMS models are designed to ensure a balance between operating costs, user well-being, emissions reduction, and consumption efficiency. There are several models for managing residential energy through a HEMS, which can reduce electricity bills, GHG emissions, and energy consumption. In [81], some different management models are presented. Table 8 provides a comparison of four of these models developed by the four cited authors.

Uncertainty is an increasingly important factor in HEMS modeling. This uncertainty has increased with the introduction of DER production at the residential level. However, other factors can also be considered uncertain, such as weather conditions and energy usage patterns. The authors in [81] identify some prediction techniques that can be incorporated into HEMS models, such as neural networks and other artificial intelligence mechanisms. However, the literature review identified few scientific contributions that added wind speed or solar radiation predictions to home energy management for at least 24 hours.

Table 8. Analysis of HEMS models in the literature (adapted from [81]).

Model	Description	Advantages	Disadvantages
Optimization based management [84]	Linear programming-based model aimed at reducing energy consumption. Time variable discretization and tariff variation in different periods of the day.	Efficient energy consumption management through appliance operation scheduling.	Scheduling technique introduces additional delays in device cycles.
Domestic Energy Management [85]	Utilizes Zigbee protocol for device communication, allowing for real-time price consideration.	Real-time demand processing with few appliance usage restrictions.	In the absence of a management program, consumption is higher during peak hours.
Suport Decision Tool (DST) [86]	Incorporates Particle Swarm Optimization model to coordinate device usage, enabling cooperation among devices, similar to optimal scheduling.	Allows for easier integration of DERs.	Requires scheduling algorithm.
Optimum load management (OLM) strategy [87]	Combines appliance activity scheduling with user usage prediction, providing data for informed prediction.	Allows for easier coordination of DERs and devices.	Requires scheduling algorithm.

2.3.1.4. Optimization Metrics for Modeling Residential Flexibility

Several calculation metrics allow home flexibility quantification. These metrics are based on simulations, measurements, and analysis. Linear, non-linear, and mixed-integer optimization methods are used several times for this determination [2].

Table 9 shows some works that use optimization to achieve flexibility in buildings. These papers are organized according to the metrics they use. One of these metrics is about buildings with their own photovoltaic production. In these situations, the use of self-consumption makes it possible to quantify energy flexibility [88], [89]. The use of the building's own production, to attend to energy consumption, does not address the resulting changes in the different loads that constitute it, which is a negative point of this methodology. Another metric used is the flexibility factor, which measures the amount of energy that can be moved from peak hours to off-peak hours [90], [91]. These models assume the existence of real-time prices.

There are still other simpler methodologies. In [92], [93], a reduction in the peak power of certain appliances is considered a flexibility metric.

Table 9. Metrics to determine flexibility in residential buildings and paper examples.

Metric	**Description**	**Example**
Peak Power Reduction	Flexible operation **reduces** energy **demand** during **peak** periods	[92], [93]
Energy Management based on price and emissions signals	Flexibility Factor - quantification of the amount of energy shifted from peak hours to off-peak hours.	[90], [91]
Energy Management	**Self-consumption (SC) -** the degree to which the on-site generation is directly consumed by the building.	[88], [89]
Response to price signals	**Flexibility Index (FI) –** comparison between a baseline and a flexible strategy and measurement of the resulting economic benefits	[94]

Table 10 presents other aspects related to the examples of papers presented in Table 9. One of the Table 10 columns is dedicated to the time base used in the analyzed models. This time base corresponds to the temporal resolution of the different tools. This resolution allows knowing how often data are collected and, consequently, flexibility is calculated. The time base characterization is important because, many times, the flexibility determination depends on price signals that vary over time [95].

Table 10. Considerations about paper examples in analysis.

Example	Purpose [Optimization Type]		Devices Considered	Time Base
[92]	Energy management optimization	[Linear]	Air conditioning, vacuum cleaner, washing machine, dishwasher, microwave, hair dryer, oven, computer, electric vehicle, heat pump and lights.	N.m.
[93]	Power evolution optimization	Not mentioned	Air conditioning	60 min.
[90]	Control strategy	[Linear]	Heat pump (hot water tank)	60 min.
[91]	Control strategy	[Nonlinear]	Heat pump (thermal heating)	60 min.
[88]	Optimal Potential Evaluation	[Nonlinear]	Electric water heater, air conditioner, heat pump	10 min.
[89]	Control strategy	[Nonlinear]	Heat pump; clothes washer; clothes dryer; dishwasher; tumbler	60 min.
[94]	Optimal potential Evolution	[Linear]	Battery storage	15 min.

The analyzed optimization problems are classified as linear or non-linear problems. Linear programming is a method to obtain an optimal solution in mathematical models whose requirements are represented by linear relationships. In these cases, the objective functions are linearly related to the decision variables and have a finite set of constraints. In contrast, nonlinear programming is a process of solving an optimization problem where the constraints or objective functions are nonlinear [96].

Generally, an optimization problem can be characterized by the following three steps: (1) definition of the problem, (2) quantitative evaluation of the impact of control actions on the problem objective, and (3) resolution of the problem by choosing the best action that enables the achievement of the objective [97]. In the analyzed papers, step (1) consists of defining the optimization objective, which actions the user wants to control and, among these actions, which ones the system can effectively control. The optimization objective is a scalar number (or a vector in the case of multiple optimizations) and represents a reward or a cost in the case of a maximization or minimization problem, respectively. Control actions depend on the available flexible resources and must meet the considerations left in Table 7. Regarding step (2), in all papers referred to, models based on physics are commonly used to relate the control actions with the objective of the problem. Finally, step (3) requires the use of numerical calculation software to solve the problem.

The baseline concept is often associated with multiple metrics, namely in [92]–[94]. In these works, flexibility constitutes a relative amount of energy or power in contrast to an inflexible scenario. This is the same as saying that inflexibility is a basis for flexibility determination. These metrics consider base energy or power profiles that are changed by a set of flexible operations [98]. These base profiles constitute the baselines and the relative amount of energy or power changed constitutes the actual flexibility.

Flexibility quantification modeling is not always dependent on optimizations. Other heuristic methods allow flexibility determination. The authors in [99], [100] study the use of rules-based control (RBC) strategies, for example, to determine the available flexibility. This type of control is applied to heat pump water heaters and hot water storage tanks. Its objective is to shift the energy consumed, for heating water, from peak periods to periods of low consumption or periods with high solar self-generation, considering user preferences. Another model that does not fit in Table 10 and Table 11 is the work presented in [101], because it is not based on an optimization problem, and because the metric followed does not fit with any of the definitions presented. The proposed model uses parametric modeling instead of optimization. The metric used is based on the reduction of energy consumption during an automated DR event, also considering the storage efficiency during it.

2.3.2. MARKET MODELS FOR COMMUNITY FLEXIBILITY TRADING

A Local Flexibility Market (LFM) is a trading platform, similar to LEMs defined in Section 2.2, for trading electricity usage flexibility in limited geographic areas, such as communities [102]. It offers flexibility as a good or service to be traded, with a market operator and participants [103].

2.3.2.1. PLAYERS AND GENERAL OPERATING PRINCIPLES

In LFM markets, residential prosumers are the providers of flexibility. Their management is handled by aggregators who participate in LFM on their behalf. The DSO and the Balance Responsible Party (BRP) act as flexibility requesters. According to [103], the main participants in local flexibility markets are as follows:

- **DSO**: requests flexibility for operational (to handle congestion, controlling voltage levels, minimizing losses) and/or planning (avoiding network reinforcement);

- **BRP**: represents client portfolios [21]. Their function is to balance their supplied and demand energy. There are associated costs if they do not ensure this balance, so they acquire flexibility mainly to fulfill this function;

- **Aggregator:** represents a group of prosumers in the flexibility market. They are responsible for collecting the available flexibility in the community and for managing and commercializing it with the LFM operator.

LFM operator is another important entity. According to [103], this entity coordinates the following tasks:

- Contracting and bidding process;

- Activation process;

- Settlement process.

During the contracting and bidding process, all the mentioned players talk to each other to agree on how much flexibility to trade and at what price. The behavior of these players during this process is described in Table 11.

Table 11. Activities performed by LFM players during the contracting and bidding process (adapted from [103]).

Player	Activities performed
DSO	Analyze if there are risks of congestion and non-compliance with voltage levels. If there is a risk, send a flexibility request to the LFM operator. Send other technical information on the grid status to the LFM operator.
BRP	Receive predicted portfolios and estimate future imbalances. If necessary, send a flexibility request to the LFM operator.
LMF Operator	Receive flexibility requirements and information from DSO and BRP and communicate them to the aggregators. Responsible for clearing the market, after the aggregators offer flexibility.
Aggregator	Accumulate the flexibility offers from their prosumers. Offer flexibility bids to the LFM operator.

During the activation process, DSO and BRP activate the flexibility they acquired after requesting it from the LFM. Aggregators respond to the request and provide flexibility after sending control signals to their prosumers' DERs and devices. In the settlement process, transactions are completed through settlement and payment agreements between the players involved in the transactions. Figure 9 outlines a generic local flexibility market operation considering the information, control and physical flows in the LFM [103].

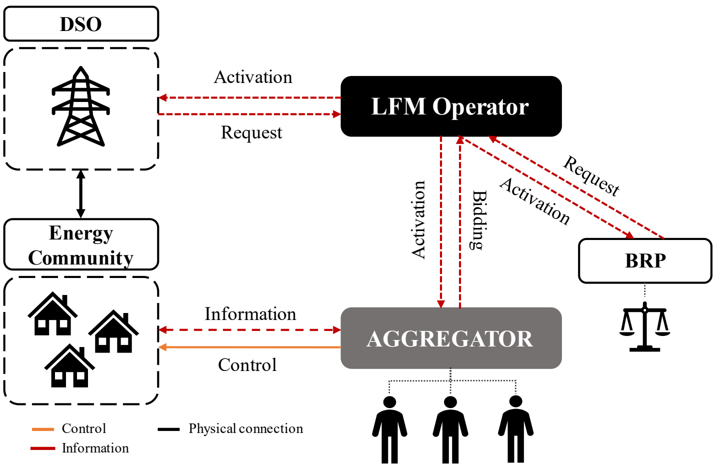

Figure 9. Relationships between players in a typical LFM (adapted from [103]).

2.3.2.2. LOCAL FLEXIBILITY MARKETS EXAMPLES

After the analysis of the flexibility markets functioning, some references proposing LFM models will now be analyzed. In the studies in [104], [105] the LFM operator, both in the day-ahead and intraday markets, receives energy profiles from consumers and flexibility requirements from the DSO and BRT separately. After that, it clears the market, verifying if the accepted bids do not result in any problems for the grid if they are accepted in the energy market. The DSO has also real-time local dispatch mechanisms to use flexibility to solve unresolved issues in Day-ahead and Intraday markets. These authors define the volumes and prices of flexibility requirements presented by the DSO in different local market sessions based on a two-level problem. The upper level minimizes the cost of acquiring the flexibility to determine the request price of the flexibility needs presented by the DSO. Upper levels are intended for clear the market. This method has one advantage. Both the DSO, BTR, and community members can present flexibility requirements/bids. However, two gaps are identified: (i) it does not specify how prosumers determine their available flexibility offered in the market to meet the requirements of the DSO and BRT and (ii) there is a strong dependence relationship between local flexibility markets and local energy markets.

In [20], according to [104], the authors propose a local market distribution grid. Loads, generators, and storage units can participate in the market individually or under aggregation. These participants provide short-term (15 minutes) and long-term (12 hours) operational point forecasts. Non-participants do not provide this data but send information to the DSO for operation prediction. The DSO first predicts the grid state for the short-term period while participants make flexibility offers. These offers are optimized and activated by the DSO based on the forecasts. Then, the DSO receives and analyzes information related to long-term operation and estimates its flexibility needs for that time horizon. After that, the participants can adjust the flexibility offers they made for the short term. The advantages of this work are:

- Presents a local flexibility market model for flexibility exchanges in both the short and long term.
- Coordination of offers made for both time-bases is allowed.

On the other hand, the main disadvantages found are:

- The local flexibility market only meets the requirements of the DSO, leaving out requirements from the BRT and prosumers flexibility bids.

- Participants transmit the flexibility they have to the market operator, but there is no reference to the metrics used to quantify it.

- It is unclear whether there are real-time measurements or network control, and there is no dedicated market platform for LFM processes.

In [94], a three-stage model is proposed to define energy and flexibility exchanges among different prosumers in a REC connected to a distribution grid. In the first stage, an individual optimization of each prosumer's consumption is performed. Each one of them can have its own PV generation and BESS. This optimization considers the constraints of BESS usage, expected PV generation capacity, and price signals of local energy market tariffs (for energy supply) and feed-in (for excess PV sales). As a result, the optimal consumption schedule for each prosumer is obtained. In the second stage, a joint optimization of all community members' consumption is performed, again considering their own PV capacity and storage constraints. In this optimization, each peer is free to exchange energy with other community members, and a pricing mechanism has been created to compensate them. Each prosumer is thus free to modify their optimal scheduling based on the social welfare of the community, which is represented by a lower global operating cost than that obtained in the first stage. In stage 3, an optimal power flow is used to validate and adjust the power flow between the distribution grid constraints and the community dispatch. In this study, flexibility sharing emerges implicitly: the flexibility needs of prosumers are met through the co-optimization of the second stage, and the DSO's requirements through the OPF of the third stage. The main advantages of this approach are:

- The optimization of each DER operation that can be adapted to other home devices, which may be compatible with HEMS;

- Allows flexibility exchanges between peers and between the DSO and the community.

The main disadvantages of this approach are:

- Flexibility is exchanged implicitly and comes from local P2P electricity market transactions;

- In stage 2, a collective consumption co-optimization of the energy community is performed, which requires the aggregator to have access to the PV generation forecasts and technical characteristics of the BESS of each prosumer to be successful. This may constitute a violation of data protection policies as it can be difficult to implement when considering a large number of prosumers.

The authors in [13] also propose a P2P trading LEM that explores the sharing of flexibility among members of an energy community. This model is based on only two stages, where a generation and consumption profile are defined for each prosumer and serve as a starting point for LEM negotiations. There is no aggregator figure, and all prosumers have autonomous energy management systems that handle all their operations in the local market. It also considers a communication platform between peers and between each peer and the community manager. In the first stage, prosumers manage their energy independently and submit offers and bids to the LEM operator. Although it is a coordinated negotiation, the price established for each transaction depends only on each P2P match, regardless of other transactions between prosumers. A stochastic programming algorithm is used to establish the ideal bid for each prosumer. In stage 2, the LMO and DSO commit flexibility provided by each prosumer, obtained in the P2P transactions, considering the distribution grid constraints. Is also in this second stage that injections and withdrawals of energy from the network occur by sellers and buyers. In stage 2, flexibility appears in the market in two distinct forms: (1) positive flexibility (upward) associated with a decreasing consumption and (2) negative flexibility associated with an increase in consumption. In stage 1, each prosumer's flexibility is determined according to these two formats. In stage two, to activate this flexibility, the model proposes that each player act as a virtual generator or consumer, respectively for situations (1) and (2). The advantages of this model are:

- Considers energy flexibility sharing both among prosumers and between the community and the DSO;

- Uses virtual generators to quantify the flexibility resulting from energy exchanges between prosumers.

On the other hand, it has some disadvantages:

- It is based on a full P2P where there is no aggregator. On the one hand, according to [103], isolated prosumers have limited negotiation power with the market operator due to the limited flexibility volume they can offer. On the other hand, the market operator may become overloaded with too many generation and consumption profiles (one for each prosumer).

- The model starts with the definition of generation and consumption profiles, as parameters, for each prosumer. It does not specify how prosumers determine their available flexibility.

2.4. Connection Between State of Art and Dissertation Objectives

This subsection aims to frame the work objectives with the analyzed literature. In subsection 2.1.1, the difference between RECs and CECs was analyzed. Given the prevalence of DER linked to each prosumer, the study will prioritize RECs over CECs, despite the availability of both options.

To achieve the main objectives stated in Section 1.2, the following is considered:

- Quantify the available flexibility of each prosumer and determine a method to aggregate it;

- To facilitate the flexibility aggregation, classify the DERs and devices of each prosumer based on the Table 7 provisions to group them by the type of flexibility they can provide, as suggested in Subsection 2.3.1.2;

- Develop a metric to determine the available flexibility in each residence. For that, optimization will be used, because this is the approach with the largest number of reviewed references in Subsection 2.3.1.4. The internal residences energy management will be considered according to aspects related to some HEMS models reviewed in Subsection 2.3.1.3;

To develop a local market model for the quantified flexibility transaction, we base it from the typical structure of an LFM presented in Subsection 2.3.2.1 and take into account all the LEMs particularities reviewed in Section 2.1, because they are very similar structures. The weaknesses of the LFM models presented in Subsection 2.3.2 also constitute an important element of analysis.

Considering the literature reviewed, the main difference between the proposed dissertation work and the already published models is the creation of a tool that allows an LFM model implementation considering the management of the internal energy of each prosumer. In Subsection 2.3.1, it is stated that residential flexibility comes from DERs and domestic devices. In this way, an efficient LFM model must be based on a direct relationship between the market operator and the prosumers HEMS systems.

The first step in designing the LFM was to define its time base, among the options presented in Subsection 2.2.2. We opted for an hourly time base to create a day-ahead market structure that serves as a basis for modeling intraday and real-time LFMs in future works. The proposed market model will be a flexibility-only type articulated with the energy market because its main objective will be to reduce the prosumer's energy costs who wish to participate in it. In addition, flexibility offers presented in the LFM will consider the tariff practiced in the LEM.

The proposed LFM model foresees the aggregation of prosumers to avoid the disadvantages identified in some works referred to in 2.3.2.2. As opposed to what happens in [94], the optimization processes to be carried out at the aggregator level will not have access to the personal information of prosumers, such as their usage preferences or DERs/devices technical characteristics. The only information to be made available to the direction HEMS-Aggregator will be the technical flexibility available in each residence. The aggregator will also represent the prosumers and, at the same time, will be the LFM operator entity, to simplify the problem, assuming the role of CM.

Prosumers will be directly remunerated for the flexibility activation proposal made to them by CM. These proposals will only be accepted if they represent an economic benefit for the prosumer, such as reducing its energy costs. In this way, as opposed to what is suggested in most of the publications we evaluated, the welfare of each prosumer (individually) is prioritized over the social welfare of the community. This is viewed as an additional motivator for community members to take part in LFM.

3. Flexibility Market Model for Renewable Energy Communities

In this chapter, it is provided a detailed overview of the proposed and implemented simulation model. The mathematical formulation for the estimation of flexibility at the prosumer level and the flexibility market model at the community level are described. A two-stage model is designed to solve this problem, which divides into two smaller and easier-to-solve sub-problems.

The first sub-problem consists of determining the available technical flexibility of each prosumer of the REC, considering that each prosumer has a HEMS installed in its facility. The HEMS allow for monitoring and controllability of consumption and generation units in the house.

The second sub-problem designs a flexibility market model for flexibility trading. This flexibility market is managed by the entity that manages the REC, which can be a community manager and/or an aggregator.

This chapter begins with a description of the objectives of the proposed LFM model. Next, a conceptual analysis of the model is conducted, and its two constituent stages are defined. After that, mathematical formulations are presented, and the remaining metrics are described.

3.1. Flexibility Market Framework in Energy Communities

Before describing the mathematical formulation of the two-stage problem, it is necessary to specify the structure of the LFM, accounting for the role each entity has in the market. In general, there are two main figures in the LFM from the REC standpoint, as depicted in Figure 10:

(i) The HEMS that is the system that monitors and manages the prosumer. It ensures the energy management and determines the available flexibility of each prosumer of the REC;

(ii) The Aggregator that collects the flexibility offers presented by each HEMS and flexibility needs of the DSO to run the market. In this framework, the aggregator (also referred to as a Community Manager) is in charge of running the market performing the role of a flexibility market operator.

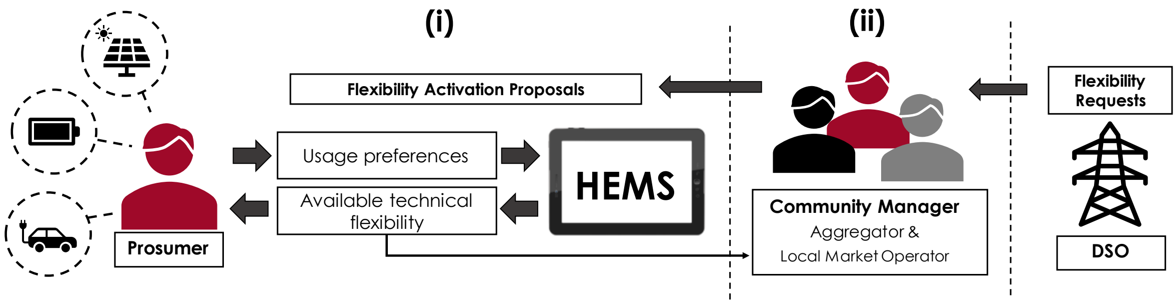

Figure 10. General framework of the flexibility problem in a energy community.

Figure 10 depicts, in a simplified way, the two stage of the problem and how they relate. At each level, there is an optimization problem to be solved. The methodology of Stage 1 is intended to be an integral part of a HEMS. Through it, it will be possible to present the available flexibility of each prosumer to the aggregator, as can be observed in Figure 10.

In stage 2, the aggregator groups the available flexibility from each HEMS and, based on the flexibility requirements it receives from the upstream DSO and the flexibility needs of the downstream prosumers, sends activation proposals to the HEMS, which has the freedom to accept or reject them.

This LFM is a day-ahead market and, for this purpose, uses an hourly time-base. Therefore, its operation must consider forecasts of predicted self-generation and consumption for the next day.

3.2. TWO-STAGE FLEXIBILITY MARKET MODEL FOR REC

Next, the problem that gave rise to the residential flexibility market model and estimation is described, and this mathematical formulation is presented.

3.2.1. PROBLEM DESCRIPTION

The two-stage model is designed to perform the dispatch of the LFM, accounting for the flexibility offers of each prosumer. To be able to understand the proposed model, Figure 11 presents a detailed flowchart representative of the structure of the two-stage problem. In Stage 1 (Figure 11– (a)), each prosumer is equipped with a HEMS that controls and manages the operation and energy consumption of DERs and home devices. Table 12 presents the household resources considered in this stage of development.

Table 12. Domestic resources considered in the development of the first stage model.

Solar PV generation	Day-ahead forecast	Parameter
Battery Energy Storage System (BESS)	Shiftable-volume flexibility unit	Variable
Electric Vehicle (EV)	Shiftable-volume flexibility unit	Variable

On the one hand, PV generation is a forecast that serves as an input parameter for the first stage. On the other hand, the energy consumed by BESS and EV constitute variables whose value (amount of energy) is affected by the result of the flexibility market. These two resources can consume more or less energy depending on the cleared flexibility activation proposals. In this way, both are considered flexible units (FU) and mathematically represented by ‘lsv’ index (shiftable-volume load units) because of the type of flexibility that they can provide.

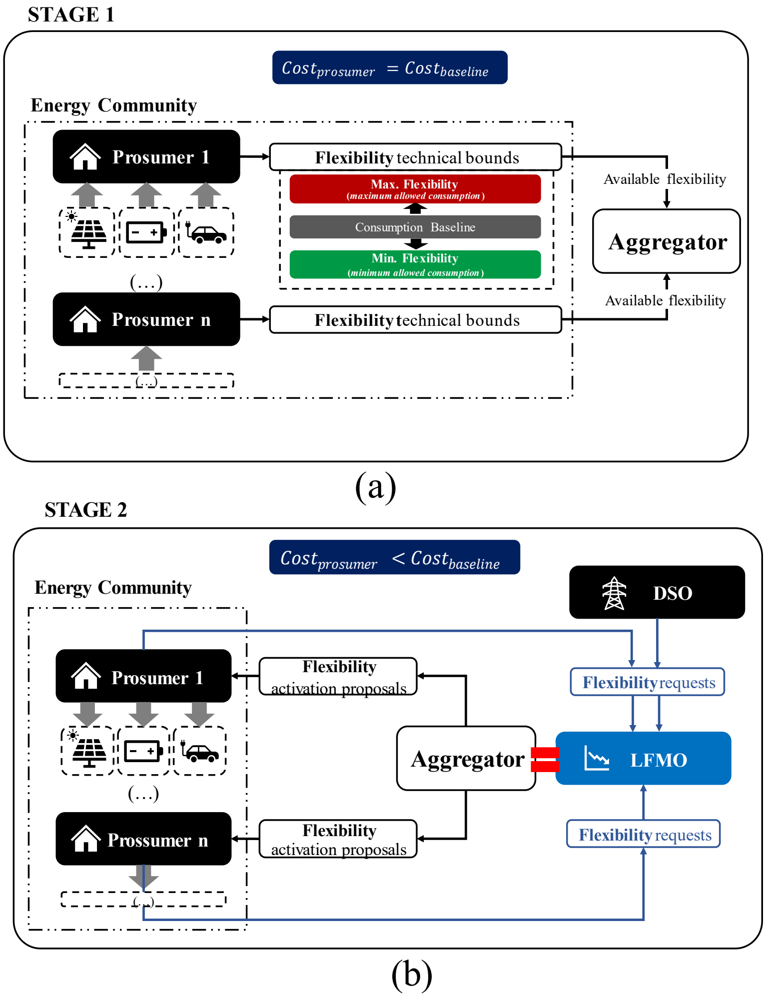

Figure 11. A two-stage model for DSO and REC flexibility services.

Still, in Stage 1, the optimal operation and consumption of each FU are optimized according to the formulation presented in Subsection 3.2.2. Then, using the same mathematical formulation, the maximum and minimum allowable consumption for each FU is determined. This determination is made by HEMS and is based on external incentives for increasing and decreasing residential energy consumption. These incentives are transmitted through energy purchase and sale price signals, that take very high and very low values for each time period.

The optimal scheduling serves as the baseline, while the profiles of maximum/minimum consumption allowed for each FU, are considered flexibility technical bounds. Thus, for each FU, three distinct pieces of information transit from Stage 1 to Stage 2: its baseline, its maximum flexibility (maximum allowable consumption), and its minimum flexibility (minimum allowable consumption), as seen in Figure 11 - (a).

In Stage 2, the LFM is structured (Figure 11- (b)). In addition to the information that transitions from Stage 1, the following parameters are added:

- DSO flexibility requests;
- Prosumers' flexibility bids;
- Constraints on flexibility activation by prosumers.

Both the DSO flexibility requirements and the prosumer flexibility needs are presented to the aggregator in the form of energy value ranges in order to increase the chances of being met by the REC. The constraints on the activation of flexibility by each prosumer have the following format:

- Maximum number of flexibility activation periods, for each FU;
- Minimum interval between two flexibility activation periods, for each FU;
- Maximum duration of a flexibility activation period, for each FU.

In this second stage, the operating costs of the Community Manager (aggregator) are minimized, considering all this information. The flexibility activation proposals are the outputs of the optimization problem and are sent by the aggregator to each prosumer. These proposals are then analyzed by the HEMS, which can accept or reject them. The activation proposals have the following format:

- Amount of energy that each FU should consume less (compared to its baseline determined in the first stage);
- Amount of energy that each FU should consume more (compared to its baseline determined in the first stage).

Each flexibility request and flexibility bid presented in the market has a monetary value associated. This value corresponds to the amount that the DSO and prosumers are willing to pay to purchase flexibility from the community. For each accepted flexibility activation proposal, prosumers are remunerated. Each HEMS can only accept proposals whose remuneration reduces the operating costs of the household, obtained in Stage 1;

otherwise, they will maintain the optimal scheduling of the FU (baseline) also obtained in Stage 1.

The following subsections will present the mathematical formulations and other details associated with each of the two stages of the problem.

3.2.2. Stage 1: Quantification of the Technical Flexibility Available in Each Prosumer Resources

The problem in Stage 1 aims to minimize the operating costs of the prosumer, equation (1), which is run by the HEMS, individually. It determines the baselines of each FU, i.e., their optimal consumption scheduling. This methodology was adapted from the mathematical formulation presented by [94]. To this adaptation, constraints describing the operation of the EV were added, among other details.

$$\min Costs_c = \sum_{t=1}^{T} E_{c,t}^{SUP} \cdot \lambda_{c,t}^{buy} - E_{c,t}^{SUR} \cdot \lambda_{c,t}^{sell} \tag{1}$$

The objective function in Equation (1) translates the costs of buying and selling energy for a prosumer's *c* home. The goal is to minimize these costs, which correspond to the difference between the sum of the product of energy bought $E_{c,t}^{SUP}$, at the buy price $\lambda_{c,t}^{buy\_h}$, and the sum of the product of the surplus sold $E_{c,t}^{SUR}$, at the selling price $\lambda_{c,t}^{sell\_h}$, for all time periods *t*.

$$E_{c,t}^{SUP} - E_{c,t}^{SUR} = E_{c,t}^{CMET} \quad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{2}$$

In Equation (2), the energy consumed by each prosumer *c*, recorded on their meter, for each time *t*, $E_{c,t}^{CMET}$, corresponds to the difference between the energy acquired (supply) and the energy sold (surplus) at that time period *t*.

$$E_{c,t}^{CMET} = E_{c,t}^{C} + E_{c,t}^{B\,Ch} + E_{c,t}^{EV\,Ch} - E_{c,t}^{G} - E_{c,t}^{B\,Dch} \quad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{3}$$

In Equation (3), energy recorded on the meter also corresponds to the difference between the sum of the energy consumed forecast, $E_{c,t}^{C}$, with the energy stored in the BESS, $E_{c,t}^{B\,Ch}$, and in the EV battery, $E_{c,t}^{EV\,Ch}$, and the energy from self-generation, $E_{c,t}^{G}$, and BESS discharge, $E_{c,t}^{B\,Dch}$.

$$E_{c,t}^{B} = E_{c,t-1}^{B} + \left(E_{c,t}^{B\,Ch} \cdot \eta_{c}^{B\,Ch} - \frac{E_{c,t}^{B\,Dch}}{\eta_{c}^{B\,Dch}} \right) \quad \forall\, t \in T \wedge \forall\, c \in C \tag{4}$$

The state of charge of the BESS is determined in equation (4). The energy remaining stored in a prosumer's *c* BESS at each time *t*, $E_{c,t}^{B}$, corresponds to the sum of the amount of energy remaining stored at the previous time *t-1*, $E_{c,t-1}^{B}$, with the amount of energy charged at that time *t*, affected by the efficiency of the BESS (in case of charging, $\eta_{c}^{B\,Ch}$) or minus the amount of energy discharged at that time *t* (in case of discharging, $\eta_{c}^{B\,Dch}$).

$$E_{c,t}^{EV} = E_{c,t-1}^{EV} + \left(E_{c,t}^{EV\,Ch} \cdot \eta_{c}^{EV\,Ch} \right) - EV_{c,t}^{trip} \quad \forall\, t \in T \wedge \forall\, c \in C \tag{5}$$

Similar to equation 4, equation 5 determines the prosumer's EV battery state of charge. The energy remaining there, at each time *t*, $E_{c,t}^{EV}$, corresponds to the sum of the amount of energy remaining stored at the previous time *t-1*, $E_{c,t-1}^{EV}$, with the amount of energy charged at that time *t*, affected by the efficiency of the EV battery (in case of charging, $\eta_{c}^{EV\,Ch}$) or minus the energy expended on a trip at that time *t* (in case the vehicle is in use), $EV_{c,t}^{trip}$.

The BESS and EV state of charge, in percentage, are defined by the constraints (6) and (7), respectively. It corresponds to the quotient between the energy stored in it at time *t* and the nominal storage capacity of the unit.

$$SOC_{c}^{B\,min} \leq SOC_{c,t}^{B} = \frac{E_{c,t}^{B}}{E_{c}^{B,N}} \times 100\% \leq SOC_{c}^{B\,max} \quad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{6}$$

$$SOC_{c}^{EV\,min} \leq SOC_{c,t}^{EV} = \frac{E_{c,t}^{EV}}{E_{c}^{EV,N}} \times 100\% \leq SOC_{c}^{EV\,max} \quad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{7}$$

The charging and discharging powers of a prosumer's *c* BESS and EV battery are defined in constraints presented in equations (8) and (9). They are the quotient between the amount of energy charged or discharged in period *t* and the absolute value of that time period. They are also limited to the maximum power required by these inverters. Note that in equation (9), the charging is only possible at times when the EV is connected to the electrical grid, i.e., at times where the binary variable $EV_{c,t}^{connection}$ is equal to 1.

$$\frac{E^{BC}_{c,t}}{\Delta t}, \frac{E^{BD}_{c,t}}{\Delta t} \leq P^{B\,Max}_{c} \qquad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{8}$$

$$\frac{E^{EVC}_{c,t}}{\Delta t}, \leq P^{EV\,Max}_{c} \cdot EV^{connection}_{c,t} \qquad \forall\, t \in T \;\wedge\; \forall\, c \in C \tag{9}$$

Figure 12 illustrates the entire procedure and shows all of the stage 1 developed methodology.

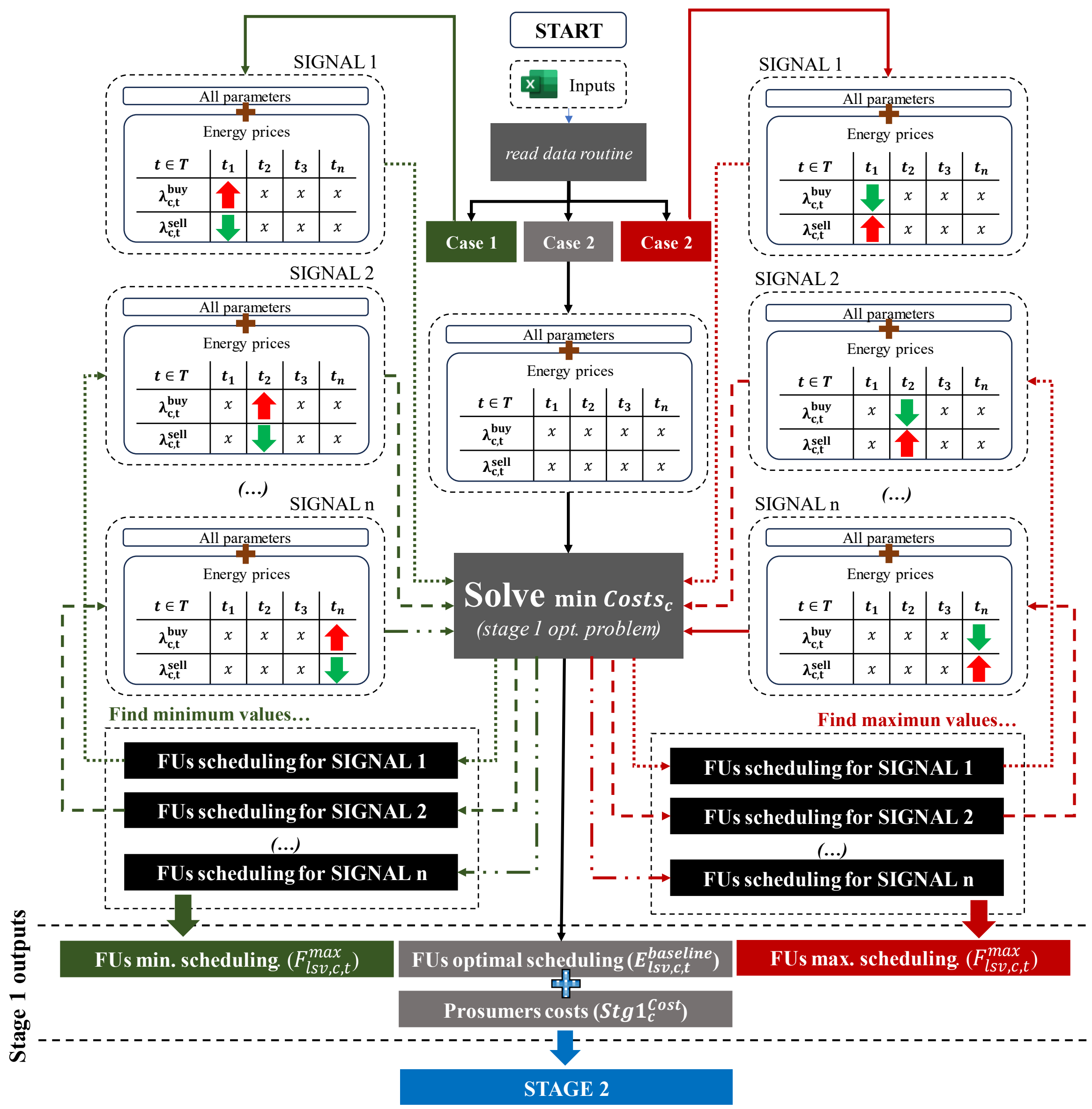

Figure 12. Flowchart of the methodology developed in stage 1.

The outputs associated with each FU, obtained in this first simulation, are passed on to stage 2, where they serve as parameters, identified by the nomenclature $E_{lsv,c,t}^{baseline}$. This structure stores the baselines of each FU *lsv* of all prosumers *c*. To determine the technical limits of the flexibility of each FU, the same mathematical formulation (equations (1) to (9)) is used. The adopted methodology requires, for the day-ahead (considering an hourly time-base), the performance of 48 distinct simulations: two for each period of the day *t*. For this, the purchase $\lambda_{c,t}^{buy\_h}$ and sale $\lambda_{c,t}^{sell\_h}$ tariffs of energy to the grid are maintained. However, for each simulation period *t*, two new price references are used: a very high value and zero. For each hour of the day, these price references are used twice, to simulate incentives for energy purchase and for energy sale by the prosumer, stimulating and disincentivizing the residential consumption, respectively.

Afterward, the results of the 48 simulations are analyzed computationally to determine the maximum and minimum energy consumption values allowed for each FU in each simulation period. These values are then considered as technical limits of their operating flexibility and transmitted to stage 2 as parameters with the nomenclatures $F_{lsv,c,t}^{max}$ and $F_{lsv,c,t}^{min}$.

3.2.3. STAGE 2: LOCAL FLEXIBILITY MARKET

The technical flexibility of each FU *lsv*, determined in stage 1 (section 3.2.2), is presented to the CM as bids from the local flexibility market. Each prosumer is also responsible for assigning a price to the capacity they make available, to consume both more $\lambda_{lsv,c,t}^{UP}$ and less $\lambda_{lsv,c,t}^{DW}$ energy compared to their baselines. At the same time, the flexibility needs of the DSO and of the prosumers and the prices that they are willing to pay for the flexibility are also considered. In addition, each prosumer sends certain parameters that serve as constraints on the activation of their FUs, as mentioned previously. In this second stage, the local flexibility market clearing is performed, taking into account the needs, bids, and their respective prices (10), where $F_{lsv,c,t}^{UP}$ and $F_{lsv,c,t}^{DW}$ represent, respectively, the capacity to consume more or less energy in the FU *lsv* of prosumer *c*, activated by the local market.

$$
\begin{aligned}
min\, Cost_{Flex\ Market} & \sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{lsv=1}^{LSV} F_{lsv,c,t}^{UP} * \lambda_{lsv,c,t}^{UP} \\
& + \sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{lsv=1}^{LSV} F_{lsv,c,t}^{DW} * \lambda_{lsv,c,t}^{DW}
\end{aligned} \tag{10}
$$

$\forall\, t \in T \ \wedge\ \forall\, c \in C \wedge\ \forall\, lsv \in LSV$

In Equation (11), the amount of energy reduced to each lsv baseline, $F_{lsv,c,t}^{DW}$, at each moment t must be less than or equal to the difference between that baseline value, $E_{lsv,c,t}^{baseline}$, and the minimum limit of energy that this lsv is authorized to consume, $F_{lsv,c,t}^{min}$, at that moment t. Equation (11) also requires $F_{lsv,c,t}^{DW}$ activation only at allowed times t. The binary variables δ indicate the times when this is allowed. At the same time, Equation (12) refers to $F_{lsv,c,t}^{UP}$, which is restricted to the difference between the maximum limit of energy that this lsv unit is authorized to consume, $F_{lsv,c,t}^{max}$, and the value of its baseline $E_{lsv,c,t}^{baseline}$.

$$F_{lsv,c,t}^{DW} \leq \left(E_{lsv,c,t}^{baseline} - F_{lsv,c,t}^{min}\right) \cdot \left(\delta_{lsv,c,t}^{DW\,start} + \delta_{lsv,c,t}^{DW\,run} + \delta_{lsv,c,t}^{DW\,end}\right) \quad (11)$$
$$\forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV$$

$$F_{lsv,c,t}^{UP} \leq \left(F_{lsv,c,t}^{max} - E_{lsv,c,t}^{baseline}\right) \cdot \left(\delta_{lsv,c,t}^{UP\,start} + \delta_{lsv,c,t}^{UP\,run} + \delta_{lsv,c,t}^{UP\,end}\right) \quad (12)$$
$$\forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV$$

Equations (13) and (14) require that the flexibility needs purchase proposals ($F_{r,t}^{DW\,needs}$ and $F_{r,t}^{UP\,needs}$) presented by the DSO (r) are met by the local flexibility market.

$$\sum_{c=1}^{C} \sum_{lsv=1}^{LSV} F_{lsv,c,t}^{DW} = F_{r,t}^{DW\,needs} \quad (13)$$
$$\forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV$$

$$\sum_{c=1}^{C} \sum_{lsv=1}^{LSV} F_{lsv,c,t}^{UP} = F_{r,t}^{UP\,needs} \quad (14)$$
$$\forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV$$

Equation (15) defines an energy budget that must be preserved from the EV charges baselines, in order to to prevent flexibility activation proposals from violating the energy needed for user mobility.

$$\sum_{t=1}^{T} F_{lsv,c,t}^{DW} = \sum_{t=1}^{T} F_{lsv,c,t}^{UP} \quad (15)$$
$$\forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv = EV$$

The total amount of energy reduced to the consumption baselines, $F_{lsv,c,t}^{DW}$, of each lsv unit must be equal to the amount of energy increased to these Fus, $F_{lsv,c,t}^{UP}$. The next set of constraints (16) to (24) concerns the determination of the scheduling of periods t in which the activation of the flexibility of each functional unit is allowed, according to restrictive parameters indicated by each prosumer. This methodology is based on a similar approach presented by [98], in a different context. In [98], the authors employ this computing technique to scale the production flexibility of a technical center based on signals emitted from the demand side.

$$\delta_{lsv,c,t}^{DW\,start} + \delta_{lsv,c,t}^{DW\,run} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{16}$$

$$\delta_{lsv,c,t}^{DW\,run} + \delta_{lsv,c,t}^{DW\,end} \leq 1 \quad \forall\, t \in T \wedge \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{17}$$

$$\delta_{lsv,c,t}^{UP\,run} + \delta_{lsv,c,t}^{UP\,end} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{18}$$

$$\delta_{lsv,c,t}^{DW\,start} + \delta_{lsv,c,t}^{UP\,start} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{19}$$

$$\delta_{lsv,c,t}^{DW\,start} + \delta_{tlsv,c,t}^{UP\,run} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{20}$$

$$\delta_{lsv,c,t}^{DW\,start} + \delta_{lsv,c,t}^{UP\,end} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{21}$$

$$\delta_{lsv,c,t}^{DW\,run} + \delta_{lsv,c,t}^{UP\,run} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{22}$$

$$\delta_{lsv,c,t}^{DW\,run} + \delta_{lsv,c,t}^{UP\,end} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{23}$$

$$\delta_{lsv,c,t}^{DW\,end} + \delta_{lsv,c,t}^{UP\,end} \leq 1 \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{24}$$

Equations (25) and (26) require that a start moment of a period of flexibility activation can only be followed by an end moment or a run moment.

$$\delta_{lsv,c,t}^{DW\,start} \leq \delta_{lsv,c,t}^{DW\,end} + \delta_{dsv,c,t+1}^{DW\,run} + \delta_{lsv,c,t+1}^{DW\,end} \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{25}$$

$$\delta_{lsv,c,t}^{UP\,start} \leq \delta_{lsv,c,t}^{UP\,end} + \delta_{lsv,c,t+1}^{UP\,run} + \delta_{lsv,c,t+1}^{UP\,end} \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{26}$$

Equations (27) and (28) define that a run moment of a period of flexibility activation can only be followed by an end moment or another subsequent run moment.

$$\delta_{t,lsv}^{DW\,run} = \delta_{t+1,lsv}^{DW\,run} + \delta_{t+1,lsv}^{DW\,end} \quad \forall\, t \in T \ \wedge\ \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{27}$$

$$\delta_{t,lsv}^{UP\,run} = \delta_{t+1,lsv}^{UP\,run} + \delta_{t+1,lsv}^{UP\,end} \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{28}$$

Constraints (29) and (30) define the maximum duration of periods of flexibility activation.

$$\sum_{i=t}^{t+H_{lsv,c}^{DW\,max}-1} \delta_{lsv,c,i}^{DW\,end} \geq \delta_{lsv,c,t}^{DW\,start} \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{29}$$

$$\sum_{i=t}^{t+H_{lsv,c}^{UP\,max}-1} \delta_{lsv,c,i}^{UP\,end} \geq \delta_{lsv,c,t}^{UP\,start} \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{30}$$

Equations (31) and (32) define the maximum number of periods of flexibility activation.

$$\sum_{t=1}^{T} \delta_{lsv,c,t}^{DW\,start} \leq G_{lsv,c}^{DW\,max} \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{31}$$

$$\sum_{t=1}^{T} \delta_{lsv,c,t}^{UP\,start} \leq G_{lsv,c}^{UP\,max} \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{32}$$

Finally, Equations (33) and (34) define the minimum pause time between two consecutive periods of flexibility activation, allowed for each flexible unit lsv of a consumer c.

$$\delta_{lsv,c,t}^{DW\,end} + \sum_{i=t}^{t+H_{lsv,c}^{DW\,min}} \delta_{lsv,c,i}^{DW\,start} \leq 1 \quad \forall\, t \in T \wedge \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{33}$$

$$\delta_{lsv,c,t}^{UP\,end} + \sum_{i=t}^{t+H_{lsv,c}^{UP\,min}} \delta_{lsv,c,i}^{UP\,start} \leq 1 \quad \forall\, t \in T \,\wedge\, \forall\, c \in C \wedge \forall\, lsv \in LSV \tag{34}$$

3.2.3.1. PROSUMERS FINAL COSTS DETERMINATION

To calculate the final prosumers energy costs, it is essential to take into account their initial costs (extracted from stage 1) and assess the impact of the local flexibility market clearing on them.

Let $Stg1_c^{COSTS}$ be a vector representing the initial costs per prosumer (c), as indicated by Equation (35). Based on this value, the final costs are determined by the operations outlined in Equation (36).

$$Stg1_c^{COSTS} = Costs_c \tag{35}$$

$$Final_c^{COSTS} = Stg1_c^{COSTS} + Stg2_c^{Costs} - Stg2_c^{PROFITS} \tag{36}$$

The initial costs are added to the costs associated with the activation of cleared flexibility UP ($F_{lsv,c,t}^{UP}$). These costs are determined by equation (*37*). It is important not to confuse them with the cost function minimized in stage 2 ($Cost_{Flex\ Market}$).

$$Stg2_c^{Costs} = \sum_{t=1}^{T} \left(\sum_{lsv=1}^{LSV} \left(F_{lsv,c,t}^{UP} \right) * \lambda_{c,t}^{buy} \right) \tag{37}$$

The acceptance of proposals for activating flexibility UP entails an increase in the amount of energy consumed by prosumers. This additional consumption comes at a cost equal to the contracted energy tariff rate ($\lambda_{c,t}^{buy}$). This immediately leads to the conclusion that the UP flexibility offers from prosumers must have a value equal to or higher than the energy tariff rate to ensure a profitable strategy.

$$Stg2_c^{PROFITS} = \sum_{t=1}^{T} \sum_{lsv=1}^{LSV} F_{lsv,c,t}^{UP} * \lambda_{lsv,c,t}^{UP} + F_{lsv,c,t}^{DW} * \lambda_{lsv,c,t}^{DW} \tag{38}$$

The profits from the local flexibility market are calculated by equation (38) and correspond to the product of the cleared offers ($F_{lsv,c,t}^{UP}$ and $F_{lsv,c,t}^{DW}$) and their respective offer prices ($\lambda_{lsv,c,t}^{UP}$and $\lambda_{lsv,c,t}^{DW}$) per prosumer.

4. Case Study and Results Discussion

This chapter is dedicated to validating the previously presented methodology and assessing its performance through different case studies. The proposed case studies allow us to draw conclusions regarding the benefits of this flexibility modelling strategy for members of a REC with high penetration of emerging technologies.

It is noteworthy that the proposed methodology (Chapter 3) has been applied in MATLab and GAMS. Input data was organized using Microsoft Excel spreadsheets. A simulation tool was constructed using MATLAB. This tool handles input data for all stages of the model and the entire data flow throughout the simulation. Multiple cycles are used to execute the problems modeled in GAMS following the guidelines presented in chapter 3.

In addition to the case study, this chapter begins with an illustrative example of how the model operates. This example features a REC with a reduced number of prosumers to facilitate the reader's understanding of the ongoing dynamics.

4.1. ILLUSTRATIVE EXAMPLE

An illustrative example was used to validate the proposed two-stage model. An hourly time-base and generation and consumption forecasts, for the next day, were considered, for each of the prosumers. For this simulation, an hourly time base (60 minutes) was used. The simulation period under analysis spans 24 hours, equivalent to one day.

4.1.1. PROSUMERS CHARACTERIZATION

Let's consider a small set of 3 prosumers with different configurations in terms of their available flexible units. Table 13 presents the technical characteristics of these resources, and this information is made available to the HEMS of each residence.

Table 13. Home resources and energy prices characterization.

Home Resources		**Prosumer ID (c)**		
		1	**2**	**3**
PV	*capacity*	17.4 kWh	12.7 kWh	---
BESS	*capacity*	5.0 kWh	------	7.5 kWh
	max.power	2.0 kW		2.5 kW
EV	*capacity*	25.0 kWh	30.0 kWh	------
	connection period	00 – 08 h	14 – 19 h	
	initial energy	10.0 kWh	10.0 kWh	
	energy needed	14.0 kWh	12.5 kWh	
Energy Prices	**00h – 10h/ 13h – 19h/ 22h – 00h**		**10h – 13h/ 19h – 22h**	
Market Price [$\lambda_{c,t}^{buy\_h}$]	0.115 mu./kWh		0.237 mu./kWh	
Feed-in tariff [$\lambda_{c,t}^{sell\_h}$]	0.0086 mu./kWh		0.0363 mu./kWh	

The table data are used as inputs for the first stage of the problem. From this information, we can deduce:

- Two prosumers have systems to charge electric vehicles, whose battery capacity is sent to the HEMS;
- Prosumers communicate to the HEMS their desired state of charge for their vehicles after a charging period;

- BESS was considered for prosumers 1 and 3;
- HEMS is informed about the batteries' capacity and their inverter power ratings;
- Time-of-use tariffs with four-hour intervals were applied for energy procurement and sales.

Figure 13. Characterization of the small energy community in the illustrative example.depicts the composition of the small community that constitutes this example. It illustrates the prosumers and the flows of power and flexibility existing among them.

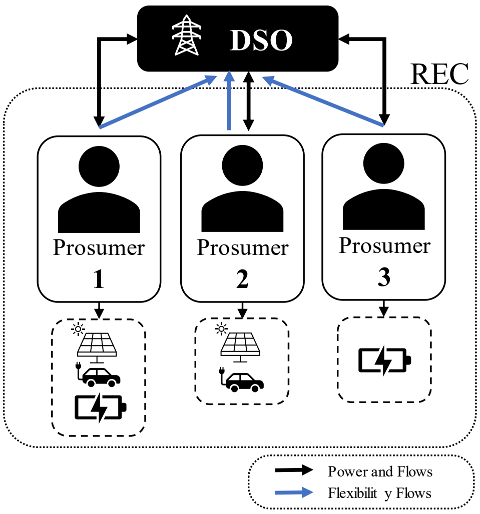

Figure 13. Characterization of the small energy community in the illustrative example.

4.1.2. Flexibility Requests

Table 14 displays the flexibility requirements submitted by the DSO in the local market. It shows the operator's required flexibility capacity and it presents a purchase price that must be equal to or higher than the flexibility offering price by prosumers for the bid to be accepted during the clearing process.

Table 15 shows extra limitations prosumers send to the CM when making offers, restricting how flexibility of their resources are activated based on their comfort and preferences. Note that:

- Each flexible unit specifies the highest number of times it can be activated, how long these activations can last, and the shortest time delay between them.

- EV reveal usage preferences, but other options can also be defined. The longest activation duration matches the vehicle's grid connection time, and the most activations allowed match the expected daily charging count.

Table 14. Flexibility requests characterization.

DSO (r) Flexibility Requests	**Time Period (t)**			
Flex. DW	**16h**	**17h**	**18h**	**19h**
Capacity [$F_{r,t}^{UP\ needs}$]	1.5 kW	2.5 kW	3.0 kW	4.0 kW
Price (mu.)	0.009	0.009	0.009	0.009
Flex. UP	**20h**	**21h**	**22h**	**23h**
Capacity [$F_{r,t}^{DW\ needs}$]	1.0 kW	3,5 kW	5.0 kW	1.5 kW
Price (mu.)	0.238	0.238	0.238	0.127

Table 15. Prosumers flexibility activation constraints.

Flexibility Activation		**Prosumer ID (c)**			
		1		**2**	**3**
		BESS	**EV**	**EV**	**BESS**
Flex. DW Proposals	*Max. Duration [$H_{lsv,c}^{DW\ max}$]*	3h	8h	5h	3h
	Max. Number [$G_{lsv,c}^{DW\ max}$]	2	1	1	2
	Minimum Delay [$H_{lsv,c}^{DW\ min}$]	1h	---	---	1h
Flex. UP Proposals	*Max. Duration [$H_{lsv,c}^{UP\ max}$]*	3h	8h	5h	2h
	Max. Number [$G_{lsv,c}^{UP\ max}$]	2	1	1	2
	Minimum Delay [$H_{lsv,c}^{UP\ min}$]	1h	---	---	1h

4.1.3. RESULTS

The results of the illustrative example are now presented. Figure 14 displays the outputs obtained in the first stage of the problem. The graphs pertain to each of the three prosumers under study. From them, the following can be inferred:

- The baselines represent the energy required for the optimal operation of the Flexible Units (FUs) over the 24-hour simulation period and are depicted as solid lines;

- The technical limits of maximum and minimum flexibility for each FU are represented with dashed lines above and below the baseline, respectively;

- The magnitude of the differences between the technical limits and the baselines constitutes the technical flexibility offered by each prosumer in the local flexibility market;

- The results pertaining to BESS are depicted in blue, while the results related to EV charging are in red.

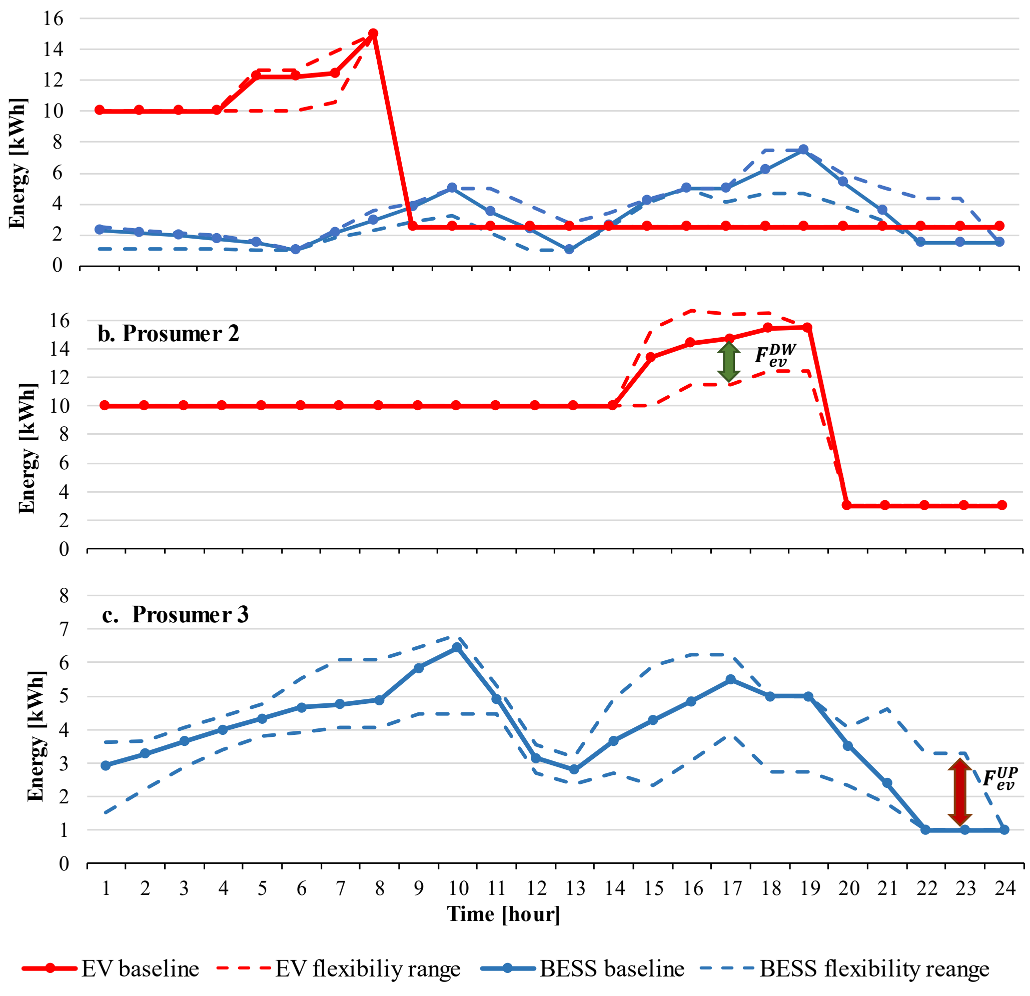

Figure 14. Optimal scheduling (baselines) and technical flexibility of REC domestic resources.

The results show greater flexibility in the operation of batteries compared to vehicle charging. This occurs because the operation of EV chargers is naturally more constrained than that of BESS. Mathematically, this is reflected in the greater number of constraints applied to modeling the operation of EVs in stage 1 and activating their flexibility in stage 2.

The graphs in Figure 15 display the outputs from the second stage of the problem. Each graph corresponds to a FU. In these graphs, the baselines (presented in blue) are compared to the rescheduling resulting from the flexibility activation proposals received by that FU after the closure of the local market. The rescheduling is presented in red and represents the change in the scheduling of each flexible unit's optimal operation after receiving flexibility activation proposals from the Market Operator.

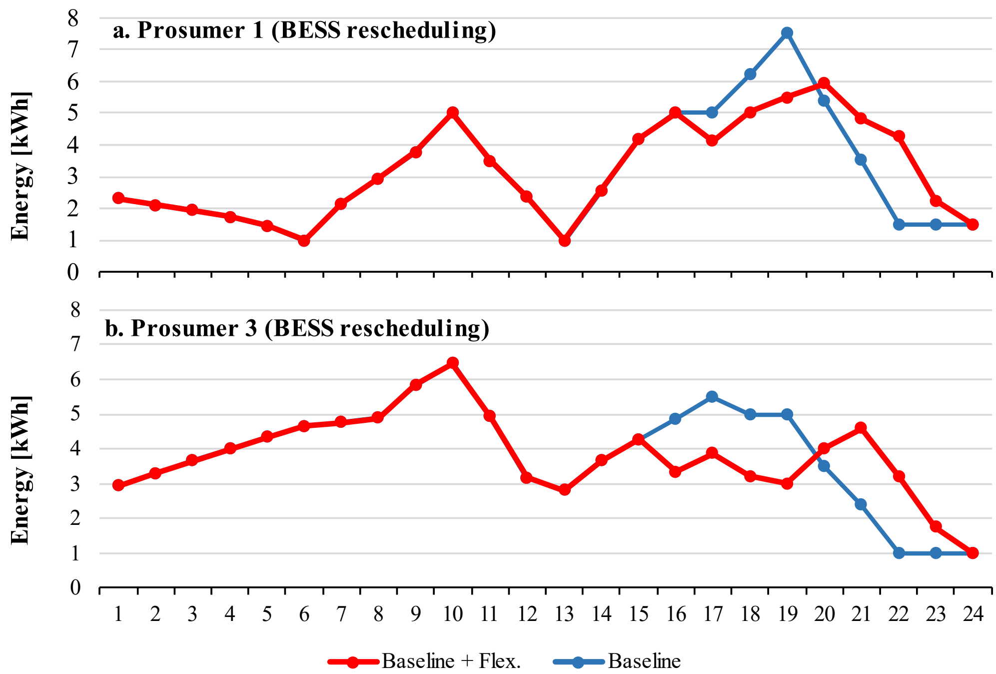

Figure 15. Baselines of the BESS of prosumers 1 and 3 and respective rescheduling after the second stage of the problem.

The graphs allow for the verification of prosumer constraints as indicated in Table 15. Simultaneously, the requirements of the DSO as outlined in Table 14 are also fully met. This is evident from the red curve, which shows baseline cuts between 4 pm and 7 pm and baseline extensions between 8 pm and 11 pm. The prosumers received a value per kWh of flexibility that was 10% higher than the energy tariff rate (in the case of $F_{lsv,c,t}^{UP}$) and 10% higher than the feed-in tariff rate (in the case of $F_{lsv,c,t}^{DW}$). This value corresponds to the purchase price offered by the requester (the DSO) in the local flexibility market. This encourages prosumers' participation in the flexibility market. Table 16 shows the energy costs of REC members before and after the flexibility activation. Note that the energy costs of prosumers whose offers were met decreased, proving the benefits of having different players participating in this market.

Table 16. Energy costs of prosumers before and after their participation in the local flexibility market.

Residential Energy Costs	**Prosumer ID (*c*)**		
	1	**2**	**3**
After stage 1 (baseline)	3.323 mu.	5.156 mu.	8.310 mu.
Revenue in the local flexibility market	1.209 mu.	0.000 mu.	1.315 mu.
Energy supply costs (for baseline extensions)	1.172 mu.	0.000 mu.	1.253 mu.
After stage 2 (flex. Activation)	3.286 mu.	5.156 mu.	8.248 mu.
Costs reduction	1.12%	---	0.75%

4.2. LOCAL FLEXIBILITY MARKET APPLIED TO A RENEWABLE ENERGY COMMUNITY

In this subsection, one can examine the impact of small-scale REC prosumers' participation in the local flexibility market. The initial step includes describing the energy community, focusing on the technical features of prosumers and their flexible resources. Following that, the structure of the simulations making up the case studies is outlined. Lastly, the obtained results are presented and subsequently analyzed.

4.2.1. TECHNICAL AND ECONOMIC CHARACTERISTICS OF THE RENEWABLE ENERGY COMMUNITY

The energy community under investigation consists of 14 prosumers. Like the illustrative example, these prosumers may have BESS and EV chargers as flexible units. Their technical flexibility is calculated using the strategy outlined in Chapter 3 . In contrast to the illustrative example, in addition to the flexibility offers provided by FUs, prosumers can also offer flexibility from other resources. This capacity is not directly calculated in the first stage of the problem but is an assumption regarding the technical flexibility of other resources that make up the household load profiles. Figure 16 illustrates the structure of the energy community. Prosumers have different combinations of flexible resources to assess their impact on their electricity expenses.

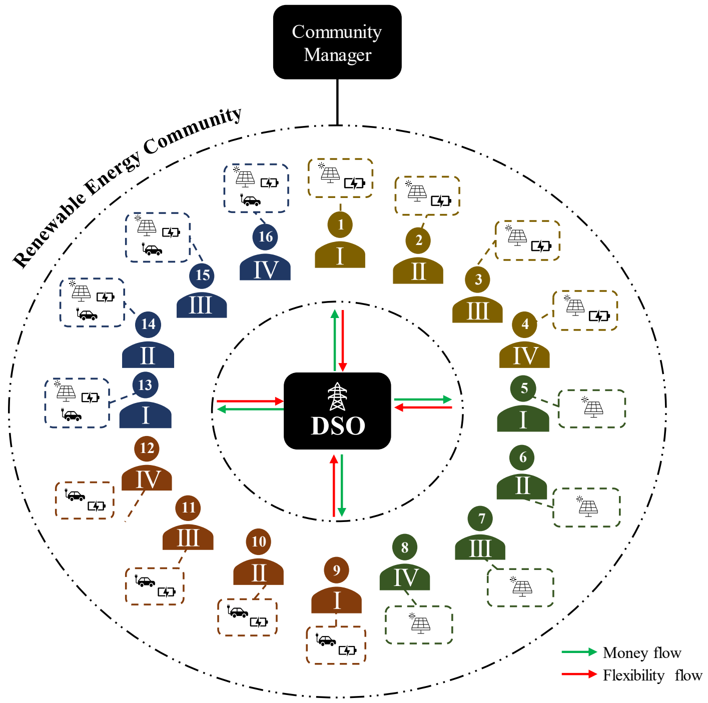

Figure 16. Renewable Energy Community structure with flexibility and money flows.

Each prosumer is represented by a color that indicates the type of FUs they possess. Table 17 summarizes the information presented in Figure 16 and explains the color code used, as well as the flexibility capacity that each prosumer can offer in the market.

Table 17. Characterization of each prosumer's resources and the source of flexibility offered in the market.

Color Code	Prosumer ID	Available Resources	Flexibility Source	Flexibility Quantification Methodology
(olive)	[1 - 4]	PV, BESS	BESS	Stage 1 methodology*
(green)	[5 - 8]	PV	Other Resources	Assumptions**
(brown)	[9 - 12]	BESS, EV	BESS, EV	Stage 1 methodology*
(blue)	[13 - 16]	PV, BESS, EV	BESS, EV	Stage 1 methodology*

* for BESS and EV technical flexibility determination

** for other resources flexibility offer determination

The presented community exhibits the distinctive characteristics of a REC as outlined in Table 1, namely: (*i*) the presence of renewable generation resources, (*ii*) geographical proximity among its members, (*iii*) engagement in self-generation, (*iv*) energy trading, and (*v*) storage activities. It is also assumed that the prosumers participate in a future energy market through a mediator/aggregator. The role of this mediator is fulfilled by the CM, who is also presented in Figure 16. Like the illustrative example, the CM serves as both a mediator and a LEM Operator. It should be clarified that prosumers' participation in the local flexibility market follows their participation in the local energy market, sequentially.

Next, a more detailed characterization of REC members is provided based on three specific parameters:

- **Energy Consumption:** This includes descriptions of the actual consumption load profiles of prosumers (excluding the operation of BESS and EV chargers) and their classification based on the housing typology;
- **PV Generation:** This entails characterizing the installed PV capacity in each residence and the typical generation profiles adopted;
- **Flexible Units:** This involves describing the technical parameters of BESS, EVs, and their chargers, as well as each user's charging preferences;
- **Local Energy Market Prices:** Description of the tariffs considered for the purchase and sale of energy by REC members in the local market where they operate.

4.2.1.1. ENERGY CONSUMPTION

Three different housing typologies were defined based on the number of occupants within each. This division aims to assess the impact of different consumption profiles on the ability to provide flexibility in the market. Table 18 illustrates the grouping of prosumers by typology and establishes the energy consumption range for each of them.

The consumption data used relied on a tool developed by Cambridge Architectural Research under contract to DECC (the Department of Energy and Climate Change) and DEFRA (the Department of the Environment, Food and Rural Affairs) [106]. This tool enables the utilization of summary data from the Household Electricity Study, which monitored electricity usage in 250 homes from 2010 to 2011. For each household, the following loads were considered: heaters, water heaters, showers, washing and drying machines, stoves, lighting, cold appliances, information and communication technologies (ICT), audiovisual appliances, and other unknown loads. Table 19 presents the consumption range for each of these appliances.

Table 18. Types of prosumers based on their energy consumption.

Prosumer Type ID	Number of occupants	Typical Energy Consumption Range	Prosumer ID
I	1	[0.30 – 2.76] kWh	1, 5, 9, 13
II	2	[0.32 – 3.72] kWh	2, 6, 10, 14
III	3	[0.28 – 4.02] kWh	3, 7, 11, 15
IV	4	[1.00 – 6.00] kWh	4, 8, 12, 16

Table 19. Energy consumption range per appliance considered.

Appliance	Typical Energy Consumption Range
Heaters,	[0.0– 0.02] kWh
Water heaters	[0.0 – 0.15] kWh
Showers	[0.00 – 1.28] kWh
Washing machines	[0.00 – 1.26] kWh
Stoves	[0.00 – 1.09] kWh
Lighting,	[0.00 – 1.77] kWh
Cold appliances	[0.14 – 0.49] kWh
ICT	[0.00 – 0.30] kWh
Audiovisual	[0.02 – 0.76] kWh
Unknown loads.	[0.01 – 3.20] kWh

In this case study, four typical consumption profiles were employed, one for each type of consumer. Note that the data about heaters and water heaters lacks clarity. Not all load profiles provided clear information regarding these appliances, and in some cases, the energy consumption related to hot water heating is mentioned in the shower-related information. Figure 17 display the four load profiles considered.

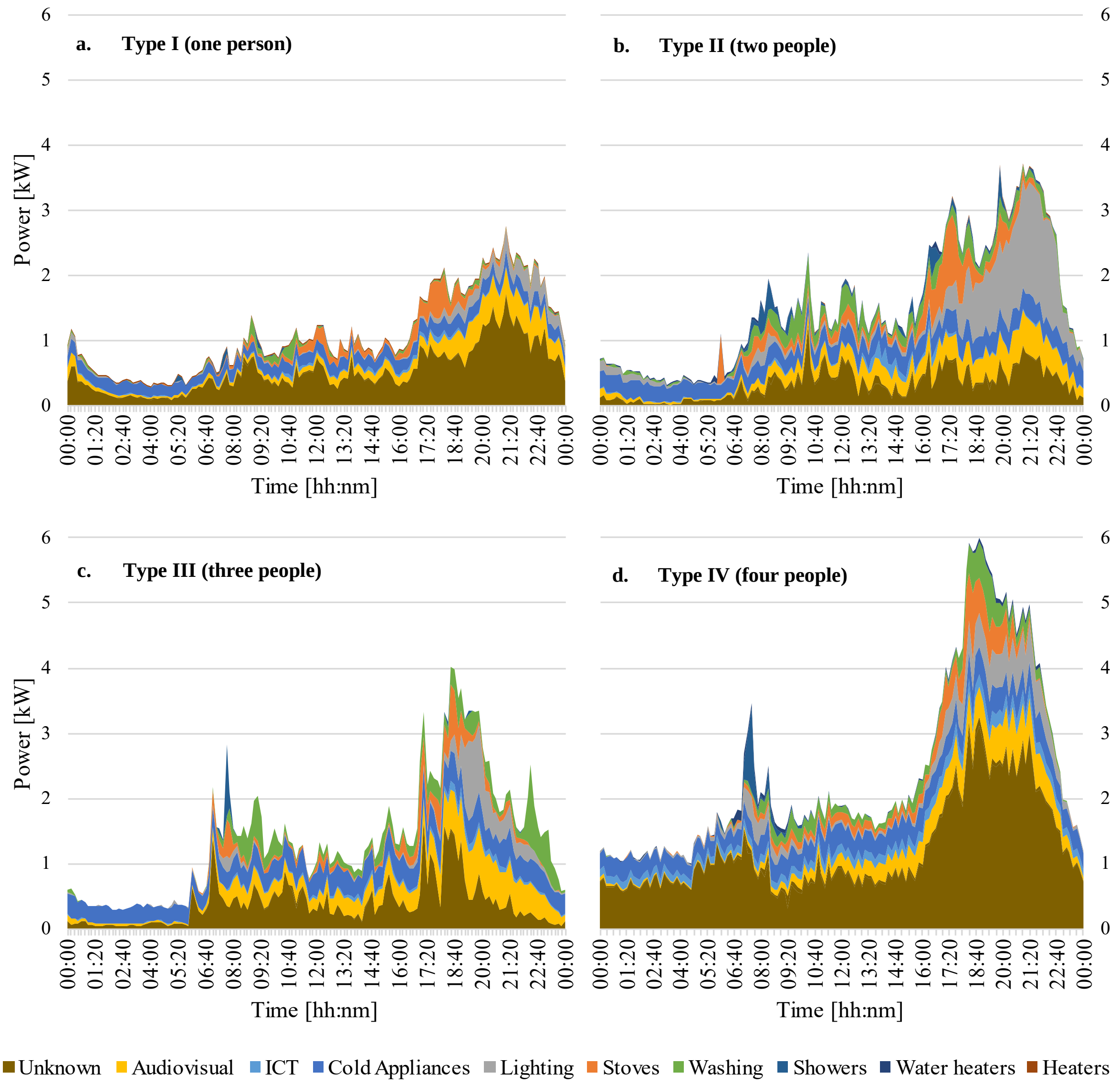

Figure 17. Reference load profiles for the four types of prosumers under study.

It's important to mention that the data depicted in the Figure 17 represent just a typical baseline profile per type of prosumer. In each simulation, prosumers get a consumption value from their typical profile, varying by around 10% to introduce diversity and mimic real-world consumption in an unpredictable way. To achieve this, MATLAB functions were used to generate random numerical values.

4.2.1.2. PV GENERATION

Except for prosumers numbered from 9 to 12, all prosumers have photovoltaic solar generation technologies. The installed capacity varies based on the number of occupants in each residence, being higher in more populated homes and lower in single-occupancy ones. Table 20 displays the installed capacity by prosumer typology and compares it with the peak power consumption in each case.

Table 20. Installed generation capacity and typical energy generation profiles per type of prosumer.

Prosumer type ID*	Installed capacity	Peak energy consumption	Typical PV generation range	
			Winter	Summer
I	5 kW	3.04 kWh	[0.0 – 3.00] kWh	[0.0 – 4.50] kWh
II	8 kW	4.09 kWh	[0.0 – 4.79] kWh	[0.0 – 7.20] kWh
III	10 kW	4.42 kWh	[0.0 – 6.00] kWh	[0.0 – 9.00] kWh
IV	15 kW	6.60 kWh	[0.0 – 8.99] kWh	[0.0 – 13.50] kWh

* according to Table 18

For each typology, a typical energy generation profile was also defined. Once again, a prosumer's actual generation of a specific typology corresponds to their typical generation profile, affected by a random variation rate of plus or minus 10% from the typical value. To establish typical values, it was assumed that all prosumers would be exposed to the same level of solar irradiance. The irradiance curves that underpinned the typical generation profiles are depicted in the graphs in Figure 18.

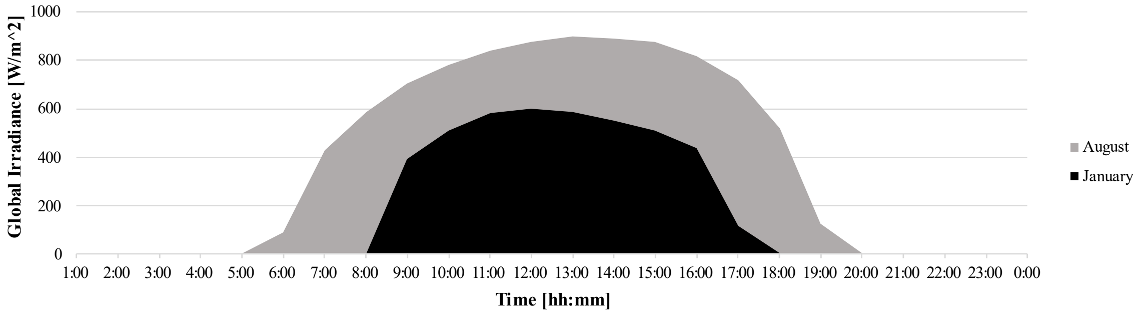

Figure 18. Hourly average irradiance curves on a 2-axis tracking plane for the Northern Region of mainland Portugal.

The irradiance data were extracted from the Photovoltaic Geographical Information System (PVGIS) of the European Union Science Hub, under the responsibility of the

European Commission. The data corresponds to the geographical area of the Northern Region of Mainland Portugal and consists of the average hourly Global irradiance on a 2-axis tracking plane for the months of January and August (representing winter and summer, respectively). The use of these two profiles enables the generation of two distinct scenarios in which the variation of effective PV generation will be the subject of study.

4.2.1.3. FLEXIBLE UNITS CHARACTERIZATION

The flexible units of community members, whose flexibility is determined by the first stage of the problem and have the lsv index, encompass BESS and EV chargers.

All members have battery storage systems except the prosumers five to eight. In each of these residences, there is a single BESS unit. Like earlier, the parameters of the BESS units are defined based on the consumption typology established for each prosumer, as outlined in Table 18: The higher the typology ID of each prosumer, the greater the capacity and power of the inverters of their storage units. Table 21 provides a summary of the technical parameterization defined for each one of them.

Table 21. Characterization of the technical parameters of the studied BESS in the REC.

Prosumer type ID*	Storage capacity	Charge and discharge power	Initial energy	Max. SOC	Min. SOC	Charge and discharge efficiency
I	5.00 kWh	3.45 kW	2.50 kWh	80%	20%	90%
II	10.00 kWh	4.60 kW	5.00 kWh			
III	15.00 kWh	5.75 kW	7.50 kWh			
IV	25.00 kWh	6.9 kW	12.50 kWh			

* according to Table 18

Despite having different storage capacities and power ratings, it was considered that all BESS would operate on the same principle. In practice, this means that they are standardized, as if they originated from the same manufacturer. Consequently, the charging and discharging efficiencies, as well as the maximum and minimum State of Charge (SOC), are standardized. The allowable SOC range for operation is set between 20% and 80% of the maximum unit capacity, following best practices as presented in [105].The chosen efficiency for both charging and discharging is 90%, based on considerations in [107].

The capacity values were assigned based on market data and considering the other technical characteristics of the current case study. Given the wide variety of options available and the academic nature of this example, the nominal charging and discharging powers of BESS were assumed to align with the power tiers defined by E-REDES for low voltage.

The definition of technical characteristics for EVs followed a similar division as before. Two types of vehicles are assigned to prosumers 9 to 16 based on their consumption typology.

Table 22 presents the battery capacity values for the EVs owned by prosumers in the four analyzed typologies. It also indicates the nominal power ratings, charging efficiencies for each vehicle, as well as the limits imposed on their state of charge and the initial energy (energy stored at $t = 0$).

Table 22. Characterization of the parameters of electric vehicle batteries and charging powers.

Prosumer type ID*	EV battery capacity	Charge power	Initial energy	Max. SOC	Min. SOC	Charge efficiency
I / II	42.20 kWh	7.00 kW	10 kWh	80%	20%	90%
III / IV	95.00 kWh	22.00 kW	40 kWh			

* according to Table 18

Since they are also lithium batteries, the same values for SOC limits and charging efficiency used in the parameterization of BESS were applied. Two types of vehicles were considered within the community: the BMW i3 model for prosumers of types I and II, and the Tesla Model S for the others. The battery capacities align with the values presented by the manufacturers in [108] and [109], respectively. Two different types of chargers are also taken into account, with one of them being a fast charger.

The graph in Figure 19 illustrates the EV charging routines and the corresponding energy required after each connection period.

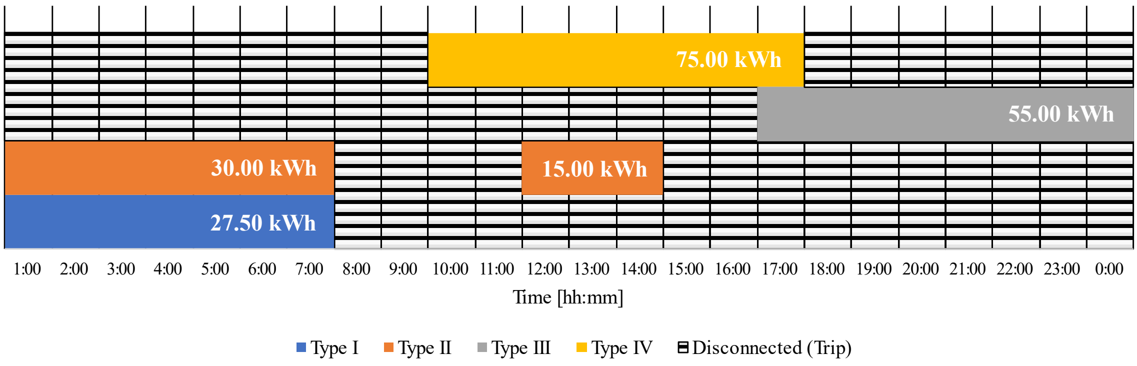

Figure 19 . Scheduling the EVs' grid connection for each posumer typology and the required energy after each charging session.

Charging routines depend on the type of prosumer (see Table 17). Each color represents one of the four analyzed typologies. During the time periods when a specific EV is connected to the charging system, its color is visible on the graph, and the user's required energy at the end of the charging session is displayed at the end of the respective bar.

Charging vehicles in the late afternoon and during the early morning hours was prioritized to reflect common charging preferences. However, charging sessions throughout the afternoon are also planned to assess their impact on residential flexibility.

4.2.1.4. Local Energy Market Prices and Tariffs

Next, the prices to which prosumers are subject for buying and selling energy at the local level are characterized. The purchase price of energy ($\lambda_{c,t}^{buy}$) corresponds to the price of the LEM to which the REC is exposed. It was assumed that prosumers pay the rate indexed to this market. Marginal prices from the Iberian day-ahead market, extracted from the months of January and August 2023, were used. This allows for the construction of simulation scenarios for two different seasons.

The selling price ($\lambda_{c,t}^{sell}$) of energy produced and fed back into the grid is based on the application of feed-in tariffs. The same tariff was established for all 16 prosumers. According to [110], feed-in tariffs in Portugal were introduced in 2008 with an average value of 6.50 cents/kWh, which has gradually decreased over the years, and in 2015 it was 4.00 cents/kWh, in average. Based on these two values, a four-hourly feed-in tariff was considered, favoring sales during peak periods.

Figure 20 graphically illustrates the temporal evolution of the prices under consideration.

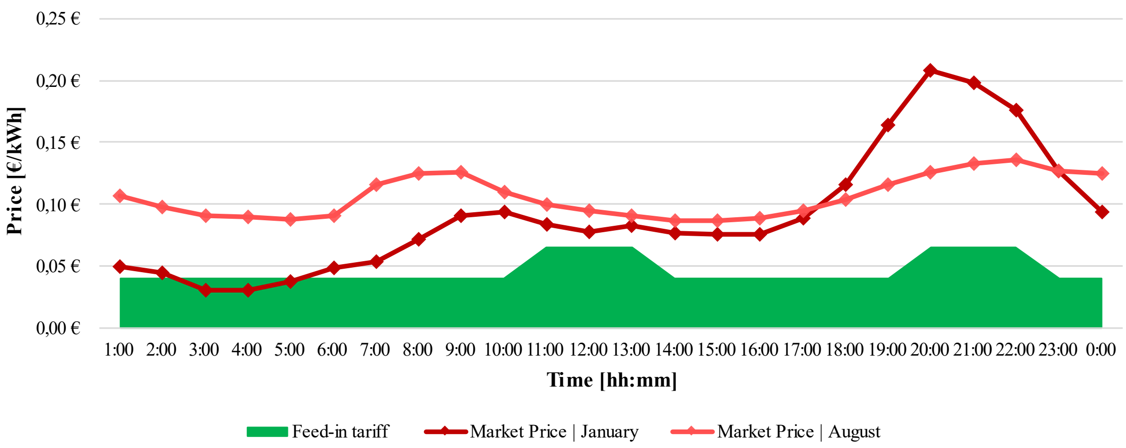

Figure 20. Temporal evolution of local energy market prices and the considered feed-in tariffs.

Note that feed-in tariffs are generally lower than market prices. This encourages self-consumption and storage, which is expected to increase flexibility in each residence.

4.2.2. LOCAL FLEXIBILITY MARKET CHARACTERIZATION

Next, the characterization of the local flexibility market is conducted. In this market, REC members described in 4.2.1 participate as flexibility providers, while the DSO participates as the requester of flexibility.

Similar to the illustrative example (4.1), the formulation of stage 2 of the problem (3.2.3) is used to perform market clearing based on the offers ($F_{lsv,c,t}^{max}$ and $F_{lsv,c,t}^{min}$) and flexibility requirements ($F_{lsv,c,t}^{UP}$ and $F_{lsv,c,t}^{DW}$). Once again, the study focuses on a day-ahead session in which the players participate on an hourly time basis. The following input parameters will be described:

- **DSO Requirements:** Indication of the amount of flexibility the DSO intends to acquire in the market from the community manager;
- **Flexibility Offers:** Description of the heuristics and assumptions considered in defining the flexibility capacity offered by each prosumer in the local market;

- **Offer Prices:** Explanation of the methodology used for price formation;

- **Flexibility Activation Constraints:** Description of parameters restricting the activation of flexibility by prosumer Flexible Units (FUs).

4.2.2.1. DSO REQUIREMENTS

The DSO acts as the requester of flexibility in the day-ahead LFM for operational and planning reasons. Two requirements, referred to as "flexibility up" (the purchase of capacity to increase community consumption) and "flexibility down" (the purchase of capacity to reduce community consumption), are presented. These two requirements are independent, and in this case study, there is the possibility of requesting both types of flexibility simultaneously.

Figure 21 illustrates the DSO's requirements and compares them with the average consumption profile of REC members.

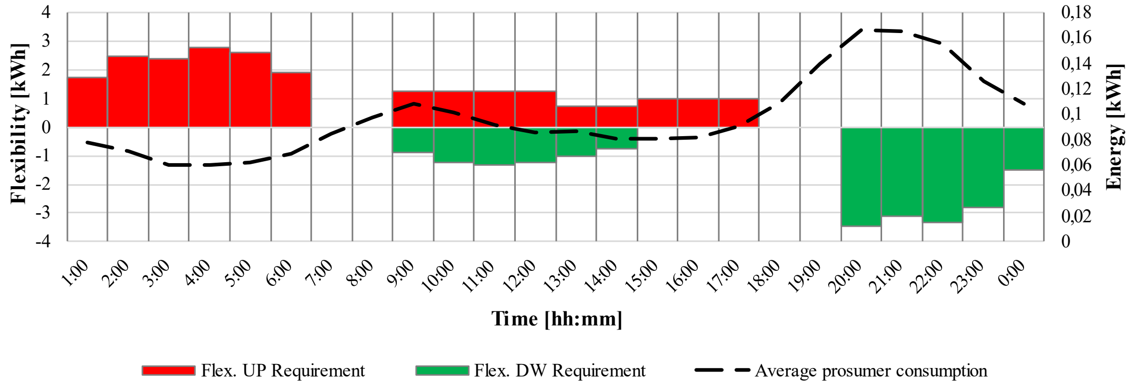

Figure 21. DSO Requirements in the Local Flexibility Market

For defining the requirements, it was presumed that the DSO might need to alleviate congestion and regulate voltage levels in the grid. Therefore, the following assumptions were made:

- A higher flexibility up requirement during peak consumption hours and a lower requirement during off-peak hours;

- A higher flexibility down requirement during off-peak hours and a lower requirement during peak hours.

4.2.2.2. FLEXIBILITY CAPACITY OFFERED

As mentioned in 4.2.1, a prosumer's ability to offer flexibility in the market depends on their flexible resources outlined in Figure 16. However, to complement this study, the possibility of prosumers who do not have BESS or EVs providing flexibility through other types of resources is also considered. Table 23 summarizes the strategy and assumptions used.

Table 23. Assumed flexibility offers for other load shiftable units.

Prosumer ID	Other shiftable load units considered	Flexibility capacity assumed	
		UP	**DW**
5 and 6	Lighting	---	5%
7 and 8	Cold appliances	10%	10%

As shown in Table 23, the other applications capable of offering flexibility selected were lighting and cold appliances. The prosumers chosen to explore the flexibility of these two loads were those who do not have BESS or electric vehicles.

The values indicated in Table 23 for each of the two types of flexibility correspond to the percentage of the baseline energy consumption of each load that prosumers are willing to consume more (flexibility up) or less (flexibility down) if the market clearing determines it. In practice, the following assumptions are made: prosumers five and six offer in the LFM the capacity to flexibly reduce lighting consumption by 5% of the forecasted consumption, while prosumers seven and eight offer the possibility to increase or decrease cold appliance consumption by 10%. These additional offers aim to demonstrate the versatility of the developed LFM, as well as the correct functioning of the model for flexible loads other than BESS and EVs.

It is worth noting that BESS and EVs automatically offer all the technical flexibility determined by the mathematical model of stage 1 (3.2.2) in the market.

4.2.2.3. PROSUMERS OFFER PRICES

For the offer prices, the strategy from the illustrative example (4.1) was used. In practice, the offers in the local flexibility market are indexed to the local energy market prices and tariffs (as shown in Figure 20) to ensure that players do not incur losses due to changes in their FUs optimal scheduling. Table 24 presents the price ranges for both a summer and a winter scenario.

Table 24 .Price offering strategy in the Local Flexibility Market.

Type of offers	Month	Range of offer prices	meaning
Flexibility UP [$\lambda^{UP}_{lsv,c,t}$]	January	[0.033 – 0.229] €/ kWh	Local electricity market price * 1,10
	August	[0.095 – 0.150] €/ kWh	
Flexibility DW [$\lambda^{DW}_{lsv,c,t}$]	---	[0.040 – 0.065] €/ kWh	Feed-in tariff rate.

According to Table 24, after the local market closes, the activation of flexibility down by the DSO requires payment to the prosumer, equivalent to the feed-in tariff for that time period. This is done to equate the reduction in the initially forecasted consumption with the injection of energy into the grid. Conversely, activating flexibility up by the DSO requires paying the prosumer for the energy they might consume in excess, along with an additional 10% to account for the deviation from their FUs' optimal operating state.

4.2.2.4. CONSTRAINTS ON ACTIVATION PROPOSALS

Now, the flexibility activation preferences expressed by the market operator as provided by prosumers are outlined. The number of activation proposals, their duration, and the time intervals between them are restricted. These constraints, along with the flexibility capacity of the FUs and the bidding prices, serve as inputs for the current LFM.

Table 25 illustrates the activation preferences set for BESS. These constraints were determined based on the consumption patterns of prosumers, and they are uniform for all prosumers of the same type.

As observed in Table 25, a more conservative strategy has been defined for the activation of flexibility in BESS for prosumers of types I and II. This strategy entails a maximum of two activation periods, each lasting only three hours, separated by a minimum of three hours. This approach is chosen due to the lower storage capacity of these prosumer types. Conversely, a contrasting strategy is applied to consumption types with higher storage capacity to maximize their anticipated flexibility activation potential.

Table 25. Constraints on BESS flexibility activation.

Prosumer type ID*	**Activation proposal type**	**Activation Preferences**		
		Max. Duration $[\boldsymbol{H_{lsv,c}^{CUT\,max}}]$	**Min. Delay** $[\boldsymbol{H_{lsv,c}^{CUT\,min}}]$	**Max. Number** $[\boldsymbol{G_{lsv,c}^{CUT\,max}}]$
I	*Flex. Up*	2h	3h	2
	Flex. Dw	2h	3h	2
II	*Flex. Up*	3h	3h	2
	Flex. Dw	3h	3h	2
III	*Flex. Up*	3h	2h	3
	Flex. Dw	3h	2h	3
IV	*Flex. Up*	3h	1h	4
	Flex. Dw	3h	1h	4

* according to Table 18

Table 26 provides details on the flexibility activation restrictions related to Electric Vehicle (EV) charging. Once again, these limitations are standardized based on consumption types.

Table 26. Constraints on EVs charging flexibility activation.

Prosumer type ID*	**Activation proposal type**	**Activation Preferences**		
		Max. Duration $[\boldsymbol{H_{lsv,c}^{CUT\,max}}]$	**Min. Delay** $[\boldsymbol{H_{lsv,c}^{CUT\,min}}]$	**Max. Number** $[\boldsymbol{G_{lsv,c}^{CUT\,max}}]$
I	*Flex. Up*	7h	0h	1
	Flex. Dw	7h	0h	1
II	*Flex. Up*	3h	4h	2
	Flex. Dw	3h	4h	2
III	*Flex. Up*	2h	1h	2
	Flex. Dw	2h	1h	2
IV	*Flex. Up*	2h	2h	2
	Flex. Dw	2h	2h	2

* according to Table 18

The strategy outlined in Table 26 is directly linked to the characterization of vehicle charging presented in Figure 19. For prosumers of types one and two, the maximum duration of flexibility activation periods is determined based on the duration of their charging periods. For the others, a more conservative strategy has been chosen.

Additionally, restrictions have been defined for activating flexibility through the lighting systems of prosumers five and six and the cold appliances of prosumers seven and eight. Table 27 illustrates the defined strategy.

Table 27. Constraints on the activation of flexibility offered by lighting and cold appliances.

Prosumer ID	Activation proposal type	Activation Preferences		
		Max. Duration $[H_{lsv,c}^{CUT\ max}]$	Min. Delay $[H_{lsv,c}^{CUT\ min}]$	Max. Number $[G_{lsv,c}^{CUT\ max}]$
5 and 6	*Flex. Up*	---	---	--
	Flex. Dw	2h	1h	2
7 and 8	*Flex. Up*	4h	2h	3
	Flex. Dw	4h	2h	3

For these flexible resources, a strategy closely mirroring reality was not imposed. Given their limited flexibility capacity, less restrictive preferences were chosen, contrary to what might be anticipated. This approach aims to maximize the amount of flexibility captured in the market.

4.2.3. SIMULATIONS SUMMARY

Based on the technical and economic characterization of the community and the local flexibility market, two simulation scenarios have been defined. The analysis of results will, among other aspects, stem from comparing the performance of the same renewable energy community under these two distinct situations. Table 28 summarizes the considered scenarios and highlights the differences and similarities among them.

The difference between the two scenarios lies in the levels of irradiance to which the REC is exposed and the local electricity market prices that determine the amounts of energy acquisition and sale by prosumers. It is important to emphasize that flexibility offers are price-indexed to the marginal prices of the LEM, meaning that a scenario change always requires a different approach from REC members in the LFM.

Table 28. Definition of Simulation Scenarios and Key Differences and Similarities Between Them.

Scenario ID	**Title**	**Origin Month**	**Main differences between scenarios**		**Similarities between scenarios**
1	Winter	January 2023	*Irradiance*	lower	DSO flexibility requirements; Prosumer characteristics; Flexible unit parameters.
			Local energy market price	lower	
2	Summer	August 2023	*Irradiance*	higher	
			Local energy market price	higher	

The average energy generation in the community in scenario 1 (winter), per prosumer, is approximately 46.8% lower than the energy generation in scenario 2 (summer), as observed by the irradiance base profiles in Figure 18. The number of daylight hours is also 20% lower. This percentage fluctuates due to the introduced randomness in consumption profiles, with variations of around ±10%. The average energy market price, also subject to a similar random factor, is 16% higher in the summer scenario compared to the winter scenario.

The requirement of the DSO remained constant in both scenarios to analyze different flexibility activation proposals obtained for the same required flexibility profile. Simulations were conducted over a 24-hour time horizon to allow for the analysis of a local day-ahead market model, following the hourly time-base previously used in the illustrative example. To achieve this, the models from Chapter 3 were once again implemented using MATLAB+GAM.

4.2.4. Presentation and Analysis of Results

This section presents the results of the case study described in 4.2.1 and 4.2.2 based on the two scenarios in Table 28. The results were obtained by executing the code containing the implementation of the mathematical models from Chapter 3. Each scenario required an execution considering the corresponding specific inputs.

For the current case study (16 prosumers and a 24-hour simulation period), running the simulation tool involved 768 resolutions of the stage 1 optimization problem in GAMS, following the strategy outlined in (3.2.2). Meanwhile, the stage 2 optimization problem is solved once for each tool execution (see 3.2.3). Out of the 1538 linear optimizations solved in the two simulations, all of them had an "optimal" model status, indicating that the solution is optimal.

The purpose of this results analysis is to evaluate the various impacts that the determination of residential flexibility and its market negotiation have on the operation of loads and energy costs for each prosumer. The study is divided into three main parts:

- **Impact of participation in LFM on prosumer operating costs:** This section assesses the energy costs of prosumers before and after participating in the local flexibility market. It addresses the impacts of different combinations of flexible units and different housing typologies on individual final costs.

- **Impact of prosumer characteristics on flexibility offers and activation proposals:** It analyzes and compares the flexibility offered by prosumers in market sessions with the hunted offers. The impacts of prosumer typologies and combinations of FUs on both flexibility offering and activation proposals determined by the market clearing process are discussed.

- **Impact of flexible units on flexibility offers and activation proposals:** The performance of flexible units throughout the simulations is examined.

4.2.4.1. Impact of Participation in LFM on Prosumers Operating Costs

Next, the impact of prosumers participation in the local flexibility market on reducing their energy bills is analyzed. Table 29 and Table 30 provide an economic characterization of the performance of each prosumer in the local flexibility market, respectively for scenario 1 and scenario 2.

Table 29 and Table 30 show the cost of prosumers after Stage 1 of the problem. These values correspond to energy costs considering the optimal operation of their flexible resources (the baselines).

The costs of prosumers in Stage 2 are also presented. These costs represent the costs that players will have to bear if they need to comply with the flexibility activation proposals decided in the market. In other words, it is the cost of increasing the consumption of a flexible unit in response to a flexibility up proposal. The Stage 2 profits correspond to the value, per prosumer, of the flexibility effectively traded in the market, based on the offering prices established in Table 24.

The 'final costs' correspond to the actual energy costs of each prosumer after their participation in the LFM. These are determined by adding the optimal energy costs (Stage 1 costs) to the costs related to complying with the flexibility activation proposals (Stage 2 costs) and subtracting the profits obtained in the LFM session (Stage 2 Profits).

Table 29 and Table 30 also indicate the type of flexible resources owned by each prosumer and whether or not there is PV generation at their residence to illustrate the impact of these variables on their actual performance.

In both scenarios, the majority of prosumers experienced an effective reduction in their costs through participation in the LFM. In scenario 1, the average cost reduction amounted to approximately 2.65%, while in scenario 2, it reached 6.58%. It is important to note that all prosumers either saw their costs reduced or maintained aftermarket clearing, in both scenarios analyzed. Furthermore, every single prosumer demonstrated, at least, one cost reduction in both two cases. Consequently, it can be concluded that participation in this LFM model is advantageous for members of a REC and serves as a complement to participation only in LEM.

Figure 22 shows graphs generated from data in Table 29 and Table 30, categorizing prosumers based on their FU ownership. The bar graphs compare the energy costs for prosumers after stages 1 and 2 and enable the observation of actual savings achieved.

Table 29. Economic impact of prosumers participation in the Local Flexibility Market (Scenario 1).

ID	Flexible Units	PV	Stage 1 Costs* (1)	Stage 2 Costs* (2)	Stage 2 Profits* (3)	Final Costs* (1+2-3)	Costs reduction		
							Absolute Value*	Percentage	
1	BESS	Yes	**1,29**	0,48	0,52	**1,24**	0,05	**3,69%**	1,56%
2		Yes	**1,06**	0,00	0,00	**1,06**	0,00	**0,00%**	
3		Yes	**-0,32**	0,08	0,09	**-0,33**	0,01	**2,53%**	
4		Yes	**0,49**	0,00	0,00	**0,49**	0,00	**0,00%**	
5	Others (lights, cold appliances)	Yes	**1,78**	0,00	0,00	**1,78**	0,00	**0,00%**	0,04%
6		Yes	**2,36**	0,00	0,00	**2,36**	0,00	**0,01%**	
7		Yes	**1,37**	0,00	0,00	**1,37**	0,00	**0,10%**	
8		Yes	**3,01**	0,00	0,00	**3,01**	0,00	**0,05%**	
9	BESS EV	No	**4,33**	0,00	0,70	**3,63**	0,70	**16,17%**	7,87%
10		No	**6,09**	0,00	0,38	**5,71**	0,38	**6,20%**	
11		No	**3,69**	0,00	0,28	**3,41**	0,28	**7,57%**	
12		No	**8,79**	1,34	1,48	**8,66**	0,13	**1,53%**	
13		Yes	**2,29**	0,77	0,85	**2,21**	0,08	**3,38%**	1,15%
14		Yes	**3,34**	0,22	0,24	**3,32**	0,02	**0,66%**	
15		Yes	**0,91**	0,00	0,00	**0,91**	0,00	**0,00%**	
16		Yes	**4,74**	0,00	0,03	**4,71**	0,03	**0,58%**	

*[€]

Prosumers with EV chargers (Figure 22.c and Figure 22.d) have higher average final costs (approximately 4,05 €) compared to those without them (0 €, in average), as expected due to the high consumption associated with EV charging. All other prosumers have solar generation, however, prosumers one through four have lower costs than prosumers five through eight, due to their storage systems. In the scenario 2 graphs, it is also noticeable that in all groups of prosumers with PV generation (Figure 22.a, Figure 22.b, Figure 22.d), there is at least one market participant with negative costs. This can be attributed to the elevated levels of irradiance on that typical day in August, which promoted self-consumption and surplus energy sales to the grid.

Table 30. Economic impact of prosumers participation in the Local Flexibility Market (Scenario 2).

ID	Flexible Units	PV	Stage 1 Costs* (1)	Stage 2 Costs* (2)	Stage 2 Profits* (3)	Final Costs* (1+2-3)	Costs reduction		
							Absolute Value*	Percentage	
1	BESS	Yes	**-0,28**	0,44	0,49	**-0,32**	0,04	**13,64%**	15,17%
2		Yes	**-1,08**	0,00	0,86	**-1,94**	0,86	**44,23%**	
3		Yes	**-2,76**	0,79	0,87	**-2,84**	0,08	**2,79%**	
4		Yes	**-3,70**	0,00	0,00	**-3,70**	0,00	**0,00%**	
5	Others (lights, cold appliances)	Yes	**0,21**	0,00	0,00	**0,21**	0,00	**0,17%**	0,24%
6		Yes	**-0,31**	0,00	0,00	**-0,31**	0,00	**0,42%**	
7		Yes	**-1,71**	0,00	0,01	**-1,71**	0,00	**0,19%**	
8		Yes	**-1,47**	0,00	0,00	**-1,47**	0,00	**0,20%**	
9	BESS EV	No	**5,50**	0,00	0,46	**5,04**	0,46	**8,35%**	4,26%
10		No	**8,13**	0,00	0,65	**7,48**	0,65	**7,98%**	
11		No	**6,30**	0,00	0,03	**6,27**	0,03	**0,47%**	
12		No	**11,00**	0,26	0,29	**10,97**	0,03	**0,24%**	
13		Yes	**1,98**	0,21	0,23	**1,96**	0,02	**1,05%**	6,65%
14		Yes	**1,92**	0,00	0,34	**1,58**	0,34	**17,80%**	
15		Yes	**-1,28**	0,61	0,67	**-1,34**	0,06	**4,52%**	
16		Yes	**0,34**	0,11	0,12	**0,33**	0,01	**3,23%**	

*[€]

Prosumers that have BESS and/or EV chargers (Figure 22 a. Figure 22.c Figure 22.d) achieved significantly higher savings (6.11%) compared to those who only provided load flexibility for lighting and cold appliances (only 0.12%). This is because the technical flexibility of BESS and EVs is far superior (see Figure 23) to the flexibility based on adjusting the consumption of these other loads by only 5% or 10% throughout the day.

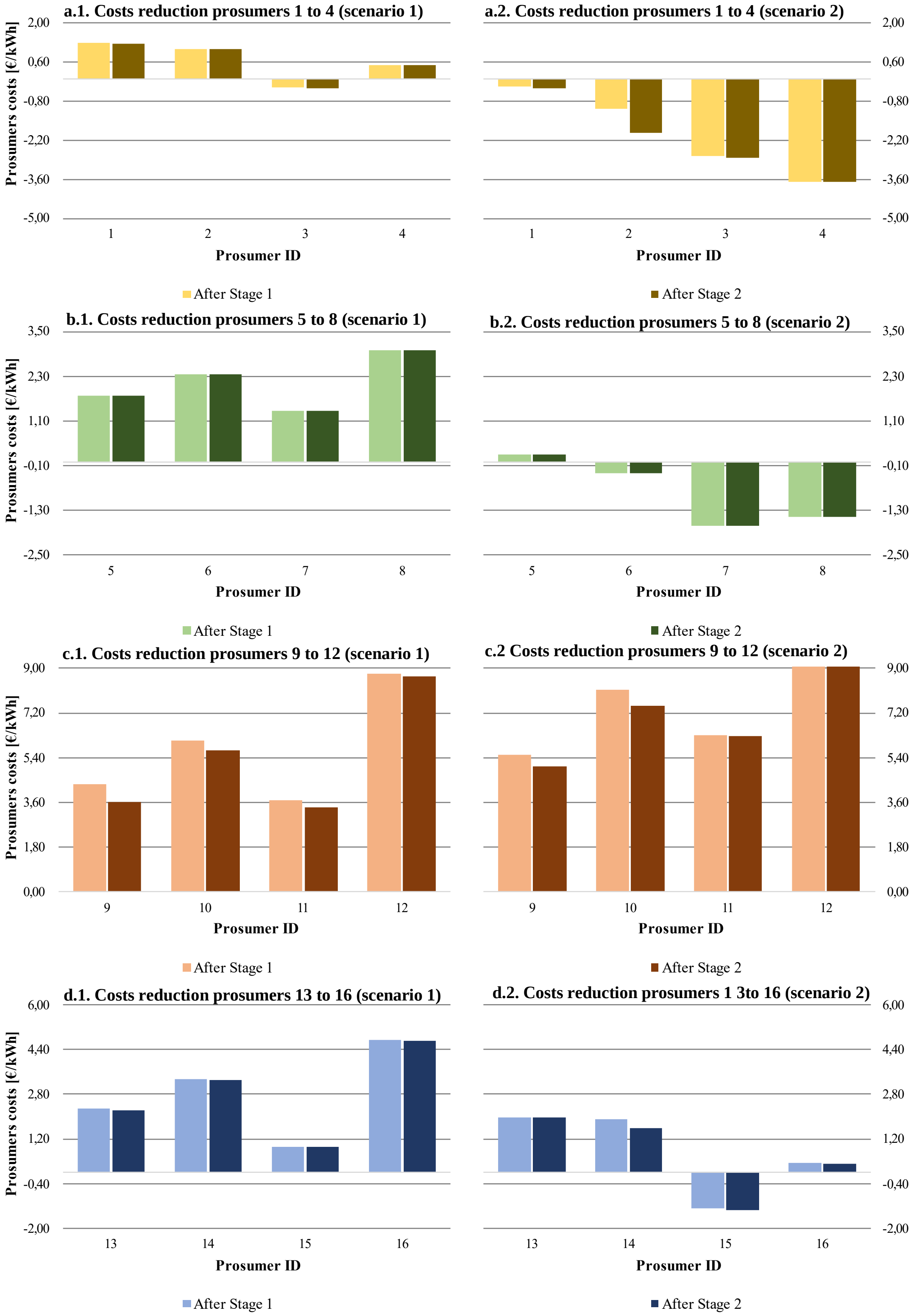

Figure 22. . Comparison of energy costs, per prosumer, before (Stage 1) and after participating in the Local Flexibility Market (Stage 2).

Prosumers from nine to twelve with EV chargers and BESS but lacking PV generation (Figure 22.c) had average savings of 7.87% and 4.26% in scenarios 1 and 2, respectively. These relative savings are either above or in line, respectively, with the overall average relative savings value for both scenarios (4.62%). However, that absolute savings amounts are 0.37€ and 0.29€ for scenarios 1 and 2, respectively, higher than the overall average per prosumer, which hovers around €0.10/day and €0.16/day, respectively. This leads to the following conclusion: this group of prosumers, despite lacking PV generation for self-consumption and cost reduction in stage 1, can use the LFM to generate above-average revenues and achieve lower overall costs. Therefore, it can be stated that this LFM model may serve as an alternative to installing one's own PV production for a prosumer, provided they possess flexible resources with great technical flexibility sharing capacity.

Table 31 and Table 32 present average savings achieved by prosumers of the same type, i.e., those with similar generation and consumption profiles (Table 18). The results indicate the following: households with one to three occupants exhibit percentage savings values that are higher or in line with the average indicators for both scenarios, with no clear pattern between them and that allows for any conclusions to be said. However, prosumers of Type IV (4 occupants per household) show significantly lower relative savings (less than 1%) in both scenarios compared to the other typologies. Therefore, it can be concluded that the participation in the LFM by prosumers with substantially higher consumption profiles does not yield as significant relative savings as compared to lower consumption profiles, even when with FUs with greater operational capacity.

Table 31. Total costs and absolute and relative cost reduction by energy consumption type (scenario1).

Prosumer type ID	**Number of people**	**After Stage 1 prosumers total costs [€/kWh]**	**After Stage 2 prosumers total costs [€/kWh]**	**Costs Reduction**	
				Absolute [€/kWh]	**Percentage [%]**
I	**1 person**	**9,68**	**8,86**	**0,82**	**8,52%**
II	**2 people**	**12,85**	**12,45**	**0,40**	**3,11%**
III	**3 people**	**5,64**	**5,35**	**0,29**	**5,12%**
IV	**4 people**	**17,03**	**16,87**	**0,16**	**0,96%**

Table 32. Total costs and absolute and relative cost reduction by energy consumption type (scenario 2).

Prosumer type ID	**Number of people**	**After Stage 1 prosumers total costs [€/kWh]**	**After Stage 2 prosumers total costs [€/kWh]**	**Costs Reduction**	
				Absolute [€/kWh]	**Percentage [%]**
I	**1 person**	**7,41**	**6,89**	**0,52**	**7,08%**
II	**2 people**	**8,66**	**6,81**	**1,85**	**21,34%**
III	**3 people**	**0,55**	**0,38**	**0,17**	**31,35%**
IV	**4 people**	**6,17**	**6,13**	**0,04**	**0,65%**

Finally, it is important to compare the cost evolution in the two simulated scenarios. There is a noticeable higher average reduction in energy costs for prosumers in scenario 2 (6.58%) compared to scenario 1 (2.65%). In addition, only five out of the 16 prosumers do not follow this trend. This can be related to the combination of two factors: (*i*) the higher solar generation observed in August (scenario 2) increased self-consumption and thereby reduced energy costs from the stage 1; and (*ii*) higher electricity prices resulted in more expensive flexibility offers (as the LFM offer values are indexed), leading to a larger stage 2 profit. This higher profit, coupled with lower consumption, origin greater savings. Thus, it can be concluded that higher flexibility offer prices, combined with strong levels of self-consumption, generate more evident economic advantages from participating in LFMs.

4.2.4.2. OFFERED VS. ACTIVATED FLEXIBILITY PER PROSUMER

This section organizes and analyzes the amount of flexibility determined/assumed as LFM offering and compares it with the activation proposals sent to prosumers after the market clearing.

Table 33 illustrates the ratio of total flexibility activated to the total flexibility offered in the two examples of the day-ahead market session, constituting scenarios 1 and 2. The amount of flexibility offered in the LFM consists of the technically determined flexibility for the set of BESS and EVs considered in the study, along with the assumptions defined for the flexibility of lighting and cold appliances for prosumers five to eight. The total quantity of activated flexibility also takes these FUs into account. The activation ratio represents the total percentage of flexibility activated relative to the total amount offered.

Table 33 also presents the total DSO requirements in both scenarios, (see Figure 21). It's worth noting that the entirety of the requirements is accepted in the market, as ruled by Equations (39) and (40). This allows us to conclude that the results are consistent with the proposed mathematical model.

Table 33. Flexibility activation ratio per total offered flexibility.

Scenario ID	Flexibility type	Total Amount offer in LFM	Total Amount activated in LFM	Total amount of DSO requirements	Activation ratio per total quantity offered.
1	*Flexibility UP*	1872.50 kWh	23.45 kWh	23.45 kWh	1,25%
	Flexibility DW	830.82 kWh	20.65 kWh	20.65 kWh	2,49%
2	*Flexibility UP*	907.796 kWh	23.45 kWh	23.45 kWh	2,58%
	Flexibility DW	1876.61 kWh	20.65 kWh	20.65 kWh	1,10%

The total offers of flexibility DW are approximately 44% of the total flexibility UP offers in scenario 1. This trend completely reverses in scenario 2, where flexibility UP offered corresponds to approximately 48% of the flexibility DW. This is understood as follows: in scenario 1, the price that prosumers pay for purchasing energy (4.2.2.3, see Table 24) is lower than the price practiced in scenario 2. Therefore, it means that a prosumer's capacity to consume more energy than needed for the optimal operation of their FUs are higher, given that their parameterization remains unchanged between scenarios. The reverse logic applies to scenario 2, where the prosumers' ability to reduce their consumption is greater due to the higher price assumed.

The ratios presented in Table 33 are objectively low. This occurs because the optimization problem in stage 2 requires that DSO requirements be fully met in each market session. Therefore, market clearing only occurs if the REC's flexible resources can provide technical flexibility equal to or greater than the DSO requirement. This becomes even more complex due to activation constraints that impose significant limitations on the amount of flexibility acquired in the market. Thus, this model is limited to the study of small requirements to ensure a feasible solution for the simulated scenarios. This detail prevents a comparison of the absolute values of the studied variables.

To address the gap identified in the preceding paragraph, the following analysis assesses only the percentages of offered flexibility per prosumer and compares them with the percentage of activated flexibility. These values are shown in Table 34 and Table 35 that display the percentages of offered and activated flexibility after each market session, categorized by consumer typology (Table 18) for scenario 1 and scenario 2, respectively.

Table 34. Percentages of offered and activated flexibility in the LFM, per prosumer (scenario 1).

ID	Flexible Units	PV	Flexibility UP				Flexibility DW			
			Available		Activated by LFM		Available		Activated by LFM	
			$F_{lsv,c,t}^{max} - E_{lsv,c,t}^{baseline}$		$F_{lsv,c,t}^{UP}$		$E_{lsv,c,t}^{baseline} - F_{lsv,c,t}^{min}$		$F_{lsv,c,t}^{DW}$	
			[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
1	**BESS**	Yes	1,31	12,07	0,00	0,00	2,76	22,07	15,53	20,57
2		Yes	1,79		0,00		4,81		0,00	
3		Yes	5,44		0,00		4,40		5,04	
4		Yes	3,54		0,00		10,10		0,00	
5	**Others (lights, cold appliances)**	Yes	0,01	0,13	0,00	0,29	0,02	0,29	0,00	0,00
6		Yes	0,04		0,03		0,09		0,00	
7		Yes	0,04		0,13		0,09		0,00	
8		Yes	0,04		0,12		0,09		0,00	
9	**BESS EV**	No	3,99	32,92	39,94	97,21	5,91	35,61	0,00	40,05
10		No	6,85		28,86		15,74		0,00	
11		No	13,48		28,41		1,97		0,00	
12		No	8,60		0,00		12,00		40,05	
13		Yes	3,75	54,88	0,00	2,50	17,46	42,03	26,79	39,38
14		Yes	6,36		0,00		10,63		12,59	
15		Yes	25,37		0,00		5,73		0,00	
16		Yes	19,40		2,50		8,21		0,00	
TOTAL			100%	100%	100%	100%	100%	100%	100%	

The observed trend indicates an increasing availability of both UP and DW flexibility as the number of people in each household rises. It's worth noting that this is just a slight trend, as there are some exceptions to the rule. However, it can be concluded that this is due to the capacity of flexible loads, which is higher in prosumer typologies with higher indices (see 4.2.1.3). According to the case study characterization, this greater capacity is also associated with more relaxed FUs activation preference parameters, which explains the above.

Table 35. Percentages of offered and activated flexibility in the LFM, per prosumer (scenario 2).

ID	Flexible Units	PV	Flexibility UP				Flexibility DW			
			Available		Activated by LFM		Available		Activated by LFM	
			$F^{max}_{lsv,c,t} - E^{baseline}_{lsv,c,t}$		$F^{UP}_{lsv,c,t}$		$E^{baseline}_{lsv,c,t} - F^{min}_{lsv,c,t}$		$F^{DW}_{lsv,c,t}$	
			[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
1	BESS	Yes	2,71	24,49	0,00	34,77	1,19	12,92	16,42	47,65
2		Yes	5,07		34,77		2,04		0,00	
3		Yes	10,10		0,00		1,82		31,22	
4		Yes	6,61		0,00		7,87		0,00	
5	Others (lights, cold appliances)	Yes	0,02	0,26	0,01	0,29	0,01	0,13	0,00	0,16
6		Yes	0,08		0,05		0,04		0,00	
7		Yes	0,08		0,11		0,04		0,16	
8		Yes	0,08		0,11		0,04		0,00	
9	BESS EV	No	3,08	39,81	19,42	49,93	3,43	48,46	0,00	12,59
10		No	8,9		29,39		7,80		0,00	
11		No	16,80		1,12		10,14		0,00	
12		No	11,00		0,00		27,10		12,59	
13		Yes	3,66	35,43	0,00	15,01	17,80	38,50	11,34	36,60
14		Yes	4,57		15,01		7,45		0,00	
15		Yes	12,21		0,00		5,29		23,89	
16		Yes	14,99		0,00		7,95		4,37	
TOTAL			100%	100%	100%	100%	100%	100%	100%	100%

Prosumers with BESS and/or EV chargers are clearly responsible for almost all of the technical flexibility offered in the market (higher than 99%, in both scenarios). On the other hand, the capacity to offer flexibility from the lighting of prosumers five and six and the cold appliances of prosumers seven and eight is less than 1%. This leads to the conclusion that BESS and EV chargers are flexible loads par excellence, and their increasing capacity drives their operational flexibility. At the same time, it justifies the decision not to include other less significant loads in the residential technical flexibility determination model (stage 1).

The groups of prosumers with BESS and EV chargers are responsible for a relative capacity to offer flexibility (an average of 40.00% in both scenarios) higher than the group of prosumers who only had BESS (17.89%). This suggests that a greater number of FUs per prosumer results in a higher capacity to provide flexibility. This is more evident for flexibility UP than for flexibility DW, according to the data from Table 34 and Table 35

The observed trend indicates an increasing availability of both UP and DW flexibility as the number of people in each household rises. It's worth noting that this is just a slight trend, as there are some exceptions to the rule. However, it can be concluded that this is due to the capacity of flexible loads, which is higher in prosumer typologies with higher indices (see 4.2.1.3). According to the case study characterization, this greater capacity is also associated with more relaxed FUs activation preference parameters, which explains the above.

This occurs because the operation of a prosumer with a greater number of FUs always requires a higher effective energy consumption to meet minimum usage preferences. In this context, it is expected that their capacity to decrease their overall consumption is somewhat restricted.

Prosumers nine to twelve have BESS and EV chargers but lack PV generation. This choice does not seem to limit their ability to offer flexibility when compared to prosumers thirteen to sixteen (prosumers with generation). Furthermore, their performance in this regard is even better in scenario 2, where solar irradiance is higher. This once again confirms the premise that these types of prosumers, despite not having their own generation for self-consumption, can utilize the local flexibility market as a means to reduce their costs.

The percentage of offered flexibility does not always correspond to the percentage of flexibility activated through market operations. There are very few cases where this happens; for example, in the flexibility DW of prosumer 12 in scenario 1 and prosumers 13 and 16 in scenario 2, or in the flexibility UP of prosumers five to eight in scenario 2. This occurs because the second stage of the problem is solely aimed at meeting the DSO's flexibility requirement, not at activating flexibility from prosumers with higher capacity to provide it. If that were the goal, it would require the use of nonlinear programming approaches. Therefore, the market operator seeks one or more flexible units with available flexibility capacity and no constraints preventing their activation.

Table 36 and Table 37 display the percentages of offered and activated flexibility after each market session, categorized by consumer typology (Table 18) for scenario 1 and scenario 2, respectively.

Table 36. Percentage of offered and activated flexibility in the LFM, by prosumer typology (scenario 1).

Prosumer type ID	**Number of people**	**Flexibility UP**		**Flexibility DW**	
		Available	**Activated by LFM**	**Available**	**Activated by LFM**
I	1 person	9,06%	39,95%	26,15%	42,32%
II	2 people	15,04%	28,89%	31,27%	12,59%
III	3 people	44,32%	28,54%	12,20%	5,04%
IV	4 people	31,57%	2,62%	30,39%	40,05%
TOTAL		100%	100,00%	100%	100,00%

Table 37. Percentage of offered and activated flexibility in the LFM, by prosumer typology (scenario 1).

Prosumer type ID	**Number of people**	**Flexibility UP**		**Flexibility DW**	
		Available	**Activated by LFM**	**Available**	**Activated by LFM**
I	1 person	9,47%	19,43%	22,42%	27,76%
II	2 people	18,65%	79,22%	17,33%	0,00%
III	3 people	39,20%	1,23%	17,29%	55,27%
IV	4 people	32,68%	0,11%	42,96%	16,97%
TOTAL		100%	100%	100%	100%

The observed trend indicates an increasing availability of both UP and DW flexibility as the number of people in each household rises. It's worth noting that this is just a slight trend, as there are some exceptions to the rule. However, it can be concluded that this is due to the capacity of flexible loads, which is higher in prosumer typologies with higher indices (see 4.2.1.3). According to the case study characterization, this greater capacity is also associated with more relaxed FUs activation preference parameters, which explains the above.

4.2.4.3. DETERMINED FLEXIBILITY VS. ACTIVATED FLEXIBILITY BY FLEXIBLE UNIT

This section is intended to assess the impact of FUs on the technical flexibility of each prosumer, which is to say, on the flexibility offers they present in the LFM (as the total technical flexibility available necessarily constitutes an offer). The impact of FUs on activation proposals resulting from the market clearing is also analyzed.

Table 38 presents the total values of flexibility offers per flexible unit and compares them to te activation proposals sent by the CM to each prosumer, based on the offers cleared in the market. As mentioned earlier and observed in Table 33, the the offers cleared in the market correspond, on average, to less than 5% of the total offers presented, which prevents direct comparison of absolute quantities. Therefore, Table 38 presents the relative weight of each component (in percentage) to enable drawing conclusions.

Figure 23 summarizes the data presented in Table 38. There, one can visualize the impact of each flexible unit on the total determined flexibility and the activation proposals resulting from the LFM. Additionally, it is possible to establish a relationship between the offers presented and cleared in the market. Different scales are used for this purpose to address what was mentioned in the previous paragraph.

Table 38. Impact of flexible units on flexibility offers and activation proposals.

Scenario ID	Flexibility Type			Flexible unit			Total
				BESS	EV	Others	
1	Flx. UP	Offered in LFM	*Value [kWh]*	826,93	1045,57	0,06	1872,56
			Percentage [%]	44,16%	55,84%	0,00%	100,00%
		Activated by LMF	*Value [kWh]*	16,46	5,89	0,060	22,41
			Percentage [%]	73,43%	26,29%	0,29%	,75%
	Flx. DW	Offered in LFM	*Value [kWh]*	458,58	372,24	0,00	830,82
			Percentage [%]	55,20%	44,80%	0,00%	100,00%
		Activated by LMF	*Value [kWh]*	14,65	5,20	0,00	19,85
			Percentage [%]	73,79%	26,21%	0,00%	100,00%
2	Flx. UP	Offered in LFM	*Value [kWh]*	669,47	238,33	0,06	907,86
			Percentage [%]	73,74%	26,25%	0,01%	100,00%
		Activated by LMF	*Value [kWh]*	18,58	3,77	0,06	22,41
			Percentage [%]	82,89%	16,82%	0,28%	100,00%
	Flx. DW	Offered in LFM	*Value [kWh]*	572,84	1303,78	0,03	1876,65
			Percentage [%]	30,52%	69,47%	0,00%	100,00%
		Activated by LMF	*Value [kWh]*	16,79	3,06	0,03	19,88
			Percentage [%]	84,45%	15,39%	0,16%	100,00%
Average Percentage	Offered in LFM		*Percentage [%]*	**50,91%**	**49,09%**	**0,00%**	**50,91%**
	Activated by LMF		*Percentage [%]*	**78,64%**	**21,18%**	**0,18%**	**78,64%**

Half of the total flexibility provided by the REC originates from BESS (50.91%), and the other half from EV chargers (40.09%). This means that these two resources are on technical parity regarding flexibility offers in the market. However, this parity does not exist in the amount of flexibility offers cleared in the market. According to Table 38, BESS are the target of 78.64% of the flexibility activation proposals sent by the CM to REC members. This can be explained by the following reasons:

i. The flexibility of EVs is limited by the constraint present in Equation (41). This equation defines an energy budget that needs to be maintained to ensure that the energy required after charging (Figure 19) matches the prosumer's desired energy, even after participating in the LFM. This implies that all UP flexibility activated must be compensated with a DW flexibility proposal of the same value, often preventing these FU offers from being cleared.

ii. EVs are connected to the grid only at specific times (Figure 19), unlike BESS, which operate 24 hours a day and can provide flexibility over a longer period. In practice, the capacity of the considered EV batteries is greater than the capacity of BESS, and their inverters are also more powerful. This explains the high technical flexibility they can offer. However, the connection periods will always be a constraint that reduces the likelihood of these offers being accepted.

These results lead to the conclusion that BESS is the resource whose flexibility has a greater capacity to be exploited in the LFM. This LFM model, therefore, serves as an additional incentive for investing in BESS and can be an extra mechanism for recouping the high initial costs of this type of technology.

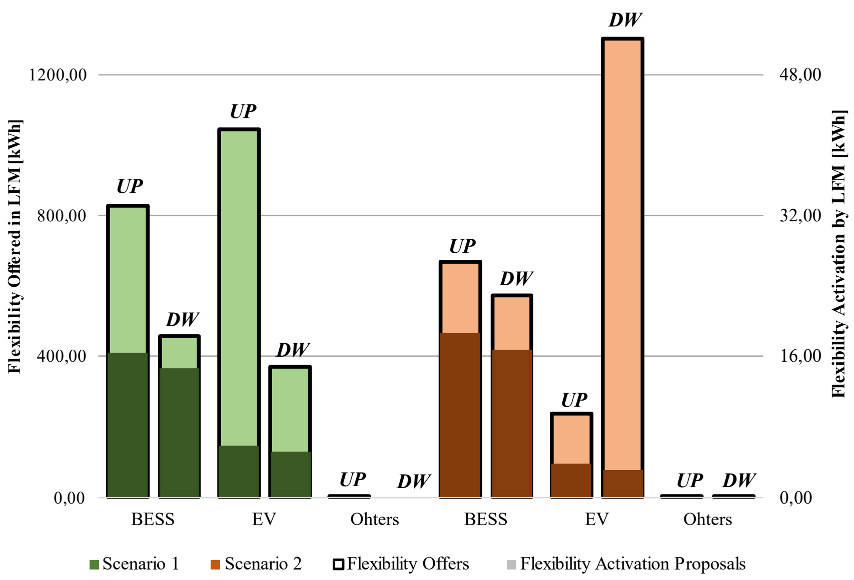

Figure 23. Total offered flexibility compared to flexibility activation proposals, per flexible unit.

In Figure 23, it is not possible to observe the total amount of flexibility made available and activated by the other FUs, excluding EV and BESS. This is because their value is residual when compared to the other units. Thus, it reinforces what was mentioned in 4.2.4.1 when it was said that the study of these loads should not be the focus in the current state of the art.

4.2.5. RESULTS SUMMARY

This section aims to summarize and clarify the main conclusions drawn from the results analysis. First and foremost, the case study allowed for testing and validating the implementation of the methodology presented in this master's thesis. For both simulated scenarios, optimal solutions were achieved in all simulations conducted. Regarding the LFM's effect on REC members and their flexible resources, consider the following:

- All prosumers experienced a reduction in their energy costs in at least one of the two scenarios;
- Participation in the LFM resulted in an average savings per prosumer of 2.65% on a typical winter day and 6.58% on a typical summer day. Prosumer two even recorded a 44% savings from their initial cost in scenario 1;
- Residences with a larger number of occupants recorded a lower average relative savings (less than 1%) compared to those with fewer people (7% to 8%) due to higher consumption. This implies that the economic impact of this LFM model will be marginal when applied to large consumers;
- The energy tariff rate influences the flexibility supply capacity of FUs. Higher prices imply lower availability of flexibility UP and higher availability of flexibility DW, and vice versa. This happens because the willingness of a flexible unit to deviate from its optimal state to consume more is reduced when prices are higher;
- BESS and EVs account for 99% of the determined flexibility in the REC, making the assumed flexibility for other FUs in the LFM negligible. This encourages further investigation into the flexibility of BESS and EVs at the expense of including other smaller loads;
- In an academic context, the existence of prosumers equipped with BESS but without PV generation was considered. Despite their lack of self-generation to reduce energy costs, these prosumers used the LFM as a means to lower expenses and achieved favorable results. This demonstrates that flexibility markets can be an alternative for those who cannot have their own energy production;

- More powerful EV chargers introduce greater flexibility into the system but increase the energy costs for their owners to the point where it may not be prudent to invest solely for LFM participation.

- Prosumers with EVs tend to offer significant amounts of flexibility in the LFM. However, restrictions associated with EVs and their limited connection to the grid during the day hinder the ability to hunt their flexibility;

- BESS performs exceptionally well in this LFM model, accounting for approximately 79% of the flexibility offers cleared in the market. This reinforces the need to delve deeper into the study of batteries as flexible units par excellence to increase the viability of such investments.

In addition to these conclusions, limitations were identified throughout the case study. An example is that the model's feasibility depends on the existence of sufficient flexibility within the REC to meet all DSO requirements whenever they are requested. This limits the study to small-scale requirements, making it challenging to execute more complex scenarios.

5. CONCLUSIONS

This chapter is dedicated to the main conclusions of the work carried out in this dissertation. This includes a critical analysis of the proposed model, the adopted methodology, and the results obtained. It also highlights the key objectives achieved and contributions to the state of the art. Lastly, future work perspectives are discussed, along with suggestions for further development.

5.1. MAIN OUTCOMES AND CONTRIBUTIONS

Political, legal, and environmental factors are encouraging the organization of prosumers into RECs. It is expected that soon, RECs will become a common reality in the daily lives of Europeans, making it urgent to study technical-scientific solutions that aid in adopting the current state of the art. In this regard, the establishment of RECs enables the existence of solutions that maximize energy consumption flexibility at the local level as a response to the loss of flexibility on the generation side, caused by the progressive replacement of centralized production with renewable and distributed production methods.

This dissertation focuses on the development and implementation of new flexibility market mechanisms within RECs environment, considering the different players and problems involved in the RECs. More precisely, the developed constitutes a contribution to the study of flexibility in communities, linking the two proposed objectives: (*i*) the development of a modeling strategy for determining residential flexibility availability and offers and (*ii*) the formulation of a local flexibility market that enables the sharing of flexibility among REC members and the DSO.

One of the contributions of this dissertation is the development of a methodology for the determination of flexibility at prosumer level. The methodology developed as the first stage of the overall problem, focuses on obtaining the technical available flexibility of EV chargers and BESS operation over a specified time horizon, usually, daily operation. The adopted strategy allows quantifying the ability of a prosumer to increase or decrease the predicted energy consumption for these two resource types, determining the possible technical flexibility. Furthermore, obtaining the technical limits of prosumer flexibility is expected to be carried out completely automatically. To this end, the prosumer is only required to provide the minimum possible number of parameters indicating their usage preferences. This methodology anticipates and relies on the existence of HEMS designed for autonomous household energy management, directly related to the concept of "smart homes" that is expected to become a reality in the short to medium term.

Other important contribution proposed in this dissertation is the design of a local flexibility market to allow the negotiation of prosumers flexibility previously determined. For the modelling of this local flexibility market, some important basic design assumptions were taken into consideration. One of these assumptions is the fact that the local market can be operated directly by the REC manager (assuming the market operator role) who, in this way, interacts with the retailer, DSO and each of the prosumers. The second assumption is the minimum sharing of personal information and usage preferences between the prosumer and the market operator throughout the process. Note that prosumers only provide flexibility offers to the market considering three constraints on the activation of the flexibility they offer (based solely on times and activation numbers). In this way, personal information such as the state of charge of their BESS or the energy profile for the use of the EV is not shared. This ensures the non-disclosure of specific personal information, even between two entities with a healthy and fully regulated commercial relationship.

Moreover, both contributions are modelled in a modular way forming a two-stage problem, designed to fill the gaps in the literature. In the first stage, the HEMS is responsible for determining the available flexibility of the prosumer and provide such flexibility offers to the REC manager. In the second stage, the REC manager is in charge of running the flexibility market considering the flexibility offers and needs of each prosumer and the DSO needs for flexibility.

The proposed methodology is validated through an illustrative example that proves and exemplifies the operability of the proposed mathematical models. Furthermore, the proposed case studies measure the benefits of sharing flexibility between REC members and the DSO. The first benefit is that the DSO can acquire demand-side flexibility to cope with the loss of flexibility on the production side. The second, and more explored, benefit is the economic benefit that prosumers derive from participating in the local flexibility market. This participation runs parallel to the energy market and serves as an additional incentive for consumers to organize into communities. More precisely, all prosumers showed reductions in their energy costs through participation in the LFM. These reductions were 2.65% for a typical summer day and 6.58% for a typical winter day. One of the prosumers even recorded a 44% reduction from their initial cost. The results obtained from the model validation led to the conclusion that BESS have the greatest impact on the developed LFM. They account for approximately 79% of the total cleared flexibility offers. As a matter of fact, the results also demonstrate greater benefits for those with higher generation and storage capacity, which also encourages private investment in distributed generation technologies, thus contributing to achieving the proposed carbon neutrality goals. EV chargers also generate significant flexibility offers, but the specificities of their operation often hinder the clearing of these offers. The positive performance of both BESS and EVs in this LFM serves as an incentive for the development of such markets, as they provide mechanisms to enhance the profitability of the substantial investments associated with these two technologies.

Finally, it was also possible to conclude that the flexibility of the operation of small residential loads such as lighting and small cold appliances has very little impact on the developed LFM model. This validates the decision not to include them in the methodology for determining technical flexibility in stage 1. However, their study should not be disregarded given the ambitious decarbonization objectives set for both 2030 and 2050.

5.2. FUTURE WORK

During the dissertation development, several ideas emerged to enhance the proposed methodology. The work undertaken is highly conceptual in nature, grounded in a strictly academic approach to the subject under analysis. Furthermore, the high level of complexity in some aspects could serve as interesting topics for future development. Therefore, it is suggested to:

- Integrate the formulation of the first stage of the problem into a pilot project for a HEMS that enhances the exploration of household consumption flexibility;

- Simplify the constraints in the second stage of the problem, using, for example, an alternative methodology for flexibility scaling in the market. This would potentially increase the capacity requested by the DSO from the REC;

- Define a pricing strategy for the offers made by prosumers in the local flexibility market;

- Explore the integration of the current flexibility market model with any local energy market model, either jointly or sequentially;

- Reduce the time interval used for market operation from 60 minutes to 15 minutes.

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