D5.2 – Performance assessment of current and new market designs and trading mechanisms for Local Energy Communities (Case Study A)

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Author(s) information (alphabetical)		
Name	**Organisation**	**Email**
Hugo Algarvio	LNEG	hugo.algarvio@lneg.pt
Nikolaos Chrysanthopoulos	Imperial College	n.chrysanthopoulos@imperial.ac.uk
António Couto	LNEG	antonio.couto@lneg.pt
Gabriel Santos	ISEP	gjs@isep.ipp.pt
Goran Strbac	Imperial College	g.strbac@imperial.ac.uk
Helleik Syse	bU	helleik@bitunitor.com
Dawei Qiu	Imperial College	d.qiu15@imperial.ac.uk

Acknowledgements/Contributions		
Name	**Organisation**	**Email**
Ferhat Özgur Catak	bU	ozgur@bitunitor.com
Chungming Rong	bU	chunming@bitunitor.com
Ricardo Faia	ISEP	rff@isep.ipp.pt
Pedro Faria	ISEP	pnf@isep.ipp.pt
Luis Gomes	ISEP	lfg@isep.ipp.pt
Meysam Khojasteh	ISEP	mey@isep.ipp.pt
Fernando Lezama	ISEP	flz@isep.ipp.pt

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Prepared by	**Reviewed by**	**Approved by**
Helleik Syse (bU)	Laurens de Vries (TU Delft)	Ana Estanqueiro (LNEG)

	Ana Estanqueiro (LNEG)	

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Executive Summary

Transitioning from centralised, fossil fuel-based power generation to decentralised, renewable energy sources necessitate significant transformations in the electricity system. This report explores the decentralisation process by focusing on Local Energy Communities (LECs) and Local Energy Markets (LEMs). These can enable consumers to produce, consume, store, and trade energy locally, thereby enhancing energy efficiency and resilience.

The primary objective of this report is to assess the performance of various market designs and trading mechanisms within LECs, particularly concentrating on peer-to-peer (P2P) markets and microgrid trading. The goal is to evaluate the impact of energy prosumption on electricity prices and to explore optimal market designs through simulations and real-world data. To achieve this, the assessment employs a two-stage approach. The first stage, Centralized Optimization, examines the role of a Market Operator in achieving optimal LEC operation. The second stage, Decentralized Operation, focuses on P2P trading, comparing Mid-Market-Rate (MMR) and Double Auction mechanisms, and incorporates machine learning to address information asymmetry.

The methodologies encompass local-wide, aggregation-wide, and wholesale-wide models to simulate interactions at different market levels and assess their impacts on prosumer behaviour, electricity costs, and market efficiency. Key findings indicate that LECs are central in the transition to sustainable, decentralized energy systems, offering economic, environmental, and social benefits. Regulatory frameworks in the EU, including the Clean Energy for All Europeans package, support the establishment and operation of LECs. However, there are regulatory difficulties linked to LEMs, including variations in national policies, the early stage of some technologies, and the evolving nature of local energy communities which can create barriers to effective implementation and integration.

Simulation results show that using the multilevel electricity trading framework, consumers and prosumers were able to reduce their electricity bills at the trading level. The Centralized P2P Electricity Sharing Optimization enabled several LECs to reduce their costs significantly compared to buying their demand from the retailer and selling their supply surplus to the grid. Similarly, the Competitive Strategic Bidding in Local Markets model also led to substantial cost reductions for participants. Participating in local-wide trading resulted in noticeable overall cost savings for all LECs involved. At the aggregation-wide level, using the P2P Discriminatory Price Auction, the overall cost reductions were modest, with trading constraints limiting the potential savings. The Iberian day-ahead market model allowed LEC participants to achieve the most significant cost reductions. Across all models, the transition from local-wide to wholesale-wide trading levels resulted in considerable overall cost savings compared to traditional retail purchases and surplus sales to the grid.

Consumers were able to achieve significant savings by selecting the best retail tariffs for their consumption behaviour. Additional savings were realized by adapting their load profiles to time-of-use (TOU) tariff schemes and investing in self-consumption. Small single and allied communities, composed of low-voltage consumers, managed to reduce electricity costs effectively by negotiating new tariffs with retailers. Large communities, composed of medium-voltage consumers, also achieved substantial cost reductions by participating in wholesale markets. Cooperative self-

consumption and flexible tariff selection further enhanced these savings. Communities with a certain level of load flexibility could achieve even greater savings by adopting real-time pricing tariffs.

The report concludes that decentralizing energy markets through LECs and LEMs can lead to significant improvements in energy efficiency, cost reduction, and sustainability. The comparative performance assessment of different market designs highlights the potential of P2P trading and cooperative self-consumption models in achieving optimal energy management. These findings support the broader goal of creating sustainable and autonomous energy systems, aligning with EU climate and energy objectives. Recommendations include strengthening regulatory frameworks to facilitate the growth of LECs, investing in technologies like blockchain and machine learning to enhance market efficiency, and promoting active participation of consumers in energy markets to leverage local energy resources effectively.

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List of Abbreviations

AGGLEC - Aggregated Local Energy Community

BESS - Battery Energy Storage System

bU - BitUnitor (Formerly bitYoga)

CEC - Citizen Energy Community

CER - Commission for Energy Regulation

CHP - Combined Heat & Power

DA - Day-ahead

DSO - Distribution System Operator

EC - Energy Community

ES - Energy Storage

EV - Electric Vehicle

FC - Flexible Consumer

FiT - Feed-in-Tariff

IDMA - Intelligent Data Mining and Analysis

IEC - International Electrotechnical Commission

IEEE - Institute of Electrical and Electronics Engineers

ISA - Intelligent System Applications

KKT - Karush-Kuhn-Tucker

LCOE - Levelized Cost of Electricity

LEC - Local Energy Community

LEM - Local Energy Market

LES - Local Energy System

LL - Lower Level

LMPI - Local Market Performance Indicators

LFM - Local Flexibility Market

LR - Load Reduction

MG - Micro-generator

MILP - Mixed-Integer Linear Programming

MLL - Multiple Lower Level

MMR - Mid-Market-Rate

MPEC - Mathematical Problem with Equilibrium Constraints

P2G - Peer-to-Grid

P2P - Peer-to-Peer

PES - Power & Energy Society

PPA - Power Purchase Agreement

PV - Photovoltaic

REC - Renewable Energy Community

RESS - Renewable Electricity Support Scheme

RTD - Real-Time Data

RTP - Real-Time Pricing

ToU - Time-of-Use

TSO - Transmission System Operator

UL - Upper Level

vRES - Variable Renewable Energy Sources

WG - Working Group

1. Introduction

The electricity sector has traditionally been composed of large, centralised power plants, which generate electricity that is transported through high, medium, and low-voltage transmission lines to the final users [1]. Due to climate change, there is a need to replace non-renewable fuels with renewable and low-emission energy sources. This imposes a major transformation in the electricity system. A key component of this transformation is a decentralising of the whole power system by including small generation units, closer to load centres, connecting them with medium and low-voltage grids, thereby reshaping the whole system's structure [1-3].

The decentralisation of the energy system and the integration of more non-dispatchable energy sources leads to both opportunities and challenges. Many of the challenges can be linked to maintaining a secure electricity supply in a system with more variability in production. Traditionally, flexibility at the production level was used to find the balance between generation and demand. However, the increased number of distributed energy sources is transforming the generation component into a more variable and sometimes referred as "intermittent" energy source. This characteristic in generation is calling for different and more efficient management approaches [4].

When it comes to opportunities, the decentralisation of energy production can put consumers as central players in the system, with an active and dynamic role.[4] One way of increasing production of renewable energy is to encourage regular consumers to also become producers of the energy (total or in part) they consume, the so -called prosumers. To facilitate this, Local Energy Communities (LECs)[1] can serve as an arena in which consumers can take control over their own energy acquisition and production. In these communities there will be a greater incentive for people to produce and consume energy locally due to potential economic benefits [5]. The members could also be able to exercise greater control over their own energy consumption by being able to view and compare prices on the local market to that of the "grid" in real time.

There are many different market designs and methodologies previously defined for LECs, which will be discussed in this deliverable. The modelling work is made more complex by the scale it is included in the modelling. The models are therefore categorised into three primary levels: i) Local-wide; ii) Aggregation-wide; and iii) Wholesale-wide, each with distinct interactions and performance criteria within the larger scale energy markets. The end goal of the task is to simulate these market designs using real data and compare their performances to determine which designs are most viable. In addition to this, a possible means of facilitating trade using a blockchain based platform is presented and demonstrated.

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[1] As defined in Article 2 of the *Directive EU 2019/944 on common rules for the internal market for electricity* (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944&from=EN)

1.1 Scope of the deliverable

This report focuses on the research activities of the TradeRES project Task 5.2 – Local Energy Communities: Case Study A under work package 5, “Performance assessment of the market(s) design(s). Application of the open-access tools to characteristic case studies”. This is the second edition of D5.2. The first edition [6] focused on developing conceptual frameworks and presenting preliminary results, while this edition provides a final assessment and includes a description of the tools developed within the scope of the Task 5.2.

This section presents the scope of the deliverable for the task of evaluating Peer-to-Peer (P2P) community-level markets and microgrid trading within Local Energy Communities (LECs), focusing on the impact of energy consumption on electricity prices.

Objective:

- To evaluate specific aspects of P2P markets and microgrid trading, including energy allocation mechanisms, legal structures, wider energy structures, proximity and control, and autonomy within LECs.

To assess the impact of energy prosumption in LECs on electricity prices, a two-stage approach will be implemented:

Stage 1 - Centralised Optimisation: Assuming a Market Operator role for the LEC, utilising centralised LEM operation to achieve first-best results.

Stage 2 - Decentralised Operation: Focusing on P2P operation with special attention to the clearing mechanism, comparing Mid-Market-Rate (MMR) with Double Auction, and employing machine learning to capture full strategic interaction under conditions of information asymmetry.

The criteria for comparing current and new market designs will include tariff selection strategies, investment in self-consumption, flexibility and RTP (Real-Time Pricing) considerations. The integration of technologies developed in WP3 and WP4 will be assessed based on their contribution to market efficiency and support for renewable energy integration. The methodologies for assessing prosumer’s demand response will include analysis of energy consumption patterns, the potential for demand-side management, and the economic benefits of demand response programs.

The baseline scenario and new market designs will be predicated on current legislative frameworks and market conditions, assuming cooperative engagement among LEC members. Limitations may arise from the nascent stage of some technologies, regulatory hurdles, varying national implementations of EU directives, and the evolving nature of LECs. The deliverable will provide a thorough examination of P2P community-level markets and the transformative potential of decentralised energy trading mechanisms within LECs, contributing to the broader goal of a sustainable and autonomous energy future.

1.2 Structure of the deliverable

Introduction: Sets the stage for the deliverable, presenting the scope, context, and interconnections with other research components within the overarching project.

Local Energy Communities and Local Energy Markets: Dives into the core concepts, real-world examples, and the envisioned trajectory for LECs and LEMs within the TradeRES project's ambit, detailing the innovation at the heart of the study.

Modelling Approaches and Methodologies: Articulates the analytical framework, focusing on the novel methodologies adopted for this research, including advanced machine-learning techniques and blockchain technology applications.

TradeRES LEM Simulation Framework: Discusses the simulation framework and its application in the evaluation of market designs, providing insights into the functioning and effectiveness of various LEM scenarios.

Results and Performance Assessment: Delivers a synthesis of the outcomes from the research, interpreting the performance of different market models and their implications for energy prosumption and pricing within LECs.

Conclusions: Draws together the threads of the research to offer conclusions and actionable insights, reflecting on the implications for policy, practice, and future research.

References: Catalogues the academic and technical references that underpin the report, ensuring transparency and rigor.

Annex A: Complements the main body of the report with a curated list of publicly available datasets, supporting the reproducibility of the research and providing resources for further investigation.

1.3 Link with other deliverables and tasks

This report draws upon a range of preceding documents and activities to collect inputs and pinpoint critical elements across a broad spectrum of associated areas, encompassing established models and their integration with principles of market design.

D3.2 lays a theoretical foundation for this work by presenting the electricity markets' actors' scene, through the identification of actor classes and the characterisation of actors from a behavioural and an operational perspective. The models and computational systems used in the deliverable, like, AMIRIS, MASCEM and RESTrade, were fully described in the deliverables of WP 4. The improved forecast methodologies presented in D4.9 ed.2 were used in some case studies. Local Market Performance Indicators (LMPIs) are computed according to the guidelines of D5.1 ed.2.

2. Local Energy Communities and Local Energy Markets

Within the energy systems research, the concepts of Local Energy Communities (LECs) and Local Energy Markets (LEMs) have emerged as elements in the transition towards more sustainable, decentralised, and participatory models of energy production, distribution, and consumption [7]. This chapter explores the definition of LECs and LEMs, examining the definitions, regulatory trends and recent developments.

LECs represent a model for energy production, distribution, and consumption, primarily focused on sustainability, decentralisation, and social engagement [4]. This concept emphasises the collective management of energy resources within a geographically defined area, enabling participants to produce, consume, store, and share energy, often from renewable sources, to achieve economic, environmental, and social benefits [4].

The establishment of LECs is a response to the growing challenges of climate change, energy security, and the need for more democratic energy systems. By leveraging local resources and fostering a participatory approach to energy management, these communities can reduce dependencies on fossil fuels, potentially lower energy costs, and, if adequately designed increase the resilience of local energy supply systems [8].

Academically, LECs have been discussed regarding their potential to contribute to the transition towards more sustainable and resilient energy systems. However, according to a review-paper on LECs by [4], *"there are different opinions regarding how local markets should operate. However, there is a common idea in the literature that local electricity should facilitate energy transactions at the local level"*. LECs are also seen as a socio-technical innovation that combines new technologies, such as solar panels and energy storage systems, with innovative organisational and business models [9]. This combination enables LECs to operate in a manner that is both environmentally sustainable and socially inclusive.

The European Union has recognised the potential of LECs in achieving its energy and climate objectives. The Clean Energy for All Europeans package, for example, provides a regulatory framework that supports the establishment and growth of LECs, defining them legally and facilitating their access to energy markets and networks.

Research on LECs often focuses on several key aspects, including:

- **Technological innovations:** The role of smart grids, renewable energy technologies, and energy storage solutions in enabling the efficient operation and management of LECs.
- **Economic models and incentives:** The financial mechanisms, business models, and policy incentives that can support the development and sustainability of LECs.
- **Social and cultural dimensions:** The importance of community engagement, trust, and social norms in the formation and success of LECs, as well as the benefits they bring in terms of social cohesion and empowerment.
- **Regulatory and policy frameworks:** The impact of national and international policies on the development of LECs, including barriers and enablers.

2.1 Definitions, regulatory trends and recent developments

This section provides an overview of Local Energy Communities (LECs) and Local Energy Markets (LEMs), key elements in Europe's shift towards decentralized renewable energy systems. It begins by defining LECs and LEMs, outlining their functions and objectives. The subsequent discussion focuses on regulatory trends influenced by EU directives and national policies. An examination of national regulatory frameworks across various European countries follows, highlighting diverse approaches to supporting energy communities. The section concludes with recent developments, including initiatives and projects that promote local energy autonomy and innovation.

2.1.1. Definitions

Local Energy Communities (LECs) and Local Energy Markets (LEMs) are core concepts in the transition towards decentralised, renewable energy systems in Europe. LECs are legal entities allowing citizens, small businesses, and local authorities to produce, manage, and consume their own energy. These communities engage in various energy activities, including production, distribution, supply, consumption, aggregation, and storage. The main objective of LECs is to provide environmental, economic, and social benefits to their members and local areas, emphasizing democratic governance and local engagement [10].

LEMs, on the other hand, facilitate the trading of locally produced energy, often through peer-to-peer (P2P) trading platforms. These markets aim to optimize local energy use, enhance energy security, and integrate renewable energy sources (RES) more effectively into the grid [11].

In addition to LECs and LEMs, the European Union's energy transition framework introduces several specific definitions that further elaborates and distinguish local energy initiatives. Renewable Energy Communities (RECs) are designed to promote renewable energy projects by enabling collective participation and ownership, thereby enhancing local energy production and consumption. Citizen Energy Communities (CECs) are broader entities that allow various energy activities beyond renewables, including traditional energy sources, with a focus on consumer empowerment and local governance.

Local Flexibility Markets (LFMs) are emerging platforms where energy flexibility services—such as demand response and energy storage—are traded. These markets support power system stability and efficiency by allowing local actors to provide and monetize their energy flexibility.

Despite these specific definitions, there is considerable overlap between LECs, RECs, and CECs. Generally, they all aim to decentralise energy production and consumption, promote renewable energy, and enhance local involvement in energy markets. This document will primarily use the terms LEC and LEM to encompass the broad activities and goals of these communities, recognising the subtle distinctions between RECs, CECs, and LFMs.

2.1.2. Regulatory Trends

The regulatory landscape for LECs and LEMs across Europe is shaped by both EU directives and national policies, creating a diverse and sometimes fragmented environment. The key EU legislative frameworks include the Renewable Energy Directive (RED II), the Internal Electricity Market Directive (IEMD), and the Directive on common rules for the internal electricity market (EU/2019/944). These directives establish the rights of consumers to become prosumers (producers and consumers) and to form energy communities, granting them access to energy markets and support schemes [10, 12, 13]

1. **Directive 96/92/EC**: This directive marked the regulatory starting point for the liberalization of electricity markets across the EU. It played a crucial role in shaping the energy landscape by introducing competition and breaking down monopolies, thus setting the stage for the development of LECs and LEMs [4].
2. **Clean Energy for All Europeans Package (2019)**: This legislative package introduced the concept of energy communities into EU legislation. It aimed to empower citizens and local authorities to take a more active role in the energy market by producing, consuming, and selling their own energy [10].
3. **Directive on Common Rules for the Internal Electricity Market (EU/2019/944)**: This directive supports the uptake of energy communities by introducing new rules that enable active consumer participation. It emphasizes the ability of consumers to participate in energy markets individually and through energy communities by generating, consuming, sharing, or selling electricity. It also highlights the role of energy communities in providing flexibility through demand-response and storage [14].
4. **Renewable Energy Directive (2018/2001/EU)**: The revised directive strengthens the role of renewable self-consumers and renewable energy communities. It aims to enhance the deployment of renewable energy sources across the EU, facilitating the creation of energy communities that can produce, consume, store, and sell renewable energy [14].

2.1.3. National Regulatory Frameworks

The Energy Communities Repository has collected data from the EU Member States on their existing policies and regulations for energy communities in the Clean Energy Package context. The information is published in an openly accessible database which can be accessed through the European Commission's Policy Database [14]. The following section provides an overview of the policy on energy communities for the countries within the European Economic Area.

Austria has a comprehensive framework for energy communities, defined through the Federal Law on the Expansion of Energy from Renewable Sources and the Federal Law on the Organisation in the Field of the Electricity Industry. These laws cover Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs), including provisions on energy sharing introduced in 2021.

Belgium's energy policy is managed by both federal and regional governments, resulting in different legislation for energy communities in Flanders, Wallonia, and Brussels-Capital. Federal laws also influence these regional frameworks, ensuring diverse approaches to energy communities.

Croatia introduced RECs through the Law on Renewable Energy Sources and CECs through the Law on the Electricity Market. Additional provisions are found in various rulebooks related to network use and energy activities.

Cyprus includes RECs and CECs in its national legislation through Law 130(I)/2021 and Law 107(I)/2022. The Cyprus Energy Regulatory Authority is tasked with creating enabling frameworks and support schemes for these communities.

Denmark has a long history of consumer-owned and municipal energy initiatives, with significant involvement in wind energy and district heating systems, reflecting strong local engagement in energy production and management.

Estonia's legal framework for energy communities includes amendments to the Electricity Market Act and the Energy Sector Organisation Act, defining RECs and ECs and granting them specific rights and obligations.

Finland's policy supports local energy communities through decrees enabling electricity sharing among members via virtual net-metering within property boundaries, primarily targeting housing associations.

France provides a legislative framework for RECs and CECs within its Energy Code, updated in 2023 to enhance support schemes and participation in renewable energy projects.

Germany's Renewable Energy Act 2023 redefines citizen energy companies, introducing exemptions from tender requirements to encourage community-led renewable projects.

Greece's legislation includes provisions for RECs and CECs through amendments to existing laws on electricity and renewable energy, focusing on enabling frameworks and transitional provisions.

Hungary's Electricity Act defines energy communities and RECs, granting them rights in electricity production, storage, and distribution, with the National Regulatory Authority overseeing their development.

Ireland's Renewable Electricity Support Scheme (RESS) includes specific mechanisms for RECs, although comprehensive national transposition of EU rules for energy communities is pending.

Italy allows RECs to share energy within the same distribution substation and defines CECs through various legislative decrees, with support schemes primarily reserved for RECs.

Latvia introduced legislative frameworks for RECs and CECs through amendments to the Law on Energy and the Electricity Market Law, effective from January 2023.

Lithuania's laws on renewable energy and electricity define RECs and CECs, granting them rights to produce, consume, store, and sell energy, with a regulatory procedure for their establishment.

Luxembourg's framework for RECs focuses on collective self-consumption and electricity sharing, with a revision expected to further develop these provisions.

Malta transposed EU provisions for RECs and CECs through subsidiary legislation, specifying their rights and the regulatory framework within national laws.

Norway as part of the European Economic Area (EEA), aligns closely with EU energy policies, including those promoting energy communities. The approach to energy communities integrates several key principles from EU directives, while also leveraging the country's hydropower.

Poland is in the process of transposing EU provisions for RECs and CECs, with existing legislation featuring energy cooperatives focused on renewable energy production.

Portugal introduced provisions for RECs and CECs through Decree 15/2022, establishing their role within the National Electrical System and replacing earlier legislation.

Romania's national legislation for RECs and CECs includes emergency ordinances, with the National Regulatory Authority responsible for developing enabling frameworks.

Slovakia's amendments to the Act on Energy and the Act on Support for Renewable Energy Sources define and support energy communities, with further regulations expected.

Slovenia's laws on renewable energy and electricity supply establish frameworks for RECs and CECs, integrating them into support schemes and local planning strategies.

Spain introduced RECs through Royal Decree 23/2020. upcoming legislation is expected to define and support CECs, emphasizing citizen and local authority participation in renewable projects.

2.1.4. Recent Developments

Recent years have seen significant developments in the regulatory landscape for LECs and LEMs, driven by the EU's ambitious climate goals. The European Commission's Clean Energy for All Europeans package, adopted in 2019, set the foundation for energy communities by providing legal recognition and support frameworks. This has been followed by various national initiatives and pilot projects aimed at promoting local energy autonomy and innovation.

For example, the Netherlands has implemented regulatory exemptions to support new business models within energy communities, while France is working on integrating these communities into its broader energy strategy [10, 11]. Additionally, EU-funded projects like eNeuron are exploring integrated local multi-vector energy systems, which include electricity, heat, and gas, to enhance the efficiency and sustainability of local energy networks [15].

In conclusion, while the regulatory environment for LECs and LEMs in Europe is evolving, significant disparities exist between countries. These variations highlight the importance of tailored national policies that align with overarching EU directives, ensuring that local energy initiatives can thrive and contribute effectively to the energy transition.

2.2 LEC and LEM initiatives and examples

This chapter will discuss the different initiatives supporting the development of LECs and LEMs. In addition, the overview Table 1 describes Local Energy Community related projects that have taken place over the last decade in Europe.

2.2.1. Supporting initiatives for Energy Communities

Several LECs and LEMs exist worldwide and in Europe. Given the scope of this report, this section will focus on European examples. First, several organisations and initiatives that bring together LECs will be highlighted, and then a selection of LECs and LEMs will be presented.

There are several organisations and initiatives that bring together and offer support to energy communities in Europe. There is the European Federation of Renewable Energy Cooperatives [16], which is a network of 2.250 energy cooperatives across Europe. Their objectives are to represent the voice of citizens and energy cooperatives to policymakers, support starting and establishing energy cooperatives, facilitate international collaboration and exchange between energy cooperatives and promote the cooperative business model in the energy sector.

The Energy Communities Repository initiative from the European Commission collected data about energy communities to show their diversity and impact on the energy system. This initiative also published several reports highlighting barriers and action drivers for developing LEMs and a roadmap for developing policy and legal frameworks. The Energy Communities Repository ended in January 2024. While the Energy Community Repository focuses on urban energy communities, there is also the European commission's Rural Energy Community Advisory Hub [17], which is focused on exploiting the opportunities and addressing the challenges experienced by rural energy communities.

2.2.2. Overview of LEM-related projects

Numerous projects over the last decade have investigated different approaches to creating local energy communities. Some have focused on local and regional flexibility, while others have dealt with renewable energy generation and P2P Trading. In Table 1, we have collected and summarised the most relevant R&D projects that are either working directly with Local Energy Communities, or in fields that closely relates to it. The table was compiled using the European Energy Communities Repository, in addition to the papers "Success of local flexibility market implementation: A review of current projects (2023)" and "Peer-to-peer and community-based markets: A comprehensive review (2019) [14, 18, 19].

Table 1 Overview of LEM-related projects

Project Name	Country	Start / End	Focus Level	Outcomes / Main Objectives	Web page
Altdorfer Flexmarkt	Switzerland	2018-2020	Owners and operators	Unlock small-scale flexibility	https://www.ffe.de/projekte/altdorfer-flexmarkt-alf-2/
CityxChange	Norway (with partners in EU)	2018-2023	P2P, community grid, EV, V2G	Common energy market and Positive Energy districts	https://cityxchange.eu/about-cityxchange/
Coordinet	European (Demonstration sites in Spain, Sweden and Greece)	2019-2022	Distribution grid level	TSO/DSO coordination, decrease peak load (DSO), and provide frequency regulation (system operator)	https://coordinet.netlify.app/

COME RES	Belgium, Germany, Italy, Latvia, Netherlands, Norway, Poland, Portugal, Spain	2020-2023	RECs and focus on socioeconomic issues	Facilitating the market uptake of renewable energy source, with focus on advancing RECs	https://come-res.eu/
Compile	Slovenia, Spain, Croatia, Portugal, Greece	2018-2022	Local grid in energy islands	Show opportunities of energy islands for decarbonisation of energy supply	https://www.compile-project.eu/
Cornwall LEM	United Kingdom	Active platform	Local level	Decrease peak load (DSO) and provide frequency regulation (system operator)	https://www.centrica.com/sustainability/energy-for-tomorrow/
DECIDE	Austria, Belgium, Estonia, Germany, Greece, France, Netherlands.	2020-2023	Local level	Communications and interactions for active energy communities	https://decide4energy.eu/
eCrew	Spain, Turkey, Germany	2020-2023	Local level	Roll-out of an innovative scheme of household cooperation in energy management, addressing Community Renewable Energy Webs (CREWs)	https://ecrew-project.eu/
Enera	European (Dutch multi-partner collaboration)	2018-2020	DSO, BRP and Aggregator	Decrease renewable curtailment	https://www.usef.energy/implementations/enera/
Enerchain	Europe	2017-2019	Wholesale market	P2P wholesale trading platform using blockchain	https://enerchain.ponton.de/index.php
Enedis' marketplace	France	Active platform	DSO	Unlock small-scale flexibility	https://www.enedis.fr/co-building-dso-local-flexibility
Energy Collective	Denmark	2017-2021	Consumer/prosumer	Deployment of local P2P markets in Denmark	https://energiforskning.dk/en/node/15513
InteGrid	Portugal, Austria, Germany, Slovenia, Sweden, Netherlands, United Kingdom, Netherlands	2017-2020	Medium voltage and low voltage grids by DSOs	Bridge the gap between citizens, technology and the other players of the energy system	https://cinea.ec.europa.eu/featured-projects/integrid_en
InterFlex	Sweden, Netherlands, Germany, Czech Republic, France	2017-2019	Local and Distribution	Unlock small-scale flexibility	https://interflex-h2020.com/
InterrFace	European	2019-2023	Transmission, distribution and local	Develop an interoperable pan-European grid services architecture	http://www.interrface.eu/content/home
LIFE_LETsGO4Climate	France	2022-2023	Local	Accelerate the production of renewable energy and by creating citizen collectives which promote the production of renewable energy	https://www.lifeletsgo4climate.eu/en/

LocalRES	Austria, Italy, Spain, Finland	2021-2025	Local Renewable Energy Communities	Promoting the participation of communities and people in the energy transition	https://energy-cities.eu/project/localres/
NOBEL	Europe (Germany, Spain, Greece, Sweden, Spain)	2010-2012	Consumer/prosumer	ICT for energy brokerage system with consumers	https://cordis.europa.eu/project/id/247926
NRG2Peers	Netherlands	2020-2023	Peer-to-peer	Peer-to-peer energy Communities facilitated by a gamified platform	https://cordis.europa.eu/project/id/890345
NRGcoin	Europe (Belgium, Spain)	2013-2017	Consumer/prosumer	P2P wholesale trading platform using blockchain	https://nrgcoin.org/
P2P-Smart-Test	Europe (Finland, United Kingdom, Spain, Belgium)	2015-2017	Distribution grid level	Advanced control and ICT for P2P energy market	https://cordis.europa.eu/project/id/646469
P2P3M	Europe (United Kingdom), Asia (South Korea)	2016	Consumer/prosumer	Prototype P2P energy trading/sharing platform	https://p2pconnecting.wordpress.com/
Piclo Flex	Great Britain	Active Platform	Local flexibility	Standardize and facilitate flexibility procurement process for DSOs	https://picloflex.com/
REScoopVPP	Belgium, France, Germany, Spain, United, Kingdom	2020-2023	Local flexibility	Develop a community-driven flexibility system	https://www.rescoopvpp.eu/
Smart Watts	Germany	2008-2011	Consumer/prosumer	ICT to control consumption in a secure manner	https://www.psi-energymarkets.de/de/unternehmen/forschung-entwicklung/smart-watts/
SmartNet	Pilots in Italy, Denmark and Spain	2016-2019	Local, distribution and transmission grid	TSO/DSO coordination	https://smartnet-project.eu/index.html
V2 Market	Denmark, Spain, Luxembourg, Belgium	2021-2024	Local and distribution	Incorporate EV batteries into the electricity system as storage and flexibility capacity	https://v2market-project.eu/
WindNode	Germany	2017-2020	Local and distribution level flexibility	Unlock small-scale flexibility	https://www.windnode.de/en

3. Modelling approaches and methodologies

3.1 Overview

In the following section, we will present the different models used in computing the Local Market Performance Indicators (LMPIs). These models are categorised into three primary levels: Local-wide, Aggregation-wide, and Wholesale-wide, each with distinct interactions and performance criteria within the energy market.

The Local-wide models concentrate on the interactions within local energy communities, focusing on the role of micro-generators, flexible consumers, and energy storage solutions. They assess individual performance indicators relevant to prosumers who both produce and consume energy within a localised framework.

Aggregation-wide models offer insights into the synergy between retail markets and local energy communities. They encapsulate the dynamics between retailers and suppliers, and the collective performance of aggregated communities, which are crucial for strategic energy management and investment decisions.

At the most expansive level of market interaction, the **wholesale-wide models** assess how local energy systems engage with and influence the wider wholesale energy market. These models delve into the complexities of market coupling, strategic bidding processes, and the financial implications of market participation, providing a macroscopic view of energy system performance.

The diagrammatic representation in *Figure 1* explains the hierarchical structure of the market levels, showcasing the flow from local production and consumption to the aggregation of such entities and their subsequent interaction with the wholesale market. The following tables and model descriptions will explain the specific methodologies and outcomes associated with each level, offering a comprehensive understanding of how these different elements unite to inform the LMPIs.

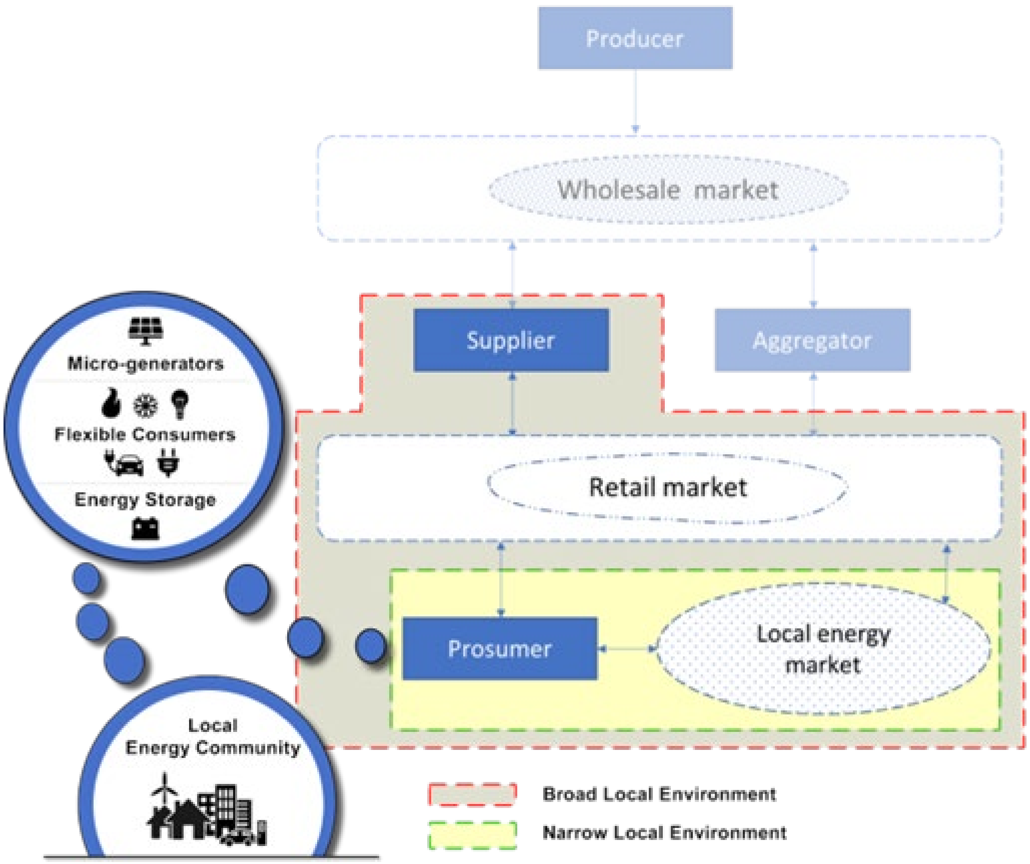


Figure 1: Overview of Energy Market Levels. This figure shows the structure of energy market interactions, from local community generation and consumption to aggregation by retailers and participation in the wholesale market.

3.1.1. Local-wide models

Local-wide models focus on the interaction between prosumers and individual performance within a defined local context. These models primarily simulate the dynamics of consumer and prosumer behaviour, such as tariff selection, investment in self-consumption, and demand-response capabilities. The aim is to optimise local energy systems to enhance efficiency and reduce electricity costs. For example, the Centralized P2P Electricity Transactions Optimization model demonstrates how a local operator can manage peer-to-peer trading to lower electricity bills. Such models explore how local actions can influence broader energy systems by fostering local energy trading and consumption flexibility. Table 2 presents the local-wide models:

Table 2: Local-wide model overview

Model name	Purpose	Features and Methodology	Outcomes/Results
MATREM: Agent-based Consumer	Demonstration of the main behaviour and outcomes of consumers and prosumers	- Selection of tariffs based on consumers' behaviour using optimization	Use of optimization models to simulate the consumption behaviour when selecting tariffs investing in

Model name	Purpose	Features and Methodology	Outcomes/Results
		- Optimization to invest in self-consumption - Demand-response capability	self-consumption respond to demand response programs and trigger some demand flexibility
MATREM: Bilateral trading	Simulation of the bilateral trading	-Alternative offers and contract-net protocols -Trading strategies	Use of bilateral trading in the negotiation of energy prices between different parties.
Centralized P2P Electricity Sharing Optimization	Simulation of LEC P2P transactions managed by a local operator	- P2P trading - Centralized optimization - Day-ahead	By using P2P transactions LEC consumers and prosumers were able to reduce their electricity bill in 11.28%
Competitive Strategic Bidding in Local Markets	Simulation of LEC competitive electricity market	- Strategic bidding - Competitive LEM - Double-sided auction - Day-ahead	Being a competitive environment, prices are not as low as in the previous model. Still, LEC consumers and prosumers can reduce their electricity bill in 12.95%
Optimal Local Flexible Consumption	Simulation of local consumption flexibility to adjust the Iberian day-ahead outcomes near real-time	- Demand flexibility - Cost minimization - Near real-time	Participation levels in load reduction increase with the budget, thereby enhancing system flexibility. The costs of load reduction vary depending on requested levels and budgets
LoRMaL-EM	Compare different clearing mechanisms and the effect of strategic behaviour	- MMR vs DA - Myopic Opt vs Dynamic RL - P2P Local market with 300 prosumers	DA under RL performs better and minimises cost for prosumers

3.1.2. Aggregation-wide Models

Aggregation-wide models investigate the interaction between different energy communities and the role of retailer suppliers in managing these interactions. These models typically encompass optimal power flow, competition among local retailers, and strategic behaviour in tariff selection. They aim to validate the impact of new investments, simulate retail competition, and demonstrate the benefits of strategic aggregation and management of local resources. For example, the OptiRES.Lines model validates how investments in renewable energy generation can impact distribution and transmission grids, reflecting on the importance of coordinated community-level strategies to enhance energy sustainability and economic outcomes. Table 3 presents the aggregation-wide models:

Table 3: Aggregation-wide models

Model name	Purpose	Features and Methodology	Outcomes/Results
OptiRES.Lines: OPF model	Validate new generation investments	- Optimal Power Flow model	Validate if new investments in local renewable energy generation affect distribution and transmission grids

Model name	Purpose	Features and Methodology	Outcomes/Results
MATREM: Agent-based LEC	Demonstration of the main outcomes of aggregating local resources local competition and strategic behaviour	- Local trades aggregation and interaction - Optimal investment in local generation resources and their management - Participation in wholesale markets using strategic behaviour	Local investment aggregation selection of tariffs and strategic bidding. Main outcomes of being part of a local community as the reduction in electricity price and increase in the local carbon-neutrality
MATREM: Agent-based retailer	Illustrate the strategic behaviour of retailers	-Profit seeking optimization -Strategic bidding and negotiation	Definition of tariffs, demand response programs and bilateral trading
MATREM: retail competition	Test competition on a local level	- Agent-based suppliers and consumers - Different tariffs	Based on different suppliers' and consumers' behaviours suppliers compete for local consumers by proposing different types of tariffs
P2P Discriminatory Price Auction	Simulation of electricity trading between several LECs	- Operators bid their LEC's demand/surplus - Pay-as-bid model - Price defined as the average between buyer and seller prices - Day-ahead	Trading at this level allows for LECs that do not have enough volume to participate in the wholesale market to reduce a bit more their consumers and prosumers electricity bills.
RetLEM	Interaction Retailer - LEM	- Strategic retail tariffs - ToU vs Dynamic - Centralised LEM Operation - Three types of prosumers (FC MG ES)	- Importance of retail sector competitiveness - LEM reduce retailers market power - Increase of social welfare - Transfer of welfare to prosumers

3.1.3. Wholesale-wide Models

Wholesale-wide models are concerned with the coupling of local or regional energy systems with the broader wholesale electricity market. These models facilitate the exploration of strategic bidding, market participation, and the computation of imbalance costs and prices. They aim to assess how communities can interact with, and benefit from, wholesale markets through simulations of day-ahead and intraday market operations. For instance, the MASCEM: Iberian day-ahead market model simulates how an aggregator can represent local energy communities (LECs) in the wholesale market, thereby achieving significant reductions in electricity costs through strategic market engagement.

Each of these levels of modelling serves to enhance understanding and guide the development of energy systems by addressing specific aspects of the energy market—from individual and local scales to broader market interactions. Table 4 presents the wholesale-wide models

Table 4: Wholesale-wide Models

Model name	Purpose	Features and Methodology	Outcomes/Results
MATREM: wholesale markets	Simulation of the participation of communities in wholesale markets	- Day-ahead and intraday continuous markets simulation	Outputs of the simulation of the participation of communities in wholesale markets
RESTrade: imbalance settlement	Simulation of the imbalance costs	- Imbalance settlement model	Computation of the communities' imbalance quantities and prices
MASCEM: Iberian day-ahead market	Simulation of the Iberian day-ahead wholesale market	- An aggregator participates on the Iberian EM on behalf of its LECs to trade missing demand/available surplus - Wholesale market - Day-ahead	The wholesale market participation of LECs allows significant cost reduction in the electricity bills of consumers and prosumers
WS2LEC	Interaction between WSM - Retailers – Energy Communities (different clusters of prosumers)	- Personalised pricing (cluster-based) - Explicit modelling of retailer business	Retailers and prosumers end better off with the tailored pricing scheme

3.2 Published work on the scope of the project – a resume

Some of the previous models have been presented and tested in publications within the scope of TradeRES and, in the next subsections a resume of each publication is provided for each wide-level model. Table 5 presents an overview of the published work associated with LECs by the project:

Table 5: Overview of published work on the scope of the project models, motivation, features and results associated with LECs.

Used models Reference	Purpose	Features	Results	Model Level
MATREM: bilateral trading, agent-based consumer and retailer [20]	Test the flexibility of consumers when responding to dynamic prices	-Consumers behaviour -Retail tariffs -Demand response	Consumers respond to retail tariffs, saving 7.5% when reducing 5% of their load in the most expensive periods.	Local
MATREM: bilateral trading, agent-based consumer, LEC and retailer [21]	To present and test the LEC agent-based model, including its formation, the interaction between members,	-LEC agent-based model -Bilateral negotiation -Team formation, interaction, management, strategies and negotiation	Small LECs without enough weight to participate in wholesale markets reduce electricity costs by 20% using the best team strategy while negotiating with retailers.	Aggregation

Used models Reference	Purpose	Features	Results	Model Level
	and team negotiation and decision making			
MATREM: bilateral trading, agent-based consumer, LEC and retailer [22]	To test how different LECs can ally and negotiate bilateral agreements using team strategies	-Automated bilateral trading -Interaction protocols -Team decision-making strategies	On top of the previous savings [21], local small LECs can save more than 10% by forming an alliance.	Aggregation
MATREM bilateral trading, agent-based consumer and LEC [23]	Review of power system alliances, and test models of LEC formation and management and bilateral trading.	-LEC formation and management -Bilateral trading -PPAs	Consumers reduced around 11% of electricity costs by being part of LECs. If PPAs with local generation are considered, the cost reduction increases to 33%. Local generation increased their remuneration by 16% in those PPAs.	Aggregation
MATREM: agent-based consumer and LEC [24]	Indicate the potential members and partners of LECs, their regulatory framework and their economic benefits	-Business models of LECs -Economic outputs of different players -Bilateral forwards and PPAs	In active LECs, consumers with cooperative self-consumption may reduce costs with electricity by 75%. Local generation may increase their remuneration around 20% by making bilateral agreements with LECs.	Wholesale-wide level
MATREM: wholesale markets, agent-based consumer and LEC. RESTrade: imbalance settlement [25]	Strategic behaviour of LECs without local generation in wholesale markets.	-LEC management -Strategic bidding	An active LEC composed of inflexible consumers reduced its costs by 35% concerning the regulated tariff, when participating in wholesale markets	Wholesale-wide level
MATREM: wholesale markets, retail competition, agent-based consumer, LEC and retailer. RESTrade: imbalance settlement [26]	Test the retail competition of LECs with local suppliers in retail markets, and their strategic behaviour in wholesale markets	-Retail competition -Consumers' behaviour -Active trading and strategic bidding of LECs -Investment in local generation	LECs can propose better tariffs than retailers, reducing the costs of their members by 30% in the case of investing in cooperative self-consumption. They achieve carbon neutrality and sustainability indexes of 87% and 36%.	Wholesale-wide level

3.3 Selected Methodologies

This section describes the methodologies that will be used to carry out the simulation and performance analysis for task 5.2. Methods of performing transactions, and designing local energy markets, market players' behaviours and how they interact, and finally how such a system can be achieved using blockchain technology.

3.3.1. Bi-level Modelling of Interactions between Wholesale – Retailer – Local Energy Community

This bi-level optimization problem is designed to elucidate the dynamic relationships between various stakeholders in the electricity market. The upper-level (UL) problem addresses the decision-making process of the electricity supplier, who sets personalized retail prices for the consumers served. The first lower-level (LL1) problem represents the flexible consumers' demand response, who strive to minimize daily energy costs by shifting consumption to times of lower retail prices. The second lower-level (LL2) problem pertains to the pool-based, day-ahead wholesale market, where the market operator seeks to minimize generation costs. The proposed bi-level optimization model accounts for the interactions among these three components, demonstrating how flexible consumers' demand response influences the wholesale market clearing process, as well as the resultant wholesale prices, retail prices, and business models in the market, as illustrated in Figure 2:

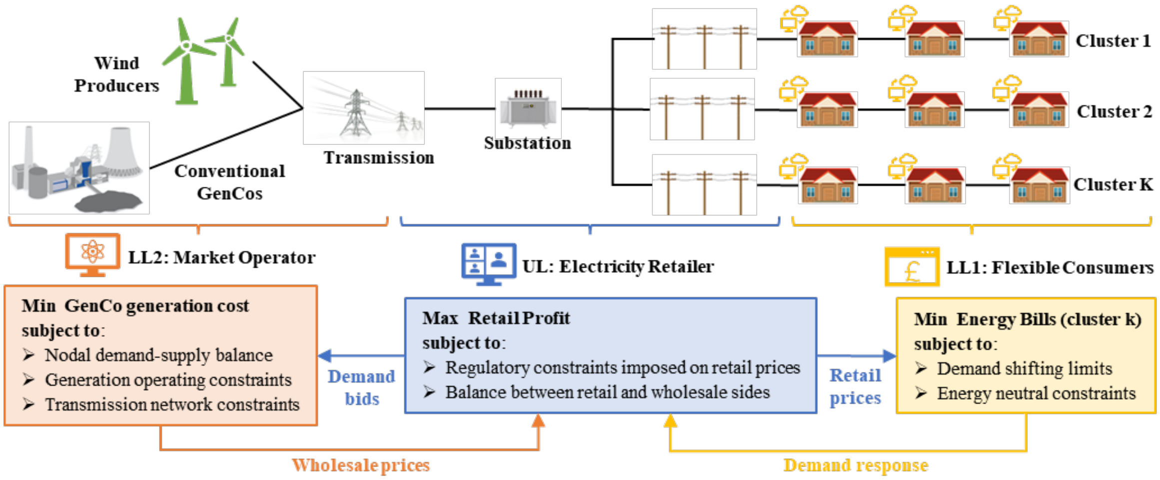


Figure 2: Decision-making process of the studied electricity market incorporating wholesale market, retail market and demand response energy communities.

Step 1 - Retail Price Determination: In the day-ahead market, the electricity supplier establishes personalized retail prices for various consumer clusters. To fully leverage the flexibility potential of these customers, the supplier optimizes time-specific retail prices instead of relying on traditional fixed or Time-of-Use (ToU) pricing.

Step 2 - Demand Response: Once personalized retail prices are communicated to customers via smart meters, consumers can individually adjust their consumption patterns to minimize their daily energy costs. This results in multiple lower-level (LL) demand response problems that align with the clusters defined by the supplier. Notably, consumer clustering is pre-processed using smart meter data prior to the daily market decision-making process.

Step 3 - Bidding in the Wholesale Market: To meet consumer demand, the supplier must purchase sufficient electricity from the wholesale market. The day-ahead wholesale market under consideration is a pool-based, energy-only market cleared by the market operator using a cost-minimization approach. The supplier has a significant market share, while other suppliers and the system demand account for the remaining market share.

Figure 2 illustrates the interdependence between the upper-level (UL) and the two lower-level (LL) problems. On one hand, the retail prices set in the UL retail problem influence consumer demand response in the LL1 problem, prompting flexible consumers to shift their energy consumption from high-cost periods to low-cost periods to reduce bills. On the other hand, the consumer response in the LL1 problem affects the wholesale market clearing process in the LL2 problem, influencing wholesale prices, retail prices, and the overall market strategies.

3.3.1.1. UL problem: strategic electricity supplier

The upper-level (UL) problem presents the decision-making process of the electricity supplier. Its mathematical formulation is expressed as follows:

$$\max_{\{\lambda_{k,t}^{R}, D_t^R\}} \sum_{k,t} \lambda_{k,t}^{R} D_{k,t}^{C} - \sum_t \lambda_t^W D_t^R \tag{1}$$

Subject to:

$$0 \leq \lambda_{k,t}^{R} \leq \lambda^{max} \tag{2}$$

$$\sum_t \lambda_{k,t}^{R} /|T| = \sum_t \lambda_t^W /|T| \tag{3}$$

$$D_t^R = \sum_k D_{k,t}^{C} \tag{4}$$

The objective function in equation (1)(1) seeks to maximize the daily profit of the electricity supplier, calculated as the difference between the revenue from served consumers (first term) and the cost of electricity purchased from the wholesale market (second term). The supplier strategically determines personalized retail prices $\lambda_{k,t}^{R}$ for its consumers and submits demand bids D_t^R to the wholesale market. The supplier's decision-making is governed by several constraints:

- Price Cap Constraint (2): Retail prices $\lambda_{k,t}^{R}$ are limited by a maximum price λ^{max} established by regulatory authorities. This cap safeguards consumers from excessive billing due to price surges.
- Average Pricing Constraint (3): Ensures that the daily average of retail prices aligns with the daily average of wholesale prices. This prevents the retailer from exploiting consumers through excessive high-priced periods, while still encouraging a time-specific price pattern to harness consumer flexibility.

- Retail Balancing Constraint (4): Guarantees that the electricity consumed by all served consumers matches the electricity purchased from the wholesale market for each time interval.

3.3.1.2. LL1 problem: demand response of flexible consumers

The demand response model for flexible consumers is based on a general, technology-neutral framework. It captures the flexibility of consumers who can redistribute their energy consumption within specific ranges while maintaining an overall energy-neutral profile. The mathematical formulation for each consumer cluster k is outlined as follows:

$$\min_{\{D_{k,t}^{S}, D_{k,t}^{C}\}} \sum_{k,t} \lambda_{k,t}^{R} D_{k,t}^{C} \tag{5}$$

Subject to

$$D_{k,t}^{C} = D_{k,t}^{B} + D_{k,t}^{S} \tag{6}$$

$$-\alpha D_{k,t}^{B} \leq D_{k,t}^{S} \leq \alpha D_{k,t}^{B} \tag{7}$$

$$\sum_{t} D_{k,t}^{S} = 0 \tag{8}$$

The objective is to minimize the energy bills for each cluster k by summing up the product of the strategic retail price $\lambda_{k,t}^{R}$ determined in the upper-level problem and the retail demand $D_{k,t}^{C}$ for each cluster over the course of a day. The consumers' demand response is governed by several constraints:

- Demand Balance Constraint (6): Defines retail net demand $D_{k,t}^{C}$, which is the baseline demand $D_{k,t}^{B}$ adjusted by the demand-shifting factor $D_{k,t}^{S}$.
- Demand Shifting Constraint (7): Imposes limits on the demand shift $D_{k,t}^{S}$ as a proportion α of the baseline demand $D_{k,t}^{B}$. A negative shift value indicates a reduction from the baseline, while a positive value signifies an increase.
- Demand Neutral Constraint (8): Enforces energy neutrality over the daily period, meaning no net energy gain or loss occurs after accounting for shifting patterns, ensuring that consumer needs remain satisfied.

3.3.1.3. LL2 problem: wholesale market clearing process

The wholesale market operates as a pool-based, energy-only market with a day-ahead horizon and a half-hour resolution. The market includes electricity suppliers/system demand as well as various conventional generation companies (GenCos) and wind producers. The mathematical formulation of the day-ahead wholesale market clearing process is given by:

$$\min_{\{P_{i,t}^{G}, P_{j,t}^{W}\}} \sum_{i,t} \lambda_{i,t}^{G} P_{i,t}^{G} \tag{9}$$

Subject to

$$D_{t}^{R} + D_{t}^{W} - \sum_{i} P_{i,t}^{G} - \sum_{j} P_{j,t}^{W} = 0 : \lambda_{t}^{W} \tag{10}$$

$$0 \leq P_{i,t}^{G} \leq P_{i}^{Gmax} \tag{11}$$

$$0 \leq P_{j,t}^{W} \leq \tilde{P}_{j,t}^{W} \quad (12)$$

This objective function (9) seeks to minimize the production costs of conventional GenCos, which is modelled as a quadratic function of the production $P_{i,t}^{G}$. The parameter $\lambda_{i,t}^{G}$ represents the coefficients of the cost function. Since wind producers are assumed to have zero marginal costs, their production costs are omitted from the objective.

- Wholesale Balance Constraint (10): Establishes the market's demand-supply balance, ensuring that the combined electricity production of conventional GenCos $P_{i,t}^{G}$ and wind producers $P_{j,t}^{W}$ meets the combined demand of the examined supplier D_{t}^{R} and the system D_{t}^{W}. The dual variable λ_{t}^{W} represents the wholesale prices at each time interval.
- Generation Limit Constraint (11): Imposes the production capacity limits of conventional GenCos, with P_{i}^{Gmax} denoting the maximum allowable power output.
- Wind Power Constraint (12): Enforces the capacity constraints of wind producers, governed by weather-dependent power limits $\tilde{P}_{j,t}^{W}$ based on wind speed conditions.

3.3.2. Bi-level Modelling of Interactions between Retailer and Local Energy Market

This modelling approach effectively captures the supplier's strategic pricing decisions and the interactions among the supplier, prosumers, and the Local Energy Market (LEM), as shown in Figure 3. The upper-level (UL) problem represents the strategic decision-making of a self-interested supplier who determines optimal time-specific retail prices for buying and selling energy. The supplier's primary objective is profit maximization while adhering to regulatory guidelines for retail tariffs, which are translated into operational constraints in the model. The UL problem is influenced by four lower-level (LL) problems. The first three LL problems pertain to the decision-making of three distinct prosumer types: the flexible consumer (FC), the micro-generator (MG), and the energy storage owner (ES). Each of these actors is also assumed to participate in the LEM, which constitutes the fourth LL problem. The LEM centralizes operations for the FC, MG, and ES participants. For the LL problems, each individual prosumer aims to optimize their demand/generation response to the given retail pricing scheme to maximize their economic surplus. Likewise, the LEM optimizes its energy exchanges with the retailer and derives optimal dispatch, maximizing total surplus by considering the retail prices offered and the techno-economic parameters of the participants' assets.

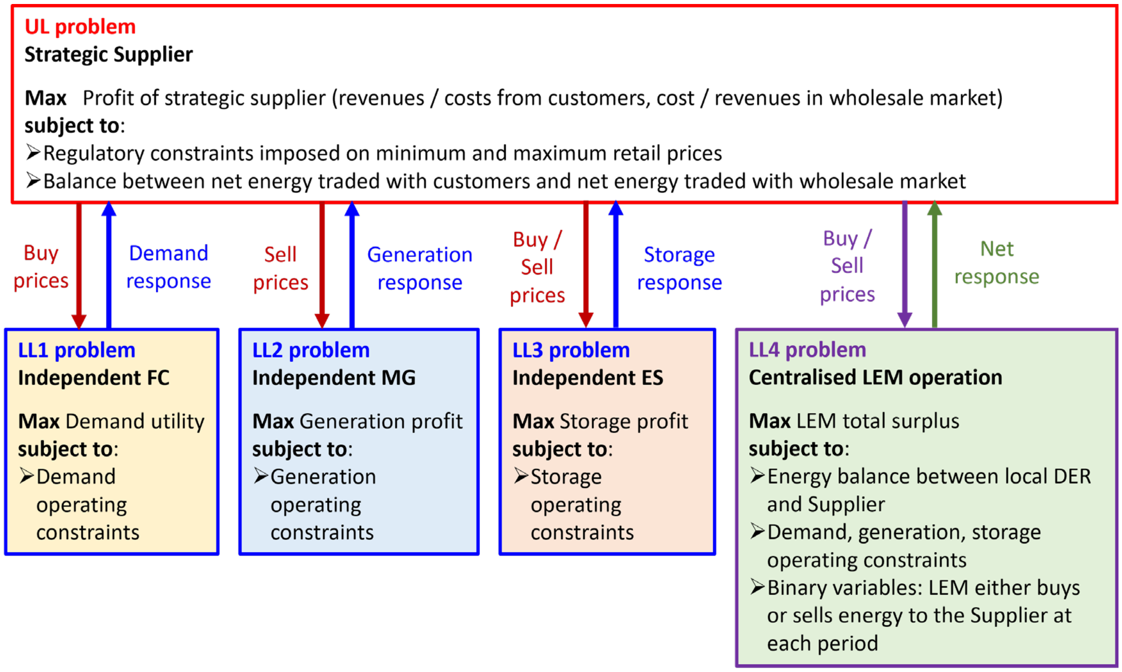


Figure 3: Decision-making process of the studied electricity market incorporating retail market and local energy market.

3.3.2.1. Upper-Level (UL) Problem: Supplier's Optimization

The upper-level (UL) problem focuses on optimizing the supplier's pricing strategies, where the offered prices differ based on the type of transaction: buying or selling energy. The supplier's objective is to maximize profits, calculated as total revenues minus operational costs.

$$\max_{\{\lambda_t^b,\lambda_t^s,w_t\}} \sum_t \lambda_t^b \left(\sum_i d_{i,t} + \sum_k s_{k,t}^c + u_t n_t\right) - \sum_t \lambda_t^s\left(\sum_j g_{j,t} + \sum_k s_{k,t}^d + (u_t - 1)n_t\right) - \sum_t \lambda_t^w w_t \qquad (13)$$

subject to:

$$\lambda^{min} \le \lambda_t^b, \lambda_t^s \le \lambda^{max}, \forall t \qquad (14)$$

$$\sum_i d_{i,t} - \sum_j g_{j,t} + \sum_k \left(s_{k,t}^c - s_{k,t}^d\right) + n_t = w_t, \forall t \qquad (15)$$

Revenues: These stem from energy sales to end users, including independent consumers, energy storage during charging, and the Local Energy Market (LEM) if it purchases energy from the supplier.

Costs: These are incurred when buying energy from generators, including independent micro-generators, energy storage during discharging, and the LEM if it sells energy to the supplier, as well as the energy procurement cost from the wholesale market.

The supplier operates under a regulatory framework that imposes a cap on retail prices in constraint (14), limiting market power. As a mediator with no resource ownership, the supplier adheres to a balance constraint (15), ensuring that the net energy traded with customers aligns with the net energy traded with the wholesale market.

3.3.2.2. Lower-Level (LL) Problems: Demand and Supply Optimization

LL1: Independent Flexible Consumer (FC) Demand Response:

The demand response of independent flexible consumers (FC) to retail prices is determined by utility (satisfaction) and energy purchasing costs. The objective function maximizes utility while minimizing the cost of purchased energy using "buy" prices. Consumer flexibility is bounded by the deferrable load limits.

$$\max_{\{d_{i,t}\}}\left(\sum_t\left(l_{i,t}^D\, d_{i,t} - q_{i,t}^D\, d_{i,t}^2\right) - \sum_t \lambda_t^b\, d_{i,t}\right) \tag{16}$$

subject to:

$$0 \leq d_{i,t} \leq d_{i,t}^{max}, \forall t \tag{17}$$

LL2: Independent Micro-Generator Response:

Given "sell" prices, the micro-generator aims to maximize profit by selling the generated energy to the retailer. Generation is limited by the asset's operational constraints, including capacity and other technical factors. The micro-generator model can also accommodate quadratic costs for thermal generators and levelized costs for renewable resources.

$$\max_{\{g_{j,t}\}}\left(\sum_t \lambda_t^s\, g_{j,t} - \sum_t\left(l_j^G\, g_{j,t} + q_j^G\, g_{j,t}^2\right)\right) \tag{18}$$

subject to:

$$0 \leq g_{j,t} \leq g_j^{max}, \forall t \tag{19}$$

LL3: Independent Energy Storage Response:

Energy storage systems (e.g., Battery Energy Storage Systems, or BESS) are represented by the independent energy storage owner. The objective function calculates operational profit, which is the difference between revenues from energy discharge (sales to the supplier) and the costs of energy charging (purchases from the supplier). Constraints include balance, storage capacity, charging/discharging rates, efficiency, and energy neutrality conditions.

$$\max_{\{s_{k,t}^c, s_{k,t}^d, E_{k,t}\}}\left(\sum_t \lambda_t^s\, s_{k,t}^d - \sum_t \lambda_t^b\, s_{k,t}^c\right) \tag{20}$$

subject to:

$$E_{k,t} = E_{k,t-1} + s_{k,t}^c\, \eta_k^c - s_{k,t}^d / \eta_k^d, \forall t \tag{21}$$

$$E_k^{min} \leq E_{k,t} \leq E_k^{max}, \forall t \tag{22}$$

$$0 \leq s_{k,t}^c \leq s_k^{max}, \forall t \tag{23}$$

$$0 \leq s_{k,t}^d \leq s_k^{max}, \forall t \tag{24}$$

$$E_k^0 = E_{k,NT} \tag{25}$$

LL4: Local Energy Market (LEM) Centralized Operation:

The LEM is represented in LL4 under a centralized operation assumption, where decisions are made based on full information and control of distributed assets. This results in an optimal benchmark outcome for evaluating decentralized market models. The LL4 objective is to maximize the total surplus of the LEM, which consists of the combined benefits of all independent prosumers participating in the market, energy generation costs, and the financial transactions between the LEM and the supplier.

$$\max_{V^{LL4}} \left[\sum_{i',t} \left(l^D_{i',t}\, d_{i',t} - q^D_{i',t}\, d^2_{i',t} \right) - \sum_{j',t} \left(l^G_{j'}\, g_{j',t} + q^G_{j'}\, g^2_{j',t} \right) - \sum_t \lambda^b_t\, u_t\, n_t + \sum_t \lambda^s_t\, (u_t - 1)\, n_t \right] \quad (26)$$

where

$$V^{LL4} = \{ d_{i',t},\, g_{j',t},\, s^c_{k',t},\, s^d_{k',t},\, E_{k',t},\, u_t,\, n_t \} \quad (27)$$

subject to:

$$\sum_{i'} d_{i',t} - \sum_{j'} g_{j',t} + \sum_{k'} \left(s^c_{k',t} - s^d_{k',t} \right) = n_t, \forall t \quad (28)$$

$$u_t \in \{0,1\}, \forall t \quad (29)$$

$$0 \le d_{i',t} \le d^{max}_{i',t}, \forall i', \forall t \quad (30)$$

$$0 \le g_{j',t} \le g^{max}_{j'}, \forall j', \forall t \quad (31)$$

$$E_{k',t} = E_{k',t-1} + s^c_{k',t}\, \eta^c_{k'} - s^d_{k',t} / \eta^d_{k'}, \forall k', \forall t \quad (32)$$

$$E^{min}_{k'} \le E_{k',t} \le E^{max}_{k'}, \forall k', \forall t \quad (33)$$

$$0 \le s^c_{k',t} \le s^{max}_{k'}, \forall k', \forall t \quad (34)$$

$$0 \le s^d_{k',t} \le s^{max}_{k'}, \forall k', \forall t \quad (35)$$

$$E^0_{k'} = E_{k',NT}, \forall k' \quad (36)$$

3.3.3. Fully Decentralized P2P Local Market

The following chapter describes the theory behind the decentralized P2P local market models.

3.3.3.1. Mid-Market Rate Pricing Scheme

The proposed Peer-to-Peer (P2P) trading platform employs a Mid-Market Rate (MMR) pricing mechanism to encourage household prosumers to cooperate within a Local Energy Market (LEM). This incentivizes participation regardless of whether a household acts as an energy buyer or seller at different times. Consider a set of households, $\mathcal{I} = \{1,2,\dots,I\}$. We define the LEM's net demand $P^{lem,d}_t$ and net generation $P^{lem,g}_t$ at time slot t. The remaining energy deficit (positive) or surplus (negative) $P^{lem,n}_t$ at time slot t depends on the individual household net load $P^n_{i,t}$.

$$P^{lem,d}_t = \sum_{i \in \mathcal{I}^d} P^n_{i,t}, \forall t \in T \quad (37)$$

$$P_t^{lem,g} = \sum_{i \in \mathcal{I}^g} P_{i,t}^n, \forall t \in T \quad (38)$$

$$P_t^{lem,n} = \sum_{i \in \mathcal{I}} P_{i,t}^n, \forall t \in T \quad (39)$$

where the sets $\mathcal{I}^d = \{\forall i \in \mathcal{I}: P_{i,t}^n \geq 0\}$ and $\mathcal{I}^g = \{\forall i \in \mathcal{I}: P_{i,t}^n \leq 0\}$ represent the consumers and producers within the LEM, respectively. The net demand (positive) or generation (negative) of a household i at time slot t ($P_{i,t}^n$) is determined by the household's distributed energy resource (DER) portfolio (e.g., which cluster it belongs to). This net load is calculated as the sum of its power demand or generation at time slot t:

$$P_{i,t}^n = P_{i,t}^d + P_{i,t}^{es} - P_{i,t}^{pv}, \forall i \in \mathcal{I}, \forall t \in T \quad (40)$$

where $P_{i,t}^d$ and $P_{i,t}^{pv}$ denote demand and PV power generation of household i. $P_{i,t}^{es} = P_{i,t}^{esc} - P_{i,t}^{esd}$ represents the charging and discharging power of storage unit of houlshold i.

The MMR method calculates the local buy price $\lambda_t^{lem,+}$ and the local sell price $\lambda_t^{lem,-}$ to be the midpoint of the utility sell price λ_t^- and the utility buy price λ_t^+, collectively referred to as the mid-market price λ_t^{mid}. However, due to mismatched total demand and generation during the day, any imbalance is traded with the grid, necessitating adjustments to the local buy and sell prices. The MMR pricing scheme is defined by three scenarios, illustrated in Figure 4.

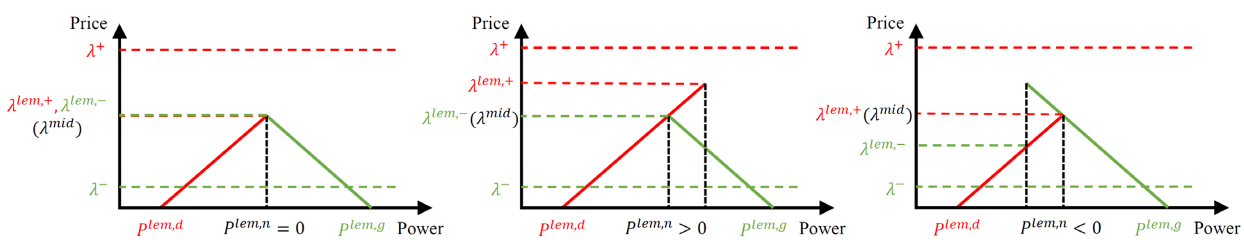


Figure 4: Mid-market rate (MMR) pricing scheme under different scenarios.

The local buy price $\lambda_t^{lem,+}$ and local sell price $\lambda_t^{lem,-}$ both equal the mid-market price λ_t^{mid} if the local demand (red line) precisely matches the local generation (green line), i.e., when $P_t^{lem,n} = 0$:

$$\lambda_t^{lem,+} = \lambda_t^{lem,-} = \lambda_t^{mid} = (\lambda_t^+ + \lambda_t^-)/2, \forall t \quad (41)$$

In cases where total demand (red line) exceeds total generation (green line), i.e., $P_t^{lem,n} > 0$, the energy deficit is supplied by the utility company at the high utility buy price λ_t^+. As a result, consumers in the LEM incur additional costs $\lambda_t^+ P_t^{lem,n}$, proportionally distributed based on each consumer's net demand $P_{i,t}^n$. In this scenario, the local buy price $\lambda_t^{lem,+}$ is higher than the mid-market price λ_t^{mid}, while producers continue to sell electricity at the mid-market price:

$$\lambda_t^{lem,+} = \left(\lambda_t^{mid} \left|P_t^{lem,g}\right| + \lambda_t^+ P_t^{lem,n}\right) / P_t^{lem,d}, \forall t \quad (42)$$

$$\lambda_t^{lem,-} = \lambda_t^{mid}, \forall t \quad (43)$$

In cases where total demand (red line) is less than total generation (green line), i.e., $P_t^{lem,n} < 0$, the energy surplus is sold to the utility company at the low utility sell price λ_t^-. Producers receive less revenue due to this shortfall, and the overall deficit $\lambda_t^-|P_t^{lem,n}|$ is allocated proportionally to each producer based on net generation $|P_{i,t}^n|$. Here, the local sell price $\lambda_t^{lem,-}$ falls below the mid-market price λ_t^{mid}, while consumers continue to purchase electricity at the mid-market price:

$$\lambda_t^{lem,-} = \left(\lambda_t^{mid} P_t^{lem,d} + \lambda_t^- \left|P_t^{lem,n}\right|\right) / \left|P_t^{lem,g}\right|, \forall t \quad (44)$$

$$\lambda_t^{lem,+} = \lambda_t^{mid}, \forall t \quad (45)$$

Under the MMR pricing mechanism, the cost for household i at time slot t is calculated based on the local buy/sell prices as follows:

$$Cost_{i,t} = \lambda_t^{lem,+} \left[P_{i,t}^n\right]^+ \Delta t + \lambda_t^{lem,-} \left[P_{i,t}^n\right]^- \Delta t, \forall i, \forall t \quad (46)$$

where $[\cdot]^{+/-} = \max/\min\{\cdot, 0\}$.

3.3.3.2. Double-Auction Market Scheme

The Double-Auction (DA) market efficiently matches multiple buyers (consumers) and sellers (prosumers) interested in energy trading and is widely regarded as a highly effective mechanism. It is frequently used for trading various commodities, such as electricity and stocks. A DA market operates for a fixed time, called the auction period (e.g., hourly resolution in the electricity market). Traders submit their bids and offers at the start of an auction period, and the auctioneer (e.g., market operator) clears the market and announces public results (e.g., trading prices and quantities) at the end of the auction period. The DA market structure includes:

- Buyers (Set $\mathcal{B}$): Each buyer $i \in \mathcal{B}$ submits a trading price p_i^b and the desired quantity of energy to purchase q_i^b, representing the willingness to buy q_i^b units at a price of p_i^b.
- Sellers (Set $\mathcal{S}$): Each seller $j \in \mathcal{S}$ defines a trading price p_i^s and the quantity of energy to sell q_i^s, indicating the willingness to sell q_i^s units at a price of p_i^s.
- Public Order Book: Managed by the auctioneer, this order book records accepted bids and offers. Buy orders $k^b(i, p_i^b, q_i^b)$ are sorted in descending order by price, while sell orders $k^s(j, p_j^s, q_j^s)$ are sorted in ascending order by price.

The matching process of a DA market can be organized as below:

- Step 1: Once the auction period starts, traders submit their bids/offers with prices and corresponding energy quantities, which are placed into the order book.
- Step 2: The matching algorithm iterates through the order books, pairing each buy order with a sell order until the buy price is lower than the sell price or no unmatched orders remain.
- Step 3: The transaction quantity is the smaller of the two matched orders' quantities.
- Step 4: The auctioneer determines the market clearing price using the mid-pricing method, calculating the midpoint between the matched buy and sell prices.

This clearing algorithm ensures maximum social welfare due to its sorting principle. At the end of the auction period, any remaining energy quantity and unmatched orders are balanced by the auctioneer with the utility company at grid prices (e.g., ToU or FiT). Pricing strategies for all traders are constrained between FiT and ToU rates to guarantee economic benefits.

3.3.4. Centralized P2P Electricity Sharing Optimization

In this model, a central optimization considering a MILP formulation is developed. The approach considers the minimization of the total social welfare costs of the community considering the equation presented in (47):

$$minimize\colon \sum_{i=1}^{Ni}\sum_{t=1}^{Nt}\left(p_{t,i}^{buy\ grid} \times ToU_{t,i} - p_{t,i}^{sell\ grid} \times FiT_{t,i}\right) \times \frac{1}{\Delta t} + FixCost_i \qquad (47)$$

where, $p_{t,i}^{buy\ grid}$ represents the power bought from grid, $ToU_{t,i}$ represents the time of use tariff paid to buy electricity from retailer, $p_{t,i}^{sell\ grid}$ represents the power sold to the grid, $FiT_{t,i}$ represents the value of feed-in tariff to sell electricity to the grid, Δt represents the scaling time factor, $FixCost_i$ represents the fixed costs paid by each player, Ni represents the total number of players and Nt represents the number of periods. Equation (48) presents the power balance of each player in each period.

$$p_{t,i}^{import} + p_{t,i}^{gen} + p_{t,i}^{dch} = p_{t,i}^{export} + p_{t,i}^{load} + p_{t,i}^{ch}, \forall t \in Nt, \forall i \in Ni \qquad (48)$$

where, $p_{t,i}^{import}$ is the power imported by the player, $p_{t,i}^{gen}$ corresponds to the power generated, $p_{t,i}^{dch}$ corresponds to the battery discharge power, $p_{t,i}^{export}$ represents the power exported by player, $p_{t,i}^{load}$ corresponds to the power of load and $p_{t,i}^{ch}$ represents the battery charge power. Equation (49) calculates the total import power of a player.

$$p_{t,i}^{import} = p_{t,i}^{buy\ grid} + \sum_{j=1 \quad j \neq i}^{Nj} p_{t,i,j}^{buy\ P2P}, \forall t \in Nt, \forall i \in Ni \qquad (49)$$

where, $p_{t,i,j}^{buy\ P2P}$ represents the power bought from P2P. Equation (50) gives the power exported by each player.

$$p_{t,i}^{export} = p_{t,i}^{sell\ grid} + \sum_{j=1 \quad j \neq i}^{Nj} p_{t,i,j}^{sell\ P2P}, \forall t \in Nt, \forall i \in Ni \qquad (50)$$

where, $p_{t,i,j}^{sell\ P2P}$ represents the power sold from P2P. Equations (51) - (53) limit the maximum quantity of power bought and sold to the grid and the simultaneous actions.

$$p_{t,i}^{buy\ grid} \leq \overline{p_{t,i}^{buy\ grid}} \times X_{t,i}^{buy\ grid}, \forall t \in Nt, \forall i \in Ni \qquad (51)$$

$$p_{t,i}^{sell\ grid} \leq \overline{p_{t,i}^{sell\ grid}} \times X_{t,i}^{sell\ grid} \ \forall t \in Nt, \forall i \in Ni \qquad (52)$$

$$X_{t,i}^{buy\ grid} + X_{t,i}^{sell\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \qquad (53)$$

where, $\overline{p_{t,i}^{buy\ grid}}$ represents the maximum limit for buying power from the grid, $X_{t,i}^{buy\ grid}$ is the associated binary variable to the buy from grid action, $\overline{p_{t,i}^{sell\ grid}}$ is the maximum limit to sell electricity to the grid and $X_{t,i}^{sell\ grid}$ is a binary variable associated with the sell to grid option. Equations (54) - (56) limit the maximum quantity of power bought and sold in P2P, and the simultaneous actions.

$$p_{t,i,j}^{buy\ P2P} \leq \overline{p_{t,i,j}^{buy\ P2P}} \times X_{t,i,j}^{buy\ P2P}, \forall t \in Nt, \forall i \in Ni \tag{54}$$

$$p_{t,i,j}^{sell\ P2P} \leq \overline{p_{t,i,j}^{sell\ P2P}} \times X_{t,i,j}^{sell\ P2P}\ \forall t \in Nt, \forall i \in Ni \tag{55}$$

$$X_{t,i,j}^{buy\ P2P} + X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{56}$$

where, $\overline{p_{t,i,j}^{buy\ P2P}}$ represents the maximum limit for buying electricity in P2P, $X_{t,i,j}^{buy\ P2P}$ represents the associated binary variable to the buy from P2P action, $\overline{p_{t,i,j}^{sell\ P2P}}$ represents the maximum limit for selling electricity in P2P, and $X_{t,i,j}^{sell\ P2P}$ represents the binary variable for the sell to P2P action. Equation (57) represents the energy balance of the P2P transactions.

$$\sum_{i=1\quad i\neq j}^{Ni} \sum_{j=1\quad j\neq i}^{Nj} p_{t,i,j}^{buy\ P2P} = \sum_{j=1\quad j\neq i}^{Nj} \sum_{i=1\quad i\neq j}^{Ni} p_{t,i,j}^{sell\ P2P}, \forall t \in Nt \tag{57}$$

Equations (58) and (59) present the conditions imposed to avoid simultaneous transactions in the grid and P2P mode.

$$X_{t,i}^{buy\ grid} + \sum_{j=1\quad j\neq i}^{Nj} X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{58}$$

$$X_{t,i}^{sell\ grid} + \sum_{j=1\quad j\neq i}^{Nj} X_{t,i,j}^{buy\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{59}$$

Equations (60) - (62) present the maximum limits for charge and discharge.

$$p_{t,i}^{dch} \leq \overline{p_{t,i}^{dch}} \times X_{t,i}^{dch}, \forall t \in Nt, \forall i \in Ni \tag{60}$$

$$p_{t,i}^{ch} \leq \overline{p_{t,i}^{ch}} \times X_{t,i}^{ch}\ \forall t \in Nt, \forall i \in Ni \tag{61}$$

$$X_{t,i}^{dch} + X_{t,i}^{ch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{62}$$

where, $\overline{p_{t,i}^{dch}}$ represents the maximum power of discharge, $X_{t,i}^{dch}$ is the binary variable associated with the battery discharge, $\overline{p_{t,i}^{ch}}$ represents the maximum power of charge, $X_{t,i}^{ch}$ is the binary variable associated to the battery charge. Equation (63) represents the batteries energy balance.

$$e_{t,i}^{bat} = e_{t-1,i}^{bat} + \left(p_{t,i}^{ch} - p_{t,i}^{dch}\right) \times \frac{1}{\Delta t}, \forall t \in \{2{:}\,Nt\}, \forall i \in Ni \tag{63}$$

where, $e_{t,i}^{bat}$ represents the energy state of a battery.

$$0 \leq p_{t,i}^{buy\ grid} \leq \overline{p_{t,i}^{buy\ grid}}, \forall t \in Nt, \forall i \in Ni \tag{64}$$

$$0 \leq p_{t,i}^{sell\ grid} \leq \overline{p_{t,i}^{sell\ grid}}\ \forall t \in Nt, \forall i \in Ni \tag{65}$$

$$0 \leq X_{t,i}^{buy\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{66}$$

$$0 \leq X_{t,i}^{sell\ grid} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{67}$$

$$0 \leq p_{t,i,j}^{buy\ P2P} \leq \overline{p_{t,i,j}^{buy\ P2P}}, \forall t \in Nt, \forall i \in Ni \tag{68}$$

$$0 \leq p_{t,i,j}^{sell\ P2P} \leq \overline{p_{t,i,j}^{sell\ P2P}}\ \forall t \in Nt, \forall i \in Ni \tag{69}$$

$$0 \leq X_{t,i,j}^{buy\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{70}$$

$$0 \leq X_{t,i,j}^{sell\ P2P} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{71}$$

$$0 \leq p_{t,i}^{dch} \leq \overline{p_{t,i}^{dch}}, \forall t \in Nt, \forall i \in Ni \tag{72}$$

$$0 \leq p_{t,i}^{ch} \leq \overline{p_{t,i}^{ch}}\ \forall t \in Nt, \forall i \in Ni \tag{73}$$

$$0 \leq X_{t,i}^{dch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{74}$$

$$0 \leq X_{t,i}^{ch} \leq 1, \forall t \in Nt, \forall i \in Ni \tag{75}$$

$$\underline{e_{t,i}^{bat}} \leq e_{t,i}^{bat} \leq \overline{e_{t,i}^{bat}}, \forall t \in Nt, \forall i \in Ni \tag{76}$$

$$\left\{X_{t,i}^{buy\ grid}, X_{t,i}^{sell\ grid}, X_{t,i,j}^{buy\ P2P}, X_{t,i,j}^{sell\ P2P}, X_{t,i}^{dch}, X_{t,i}^{ch}\right\} \in \mathcal{Z} \tag{77}$$

$$\{t, i, j\} \in \mathcal{Z}_+ \tag{78}$$

where, $\overline{e_{t,i}^{bat}}$ and $\underline{e_{t,i}^{bat}}$ represent the maximum and minimum limits for the battery's states. Equation (77) defines the integer variable and equation (78) the integer positive indices.

3.3.5. Competitive Strategic Bidding in Local Markets

This model considers strategic bidding by small producers with combined heat and power units (CHPs) and end-users with PV generation in a competitive market. The LEM is structured as an auction-based symmetric market and clearance is achieved through an LP model, maximizing participant transactions [27, 28].

Players aim to maximize their individual profits, essentially constituting a non-cooperative game. The modelling of the problem considers a set of consumers $I = \{1,2, \dots, N_c\}$, and producers

$J = \{1, 2, \dots, N_p\}$. Prosumers act as consumer when their PV generation is not enough to satisfy their total consumption, or as a producer in the periods where they have PV generation surplus. Thus, a bi-level model for strategic bidding is proposed as follows [27]:

Upper-level (multiple-followers): The upper-level models the independent costs/profits that market participants expect by putting bids/offers in the LEM. Consumers' bids are characterized as a tuple $(s_{i,t}, d_{i,t})$, where $s_{i,t}$ is a price bid for energy $d_{i,t}$ at time t. Consumers' minimization of costs is modelled as:

$$\min_{s_{i,t}, d_{i,t}} C_i = \sum_{t=1}^{T} \left(\sum_{j} cp_t \cdot x_{j,i,t} + c_t^{\mathrm{grid}} \cdot E_{i,t}^{\mathrm{buy}} \right) \tag{79}$$

$$d_{i,t}^{Total} = \sum_{j, j \neq i} x_{j,i,t} + E_{i,t}^{buy} \qquad \forall t \in T \tag{80}$$

$$0 \leq c_t^F \leq cp_t \leq s_{i,t} \leq c_t^{grid} \qquad \forall t \in T \tag{81}$$

where $x_{j,i,t}$ is the energy bought by agent i from agent j in the LEM (kWh); $E_{i,t}^{\mathrm{buy}}$ is the energy bought by agent i from the grid (kWh); cp_t is the LEM clearing price (EUR/kWh); and c_t^{agg} is the grid tariff (EUR/kWh). Equation (80) guarantees that the total demand of agent i ($d_{i,t}^{\mathrm{Total}}$) is supplied either by the LEM or the grid; (81) guarantees that the LEM cp_t is higher than the feed-in tariff c_t^{F}, and lower or equal to the bid price $s_{i,t}$ and the grid tariff c_t^{grid} (making the LEM profitable for consumers). All variables are considered non-negative.

On the other hand, producers' incomes are calculated in function of their offers modelled as a tuple $(s_{j,t}, g_{j,t})$, where $s_{j,t}$ is a price offer for energy $g_{j,t}$ at time t. Thus, producers maximize incomes as:

$$\underset{s_{j,t}, g_{j,t}}{max} \; In_j = \sum_{t=1}^{T} \left(\sum_{i} cp_t \cdot x_{j,i,t} + c_t^F \cdot E_{j,t,s}^{sell} - C_{j,t}^{total} \right) \tag{82}$$

$$g_{j,t}^{Total} = \begin{cases} \displaystyle\sum_{i, j \neq i} x_{j,i,t} + E_{j,t}^{sell} & for\ PV \\ \displaystyle\sum_{i, j \neq i} x_{j,i,t} & for\ CHP \end{cases} \qquad \forall t \in T \tag{83}$$

$$0 \leq c_t^F \leq s_{j,t} \leq cp_t \leq c_t^{grid} \qquad \forall t \in T \tag{84}$$

where $x_{j,i,t}$ is the energy sold by agent j to agent i in the LEM (kWh); $E_{j,t}^{\mathrm{sell}}$ is the energy sold by agent j to the grid (only PV generation can be injected into the grid) in kWh; cp_t is the LEM clearing price (EUR/kWh); c_t^{F} is the feed-in tariff (EUR/kWh); and $\mathrm{C}_{j,t}^{\mathrm{total}}$ is the total production cost of local generation. Equation (83) is used to guarantee that PV generation of player j is transacted in the LEM and feed into the grid, or that CHP production is limited to the one transacted in the LEM; constraint, equation (84) bounds producers' offers $s_{j,t}$ between the feed-in tariff c_t^{F} and the grid tariff c_t^{grid}; all variables are non-negative. The production cost $\mathrm{C}_{j,t}^{\text{total}}$ is 0 for PV generation and $(2 \cdot b_{CHP} \cdot \sqrt{G_{j,t}})$ for CHP producers, where b_{CHP} is a cost factor and $G_{j,t}$ is the energy produced by the CHP unit.

Lower-level (single-follower): The expected costs and incomes of the upper-level problem are directly related to the LEM clearing price cp_t. To solve the lower-level problem efficiently, we modelled it as a symmetric pool-based market mechanism [29]. In a first step, the supply curve is obtained by defining GE containing the offers of energy $(s_{j,t}, g_{j,t})$ in ascending order of price, and the demand curve DE containing the bids for energy $(s_{i,t}, d_{i,t})$ in descending order of price. The price at which supply equals demand is known as the equilibrium price (or clearing price) and can modelled as:

$$\max_{d_i^*, g_j^*} \sum_{i=1}^{N_c} \lambda_i^d \cdot d_i^* - \sum_{j=1}^{N_p} \lambda_j^g \cdot g_j^* \tag{85}$$

$$\sum_{i=1}^{N_c} d_i^* - \sum_{j=1}^{N_p} g_j^* = 0 \qquad : cp_t(dual\ variable) \tag{86}$$

$$0 \leq d_i^* \leq DE_i, \qquad i = 1, \dots, N_c \tag{87}$$

$$0 \leq g_j^* \leq GE_j, \qquad j = 1, \dots, N_p \tag{88}$$

where d_i^* and g_j^* are the demand bids and supply offers ordered by price (i.e., belonging to the sets DE_i and GE_j), and λ_i^{d} and λ_j^{g} are their corresponding bid/offer prices. Equation (85) maximizes the social welfare of players; Equation (86) is the balance equation from which the clearing price cp_t can be obtained taking its corresponding dual variable; Equations (87) and (88) guarantees that generation/consumption limits are respected. Any commercial mathematical software can solve the corresponding linear model. A reverse procedure is implemented to determine the corresponding LEM transactions $x_{i,j}$ and $x_{j,i}$ from the accepted d_i^* and g_j^*

The resulting bi-level problem involves different actors with different objectives and private information. To keep all optimization procedures separately (i.e., profits maximization of agents, and transacted energy maximization of LEM), we implemented a simulation framework using the ACO algorithm for the strategic bidding of players, an LP model for market-clearing.

We use a distributed ACO algorithm to learn/improve players decisions over time. ACO is a swarm intelligence approach that mimics the social behaviour of ant species. To do so, learning matrices are programmed to represent the process of ants depositing pheromone on the ground to mark clear paths to food. In other words, ACO exploits a problem-solving mechanism by reinforcing paths (solutions) that show good performance in each fitness function [30]. The details on the implementation of distributed ACO for this problem are omitted due to space constraints but can be found in [28].

Important to recall the following: each prosumer k with PV surplus is forced to inject this energy into the grid at the feed-in tariff; CHP offer price $s_{j,t}$ is adjusted to be higher or equal than the resulting $g_{j,t}$ production cost (or set to 0 otherwise); consumers are price takers ($s_{i,t} = c_t^{\text{grid}}$) and inelastic loads ($d_{i,t} = d_{i,t}^{\text{Total}}$); we only focus on the learning process of CHPs. After having all bids and offers from market participants, the lower-level problem is solved by first performing a merit order procedure and solving the LP model. The results from this step are the accepted bids/offers $x_{i,j,t}/x_{j,i,t}$ and clearing price cp_t.

3.3.6. P2P Discriminatory Price Auction

The use of distributed energy resources enables the appearance of prosumers. Which in turn promotes the appearance of peer-to-peer (P2P) energy trading markets, where customers can buy and sell energy directly from their peers. Auction mechanisms play a crucial role in determining fair prices and facilitating efficient energy exchange within these P2P platforms. Two auction formats were considered [31]: uniform-price auctions and discriminatory-price auctions.

In a uniform-price auction (UPA) for P2P energy trading, both buyers (i.e., customers seeking energy) and sellers (i.e., prosumers with excess of generation) submit bids. Bids represent the maximum price a buyer is willing to pay or, in the case of sellers, the minimum price a seller is willing to accept for a unit/lot of energy. The auction then determines a clearing price based on the biding curves. All winning bids, whether buyers or sellers, are matched at this clearing price. In our case, the UPA implementation used the highest losing bid marker clearing price, as presented in [32].

Discriminatory-price auction (DPA) offers an alternative approach from UPA. Where winners pay their individual bid prices, rather than a common clearing price. This can incentivize strategic bidding models, as buyers and sellers have a stronger chance of receiving a price closer to their true valuation. However, DPA can be computationally more complex and might raise privacy concerns, as individual bids become directly visible to the market.

3.3.7. MASCEM: Iberian day-ahead market

The Iberian day-ahead market (also known as Single Day-Ahead Coupling – SDAC) [33] aims to trade electricity for the 24 hours of the following day, through the submission of buying and selling bids by market participants. The energy price and volume at a specific hour are established by the point supply and demand curves intersect (Figure 5), following the double auction model [34].

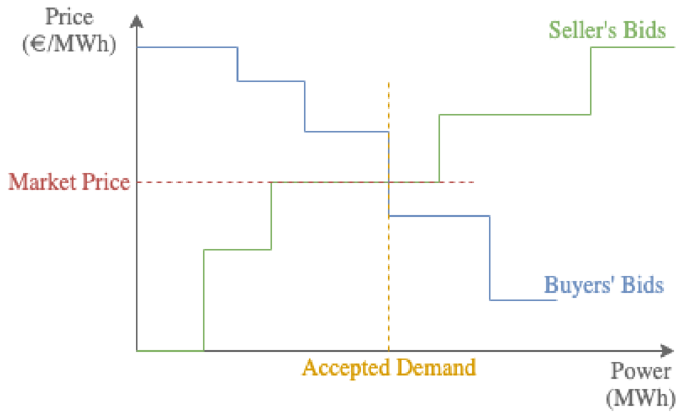


Figure 5: Double auction model.

In the double auction model, buyers and sellers participate by submitting their bids to the market operator. Bids consist of pairs of energy volume and price per energy unit. Bids from buyers are ordered by price in descending order. In the seller case, the bids are ordered in an ascending way. These bids form the demand and supply step curves. The point where both curves intersect (Figure 5) defines the quantity of energy to trade and the market price. Buying bids offering prices higher than the market price and selling bids offering prices lower than the market price trade in the market pool. Bids determining the market price may only partially trade their total volume. In the end, each buyer must pay the market price for each accepted supply unit.

Iberian market participants submit their bids though the Iberian market operator (OMIE) [33]. Bids are accepted according to their merit order (as detailed above) and depending on the available capacity for cross boarder interconnection between the two countries (i.e., prices zones). When the capacity for interconnection between the two zones is sufficient to allow the flow of electricity resulting from the negotiation, the price of electricity at that period of time will be the same in both zones. Otherwise, if the interconnection is maxed out for a certain period of time, the algorithm will split the participant bids by price zone (i.e., Portuguese and Spanish) clearing the market for each zone independently. Thus, in these cases, the electricity prices may differ between the two price zones at that time period. To ensure the technical feasibility of the system, market results are sent to the System Operator for the validation of the physical constraints, ensuring that the market results can be technically accommodated on the transportation network. Thus, results from the day-ahead market may be altered slightly because of the analysis of technical limitations done by the System Operator, giving rise to a viable daily program.

3.3.8. Optimal Local Flexible Consumption

Load flexibility refers to the ability to adjust electricity demand in response to changes in supply, prices, or grid conditions [35]. In near real-time, load flexibility can be utilized in various ways, including load reduction and load shifting. Instead of load shifting, which typically involves moving electricity consumption from peak to off-peak periods, load reduction focuses on immediate demand reduction. In near real-time, load reduction can be particularly useful during grid emergencies, supply shortages, or when renewable energy generation fluctuates rapidly. By actively managing load flexibility, grid operators can maintain system stability, avoid blackouts, and optimize the use of renewable energy resources. Furthermore, load reduction strategies can also provide financial benefits for consumers by participating in demand response programs or receiving incentives for reducing electricity usage during critical periods. Implementing load reduction strategies can help energy communities reduce their electricity bills by avoiding peak demand charges or participating in demand response programs that offer financial incentives for load reduction. Overall, leveraging load flexibility, including load reduction, in near real-time can contribute to a more resilient, efficient, and sustainable electricity system [36].

In this section, two models are presented for scheduling flexible consumption in near real-time operation, as follows:

- **Fixed LR level**: the requested load reduction (RLR) is stipulated by the operator, and the participation level of consumers (LR_i) is determined through cost minimization. The cost of load reduction is directly influenced by both the quantity of reduced load and the inconvenience cost of consumers (IC_i). Accordingly, the objective function of the fixed LR level model is formulated by equation (89), as follows:

$$\boldsymbol{Objectivefunction = \ min \sum_{i \in N_C} LR_{t,i} . IC_{t,i}} \tag{89}$$

  The main constraints of the model are the load reduction capacity allocated to individual consumers and the equilibrium between the requested and committed load reductions, represented by equations (90) and, (91) respectively.

$$\mathbf{0 \le LR_{t,i} \le LR_{t,i}^{max}} \tag{90}$$

$$\mathbf{RLR_t = \sum_{i \in N_C} LR_{t,i}} \tag{91}$$

- **Fixed LR budget**: the participation level of consumers in load reduction is calculated based on the load reduction budget that is defined by the operator. For a fixed load reduction budget, the maximum load reduction capacity is essential because it delineates the upper boundary of feasible load reductions for each consumer. By defining this maximum capacity, operators can allocate resources efficiently and prioritize reductions based on their impact on cost. Additionally, it helps prevent scenarios where reductions exceed the allocated budget. Therefore, understanding and adhering to the maximum load reduction capacity is crucial for maintaining cost-effectiveness within the fixed load reduction budget framework. As shown in equation (92), in this model, the objective function is the maximum load reduction.

$$\textit{Objective function} = max \sum_{i \in N_C} LR_{t,i} \quad (92)$$

Same as the previous mode, the load reduction capacity of consumers, and the budget of load reduction are the main constraints of this model, represented by equations (93) and (94), respectively.

$$0 \leq LR_{t,i} \leq LR_{t,i}^{max} \quad (93)$$

$$BLR_t = \sum_{i \in N_C} LR_{t,i}.IC_{t,i} \quad (94)$$

3.3.9. Agent-based LEC

In the current stage of development of the methodology proposed by the LNEG within the scope of local (citizen) energy communities (LECs), focuses on the aggregation of local consumers and prosumers as part of large active LECs with local generation, storage and operators as partners [21-23]. The community is managed by an aggregator who communicates with the members of the community and the market operator. Local distributed generation and storage may also be considered as part of the community [23-26]. The small local citizen energy communities are assigned to portfolios of retailers by signing bilateral agreements as presented in [21]. Furthermore, they can also ally at the local level to negotiate better agreements with retailers [22]. Figure 6 presents a schematic representation of the interactions between the different partners in the developed methodology.

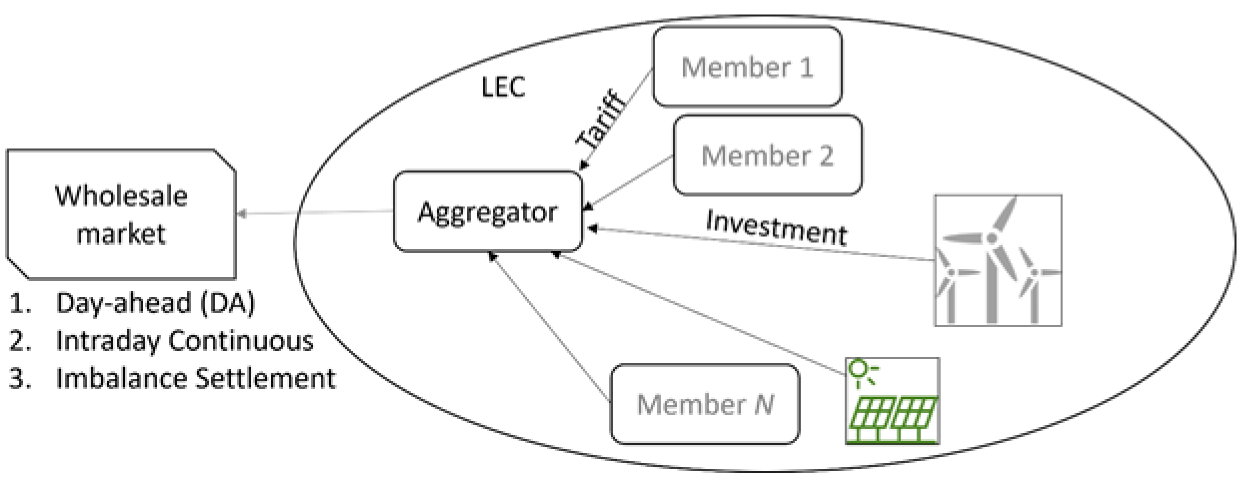


Figure 6: Agent-based model of the LEC. A Member can be a consumer or a prosumer.

3.3.9.1. Market Players' Behaviours

For the developed methodology, the *aggregator* has the main function of managing the local resources of the LEC to achieve its main goal of minimizing/maximizing its costs/revenues with energy [23, 25]. Under this approach, the *aggregator* agent uses the input data (the day-ahead price, and the consumption and production forecasts), and an optimization model with an objective function to achieve its goals. The *aggregator* communicates the expected hourly price of energy in the day-ahead market to each LEC *member* and receives information regarding the inflexible and flexible loads for each step in the case of active *members*. Otherwise, the *aggregator* bids according to the informed net load of the active *members* plus the expected net load (consumption minus the energy produced) of non-active *members* [25]. The LEC *aggregator* signs contracts with its *members* considering different types of tariffs such as flat, time-of use (TOU) and real-time pricing (RTP) tariffs. In the case of RTP tariffs, the aggregator does not have any markup (return over market prices). Furthermore, the LEC has an optimization model to invest in local cooperative renewable generation according to its fixed and marginal costs, expected net load and wholesale market prices [26].

Consumers and *prosumers* have information regarding some of the electrical equipment, generation, and storage assets. They have an optimization model that allows them to decide if they will invest in self-consumption, according to fixed and variable costs of the technologies and the retail tariffs of the retail competition as presented in the white blocks of Figure 7 [20, 26, 37]. These players are equipped with an optimization model that minimizes/maximizes their expected costs/revenues with energy. This is based on the expected cost of energy in the day-ahead and intraday markets and their daily expected consumption. Furthermore, they are also equipped with an optimization model that maximizes their utility function according to the market prices, their consumption behaviour, and their flexibility preferences [20, 26]. The main daily functions of active flexible *members* consist in providing their expected inflexible and flexible net loads before the closure of the day-ahead and intraday markets and their net load before the closure of the continuous intraday market to the LEC *aggregator* as presented in the green blocks of Figure 7. Non-active *members* rely on the forecasts made by the *aggregator*, paying penalties in the case of deviations.

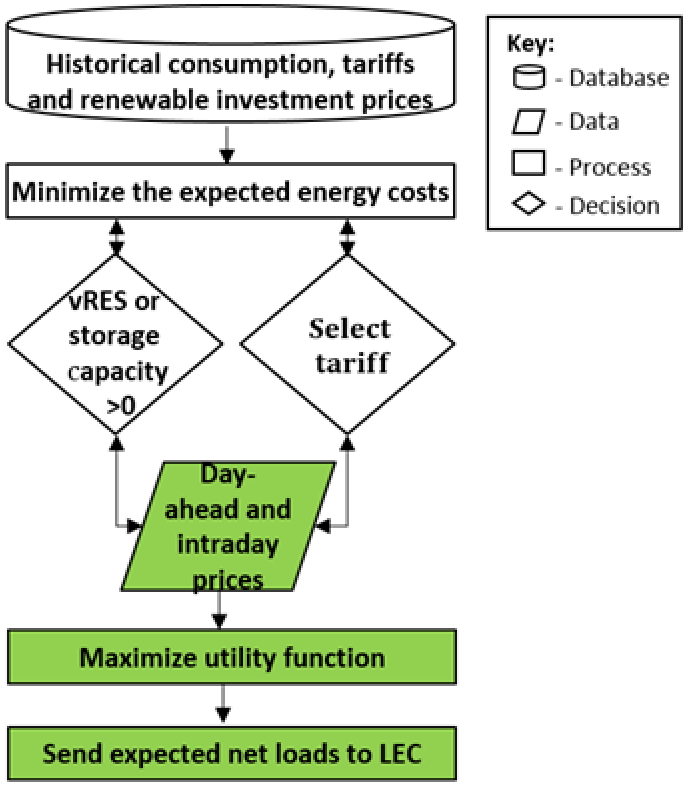


Figure 7: Members strategic decisions. White blocks for all members long-term continuous decision strategy regarding investment in renewable energy and tariff selection. Green blocks for day-ahead and intra-day strategic behaviour of flexible members.

The *market operator* has the main function of clearing the markets and computing the cost of the imbalance settlement using the agent-based MATREM [38] and RESTrade [39] tools, respectively. This market player receives bids (prices and quantities) from all market participants, including, the *aggregator,* and informs each one regarding the market clearing (prices and power dispatch). In case of energy imbalances concerning the programmed dispatch of the *aggregator*, the *market operator* informs the *aggregator* about the penalties it must pay [25, 26, 39].

The *system operator* computes the expected local power flow based on the programming dispatches defined in the market clearing, informing the *market operator* in the case of occurrences of load shedding and variable renewable energy sources (vRES) curtailments to avoid congestions using the Optimal Power Flow (OPF) model of the OptiRES.Lines tool [40]. The bids that originated those occurrences are removed from the market and the *market operator* clears the market again.

3.3.9.2. Detailed Communication Protocol and Interactions Between Market Players

Figure 8 presents the communication protocol between the different market players.

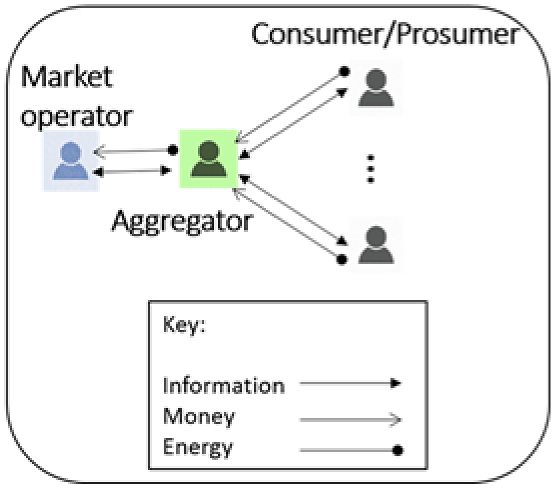


Figure 8: Communication protocol between players and the different interactions between the aggregator and the market operator.

The *aggregator* and the *market operator* communicate using a bilateral protocol. The *aggregator* submits bids to the different markets and receives information about the market prices and its programmed dispatch. Furthermore, in case of any deviations concerning the *aggregator* programmed dispatch, the *market operator* will inform the *aggregator* about the cost/revenue it has to receive because of those deviations. Figure 9 presents the interactions between the *aggregator* and the *market operator*.

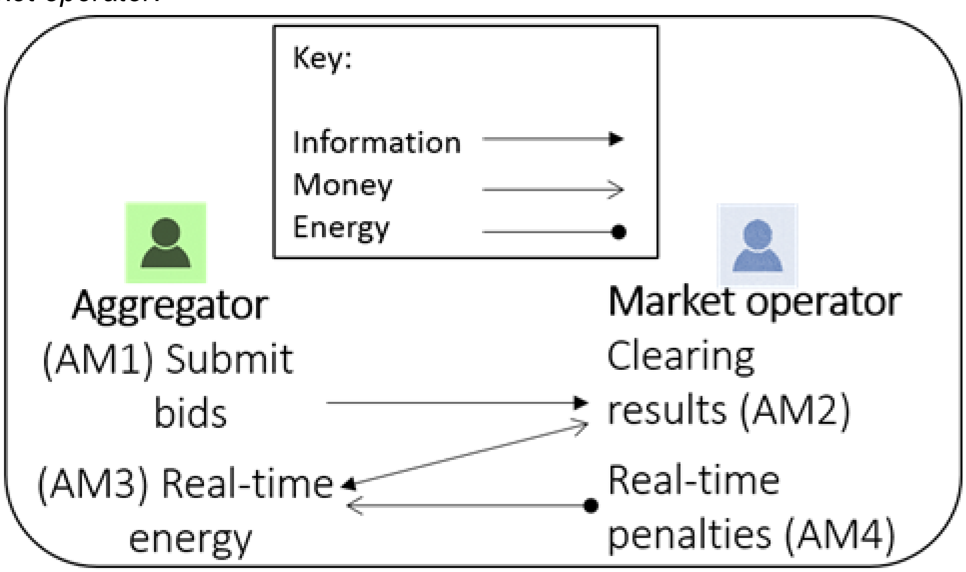


Figure 9: Interactions between the aggregator and the market operator.

The *aggregator* communicates with the members of the LEC using the contract net protocol, which means that it can communicate with all members, but the members cannot communicate with each other [21, 22].

Figure 9 presents the communication interactions between the LEC *aggregator* and each of its members, such as the methodologies that will be used to provide the information needed in these interactions.

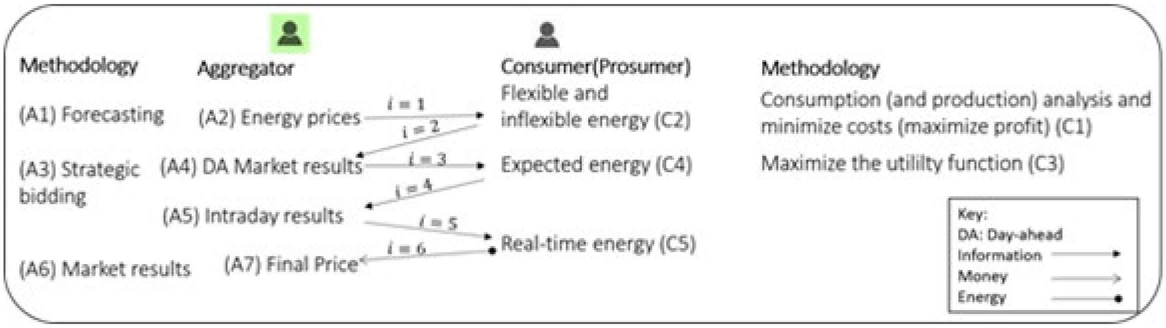


Figure 10: Interactions between the LEC aggregator and its members, and their methodologies.

Figure 10 presents a protocol with six interactions, *i*, between the *aggregator* and its members. The *aggregator* starts by computing the expected prices of the day-ahead market, using a forecast methodology (*A1*). Then, it sends the prices to the members (*A2*).

Each *member* computes their flexible and inflexible net load according to an analysis of their expected net load and equipment preferences and flexibility, using an objective function that minimizes costs (or that maximizes revenues) [20, 26]. According to their preferences concerning the usage of their electrical appliances, the optimization model computes all possible solutions to change their expected consumption, obtaining their flexible and inflexible net load (*C1*), and sending this information to the *aggregator* (*C2*). The *aggregator* receives these values and computes aggregated bids to the day-ahead market that minimizes/maximizes the costs/revenues of the LEC (*A3*), sending them to the *market operator* (*AM1*), who will reply with the market results (*AM2*).

The *aggregator* will inform the LEC's members about the market prices and the programmed dispatch of each one, waiting for their response with the expected final dispatch (*A4*). Then, each *member* computes its expected net load according to the maximization of a utility function (*C3*), which considers both consumption comfort and energy costs, sending it to the *aggregator* (*C4*). The *aggregator* receives the final expected dispatch of its members and using a strategic bidding algorithm (*A3*) [20,25] submits the bids to the intraday market (*AM1*), receives the market results from the *market operator* (*AM2*). The strategic bidding considers the minimization of energy costs but in the case of negative costs, i.e., profit, it maximizes the profit. Then, each *member* receives information regarding its final programmed dispatch (*A5*). In this conceptual approach, the members are aware that if they do not comply with the expected final dispatch, they must pay penalties – different methodologies and plan templates were tested for this penalization [25, 26].

The *market operator* verifies if the *aggregator* complies with the final dispatch (*AM3*) and computes the imbalance prices (*AM4*). In case of deviations (*C5*), the *aggregator* will verify the members responsible for them (A6) and charge them according with the tariff (*A7*). The full communication protocol is presented in [22].

3.3.10. Blockchain for Energy trading

Blockchain technology is a decentralized digital ledger that is used to record and verify transactions. It is a secure, transparent, and immutable database that uses cryptographic algorithms to ensure the integrity and privacy of data. A blockchain is made up of a network of computers that collectively maintain the database and verify each transaction [41].

When a transaction is initiated, it is verified by a network of computers called nodes, which use complex mathematical algorithms to ensure the transaction is authentic and secure. Once a transaction is verified, it is added to a block, which is then added to the chain of blocks, hence the name “blockchain.” Each block in a blockchain contains a unique digital signature, called a hash, that is created by the mathematical algorithm used to verify the transaction. The hash of each block is used to verify the integrity of the entire blockchain, making it difficult for anyone to alter the data in the blockchain without being detected [42].

Energy trading using blockchain technology can offer several benefits, including:

- Decentralization: Blockchain technology enables a decentralized, peer-to-peer network for energy trading. This means that energy transactions can take place directly between buyers and sellers without the need for intermediaries such as utilities or brokers. This can reduce transaction costs and increase efficiency [43].
- Transparency: Blockchain technology can provide transparency in energy trading by enabling all parties to view the transaction history. This can improve trust between parties and reduce the risk of fraud [44].
- Security: Blockchain technology provides a secure way to store and transfer energy transaction data. Transactions are verified through a consensus mechanism, and once verified, they are added to the blockchain in an immutable and tamper-proof manner. This can reduce the risk of hacking and data breaches [45].
- Efficiency: Energy trading using blockchain technology can be more efficient than traditional methods because it enables real-time settlement and eliminates the need for intermediaries. This can result in faster, more cost-effective transactions [44, 46].
- Renewable energy integration: Blockchain technology can enable the integration of renewable energy sources into the energy grid by allowing for the direct trading of renewable energy between buyers and sellers. This can encourage the adoption of renewable energy and reduce carbon emissions [47].

In a local energy community, prosumer incentivization for peak mitigation may use blockchain technology as the decentralized consensus platform for market trading. The trend of incorporating renewable energy, particularly solar energy, into energy infrastructure is increasing, on the one side because of financial incentives from the government and cost savings, and on the other side because more people are becoming aware of the advantages for the environment. Prosumers use on-site micro-generation equipment to produce a portion of their own energy to meet their own needs, or if there is excess, they can sell it to the grid or other customers [43, 47].

We designed a blockchain-based transaction system that includes consumers and prosumers. Producers can be connected to the grid and also trade energy among each other by utilising a decentralized blockchain based system. By participating in the local energy market, producers can earn credits on their electricity bills, thereby deriving more value from solar investments without needing to own and maintain individual battery systems. The power company and the user platform must agree on the calculation logic of the reward. Since the user platform represents the producer, it must also check and approve all transactions. Figure 11 shows how a decentralised blockchain platform operates.

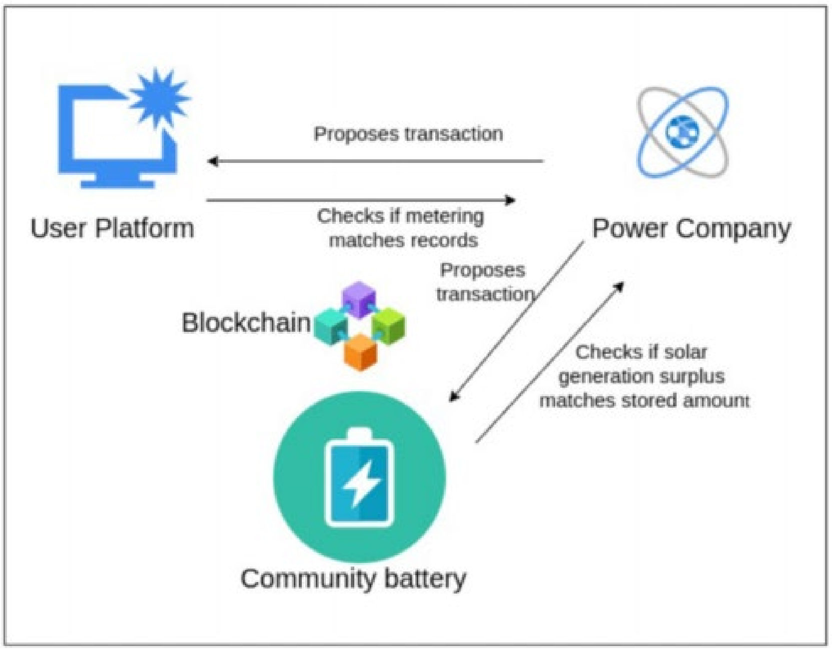


Figure 11: Visualisation of how the blockchain-based energy trading platform is set up

4. TradeRES LEM Simulation Framework

This chapter describes the TradeRES Local Energy Market (LEM) Simulation Framework, detailing the benchmarking data used, and the various case studies. This framework is designed to assess the performance of different market designs and trading mechanisms within Local Energy Communities (LECs). It includes three primary levels of modelling: local-wide, aggregation-wide, and wholesale-wide, each addressing distinct interactions and performance criteria within the energy market. By integrating these levels, the framework provides a general evaluation of market dynamics and their impact on energy efficiency, cost savings, and sustainability.

At the local-wide level, the models focus on the interactions within individual LECs, examining the behaviour of consumers, prosumers, and micro-generators. Key models in this category include the Centralized P2P Electricity Sharing Optimization, which simulates peer-to-peer transactions managed by a local operator, and the Competitive Strategic Bidding in Local Markets model, which explores competitive electricity markets within LECs. These models assess individual performance indicators relevant to local energy trading and self-consumption, aiming to optimize energy use and reduce costs at the community level.

The aggregation-wide level extends the analysis to the interactions between multiple LECs and the retail market. This level includes models such as the P2P Discriminatory Price Auction, which simulates electricity trading between several LECs, and the MATREM Agent-based LEC model, which demonstrates the outcomes of aggregating local resources and strategic behaviour. These models explore the synergies between local energy communities and retail markets, focusing on strategic energy management, optimal investment in local generation, and the benefits of coordinated community-level strategies.

At the wholesale-wide level, the models address the engagement of local energy systems with the broader wholesale electricity market. This level includes the MASCEM Iberian Day-Ahead Market model, which simulates how an aggregator can represent LECs in the wholesale market, and the RESTrade Imbalance Settlement model, which calculates the imbalance costs and prices for communities. These models provide insights into market coupling, strategic bidding processes, and the financial implications of wholesale market participation.

The overarching TradeRES LEM Simulation Framework integrates these three levels of modelling to provide a comprehensive evaluation of market designs and their impact on LECs. By leveraging advanced technologies such as machine learning and blockchain, the framework aims to optimize market operations, enhance energy trading efficiency, and address information asymmetry. This integrated approach enables a thorough performance assessment of current and new market designs, facilitating the identification of optimal strategies for energy management within LECs.

4.1 Benchmarking Data

The following sections describe the datasets used for the different case studies. In the specific case studies, the relevant datasets will be referenced.

The most commonly used tariffs in energy markets are flat and time-of-use (TOU) tariffs. TOU tariffs come in different variations like two-rate, three-rate, and four-rate tariffs, each with peak, mid-peak, off-peak, and super off-peak periods. Consumers opt for TOU tariffs when they use more energy during off-peak periods or have the flexibility to adjust their usage accordingly. In liberalized markets, retailers offer tariffs linked to wholesale market prices, such as real-time pricing (RTP), day-ahead hourly pricing (DAHP), and monthly pricing (DAMP) tariffs. These tariffs help retailers manage risk and encourage consumers to adjust their short-term consumption habits. They also include retailer commissions, which, although fixed and lower compared to single and TOU tariffs, come with high-risk premiums [48, 49].

Indexed tariffs create uncertainty for consumers as they do not know the exact price until consumption due to energy losses factored in by regulators. DAHP tariffs provide consumers with more precise hourly price information between 12 to 36 hours before real-time dispatch, incorporating day-ahead hourly prices plus a fixed value for real-time imbalances. While these tariffs enable consumers to plan their energy use, forecast errors can lead to energy scarcity or excess, impacting imbalance costs. RTP tariffs offer the most accurate prices based on actual wholesale energy prices, but consumers receive this information after consumption, limiting their ability to plan effectively. These tariffs suit flexible consumers who can adhere to their planned energy use without deviations, potentially avoiding risk premiums and imbalance penalties. On the other hand, DAMP tariffs, based on average monthly day-ahead prices plus fixed fees for real-time imbalances, do not incentivize consumers to change their consumption habits [26].

4.1.1. Dataset of an energy community with prosumer consumption, photovoltaic generation, battery storage, and electric vehicles

Location: Portugal

Parameters available: Power consumption, Power generation, Electricity tariffs, EV consumption, EV characteristics, stationary batteries characteristics, Domestic EV charger characteristics and house connection to main grid limits

Measurement period: n.a.

Temporal resolution: 15 min

Type of aggregation (Building, house, etc.): Houses

Overall Quality: Good

Link: https://www.sciencedirect.com/science/article/pii/S2352340923003372

Description: Energy community dataset comprising consumption, PV generation, battery storage, and EVs.

The dataset referenced [50] examines a community comprising 250 residential households. Of these, 200 households had photovoltaic generation, and 150 owned a battery storage system. Additionally, each household was assigned one regular and one premium electric vehicle, totalling 500 electric vehicles, along with details regarding their capacity, state of charge, and usage. The dataset presents considers data for one day with 96 periods (15 min).

The data utilized in the simulations using the Centralized P2P Electricity Sharing Optimization model in section 4.3.2 considers 30 days of operation. Both power consumption and power generation data were randomly generated based on the previously presented dataset, following the approach outlined in reference [51]. The electric vehicle profiles remain consistent throughout all simulated days. For the simulation, we considered 100 houses, each with 2 electric vehicles (totalling 200 EVs), 43 stationary batteries, and 60 photovoltaic systems. Five different local communities were generated, differing in the number of assets presented in each one.

4.1.2. Dataset of an energy community with prosumer consumption, photovoltaic generation, combined head and power generation, and electric vehicles

Location: Portugal

Parameters available: Power consumption, PV generation, CHP generation capacity, Electricity tariffs, EV consumption, EV characteristics, house contracted power.

Measurement period: n.a.

Temporal resolution: hourly

Type of aggregation (Building, house, etc.): Houses

Overall Quality: Good

Link: https://ieeexplore.ieee.org/abstract/document/10161857

Description: Energy community dataset comprising consumption, PV and CHP generation, and EVs.

This data set, is an extended version of [52], comprising a LEC with 55 prosumers (from which 12 consumers without PV generation and 42 prosumers with PV generation), and 6 CHP generators, having a total of 61 different players. Also, we assume that 29 prosumers have EVs. The dataset presents considers data for one month with 24 periods per day (1-hour resolution).

The data utilized in the simulations using the Competitive Strategic Bidding in Local Markets model in section 4.3.2 considers 31 days of operation. Both power consumption and generation data were randomly generated based on the previously presented dataset, following the approach outlined in reference [51]. The electric vehicle profiles remain consistent throughout all simulated days. Three different local communities were generated, differing in the tariff in each one as follows:

- LEC6 with a flat tariff with 0.158 EUR/kWh for all periods.
- LEC7 with a double tariff with 0.1023 EUR/kWh in off-peak periods (23h to 7h), and 0.1924 EUR/kWh in peak periods (8h to 22h).
- LEC8 with a triple tariff with 0.1023 EUR/kWh in off-peak periods (23h to 7h), 0.1696 EUR/kWh in the middle periods, and 0.2358 EUR/kWh in peak periods (11h-13h, and 21h).

For exporting energy into the grid, a feed-in tariff of 0.045 EUR/kWh was considered for all periods.

4.1.3. Elergone Project dataset used in the large agent-based LEC study

Location: Portugal

Parameters available: Power consumption Measurement period: 2011-2014 Temporal resolution: 15 min

Type of aggregation (Building, house, etc.): Medium tension aggregation

Overall Quality: Good in 2012 and 2013

Link: https://archive.ics.uci.edu/ml/datasets/ElectricityLoadDiagrams20112014\

Description: Aggregated consumption data of 370 medium voltage Portuguese consumers.

This project monitored the data of 370 Portuguese medium voltage consumers from the period between 2011 to 2014 with a temporal resolution of 15 minutes [53]. These data cover the consumption of around 5% of the Portuguese demand. This dataset aggregates data of several types of consumers with some missing data (only 312 consumers in the period 2012-13 have consistent data), extrapolated to 2018-19 [24-26]. No information regarding individual appliances is available, therefore, flexible, and inflexible demands must be extrapolated.

Iberian market data are available online:

Link: https://mercado.ren.pt/EN/Electr/MarketInfo/MarketResults/OMIE/Pages/default.aspx

Observed and forecast meteorological data are online:

Link: http:// www.meteomanz.com/index?l=1

The 2019 prices of each part of the variable term of the regulated TOU electrical energy tariff for medium voltage consumers are (all in EUR/MWh):

Energy (only for regulated tariffs): Peak: 77.2, Mid-Peak: 72.4, Off-Peak: 59.0, Super Off-Peak: 54.7 (check [20] for the tariff structure). Grid access: 19.15 (Single self-consumption: −5.36 and CEC self-consumption: −10.72). Global system use: 6.37. Transport grid use: 1.30. Distribution grid use: (High voltage 60 kV: 0.60 and medium voltage 30 kV: 1.38).

Link: https://www.erse.pt/media/1kifgvjh/estrutura-tarifária-2019-dez2018.pdf

The tariffs proposed by Portuguese retailers are available at:

DAHP:

Link: https://www.coopernico.org/files/documents/Coopernico_Tarifario_Indexado.pdf

DAMP (BTN SPOTDEF):

Link: https://luzboa.pt/tarifas/domestico/1

RTP (EZU Indexada):

Link: https://ezu.pt/tarifas

4.2 Case Studies

The aim of the presented case studies lies in analysing the techno-economic outcomes at the local level. Structural components related to market design considerations (e.g., structure of retail tariffs, local energy trading, flexibility procurement mechanisms) affect the interactions between the prosumers, the communities, and the aggregating entities. The effects that arise from the introduction of local trading as well as the efficiency and facilitation of the market mechanisms are the main aim of the conducted analysis.

4.2.1. Blockchain trading for local energy communities

This case study investigates the use of blockchain technology to improve energy trading within LEMs, enhancing transaction efficiency, security, and transparency. The case study employs Ethereum blockchain technology to enable decentralized energy trading. Through smart contracts—specifically, the EnergyToken and EnergyExchange contracts—it automates trading processes and reduces the need for intermediaries, potentially lowering costs and improving reliability. The EnergyToken Contract digitizes energy units, ensuring their transferability across the Ethereum network using the ERC-20 standard. The EnergyExchange Contract serves as a marketplace for these tokens, maintaining a secure and transparent record of all transactions.

To participate in the TradeRES Blockchain Project, users must install Node.js, npm, and Truffle, a development environment for Ethereum. Project resources are available at the [TradeRES GitHub repository], and necessary dependencies must be installed following cloning. Contracts are deployed to an Ethereum testnet, such as Rinkeby, allowing interaction through the Truffle console or web applications using APIs like web3.js or ethers.js.

Community engagement is encouraged through bug reporting, enhancement suggestions, and discussions to refine and expand the platform's capabilities. The project's operational dashboard can be accessed at [TradeRES Dashboard]. Figure 12 shows a screenshot of the dashboard:

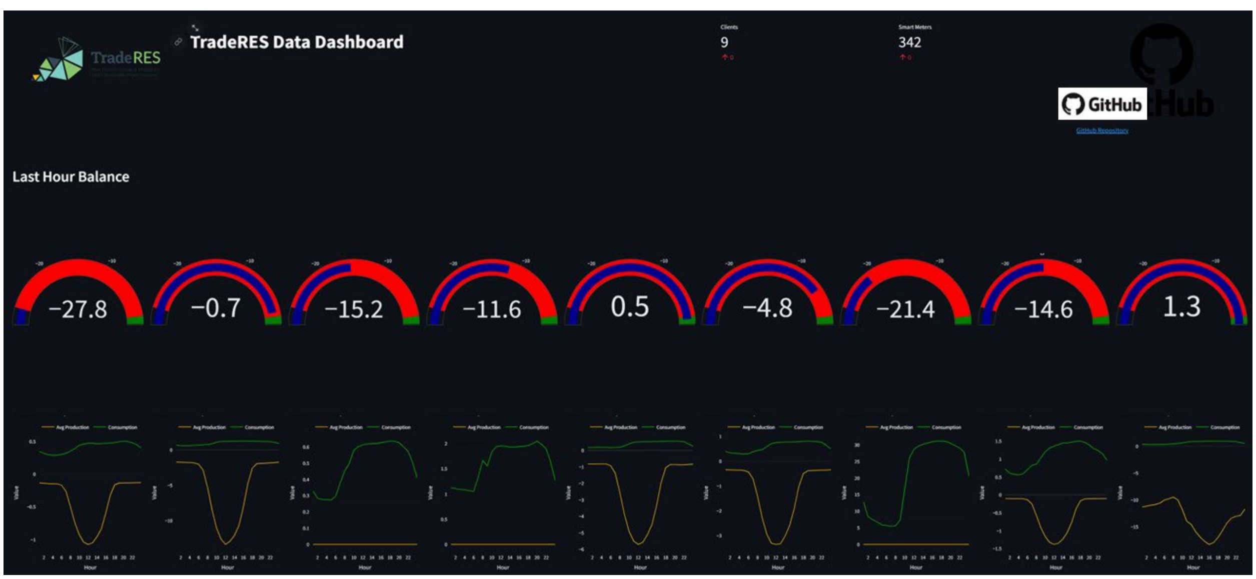


Figure 12: Screenshot of the blockchain based energy data dashboard, showing both last hours balance, and the consumption and production over the last day

The TradeRES EU Blockchain Project demonstrates how blockchain can streamline energy transactions, making energy markets more robust and efficient for Local Energy Communities.

This case study supports the broader TradeRES project's goal of advancing energy system performance through innovative technology.

4.2.1.1. Blockchain Portal Setup

The TradeRES-BC-Portal is structured to facilitate secure and efficient energy trading using blockchain technology. The main structure of the solution is the following:

1. Smart Contracts:

- **EnergyToken:**
- An ERC-20 compliant token representing energy units.
- Represents energy as tradable tokens.
- Implements standard functions such as transfer, approve, transferFrom, etc.

```
pragma solidity ^0.8.0;
import "@openzeppelin/contracts/token/ERC20/ERC20.sol";

contract EnergyToken is ERC20 {
    constructor(uint256 initialSupply) ERC20("EnergyToken", "ETK") {
        _mint(msg.sender, initialSupply);
    }
}
```

Figure 13: Code for the EnergyToken

- **EnergyExchange:**
- Manages energy production, consumption, and trading.
- Integrates with EnergyToken for token transfers and records transactions on the blockchain.

```
pragma solidity ^0.8.0;
import "./EnergyToken.sol";

contract EnergyExchange {
    EnergyToken private token;

    constructor(address tokenAddress) {
        token = EnergyToken(tokenAddress);
    }

    function produceEnergy(uint256 amount) public {
        token.transferFrom(msg.sender, address(this), amount);
        // Logic to handle energy production
    }

    function consumeEnergy(uint256 amount) public {
        token.transfer(msg.sender, amount);
        // Logic to handle energy consumption
    }
```

Figure 14: Code for the EnergyExchange Contract

2. Decentralization:

- **Transparency and Security**:
  - All transactions (production, consumption, and trading of energy tokens) are recorded on the Ethereum blockchain.
  - This ensures an immutable and transparent ledger, preventing fraud and ensuring trust among participants.

3. Deployment:

- The smart contracts are deployed on the Ethereum network, leveraging its decentralized nature.
- Users interact with the contracts through a web interface or directly via Ethereum wallets.

The case study shows that by using real data from a local energy market in Portugal, Energy can be traded in a decentralised manner using an Ethereum-based blockchain solution. The code for the solution is available at GitHub and can therefore be further developed by other stakeholders.

4.2.2. Multilevel Electricity Trading considering LECs Wholesale participation

The present case study proposes a multilevel electricity trading framework from LECs to wholesale EM. The study considers ten LECs with local RES-based generation. Each LEC runs its day-ahead internal community trading attempting to satisfy the local demand. Different LECs using distinct trading mechanisms are considered. Such mechanisms are the Centralized P2P Electricity Sharing Optimization (see 3.3.4) and the Competitive Strategic Bidding in Local Markets (see 3.3.5) methodologies. After the local-wide transactions have been set, LECs trade electricity among each other to sell their surplus or buy faulty demand on an aggregation-wide trading. For such, the P2P Discriminatory Price Auction (see 3.3.6) methodology is used by a LEC's aggregator, acting as a LEC's market operator. With the remaining demand and supply, the LEC's aggregator participates in the wholesale EM (see 3.3.7) aiming to trade electricity at most interesting prices to their aggregates. After the wholesale day-ahead market clearing and the results being sent to the LECs, each community is able to adjust the daily program according to new forecasts or to try avoiding the need to buy extra electricity from the retailer. To this end, the Optimal Local Flexible Consumption (see 3.3.8) methodology is selected.

Figure 15 illustrates the proposed multilevel trading framework for local communities' electricity trading, comprising three negotiation levels as follows:

i. Local-wide level – internal trading within a LEC.
ii. Aggregation-wide level – trading among multiple LECs.
iii. Wholesale-wide level – trading in the wholesale market.

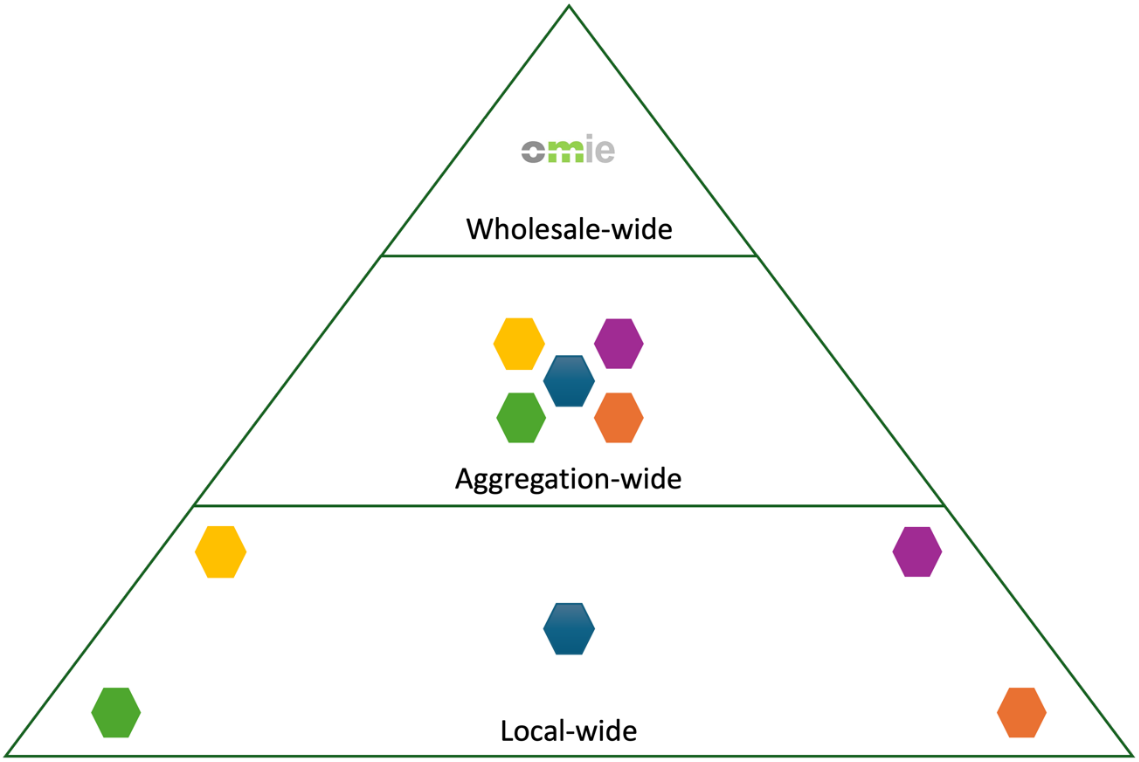


Figure 15: Multilevel electricity trading simulation framework.

The first negotiation level, i.e., the local-wide trading, represents the typical LEMs where the consumers and prosumers trade electricity with their neighbours, composing a LEC. For this level, the methodologies Centralized P2P Electricity Transactions Optimization and the Competitive Strategic Bidding in Local Markets were selected for different LECs. In the Centralized P2P Electricity Sharing Optimization (see 3.3.4) the LEC manager runs a centralized optimization model to improve the community's energy efficiency while reducing its customers' electricity bills. Using the Competitive Strategic Bidding in Local Markets (see 3.3.5), in turn, each consumer and prosumer run a learning optimization model to strategically determine their bid prices and energy volumes according to the market response. Both methodologies are executed as day-ahead models.

Using the untraded demand and supply of the local-wide negotiation, each LEC manager submits bids to an aggregator of LECs in the aggregation-wide trading level. The aggregation-wide trading level provides a platform where multiple LECs trade electricity among them, thus, consumers and prosumers from different LECs are able to trade their demand and supply surplus between each other. For this level, the methodology P2P Discriminatory Price Auction (see 3.3.6) was selected for electricity trading between the aggregated LECs. The LECs aggregator runs this pay-as-bid model on a daily basis for the next day and trading prices are determined by the average of the prices of the bids matched. At this level, consumers aim to avoid buying electricity from the retailer at higher prices while prosumers try to sell their surplus electricity at higher prices than the feed-in tariff. Moreover, by participating in the aggregation-wide trading level, consumers and prosumers realize that the untraded energy volume will be submitted for trading in the wholesale day-ahead market, i.e., the wholesale-wide trading level.

In the wholesale-wide negotiation, the LECs aggregator utilises the untraded energy volume to participate in the Iberian wholesale day-ahead market (see 3.3.7), aiming to trade electricity at the best possible prices. To participate in OMIE's wholesale market, the aggregator must ensure a minimum energy volume per hour, otherwise he will not be able to trade in the wholesale-wide level in those hours, enforcing its aggregated consumers and prosumers to buy electricity from the retailer at higher prices and sell it to the grid at the feed-in tariff.

After wholesale clearing, each LEC manager can still adjust the community's energy consumption in a demand flexibility event. Thus, the demand flexibility trading is also at the local-wide trading level. The consumers and prosumers participation in these events is voluntary. The community's manager announces the event and respective features, such as, e.g., the energy amount to curtail at a specific period of time and the price incentive paid per kWh. Each consumer and prosumer decide if it is interested in participating or not in the demand flexibility event according to its needs, always having in mind the goal to reduce the electricity bill at the end of the month. The demand flexibility trading uses the Optimal Local Flexible Consumption (see 3.3.8) methodology. Furthermore, it's imperative to highlight that our analysis is based on comprehensive data spanning one month, ensuring a holistic understanding of the communities' energy ecosystems.

4.2.2.1. LECs characterization

This subsection presents the different LECs considered for the present case study scenario. It starts by introducing the five LECs that are considering the Centralized P2P Electricity Sharing Optimization methodology for internal electricity trading. After, the three LECs using the Competitive Strategic Bidding in Local Markets for internal negotiation are presented. Finally, two extra LECs composed of PV generation, aiming to profit from LEMs, are introduced. Since the profile of these two last LECs is only PV-based, they do not participate in the local-wide trading level.

When participating in the aggregation-wide negotiation, the ten communities are aggregated by the same LECs aggregator who, besides managing the aggregation-wide trading, also participates on the Iberian day-ahead market (i.e., the wholesale-wide trading) on behalf of the aggregated communities with the untraded demand and supply of the aggregation-wide negotiation. For the wholesale-wide simulation, OMIE's real data has been gathered for March 2023, being the aggregator's bids included after for simulating the present case study scenario.

To conclude, the demand flexibility trading also occurs internally for each LEC, being managed by the respective LEC manager. To this end, each manager requests the community consumers and prosumers for demand flexibility to adjust (some of) the day-ahead untraded volume and unforeseen consumption revealed by closer to real-time forecasts.

LECs using the Centralized P2P Electricity Sharing Optimization methodology

Using the Centralized P2P Electricity Sharing Optimization methodology it is possible to simulate multiple variants of a LEC considering the available resources. The five LECs data were generated based on real data given five different energy profiles according to the resources selected for each community. Table 6 presents the characterization of each LEC using the Centralized P2P Electricity Sharing Optimization methodology for their internal electricity trading.

Table 6: Characterisation of LECs using the Centralised P2P Electricity Sharing Optimization methodology.

LEC#	Consumers	Prosumers (PV)	Batteries	EVs	Tariff
LEC1	39	61	43	200	Triple
LEC2	39	61	43	0	Triple
LEC3	39	61	0	200	Triple
LEC4	39	61	0	0	Triple
LEC5	39	61	43	100	Triple

Analysing Table 6, it is possible to confirm that the number of consumers and prosumers is the same for each of the five communities, 39 consumers and 61 prosumers, totalizing 100 participants per LEC. As previously stated, the difference between these five LECs is in the number of resources each comprises. It must be noticed that for all of these five LECs, prosumers are PV-based only.

LEC1 is the most complete, including 43 prosumers with residential batteries installed and two EVs per consumer and prosumer, in a total of 200 electric vehicles (EVs). LEC2 is a version of LEC1 where there are no EVs at all, while LEC3 is a version of LEC1 without any battery; only EVs. LEC4 is the simplest community, where no batteries nor EVs are included. Finally, LEC5 is similar to LEC1 but considering only one EV per community player, thus, a total of 100 EVs.

All LEC participants contract a triple tariff to their retailer. A triple tariff, or three-hourly tariff, comprises three consumption periods per day with different prices, where the cost of electricity directly depends on the time it is being used. It includes Peak hours, Off-peak hours, and Middle hours. Peak hours represent the hours of the day when electricity demand is usually higher, thus, more expensive. Off-peak hours, on the other hand, are the hours of the day when electricity demand is usually lower, and therefore, less expensive. Middle hours are the hours in between Peak and Off-peak hours, when electricity demand is at an average level at an average price. Regarding the sale of electricity to the grid, there is a static national feed-in tariff for all periods of the day, being set at 0.045 EUR/kWh. Figure 16 presents the triple tariff daily profile and the feed-in tariff.

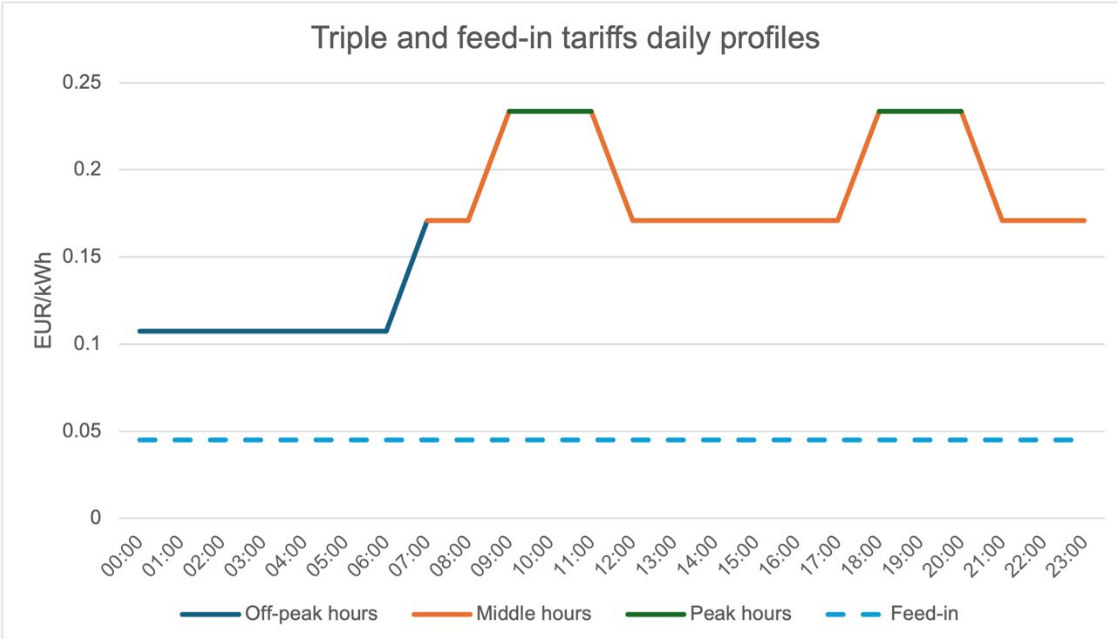


Figure 16: Triple tariff daily profile.

The triple tariff contracted by the participating players of LEC1 to LEC5 sets the Off-peak hours price at 0.1073 EUR/kWh from 0:00 to 6:00, the Peak hours price at 0.2336 EUR/kWh, and the Middle hours price at 0.171 EUR/kWh. Again, the feed-in tariff is set at 0.045 EUR/kWh. When participating in the aggregation-wide trading level, each LEC manager will submit bid prices for each trading period in between the feed-in and the retailer's tariff.

LECs using the Competitive Strategic Bidding in Local Markets methodology

Similarly to the previous approach, the LECs using the Competitive Strategic Bidding in Local Markets methodology were generated from real data, being the only variation among them the retailer's tariff. Table 7 presents the characterization of the LECs using the Competitive Strategic Bidding in Local Markets methodology for electricity trading within the community.

Table 7: Characterization of LECs using the Competitive Strategic Bidding in Local Markets methodology.

LEC#	Consumers	Prosumers (PV)	CHP	EVs	Tariff
LEC6	13	42	6	29	Flat
LEC7	13	42	6	29	Double
LEC8	13	42	6	29	Triple

Analysing Table 7, it can be seen that all LECs have the same number of consumers, prosumers, and respective resources. Each LEC comprises 13 consumers and 42 prosumers. All prosumers include PV-based generation. From these, 6 prosumers also have small capacity

(10kW) combined heat and power (CHP) units, and 29 prosumers have EVs, further enhancing the complexity and dynamics of the community's energy landscape. The main difference among these LECs is the retailer's tariff, a parameter shaping bid prices within the local energy market. The contracted tariff is an important parameter to consider since it bounds the bid prices submitted by the LECs' participants to the local-wide LEM.

The players of LEC6 contract a flat, or simple, tariff where the electricity price is constant regardless of the time and day of the week. The participants of LEC7, in turn, contract a double, or bi-hourly, tariff. In this case, the daily consumption is divided in two periods, i.e., the Peak hours and the Off-peak hours. Finally, LEC8 players use a triple tariff, likewise the previously explained for LEC1 to LEC5. Concerning electricity supply to the grid, the same national static feed-in tariff is considered, i.e., 0.045 EUR/kWh. Figure 17 illustrates the daily profiles of the tariffs contracted by each LEC and the feed-in tariff.

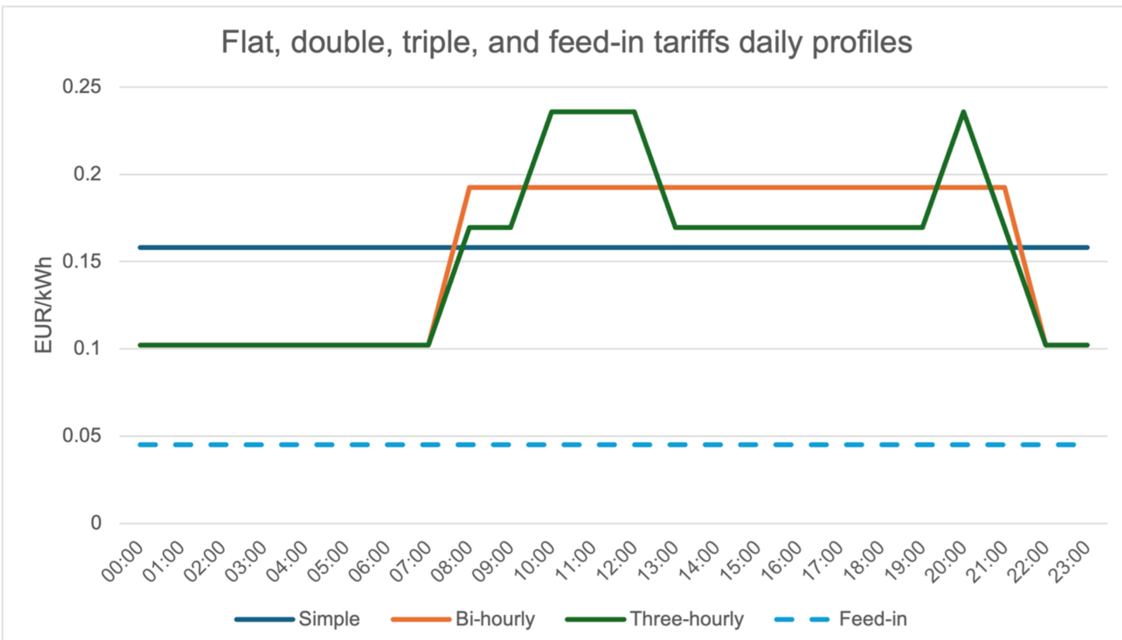


Figure 17: Flat, double, triple, and feed-in tariffs daily profiles.

The flat tariff contracted by the elements of LEC6 is set at 0.158 EUR/kWh. The double tariff of the players of LEC7 sets the Off-peak hours price from 0:00 to 7:00 and from 22:00 to 23:00 at 0.1023 EUR/kWh, and the Peak hours price from 8:00 to 21:00 at 0.1924 EUR/kWh. The triple tariff contracted by the participants of LEC8, in turn, sets the Off-peak hours from 0:00 to 7:00 and from 22:00 to 23:00 at 0.1023 EUR/kWh, the Peak hours from 10:00 to 12:00 and the hour 20:00 at 0.2358 EUR/kWh, and the Middle hours from 8:00 to 9:00, from 13:00 to 19:00, and the hour 21:00 at the price 0.1696 EUR/kWh. Being the feed-in tariff set at 0.045 EUR/kWh, the players of each community will submit bid prices within this value and their retailer's tariff for each trading period of the local-wide electricity trading.

PV-based LECs

Using distinct PV-based generation profiles, two extra LECs were generated with the goal of including different types of LECs into the aggregation-wide trading level, where all LECs benefit from trading at this level instead of fully buying or selling from the grid. Being PV-based, both LECs are very similar due to the inherent solar hours. Figure 8 shows the daily generation profiles of the PV-based LECs.

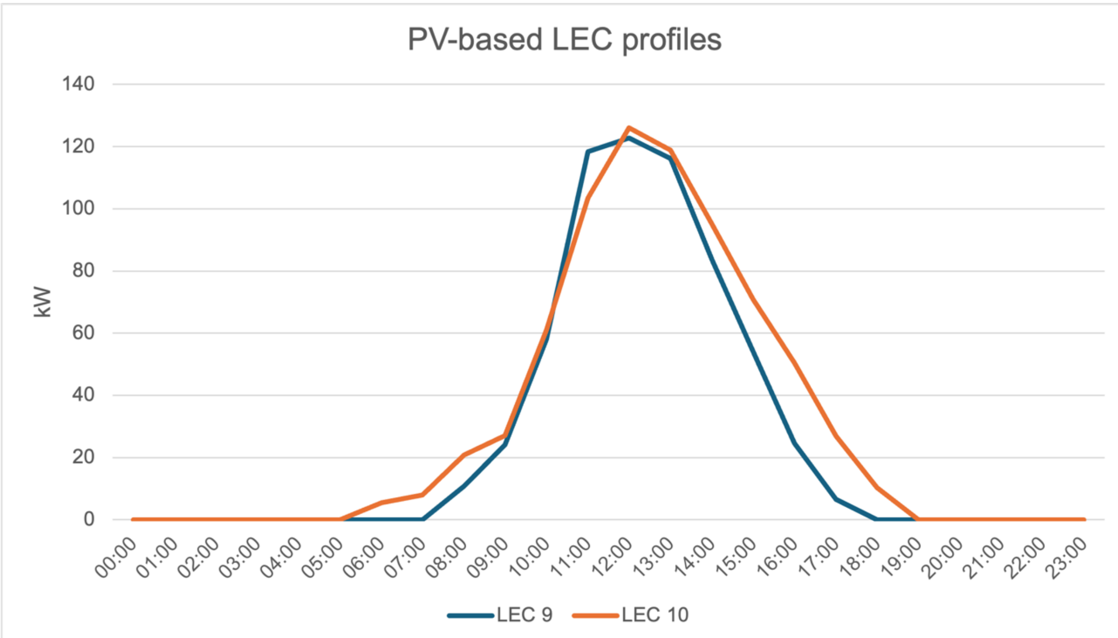


Figure 18: PV-based LEC generation profiles.

According to Figure 18, the peak of PV generation is registered around mid-day, being the peak power of LEC9 at 122.8 kW, and of LEC10 at 125.99 kW. The main goal of both LECs is to preferentially sell electricity to other LECs through the aggregation-wide trading level or else sell it on the wholesale market via aggregation, since selling it to the grid is less advantageous. Again, the feed-in tariff paid for injecting supply in the grid is set at 0.045 EUR/kWh. Thus, these LECs will bid above these values aiming to profit the best possible from the aggregation-wide and whole-sale-wide trading levels.

4.2.3. Large agent-based LEC with cooperative self-consumption

This work focuses on a single large LEC with 312 Portuguese local customers assuming its formation in 2019, [53] provides additional consumer details. This community competes directly with the tariffs offered by regulatory bodies and retailers. These customers are linked to the 30 kV medium-voltage grid, indicating that some of them belong to groups of residential and small business consumers (see crosses in Figure 19 for the location of substations they are connected to). By employing the K-means clustering technique alongside the Calinski–Harabasz criterion, these consumers can be categorized into five distinct consumption segments: 10 industrial, 11 large commercial, 189 small commercial groupings, 71 residential groupings, and 31 other groupings with all or part of the previous segments.

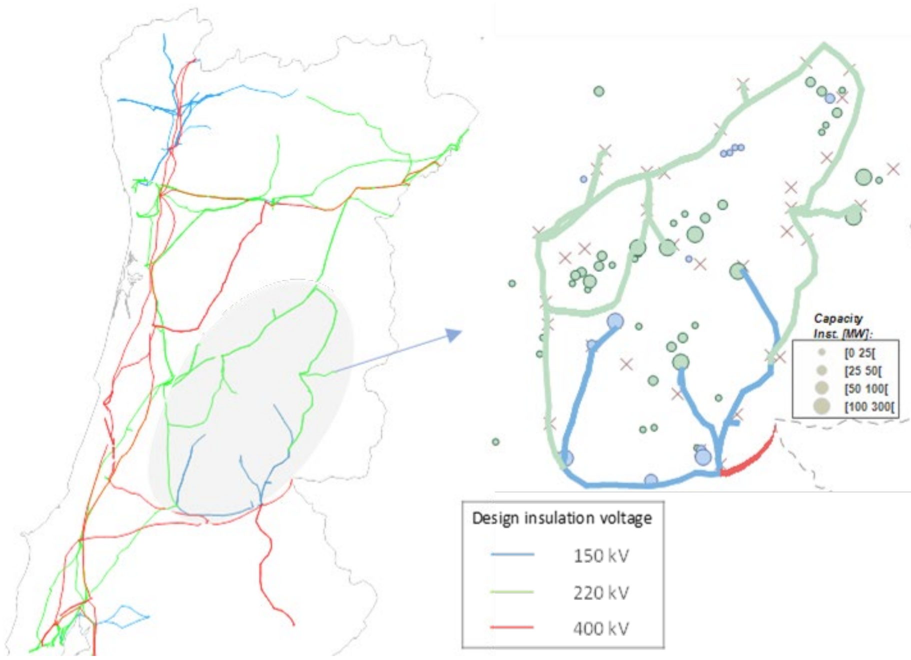


Figure 19: Location and capacity of the transmission lines, the distribution substations where consumers are connected to (crosses), the hydro (blue circles) and wind power plants (green circles) before investing in solar PV.

Actual consumption data from January 1, 2012, to December 31, 2013, was utilized and projected to 2018 and 2019 using multivariate time series (MTS) forecasts as detailed in [20, 49]. This study considers the active participation of the LEC in the day-ahead and continuous intraday markets, paying penalties for its deviations. Additionally, market prices from MIBEL and the most existing competitive tariffs proposed by Portuguese regulatory bodies and retailers in 2019, are considered as presented in Table 8.

Table 8: Tariff prices in 2019 excluding VAT.

Tariffs	Fixed Energy Price (€/MWh)	Indexed Energy Price (EUR/MWh)	Risk Premium and Commission
TOU	{106.15; 101.35; 87.95; 83.65}	No	No
DAHP	Other fees	Hourly day-ahead	14 EUR/MWh
DAMP	Other fees	Monthly day-ahead	16.5 EUR/MWh
RTP	Other fees	Hourly day-ahead and balancing	20 EUR/MWh

This study consists of four different scenarios:

a) Baseline: Inflexible consumer behaviour in a LEC without self-consumption.
b) Inflexible: Inflexible consumer behaviour in a LEC that invests in cooperative self-consumption.
c) Best forecasts: improved renewable power forecast accuracy from Deliverable 4.9 ed. 2.
d) Flexible: the same as 3 considering a 10% flexibility of consumer's demand.

5. Results and performance assessment

This section presents the results on a case study basis to account for variations in outcomes based on the model, model level, and data used. Each case study provides insights into the performance of different market designs and trading mechanisms within Local Energy Communities (LECs).

The performance assessment relies on computing the Local Market Performance Indicators (LMPIs) for each case study. The LMPIs include six key metrics: Local Energy Neutrality, Nodal Consumption, Import-Export Ratio, Total Local Costs, Levelized Local Costs, and Local Autarky (self-sufficiency). Further elaboration on the LMPIs can be found in “Annex A - Local market performance indicators – LMPIs“ These indicators offer a comprehensive evaluation of the effectiveness and efficiency of the market designs in promoting energy self-sufficiency and cost savings within LECs.

The results will illustrate how different market models and levels impact these performance indicators, providing an understanding of the benefits and challenges associated with each approach. By presenting the results in this structured manner, we aim to highlight the specific conditions under which each market design performs best, thereby guiding future implementations and policy decisions.

5.1 Multilevel Electricity Trading considering LECs Wholesale participation

This section presents the results of the proposed multilevel electricity trading framework considering LECs wholesale participation. The present section comprises a subsection per selected model attending the framework’s workflow. It culminates with the final remarks highlighting the main results of the framework.

5.1.1. Centralized P2P Electricity Sharing Optimization

Using the Centralized P2P Electricity Sharing Optimization model (see 3.3.4), a simulation was run considering the communities from LEC1 to LEC5 for the month of March 2023. Table 9 presents a comprehensive analysis of electricity transactions (in kWh) among the different LECs under the Centralized P2P Electricity Sharing Optimization, comparing scenarios with and without P2P transactions, over March 2023.

Table 9: LECs comparison of electricity transactions with and without the Centralized P2P Electricity Sharing Optimization (kWh).

Scenario		LEC1	LEC2	LEC3	LEC4	LEC5
Baseline	**Buy retailer [kWh]**	109 043.05	58 163.73	109 339.96	63 572.23	84 905.76
	Sell grid [kWh]	252.95	5 508.12	549.87	10 916.63	897.06
Centralized P2P Electricity Sharing Optimization	**Buy P2P [kWh]**	19 797.07	21 259.17	10 492.01	10 263.47	20 804.48
	Sell P2P [kWh]	19 797.07	21 259.17	10 492.01	10 263.47	20 804.48
	Buy retailer [kWh]	108 790.09	52 655.60	108 790.09	53 308.75	84 008.69
	Sell retailer [kWh]	0.00	0.00	0.00	653.15	0.00

LEC1, with a substantial number of prosumers (61) and EVs (200), demonstrates a high potential for energy storage. In scenarios without P2P transactions, LEC1 relies primarily on imports from the retailer. However, the integration of P2P transactions enables LEC1 to reduce its reliance on external suppliers and foster direct energy exchanges among community members, showcasing a shift towards self-sufficiency and optimized energy utilization.

LEC2 features a significant number of prosumers (61), indicating a considerable capacity for energy generation. However, unlike LEC1, LEC2 does not have EVs. In scenarios without P2P transactions, LEC2 relies on imports from the retailer for its electricity needs. With the introduction of P2P transactions, LEC2 facilitates direct energy sharing among its members.

LEC3 has a substantial number of consumers (39) and EVs (200), indicating a considerable electricity demand and potential for electricity surplus through renewable sources. In scenarios without P2P transactions, LEC3 relies on imports from the retailer to meet its energy demand. However, the integration of P2P transactions presents an opportunity for LEC3 to optimize energy distribution within the community, reducing dependence on external suppliers and enhancing energy self-sufficiency.

LEC4 presents a balanced constitution of consumers (39) and prosumers (61). However, unlike LEC1 and LEC3, LEC4 does not include EVs in its setup. In scenarios without P2P transactions, LEC4 relies on imports from the retailer and exports to the grid to manage its energy balance. With the introduction of P2P transactions, LEC 4 can potentially leverage its diverse energy assets more efficiently, minimizing reliance on external suppliers and optimizing energy utilization within the community.

Finally, LEC5 has a similar composition to LEC1, with a substantial number of prosumers (61) and EVs (100). In scenarios without P2P transactions, LEC5 relies on imports from the retailer and exports to the grid to meet its energy requirements. However, the integration of P2P transactions presents an opportunity for LEC5 to further optimize its energy distribution and storage, fostering greater energy resilience and sustainability within the community.

Table 10 presents a comparison between the costs of fully buying electricity from the retailer and sell surplus to the grid and trading electricity within the Centralized P2P Sharing Optimization.

Table 10: Comparison of electricity costs with and without the Centralized P2P Electricity Sharing Optimization (EUR).

Scenario		LEC1	LEC2	LEC3	LEC4	LEC5	Cost [EUR]
Baseline	**Buy retailer [EUR]**	15 155.90	9 696.55	16 206.25	11 295.20	12 565.97	64 104.26
	Sell grid [EUR]	- 11.38	- 247.87	- 24.74	- 491.25	- 40.37	
Centralized P2P Electricity Sharing Optimization	**Buy P2P [EUR]**	0.00	0.00	0.00	0.00	0.00	56 873.65
	Sell P2P [EUR]	0.00	0.00	0.00	0.00	0.00	
	Buy retailer [EUR]	13 620.72	7 598.11	15 337.86	9 384.67	10 961.68	
	Sell grid [EUR]	0.00	0.00	0.00	- 29.39	0.00	
Cost reduction (%)		10.06 %	19.59 %	5.21 %	13.14 %	12.49 %	11.28 %

Table 10 provides a comparative analysis of electricity costs with and without P2P transactions within each LEC, focusing on the economic outcomes. In general, the integration of P2P transactions results in adjustments to the economic dynamics within the several LECs members, leading to final costs reduction although in this model the surplus of local generation being shared among the elements of each community. However, the economic performance shift is influenced by multiple factors, such as changes in the electricity exchange patterns facilitated by the local P2P transactions.

Analysing the costs reduction of each LEC, LEC2 was the community with the most significant gains, namely a reduction of 19.59 % in the overall electricity costs. In turn, LEC3 only reduced the overall energy bills of their players in 5.21 %. LEC2 includes batteries and no EVs, while LEC3 includes 2 EVs per player and no batteries. The use of batteries improves the results of the optimization model since prosumers are able to save PV generation surplus energy for the hours when the consumption tariff is higher and during the night hours. The use of EVs, in turn, degrades the results since in the sunny hours the EVs are not at home to recharge, but instead they charge at night to leverage from the Off-peak tariff. The overall gain of the five LECs was of 11.28 % in March 2023.

5.1.2. Competitive Strategic Bidding in Local Markets

The Competitive Strategic Bidding in Local Markets model (see 3.3.5) offers a framework for optimizing the strategic bidding strategies in a LEC, which notably includes EVs and several small capacity (10kW) CHP units. Following the implementation and simulation of the model, experiments were conducted to analyse strategic bidding strategies within the various communities. Subsequently, Table 9 provides a comprehensive analysis of electricity transactions (in kWh) among the different LECs under the Competitive Strategic Bidding in Local Markets, comparing scenarios with and without LEM transactions, over March 2023.

Table 11: LECs comparison of electricity transactions with and without the Competitive Strategic Bidding in Local Markets (kWh).

Scenario		LEC6	LEC7	LEC8
Baseline	**Buy retailer [kWh]**	76 206.98	82 834.24	84 052.12
	Sell grid [kWh]	0.00	0.00	0.00
Competitive Strategic Bidding in Local Markets	**Buy LEM [kWh]**	10 993.30	7 972.61	7 592.10
	Sell LEM [kWh]	10 993.30	7 972.61	7 592.10
	Buy retailer [kWh]	65 213.67	74 861.63	76 460.02
	Sell retailer [kWh]	0.00	0.00	0.00

Table 11 presents the total energy demand and supply volumes for each LEC under the baseline scenario – i.e., the business-as-usual (BaU) where each player buys electricity from retailer and sell generation surplus to the grid – and the Competitive Strategic Bidding in Local Markets LEM scenario. Analysing the results on Table 11, it can be seen that LEC6 is the community with higher traded energy volume, while LEC7 and LEC8 have very similar results.

Table 12 presents a comparative analysis of the cost reductions achieved through energy trading within each community for the whole month.

Table 12: Comparison of electricity costs with and without the Competitive Strategic Bidding in Local Markets (EUR).

Scenario		LEC6	LEC7	LEC8	Cost [EUR]
Baseline	**Buy retailer [EUR]**	12 040.70	12 357.12	11 990.64	36 388.46
	Sell grid [EUR]	0.00	0.00	0.00	
Competitive Strategic Bidding in Local Markets	**Buy P2P [EUR]**	1 643.65	1 368.90	1 263.38	31 674.98
	Sell P2P [EUR]	- 1 643.65	- 1 368.90	- 1 263.38	
	Buy retailer [EUR]	10 303.76	10 823.19	10 548.03	
	Sell grid [EUR]	0.00	0.00	0.00	
Cost reduction (%)		14.43 %	12.41 %	12.03 %	12.95 %

Table 12 shows a comparison between the costs of the baseline scenario, i.e., BaU, and the costs after the Competitive Strategic Bidding in Local Markets scenario, highlighting the percentage of cost reduction for each LEC and the overall percentage of cost reduction of all LECs as a whole as well, for March 2023. This evaluation sheds light on the efficacy of bidding approaches in optimizing cost savings and fostering energy exchange within the LECs.

Analysing each LEC's cost reduction, LEC6 is the community with the most significant improvements, namely a reduction of 14.43 % in the overall electric bill costs. LEC8, in turn, is the LEC that had the lowest cost reduction, but still a reduction of 12.03 % in the electricity costs of its aggregates. Given the communities resources and features, the main drivers for the cost reduction percentage values are the electricity tariffs. LEC6 participants assume a flat tariff throughout the day while the players of LEC7 and LEC8 contract a double and triple tariff, respectively. Besides, being the Competitive Strategic Bidding in Local Markets a competitive model, selling players try to maximize their profits while keeping prices below the consumers tariffs. In fact, the lower percentage of LEC7 and LEC8 in the costs reduction is due to the participation of small CHP units with a generation marginal cost higher than the off-peak double and triple tariffs, not trading within the community in those periods [27].

5.1.3. P2P Discriminatory Price Auction

Considering the import and export energy volume of each LEC at the local-wide trading models, an aggregation-wide trading is performed between LECs aiming to reduce the final consumers' electricity bill costs. To this end, the P2P Discriminatory Price Auction model (see 3.3.6) is used. At this level, the previously introduced LECs (LEC1-LEC8) are able to trade not only among each other, but also with other communities (LEC9-LEC10) participating in the aggregation-wide trading. Figure 20 presents the energy demand submitted by each LEC to the aggregation-wide trading on March 15th, 2023, per hour.

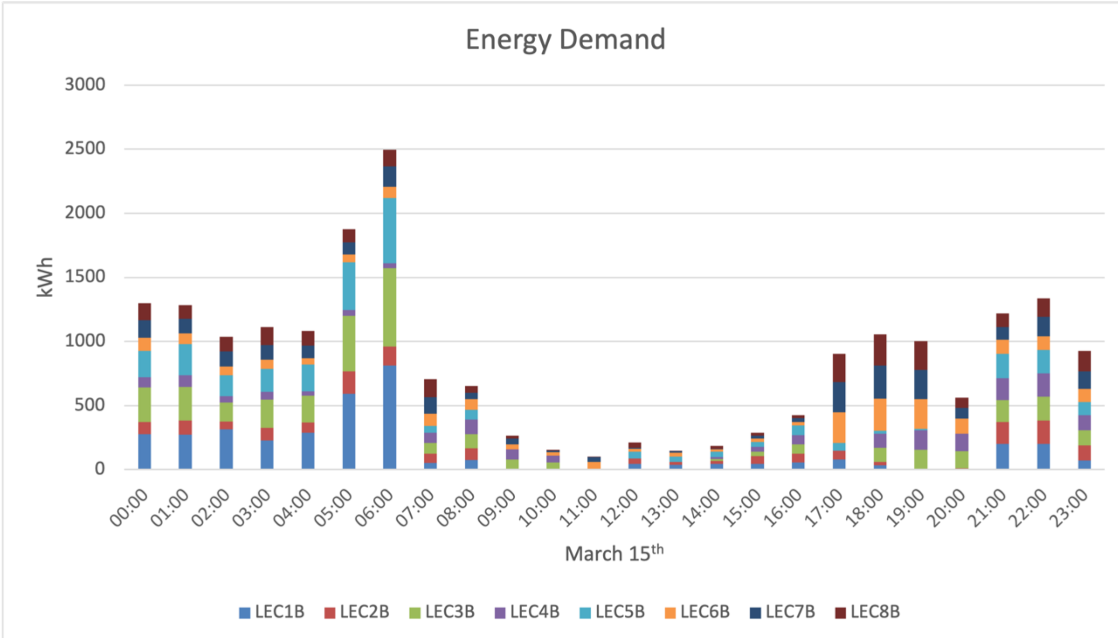


Figure 20: Energy demand submitted by each LEC on March 15th, 2023.

Analysing Figure 20 it is clear that the sunny hours, from 7:00 to 17:00, are the hours with less demand after the local-wide trading. In turn, the first hours of the day, from 0:00 until 6:00, are the hours with higher demand since in the local-wide trading the LECs were not able to trade a significant amount of energy in these hours. Figure 21 presents the energy supply submitted by each LEC to the aggregation-wide trading on March 15th, 2023, per hour.

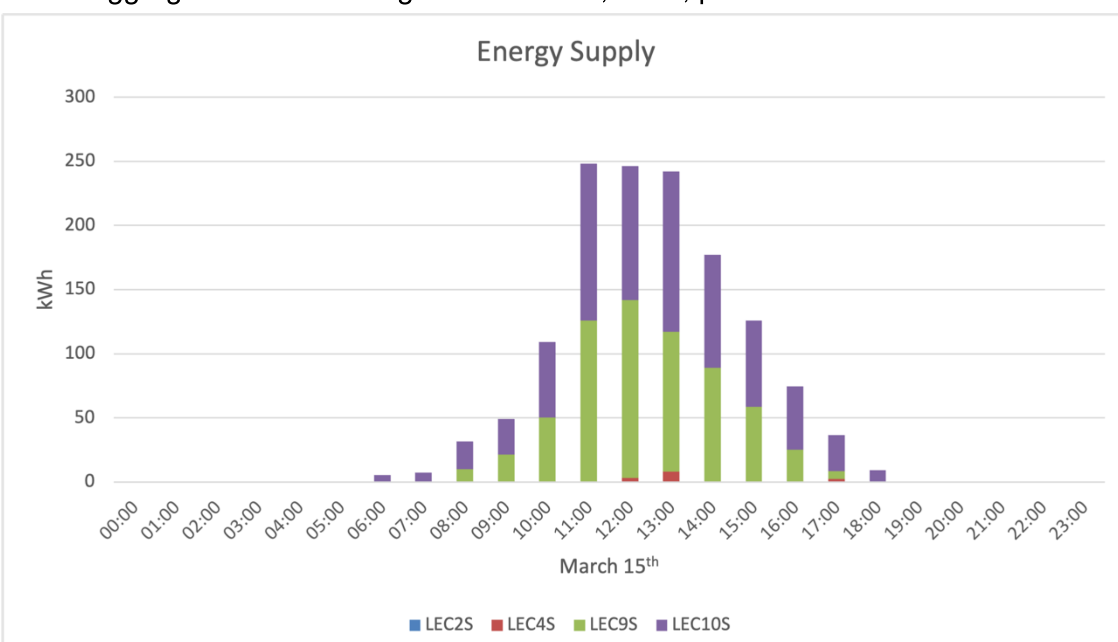


Figure 21: Energy supply submitted by each LEC on March 15th, 2023.

From Figure 21 it can be seen that the PV-based LECs 9 and 10 present bids with the most significant amount of generation, as expected. Nevertheless, LECs 2 and 4 also submit selling bids to the aggregation-wide level trading. Being these communities' generation based on PV generation, there's only available energy to sell during sunny hours.

Bid prices of each LEC are determined according to the retailer and feed-in tariffs of their consumers and prosumers. Each LEC's bid price is within the exclusive interval feed-in tariff; retailer tariff to ensure that if their consumers are buying, they are buying at a lower price than the retailer's price and if prosumers are selling, they are selling at a higher price than the feed-in tariff remuneration. Figure 22 presents the demand bid prices submitted in the aggregation-wide trading of March 15th, 2023.

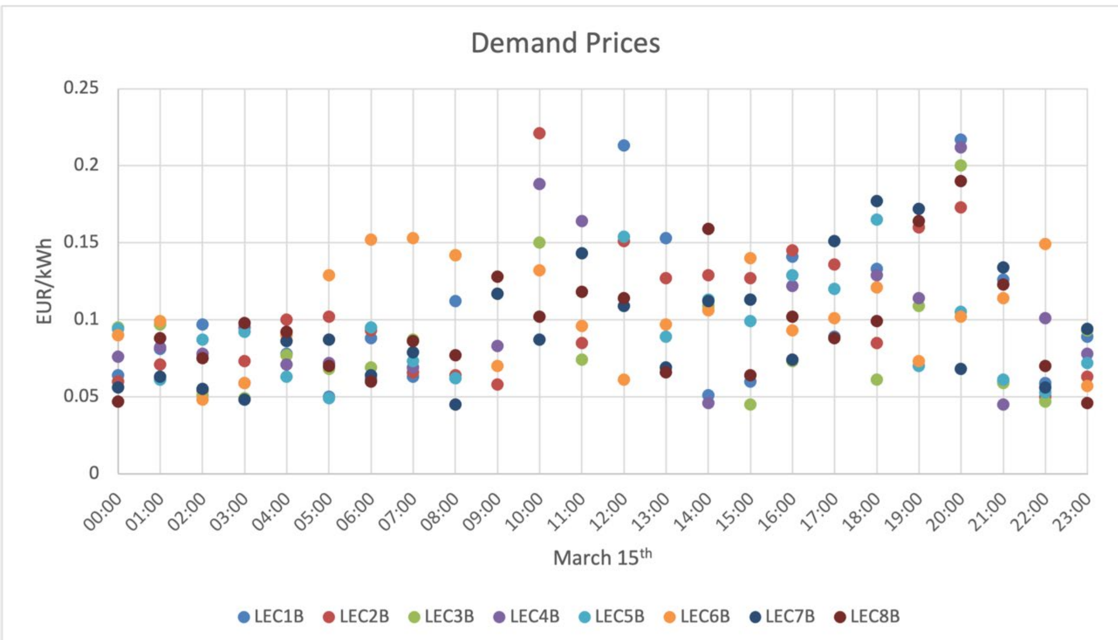


Figure 22: Demand bid prices submitted by each LEC on March 15th, 2023.

Observing Figure 22 it is perceptible that the hours with higher demand prices are 10:00, 13:00, and 20:00. These hours are also in the group of the most expensive for consumers with a triple tariff. Figure 23, in turn, illustrates the supply bid prices submitted for trading in the aggregation-wide level of March 15th, 2023.

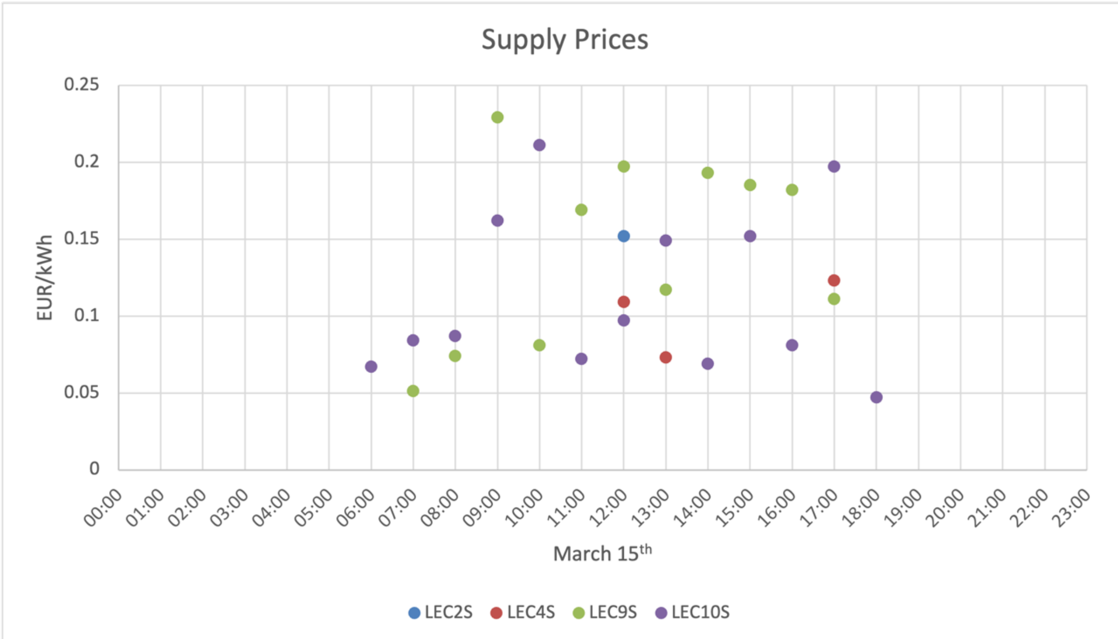


Figure 23: Supply bid prices submitted by each LEC on March 15th, 2023.

As it can be seen in Figure 23, there are only selling bids for the hourly periods between 6:00 and 18:00, as expected. Being PV-based prosumers and producers, these players are only able to generate and trade electrical energy during sunny hours. Besides, LECs 9 and 10, being PV parks, submit high prices (close to the retailer's cost) strategically trying to increase their profits. Finally, LEC 2 only submits one bid in the hour 12:00 while LEC 4 submits bids in the 12:00 and 13:00 hours.

From the input data analysis, it is perceptible that there will only be trading in the sunny hours due to the available supply for the aggregation-wide level being PV-based. Thus, meaning that at least the demand submitted in the remaining periods will be submitted for trading in the wholesale-wide trading through the OMIE's day-ahead market. Figure 24 presents the total traded volume per hour for March 15th, 2023. To ease readability, the results presented only include the sunny hours.

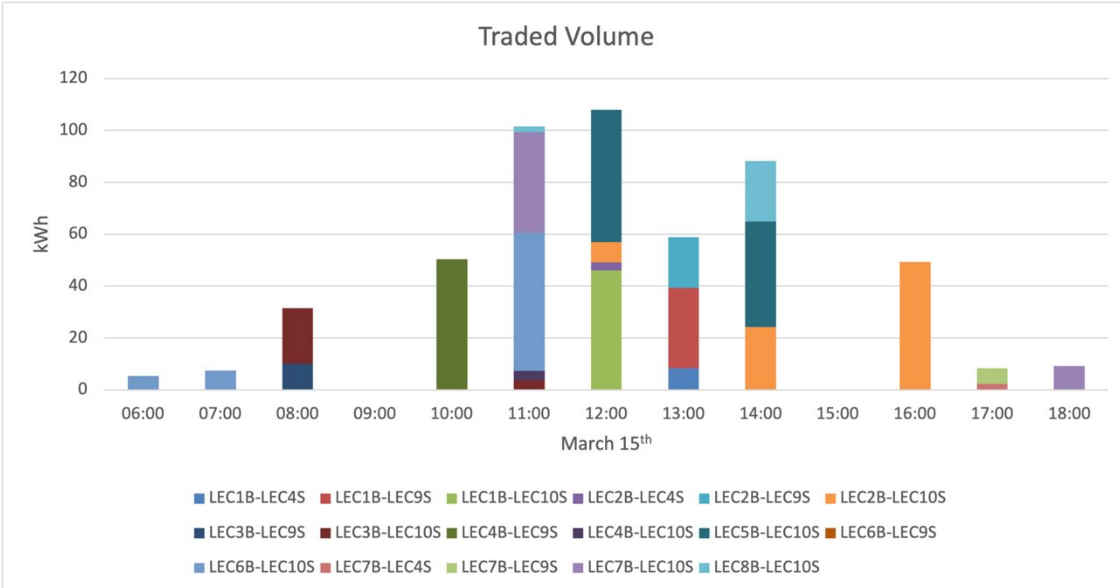


Figure 24: Aggregation-wide traded volume on March 15th, 2023.

Observing Figure 24, it is clear that there was no trading in the hours 9:00 and 15:00. Taking a closer look at Figure 22 and Figure 23, it is visible that the supply bid prices are all higher than the demand bid prices in both hours, explaining why there's no trading in any of them. Thus, this untraded volume is also available for the wholesale market. It should be noted that each colour identifies the trading volume between two specific LECs. This has to do with the fact that in the aggregation-wide trading the DPA model is being used. In this trading model there is no market clearing price, but instead each trade has its own price determined by the average between the demand and supply bid prices.

Figure 25 displays the aggregation-wide trading prices for March 15th, 2023.

Figure 25: Aggregation-wide trading prices on March 15th, 2023.

From Figure 25 it is also visible that there are no prices for the hours 9:00 and 15:00, confirming that there was no trading in these periods. Again, each colour identifies the trading prices between two specific LECs as for the trading volume previously presented.

Figure 26 shows the daily total traded electricity volume and the volume-weighted average price for March 2023.

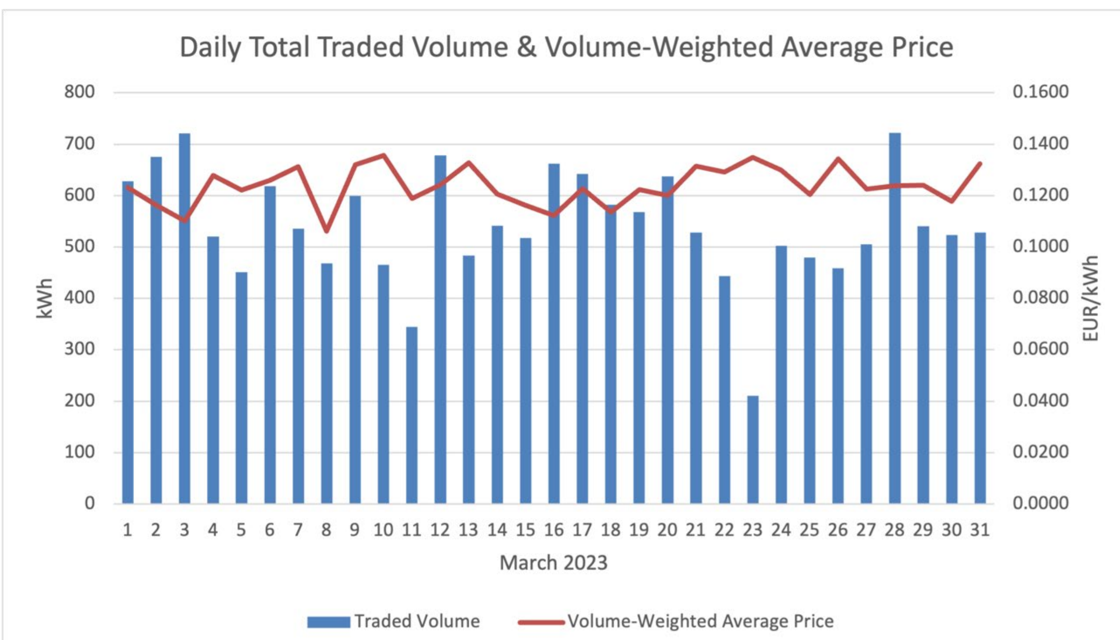


Figure 26: Aggregation-wide total traded volume and volume-weighted average price for March 2023.

Analysing Figure 26, the day with the lowest traded volume was March 23rd with a total traded volume of 210.751 kWh. In turn, March 3rd and March 28th where the days with highest traded volumes, i.e., 720.635 kWh and 722.129 kWh, respectively. Regarding the daily volume-weighted average price (VWAP), March 8th was the day with the lowest VWAP with 0.1063 EUR/kWh, and March 10th presented the highest VWAP at 0.1357 EUR/kWh. Finally, the monthly total traded volume in the aggregation-wide level was of 16.784 MWh and the VWAP of 0.1232 EUR/kWh.

Table 13 presents a comparison between the outcomes of participating in the local-wide trading scenario – i.e., buy untraded demand from the local-wide level at the retailer's tariff and sell the untraded supply at the feed-in tariff – and the outcomes after the participation in the aggregation-wide trading scenario.

Table 13: Local-wide and aggregation-wide results' comparison.

Scenario		**Costs/Profits [EUR]**	**Total [EUR]**	**Savings [EUR]**
Local-wide	**Buy retailer**	88 578.16	86 668.21	2 347.44
	Sell grid	- 1 909.95		
Aggregation-wide	**Buy aggregation-wide**	2 067.63	84 320.77	
	Sell aggregation-wide	- 2 067.63		
	Buy retailer	85 475.40		
	Sell retailer	- 1 154.63		
Cost reduction (%)				2.71 %

Observing Table 13, it can be seen that at the end of the month, the LECs were able to save an extra amount of 2 347.44 EUR in the aggregation-wide trading when comparing to only participating in the local-wide trading, i.e., proximally 2.71% extra savings. However, it should be noted that, due to the prosumers and electricity producers being PV-based, there is a significant amount of untraded energy in the hours without sun. Additionally, due to different LECs strategic bidding in the aggregation-wide trading, there's also some energy available in the sunny hours to trade.

Given the amount of untraded energy in the aggregation-wide LEM, LECs are able to participate in the wholesale-wide trading resorting to a virtual power player, who gathers energy volume from its aggregates to participate in the wholesale market on their behalf. The following subsection presents the outcomes of the LECs participation in OMIE's wholesale day-ahead market.

5.1.4. MASCEM: Iberian day-ahead market

To participate in the Iberian day-ahead market (see 3.3.7), the LECs' aggregator, named AGGLEC, considers the untraded demand and supply of the aggregation-wide trading while respecting the minimum allowed energy volume per hourly period. According to the recent EU's Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending

Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 [54], Article 19, paragraph 2 is amended as follows:

> *'2. To that end, Member States shall ensure that a guarantee of origin is issued in response to a request from a producer of energy from renewable sources, including gaseous renewable fuels of non-biological origin such as hydrogen, unless Member States decide, for the purposes of accounting for the market value of the guarantee of origin, not to issue such a guarantee of origin to a producer that receives financial support from a support scheme. Member States may arrange for guarantees of origin to be issued for energy from non-renewable sources. Issuance of guarantees of origin may be made subject to a minimum capacity limit. A guarantee of origin shall be of the standard size of 1 MWh. Where appropriate, such standard size may be divided to a fraction size, provided that the fraction is a multiple of 1 Wh. No more than one guarantee of origin shall be issued in respect of each unit of energy produced.'*

According to OMIE's publicly available data [33] the minimum bid volume on March 2023 was of 0.1 MWh.

Figure 27 illustrates the demand and supply energy volumes and prices per MWh submitted by AGGLEC to the wholesale market on March 15th, 2023.

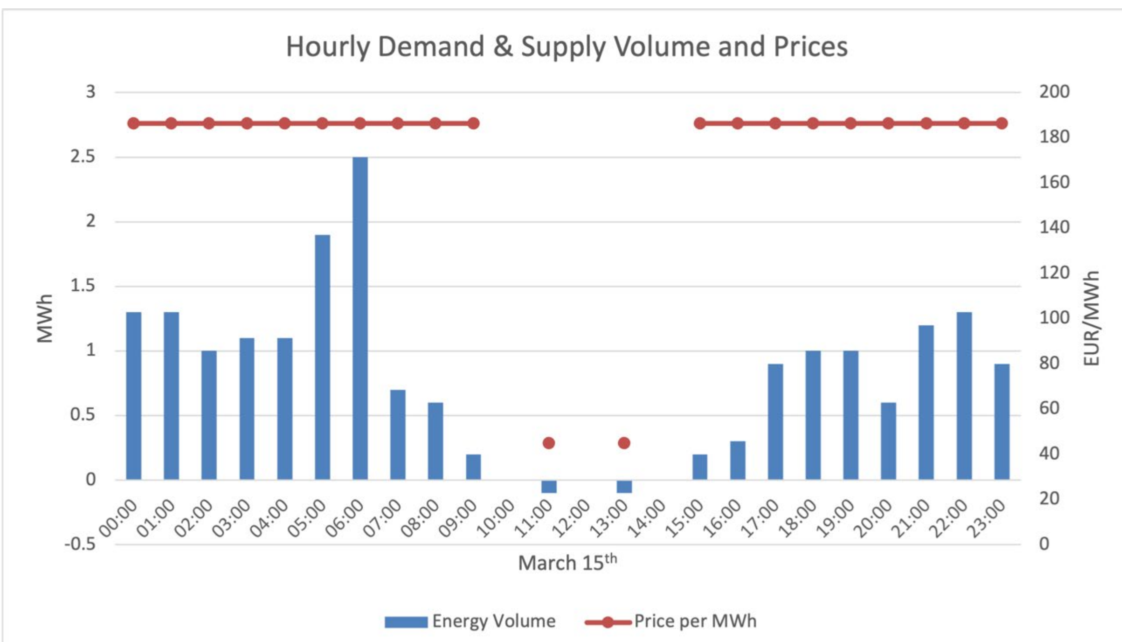


Figure 27: Hourly demand and supply energy volumes and prices per MWh.

Analysing Figure 27, it can be seen that there are no bids submitted in the hours 10:00, 12:00, and 14:00, meaning that there was no energy demand or supply to trade or that the difference between the demand and supply was below the minimum accepted energy volume, i.e., 0.1 MWh. Moreover, in the hours 11:00 and 13:00 the available supply for the wholesale market surpasses the demand. Please note that the supply volume is represented as a negative volume to ease the readers' understanding.

Regarding prices' definition, for supply bids AGGLEC defined the price equal to the sum of the feed-in tariff and a price increment of 0.1 EUR/MWh, i.e., 45.1 EUR/MWh. Bellow this value the LECs' prosumers are not interested to sell in the wholesale market. On the other hand, since LECs' consumers present different retailer tariffs, for demand bids the AGGLEC considered the different consumers' tariffs to compute a weighted price per MWh considering the demand capacity of each LEC, setting the unit price at 186.4 EUR/MWh.

Figure 28 illustrates the hourly traded and untraded energy volumes for March 15th, 2023.

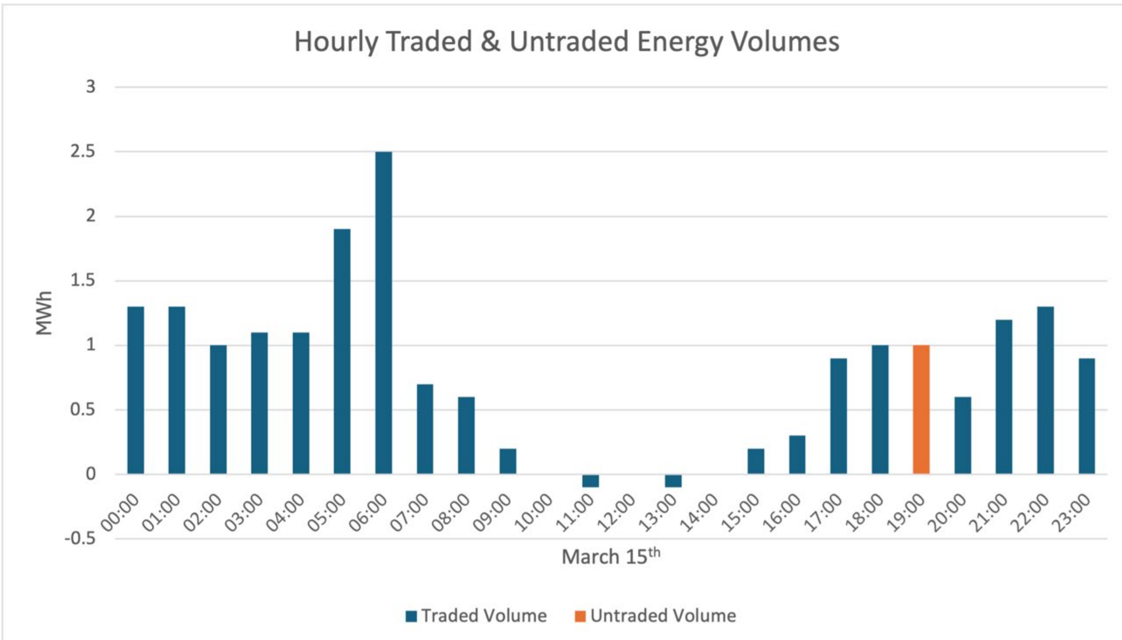


Figure 28: Hourly traded and untraded energy volumes.

From Figure 28, it can be seen that on March 15th the AGGLEC was only not able to trade in the hour 19:00, trading all energy from the remaining hours. Figure 29 presents the hourly bid and market clearing prices for March 15th, 2023.

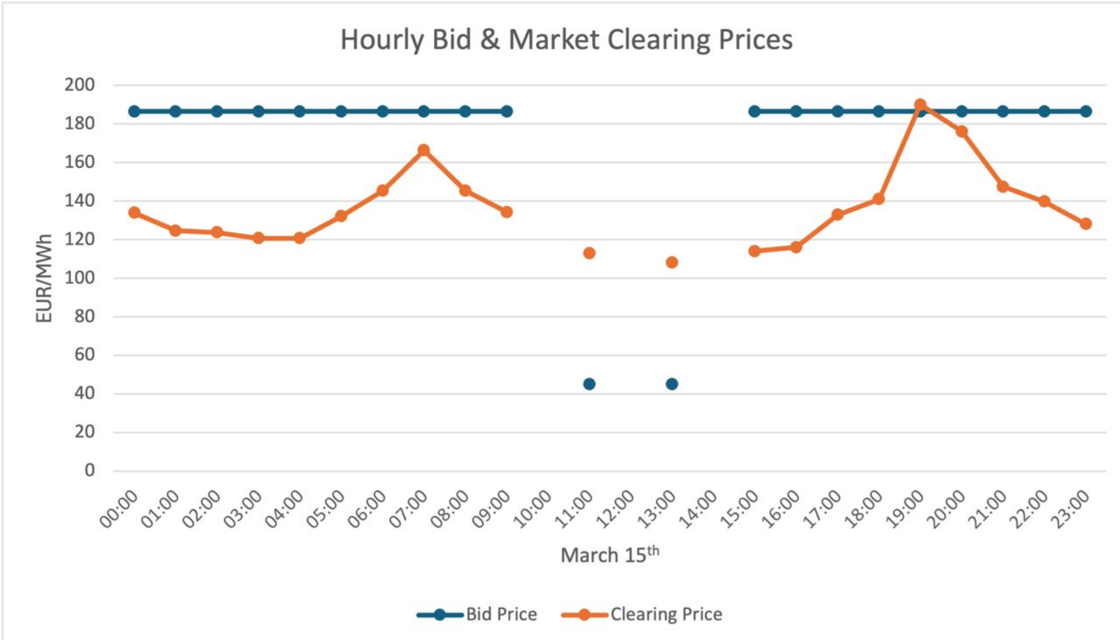


Figure 29: Hourly bid and market clearing prices.

From Figure 29, one can see that the market clearing prices are all above the supply bid prices (see hours 11:00 and 13:00), confirming that all of the AGGLEC supply for this day was traded. However, in terms of demand bid prices, at the time 19:00, the market clearing price (190 EUR/MWh) is higher than the demand bid price (186.4 EUR/MWh), validating the untraded electricity volume in this period (see Figure 28).

Figure 30 shows daily total traded electricity volume of AGGLEC and the volume-weighted average clearing price for March 2023.

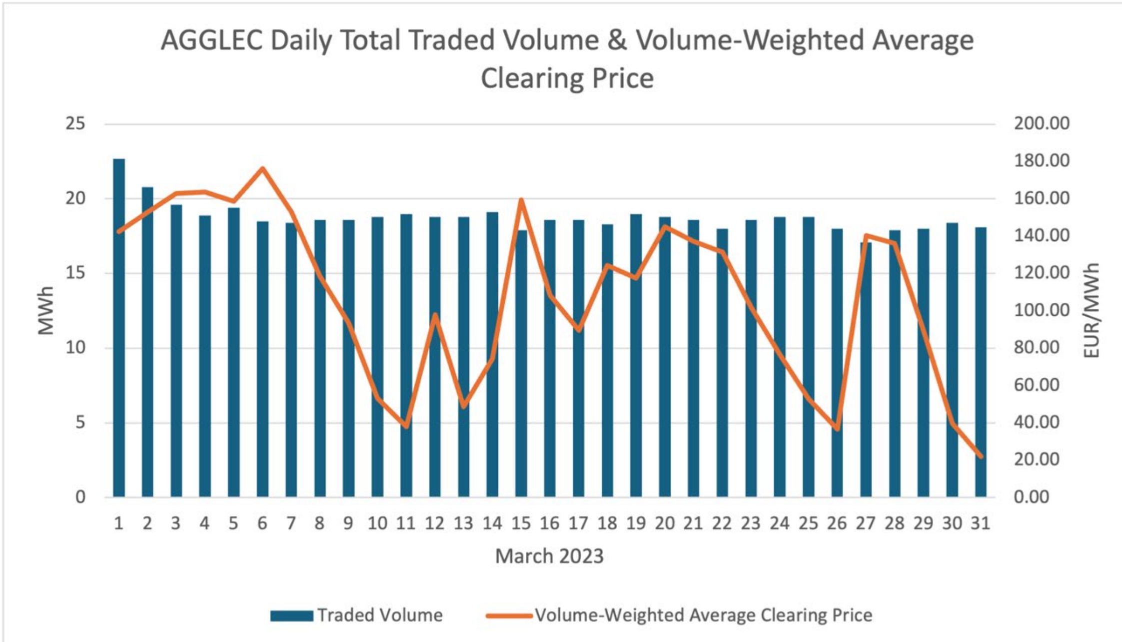


Figure 30: AGGLEC's daily total traded volume and volume-weighted average clearing price.

Analysing Figure 30, the day with the highest traded volume was March 1st with a total of 22.7 MWh, while the day with lowest traded volume was March 27th with 17.1 MWh. Regarding the daily volume-weighted average clearing price (VWACP), March 11th and March 26th were the days with the lowest VWACPs, with 37.92 EUR/MWh and 36.68 EUR/MWh respectively. In turn, the day with the highest VWACP was March 6th, with 176.17 EUR/MWh. Lastly, AGGLEC's monthly total trade volume in the wholesale market was of 581.5 MWh, while the monthly VWACP was of 108.24 EUR/MWh.

Table 14 introduces a comparison between the outcomes of the participation in the aggregation-wide trading scenario – i.e., buy untraded demand from the aggregation-wide level at the retailer's tariff and sell the untraded supply at the feed-in tariff – and the outcomes of participating in the wholesale-wide trading scenario.

Table 14: Aggregation-wide and wholesale-wide results' comparison.

Scenario		Costs/Profits [EUR]	Total [EUR]	Savings [EUR]
Aggregation-wide	Buy retailer	85 475.40	84 320.77	26 350.02
	Sell grid	- 1 154.63		
Wholesale-wide	Buy wholesale-wide	58 258.89	57 970.75	
	Sell wholesale-wide	- 512.90		
	Buy retailer	400.26		
	Sell retailer	- 175.50		
Cost reduction (%)				31.25 %

From Table 14, it is clear the significant savings, i.e. 26 350.02 EUR, at the end of the month from participating in the wholesale market when comparing with only participating in the local-wide and aggregation-wide trading levels, representing a 31.25% of extra savings. It must be stressed that such positive outcome results from the fact that, in the whole month, AGGLEC was only unable to buy 2.2 MWh of demand, nor was he able to sell 3.9 MWh of supply.

Given the untraded demand volume in the wholesale-wide trading and also due to closer to real-time forecasts, adjustments can still be made by participating in OMIE's intraday markets and/or in demand flexibility events. For this specific case study, the following sub-section will demonstrate the participation of the members of a LEC in a demand response event, aiming to avoid as much as possible to buy electricity from the retailer and reduce the electrical bill costs.

5.1.5. Optimal Local Flexible Consumption

After wholesale clearing, untraded demand volumes and closer to real time forecast may require the need to demand flexibility events aiming to reduce as much as possible the energy bills of the communities' participants. According to the wholesale-wide trading results, the AGGLEC was only not able to trade the demand of March 15th at 19:00 and of March 27th at 20:00 since the submitted bid prices were higher than the market clearing price of both hourly periods, as highlighted in Figure 31.

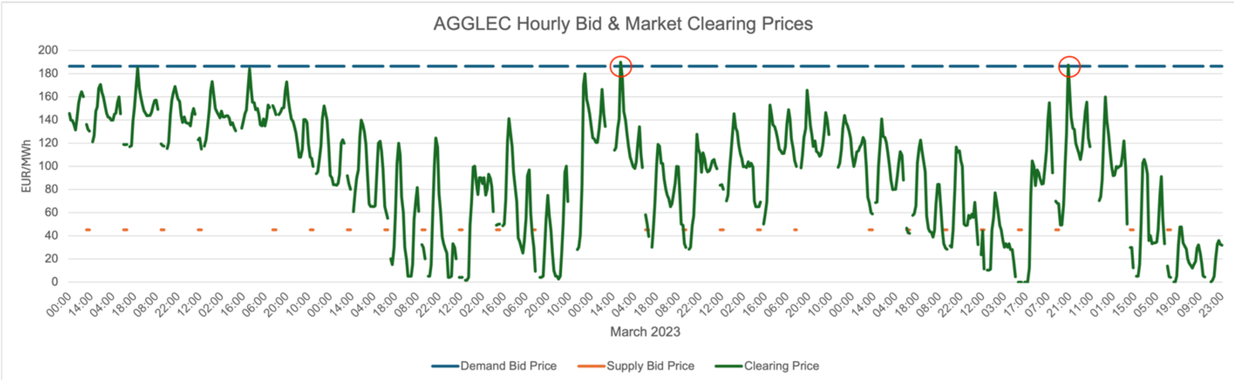


Figure 31: AGGLEC demand and supply bid prices versus market clearing prices in March 2023.

Observing Figure 31, it can be seen in blue the demand bid prices, in orange the supply bid prices, and in green the market clearing prices. Thus, all demand bids with prices lower than the market clearing price and all supply bid with prices higher than the market clearing price were not traded in the wholesale market. Regarding the untraded supply, LECs' prosumers prefer to sell the available surplus to the grid whenever the market clearing prices are lower than the feed-in tariff. However, when it comes to the untraded demand, in this specific case, it is more profitable to go and try to trade it in a demand flexibility event to the retailer for an acceptable incentive. The two hourly periods with untraded demand in March 2023, and highlighted with a red circle in Figure 31, were March 15th at 19:00 and March 27th at 20:00. On March 15th there's an untraded volume of 1 MWh and on March 27th the untraded volume was of 1.1 MWh.

To perform the demand flexibility event(s), the Optimal Local Flexible Consumption model (see 3.3.8) was used. To evaluate the flexibility of consumers, the load reduction program is assessed across the time slot identified with untraded demand, namely:

- Slot 1: 19:00 of March 15th, 2023
- Slot 2: 20:00 of March 27th, 2023

To ease the reader's follow up, LEC3 has been selected for the local flexibility results' demonstration. In the time slots identified with untraded demand, LEC3's total demand was of 151.82 kWh on March 15th at 19:00, and of 131.93 kWh at 20:00 of March 27th. Table 15 presents the expected consumption, the inconvenience cost (Inc. Cost (EUR)), and the maximum participation level (Max LR (%)) of LEC3's consumers and prosumers in the respective load reduction programs of the identified time slots (L_Slot1 (kWh), L_Slot2 (kWh)).

Table 15: The consumption of different time slots (L_Slot1 (kWh), L_Slot2 (kWh)), Inconvenience cost (Inc. Cost (EUR)), and the maximum participation level (Max LR (%)) in the load reduction program for 100 players.

Consumer	1	2	3	4	5	6	7	8	9	10
L_Slot1 (kWh)	5.266	0.252	0.144	0.290	1.891	1.432	4.842	0.159	4.397	1.485
L_Slot2 (kWh)	5.890	0.307	0.216	0.551	0.927	0.878	2.686	0.250	3.095	0.919
Inc. Cost (EUR)	0.0345	0.0338	0.0163	0.0107	0.0016	0.0239	0.0107	0.0360	0.0314	0.0335
Max LR (%)	18.72	19.81	12.33	19.52	14.17	18.73	12.43	18.25	18.51	10.41
Consumer	11	12	13	14	15	16	17	18	19	20
L_Slot1 (kWh)	5.337	0.440	0.458	0.246	1.416	1.513	0.317	1.309	0.371	1.727
L_Slot2 (kWh)	3.284	0.703	0.901	0.300	0.624	0.840	0.752	0.797	0.696	0.741
Inc. Cost (EUR)	0.0039	0.0019	0.0316	0.0331	0.0415	0.0228	0.0144	0.0445	0.0389	0.0040
Max LR (%)	16.17	18.85	12.1	13.87	17.77	18.2	13.96	15.23	19.77	16.51
Consumer	21	22	23	24	25	26	27	28	29	30
L_Slot1 (kWh)	0.661	1.547	1.839	0.621	1.323	1.410	0.299	3.100	2.686	3.104
L_Slot2 (kWh)	1.294	0.919	0.836	0.844	0.754	0.797	0.477	1.349	1.561	1.206
Inc. Cost (EUR)	0.0113	0.0212	0.0027	0.0407	0.0129	0.0437	0.0340	0.0196	0.0248	0.0307
Max LR (%)	11.95	17.79	15.39	15.77	10.6	14.51	14.14	10.34	16.96	11.37
Consumer	31	32	33	34	35	36	37	38	39	40
L_Slot1 (kWh)	0.159	4.334	1.843	1.361	0.413	0.548	1.776	0.482	0.420	1.915
L_Slot2 (kWh)	0.310	1.978	1.019	0.961	0.878	0.817	1.329	0.691	0.970	0.904
Inc. Cost (EUR)	0.0436	0.0167	0.0193	0.0215	0.0414	0.0081	0.0233	0.0098	0.0360	0.0030
Max LR (%)	14.33	15.89	11.25	11.71	17.71	11.42	13.57	13.39	10.41	17.29
Consumer	41	42	43	44	45	46	47	48	49	50
L_Slot1 (kWh)	0.733	1.448	1.460	0.167	0.581	0.668	1.383	1.604	0.765	0.707
L_Slot2 (kWh)	0.346	0.524	0.772	0.286	0.345	0.367	0.712	0.967	0.361	0.329
Inc. Cost (EUR)	0.0352	0.0090	0.0308	0.0243	0.0075	0.0063	0.0380	0.0339	0.0344	0.0179
Max LR (%)	11.18	19.79	17.48	17.05	19.02	10.53	16.25	12.02	10.5	12.37

Consumer	51	52	53	54	55	56	57	58	59	60
L_Slot1 (kWh)	2.818	1.511	0.979	2.098	2.768	1.138	3.181	0.119	3.774	1.017
L_Slot2 (kWh)	4.075	0.337	0.189	0.491	3.898	0.685	2.531	0.256	3.141	0.656
Inc. Cost (EUR)	0.0190	0.0269	0.0388	0.0226	0.0111	0.0441	0.0254	0.0159	0.0016	0.0432
Max LR (%)	11.9	12.92	13.31	15.21	12.54	18.29	10.6	16.23	11.83	16.97
Consumer	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
L_Slot1 (kWh)	3.608	3.318	0.351	1.632	2.798	1.358	0.268	2.303	0.240	0.898
L_Slot2 (kWh)	2.929	0.497	0.750	0.311	2.848	0.734	0.507	4.166	0.583	0.739
Inc. Cost (EUR)	0.0094	0.0156	0.0036	0.0342	0.0072	0.0240	0.0188	0.0298	0.0302	0.0176
Max LR (%)	13.15	11.89	12.25	13.34	14.02	16.11	13.57	19.23	19.05	17.6
Consumer	**71**	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**	**80**
L_Slot1 (kWh)	0.461	0.903	3.385	0.396	1.902	2.471	0.203	2.064	2.085	3.422
L_Slot2 (kWh)	0.905	0.979	4.281	0.961	2.785	3.564	0.498	1.285	1.849	5.015
Inc. Cost (EUR)	0.0412	0.0367	0.0192	0.0320	0.0269	0.0087	0.0170	0.0280	0.0253	0.0396
Max LR (%)	16.79	11.26	18.5	12.15	11.5	13.36	10.79	17.97	16.59	16.26
Consumer	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**
L_Slot1 (kWh)	0.130	2.892	3.697	2.362	0.245	0.375	4.179	0.336	0.395	1.035
L_Slot2 (kWh)	0.334	1.698	3.526	2.798	0.492	0.897	5.057	0.789	0.834	0.895
Inc. Cost (EUR)	0.0402	0.0223	0.0269	0.0154	0.0112	0.0431	0.0303	0.0193	0.0110	0.0063
Max LR (%)	11.47	10.13	13.07	10.99	18.73	14.58	18.94	15.29	12.69	15.06
Consumer	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**100**
L_Slot1 (kWh)	1.251	0.982	1.028	0.113	0.879	0.991	1.151	1.137	1.246	1.274
L_Slot2 (kWh)	2.203	0.857	0.761	0.201	1.316	1.602	0.764	0.872	1.733	1.594
Inc. Cost (EUR)	0.0396	0.0433	0.0153	0.0239	0.0152	0.0220	0.0186	0.0281	0.0185	0.0435
Max LR (%)	17.58	15.26	19.9	10.65	17.7	16.17	11.62	14.08	13.11	13.42

The Optimal local flexible consumption model provides two different approaches for the results presentation and analysis. Simulation results are presented next for both approaches, as follows:

e) **Fixed LR level** – In the Fixed Load Reduction (LR) level approach, the LEC manager, or operator, stipulates the amount of load reduction to request to its players. The participation level of each player is determined through cost minimization in the perspective of the community's manager.

f) **Fixed LR budget** – In the Fixed LR budget approach, the participation level of each player in load reduction is calculated based on the LR budget determined by the LEC manager, or operator.

5.1.5.1. Fixed LR Level

The participation levels of consumers and prosumers in the load reduction program for the first and second time slots are depicted in Figure 32 and Figure 33, respectively. As anticipated, the participation levels of LEC3 members increase with the escalation of the requested load reduction by the operator.

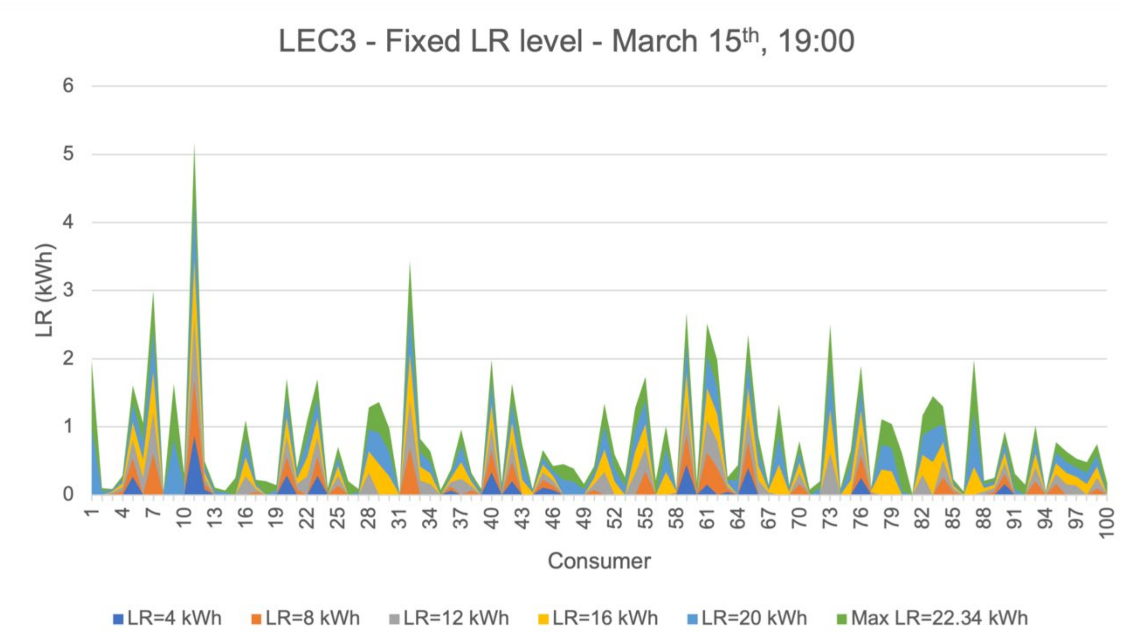


Figure 32: Participation level of LEC3 players in LR program based on the fixed LR level on March 15th, 19:00.

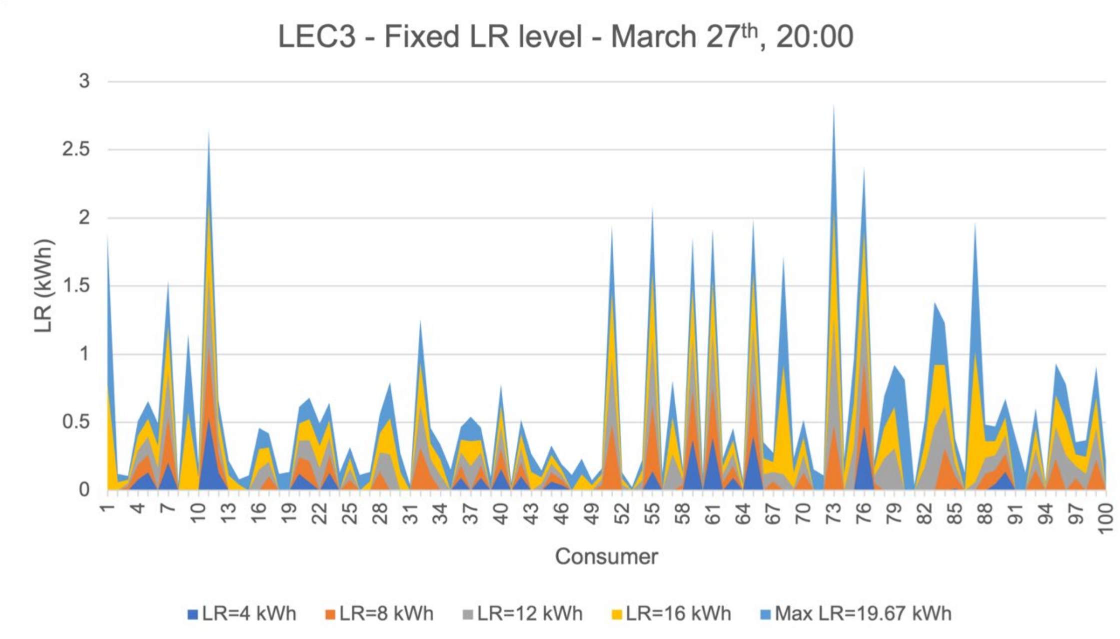


Figure 33: Participation level of LEC3 players in LR program based on the fixed LR level on March 27th, 20:00.

Using the Fixed LR level, the operator of LEC3 prioritizes the consumers and prosumers with the lowest inconvenience costs to fulfil the required load reduction, aiming to minimize his own operational cost. The total costs of providing different load reduction levels for the first and second time slots are shown in Figure 34 and Figure 35, respectively.

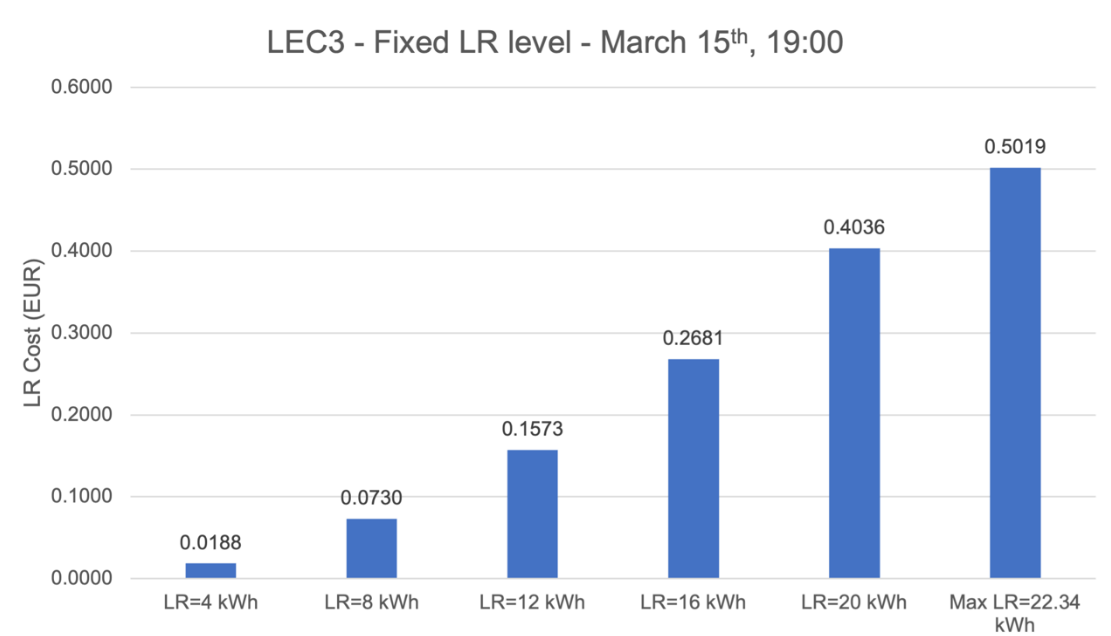


Figure 34: Cost of load reduction for different requested LR levels on March 15th, 19:00.

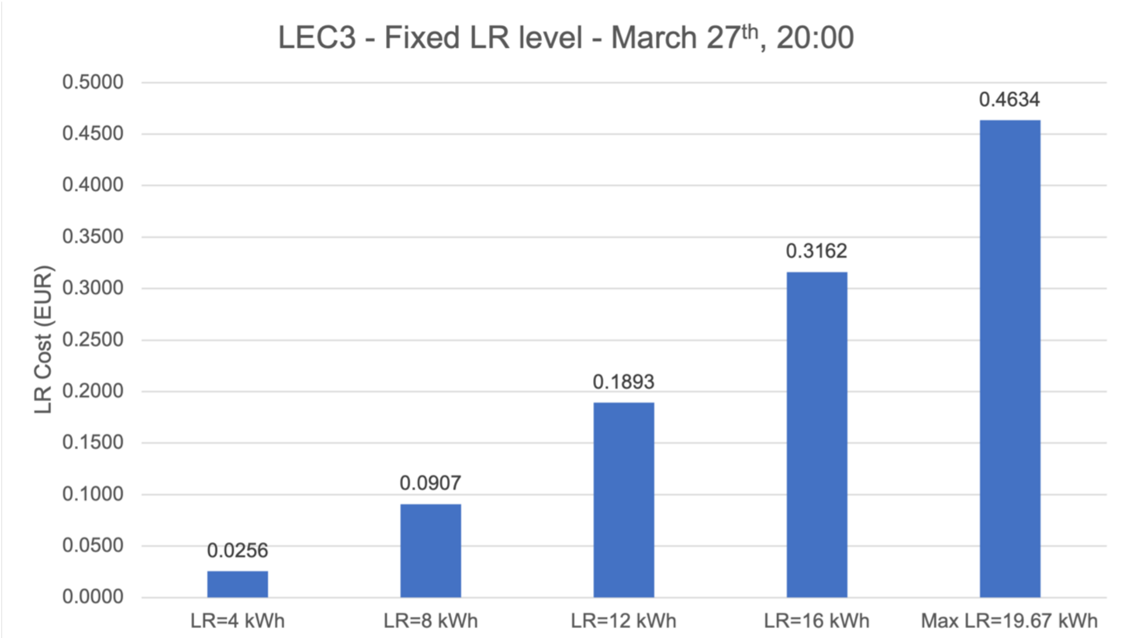


Figure 35: Cost of load reduction for different requested LR levels on March 27th, 20:00.

Based on LEC3's data (see Table 15), the maximum achievable load reductions on March 15th at 19:00 was of 22.34 kWh, and on March 27th at 20:00 of 19.67 kWh. Thus, resulting in a load reduction cost of 0.5019 EUR and 0.4634 EUR, respectively.

5.1.5.2. Fixed LR Budget

The participation levels of LEC3's consumers and prosumers in the load reduction, based on the fixed load reduction budget for March 15th at 19:00 and March 27th at 20:00, are illustrated in Figure 36 and Figure 37, respectively.

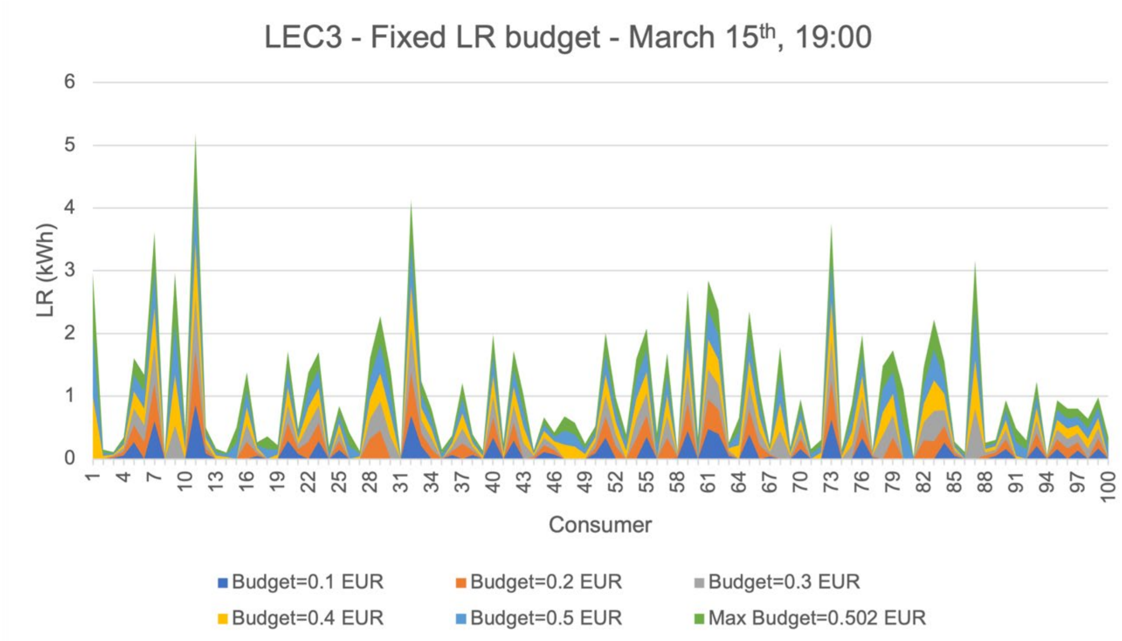


Figure 36: Participation level of LEC3 players in LR program based on the fixed LR budget on March 15th, 19:00.

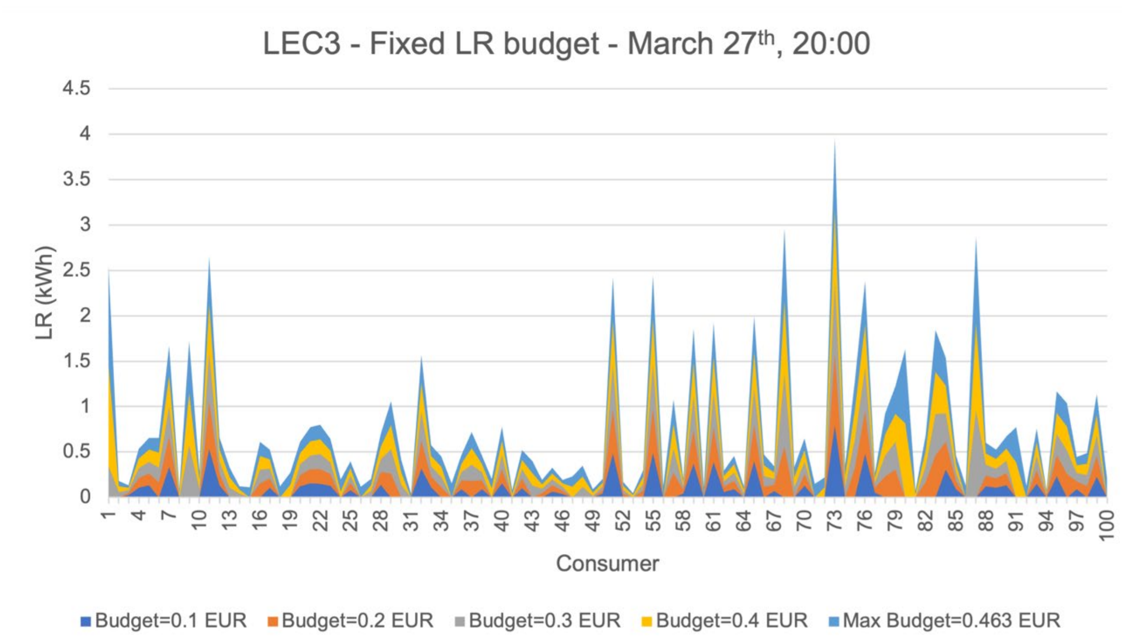


Figure 37: Participation level of LEC3 players in LR program based on the fixed LR budget on March 27th, 20:00.

As it is possible to see in Figure 36 and Figure 37, the participation levels of consumers and prosumers increase as the budget allocated for load reduction increases. This augmentation in budget empowers the operator to enhance the flexibility of the system.

The total load reduction for various budgets for March 15th at 19:00 and March 27th at 20:00 is displayed in Figure 38 and Figure 39, respectively.

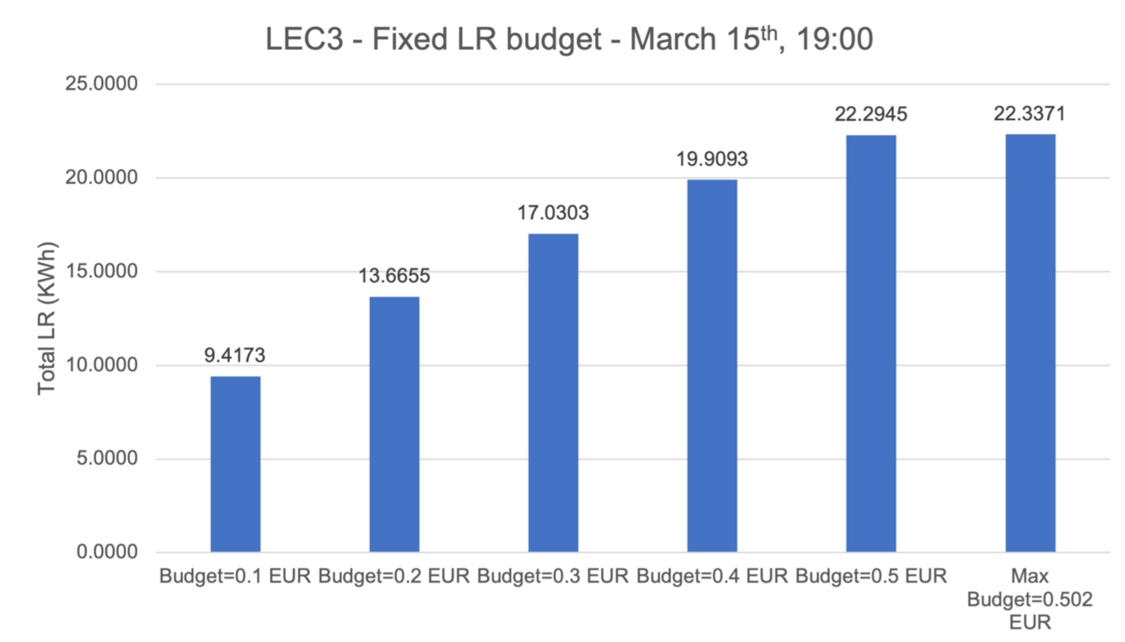


Figure 38: Cost of load reduction for different LR budget on March 15th, 19:00.

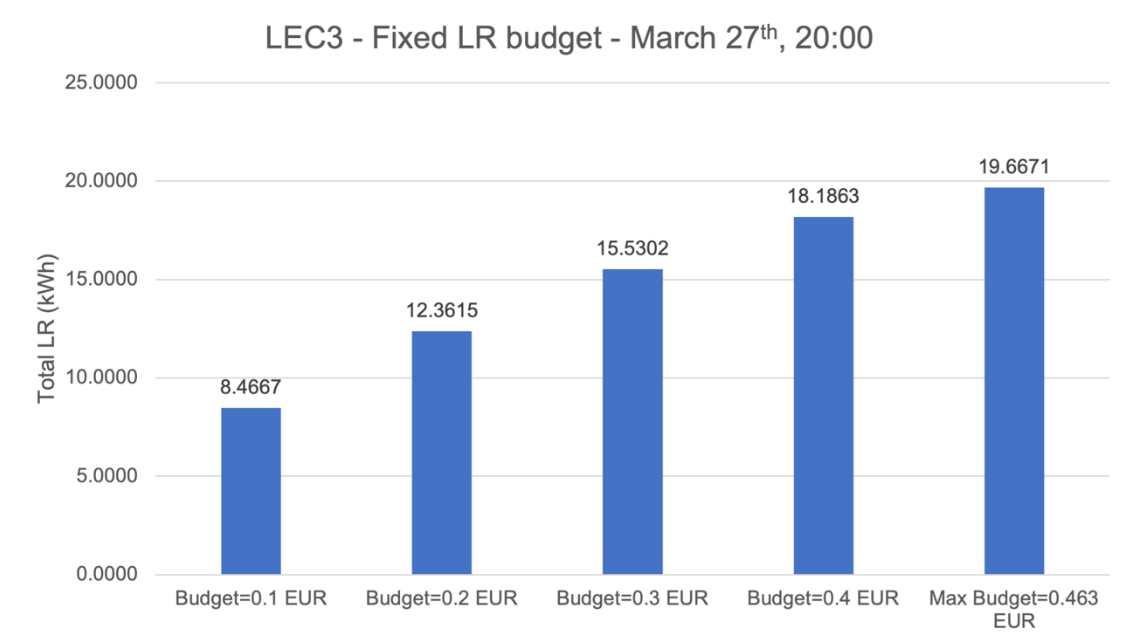


Figure 39: Cost of load reduction for different LR budget on March 27th, 20:00.

Figure 38 and Figure 39 demonstrate that increasing the load reduction budget enhances the participation level of LEC3's consumers and prosumers in the load reduction program.

5.1.6. Final remarks

Using the multilevel electricity trading framework, consumers and prosumers were able to reduce their electricity bills at each step of the way. Table 16 presents an overall results comparison between a baseline scenario where consumers buy demand to the retailer and prosumers sell supply to the grid, and the multilevel trading scenario where local community participants trade electricity from the local-wide level to the aggregation-wide and wholesale-wide levels.

Table 16: Overall results comparison between baseline and multilevel trading scenarios.

Scenario		Cost [EUR]	Total [EUR]	Savings [EUR]
Baseline	**Buy retailer**	101 308.33	100 492.72	42 746.73
	Sell grid	- 815.61		
Multilevel trading	**Buy local-wide**	4 275.93	57 745.99	
	Sell local-wide	- 4 275.93		
	Buy aggregation-wide	2 067.63		
	Sell aggregation-wide	- 2 067.63		
	Buy wholesale-wide	58 258.89		
	Sell wholesale-wide	- 512.9		
Cost reduction (%)				42.54 %

Using the Centralized P2P Electricity Sharing Optimization, LEC1 to LEC5 were able to reduce their costs by 11.28% when compared to buying their demand to the retailer and selling their supply surplus to the grid. In turn, the players of LEC6 to LEC8 were able to reduce their bills by 12.95% by using the Competitive Strategic Bidding in Local Markets model. By participating in the local-wide trading, LEC1 to LEC8 achieved an overall cost reduction of 11.89%.

By participating in the aggregation-wide level, the consumers of LEC1 to LEC8 tried to reduce their costs, and prosumers aimed at profiting as much as possible while keeping the prices below the retailer's tariff. This trading level allows players from different communities to trade electricity at prices below the retailer's tariff and above the feed-in tariff, making it more interesting to all participants. Using the P2P Discriminatory Price Auction at the aggregation-wide level, the overall cost reduction of LEC1 to LEC10 was of 2.71 %. However, it should be noticed that being the prosumers PV-based, it was only possible to trade electricity in the sunny hours. Another important factor to consider is that the P2P Discriminatory Price Auction model is a pay-as-bid model, where there is no market clearing price. Instead, each trade has its own price.

Leveraging from the aggregation-wide participation, LEC1 to LEC10 were able to trade in the day-ahead wholesale market. At the wholesale-wide level consumers are able to buy electricity at lower prices than the retailer's tariffs. In turn, prosumers are only interested to trade their surplus if the market clearing price is above the feed-in tariff. Using the Iberian day-ahead market model, LECs participants achieved the most significant cost reduction of all, at 31.25 %.

As it is possible to observe in Table 16, the overall cost reduction from the local-wide to the wholesale-wide trading levels was of 42.54 % when comparing to the baseline scenario. Given the wholesale-wide trading results and new consumption and generation forecasts closer to the execution time, LEC's managers were able to adjust the day-ahead trading results using the Optimal Local Flexible Consumption model. A demonstration example has been presented for LEC3, applying two district approaches: the Fixed LR level were the community operator sets a fixed load reduction value; and the Fixed LR budget where the operator determines a fixed budget for paying incentives to its players to reduce their consumption. It must be stressed that this model optimizes costs in the perspective of the LEC manager.

Table 17 presents the LMPIs computed for each prosumer LEC of the local-wide level of the simulation scenario.

Table 17. Computed LMPIs for the local-wide level of the simulation scenario.

LMPI #	LEC1	LEC2	LEC3	LEC4	LEC5	LEC6	LEC7	LEC8
1	15.648 %	28.897 %	15.648 %	28.897 %	15.648 %	32.65 %	32.65 %	32.65 %
2	0.221 %	0.276 %	0.221 %	0.276 %	0.221 %	0.525 %	0.525 %	0.525 %
3	n.a.	n.a.	n.a.	81.618	n.a.	n.a.	n.a.	n.a.
4	2 553.87 EUR	2 762.01 EUR	1 190.34 EUR	1 186.19 EUR	2 620.16 EUR	1 643.65 EUR	1 368.90 EUR	1 263.38 EUR
5	128.11 EUR/MWh	126.57 EUR/MWh	115.55 EUR/MWh	115.57 EUR/MWh	126.54 EUR/MWh	149.51 EUR/MWh	171.70 EUR/MWh	166.41 EUR/MWh

LMPI #1 concerns the local energy neutrality, and it measures the ratio between local generation and consumption. As it can be seen, at local-wide level, LECs 6 to 8 present the highest ratio between local generation and consumption, being followed by LECs 2 and 5. Analysing these ratios it is clear the need to buy demand to the grid, or in participating in an aggregation wide trading, as proposed with the present framework.

LMPI #2 refers to the nodal consumption, i.e., the real time demand covered by local or prosumer renewable generation. In this matter, it can be observed the low ratio of demand covered by the local generation, which is explained by the LECs characteristics. These values also confirm the need to trade with neighbouring communities (i.e., aggregation-wide level) aiming to reduce the electricity bills.

LMPI #3 relates to the import/export ratio of each LEC. Only LEC4 was able to export local generation. The remaining LECs do not possess enough generation to be able to export their generation surplus.

LMPI #4 presents the total costs of each LEC at the local-wide trading. It includes the local power system costs, investment costs, operation costs, and trading costs. In this subject, LECs 1, 2, and 5 present the highest costs.

LMPI #5, in turn, discloses the levelized costs, i.e., the cost of the consumed energy per MWh at the local-wide level. In this case, LECs 7 and 8 present the highest costs per MWh. However, it must be noticed that, besides being only locking at the local-wide trading level, these costs are already below the retailers' costs per MWh for the same period of time.

The computed LMPIs for the local-wide trading level confirm the need for further trading levels, given the LECs characteristics, aiming to achieve the lowest possible electricity bills.

5.2 Large agent-based LEC with cooperative self-consumption

The results of this study are divided into two subsections. In the first and second subsections are evaluated the impact of investing in local cooperative renewable generation in the transmission grid and distribution grid and in the tariffs, respectively, in the following four scenarios:

g) Baseline: Inflexible consumer behaviour in a LEC without self-consumption.
h) Inflexible: Inflexible consumer behaviour in a LEC that invests in cooperative self-consumption.
i) Best forecasts: improved renewable power forecast accuracy from Deliverable 4.9 ed. 2 [55].
j) Flexible: the same as 3 considering a 10% flexibility of consumer's demand.

5.2.1. Using OptiRES.Lines to detect congestions

This section uses the OPF model of the OptiRES.Lines tool to detect potential congestions in the transmission and distribution grid in the aforementioned four scenarios [40]. In all scenarios, the OPF considers the minimization of the active power generation in the transmission grid.

5.2.1.1. Results from the Baseline scenario

Using the OptiRES.Lines tool to verify the power flows in the region during 2018 to evaluate the possible investment in solar PV for 2019 it is possible to verify that there is no congestion both in the transmission grid presented in Table 17 and in the substations connecting the distribution grid to the transmission grid presented in the Baseline scenario. According to equal or below 35%, while the maximum value identified was 64% for two power lines.

Table 18: Load factor of each transmission line considering the minimization of the generated active power according to the percentage of time during 2018.

Start	End	Line ID	Min.	5%	10%	25%	50%	75%	90%	95%	Max.
Cabril150	Bouca150	1010	1	1	1	1	1	1	1	1	1
Bouca150	Zezere150	1015	6	6	6	6	6	6	7	7	7

Falagueira150	Zezere150	1089	2	4	4	6	9	13	17	19	64
Vila Cha220	Gouveia (Refer)220	1107	0	1	1	1	1	2	2	2	7
Falagueira150	Castelo Branco150	1108	1	2	3	5	6	7	8	8	28
Falagueira150	Corgas150	1114	0	0	0	0	0	0	0	0	0
Gardunha150	Castelo Branco150	1115	1	1	1	1	1	1	1	1	1
Falagueira150	Subs, Rodao (Refer)	1616	0	0	0	0	0	0	0	0	0
Aguieira220	Pereiros220	2054	0	0	0	0	0	0	0	0	0
Chafariz220	Ferro220	2124	4	4	5	7	11	15	18	19	41
Chafariz220	Vila Cha220	2135	0	4	4	5	8	11	13	14	49
Penamacor220	Ferro220	2155	0	0	0	0	0	0	0	0	0
Castelo Branco220	Ferro220	2160	5	6	6	7	8	9	10	11	37
Pereiros220	Penela220	2163	2	2	2	3	3	3	4	5	26
Penela220	Zezere220	2164	1	2	2	2	2	2	2	3	39
Penela220	Tabua220	2168	3	3	3	3	4	4	5	5	26
Pampilhosa da Serra220	Tabua220	2169	0	0	0	0	0	0	0	0	0
Vila Cha220	Tabua220	2170	0	0	1	1	3	5	6	7	46
Pereiros220	Tabua220	2173	1	1	2	2	4	5	6	7	16
Pereiros220	Mortagua (Refer)220	2615	0	0	0	0	0	0	0	0	0
Chafariz220	Gouveia (Refer)220	2617	0	1	1	1	1	2	2	2	7
Falagueira400	Pego400	4055	0	2	4	9	16	24	31	35	64
Falagueira400	Cedillo	4056	1	2	4	9	16	23	31	35	55

Figure 40 presents the 2018 load factors of the most loaded substations. Positive load factors indicate the energy flow is going from the transmission to the distribution grid. Otherwise, the flow direction is the opposite.

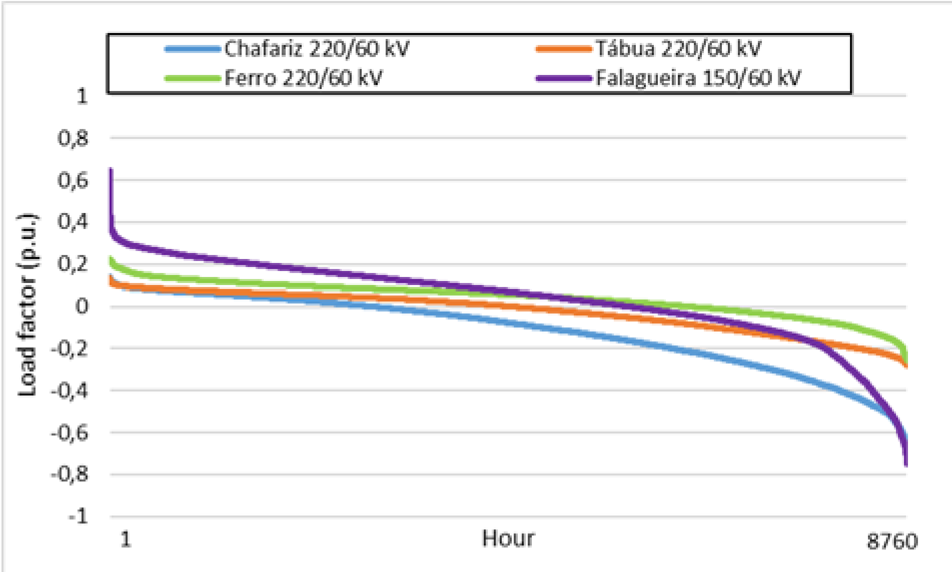


Figure 40: Load factors during 2018 of the most loaded substations. A positive load factor means the energy flow goes from the transmission to the distribution grids.

Analysing the load factors of the most heavily loaded substations presented in Figure 6, it is possible to conclude that they are not congested. Still, margins for more renewable generation are slightly higher than 20% in Chafariz and Falagueira in a few hours. This means that without demand-side flexibility in these substations, installing more renewable generation may lead to curtailments to avoid congesting them.

5.2.1.2. Results from the Inflexible and Best Forecasts scenarios

In these scenarios, it was considered that the LEC invests in 745 MW of cooperative large-scale solar PV in the location of existing wind parks (see Figure 5) assuming the hybridization of these parks without constraints in the injected power in each period. In addition, the LEC contracted more 207 MW of local onshore wind in 2019, resulting in sustainability and carbon-neutrality indexes of 36% and 87% (LMPIs #1 and #6). The system operator uses the OptiRES.Lines tool to verify the potential impact of this investment considering the 2018 power flows presented in Table 18.

Table 19: Load factors according to the percentage of time during 2018 for each transmission line considering the projected 745 MW of PV.

Start	End	Line ID	Min.	5%	10%	25%	50%	75%	90%	95%	Max.
Cabril150	Bouca150	1010	1	1	1	1	1	1	1	1	1
Bouca150	Zezere150	1015	5	6	6	6	6	6	6	7	7
Falagueira150	Zezere150	1089	2	4	4	6	10	16	30	41	100
Vila Cha220	Gouveia (Refer)220	1107	0	1	1	1	1	2	2	3	14

Falagueira150	Castelo Branco150	1108	1	4	5	6	7	11	17	23	91
Falagueira150	Corgas150	1114	0	0	0	0	0	0	0	0	0
Gardunha150	Castelo Branco150	1115	1	1	1	1	1	1	1	1	1
Falagueira150	Subs, Rodao (Refer)	1616	0	0	0	0	0	0	0	0	0
Aguieira220	Pereiros220	2054	0	0	0	0	0	0	0	0	0
Chafariz220	Ferro220	2124	4	5	5	9	17	32	52	63	98
Chafariz220	Vila Cha220	2135	0	3	4	5	7	11	15	18	100
Penamacor220	Ferro220	2155	0	0	0	0	0	0	0	0	0
Castelo Branco220	Ferro220	2160	5	6	7	7	9	11	13	14	42
Pereiros220	Penela220	2163	2	3	3	7	13	19	26	30	53
Penela220	Zezere220	2164	2	2	2	3	6	9	12	13	49
Penela220	Tabua220	2168	3	3	3	4	5	6	9	11	59
Pampilhosa da Serra220	Tabua220	2169	0	0	0	0	0	0	0	0	0
Vila Cha220	Tabua220	2170	0	4	5	8	13	18	24	27	100
Pereiros220	Tabua220	2173	1	2	2	4	10	20	32	43	100
Pereiros220	Mortagua (Refer)220	2615	0	0	0	0	0	0	0	0	0
Chafariz220	Gouveia (Refer)220	2617	0	0	1	1	1	2	2	3	14
Falagueira400	Pego400	4055	0	1	3	7	13	20	28	33	64
Falagueira400	Cedillo	4056	1	2	4	9	16	23	31	35	55

Analysing Table 18 it is possible to verify four congested and two nearly congested transmission lines (values above 90%). Figure 40 presents the 2018 load factors of the most loaded substations according to the new projected 745 MW of local cooperative solar PV.

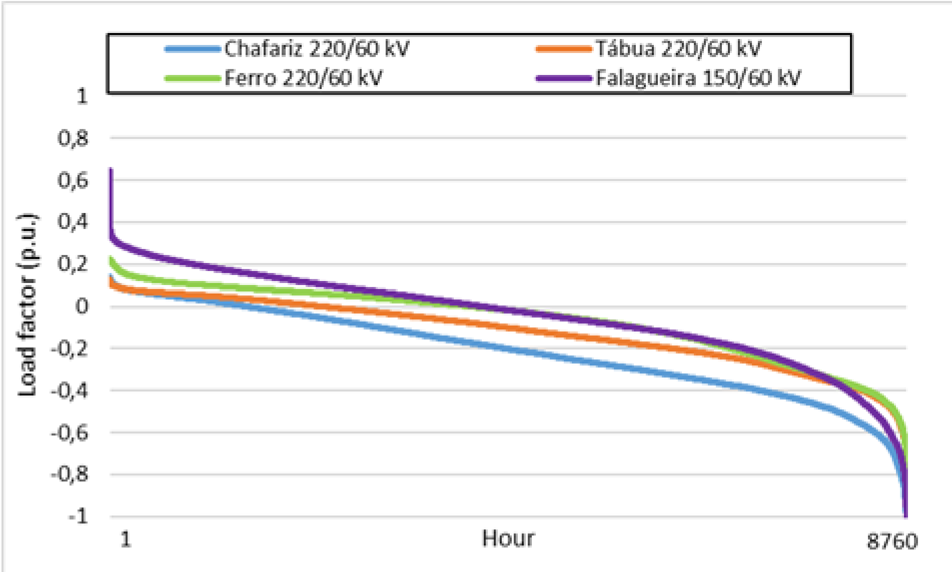


Figure 41: Substations load factors during 2018 using the new projected 745 MW of solar PV.

Analysing Figure 41 it is possible to conclude that the Chafariz substation is congested for 1 hour and near congested for 18 hours and the Falagueira substation is congested for 1 hour and near congested during 7 hours because of excess of local generation (negative load factors). During the congested hour, local vRES production need to be curtailed, unless consumers use their flexibility to respond to these events.

5.2.1.3. Results from the Flexible scenario

The fourth scenario considers that on average the LEC has a flexibility of 10% to shift consumption, enabling consumers to respond to real-time market prices according to the optimal-load shifting tactic (OLST) strategy presented in [20] [21]. This strategy enables to increase the local sustainability index of the LEC to 65%. Table 19 presents the load factors of 2018 considering the projected 745 MW of PV and the response of consumers to real-time prices according to their 10% of load shifting capability.

Table 20: Load factors during 2018 of each transmission line considering the projected 745 MW of PV and 10% flexibility of consumers.

Start	End	Line ID	Min.	5%	10%	25%	50%	75%	90%	95%	Max.
Cabril150	Bouca150	1010	1	1	1	1	1	1	1	1	1
Bouca150	Zezere150	1015	6	6	6	6	6	6	7	7	7
Falagueira150	Zezere150	1089	1	4	4	6	10	16	28	38	100
Vila Cha220	Gouveia (Refer)220	1107	0	1	1	1	1	2	2	2	8
Falagueira150	Castelo Branco150	1108	1	4	5	6	7	11	16	22	59
Falagueira150	Corgas150	1114	0	0	0	0	0	0	0	0	0

Gardunha150	Castelo Branco150	1115	1	1	1	1	1	1	1	1	1
Falagueira150	Subs, Rodao (Refer)	1616	0	0	0	0	0	0	0	0	0
Aguieira220	Pereiros220	2054	0	0	0	0	0	0	0	0	0
Chafariz220	Ferro220	2124	4	5	5	9	16	30	51	62	97
Chafariz220	Vila Cha220	2135	0	3	4	5	7	11	15	18	55
Penamacor220	Ferro220	2155	0	0	0	0	0	0	0	0	0
Castelo Branco220	Ferro220	2160	5	6	7	7	9	11	13	15	36
Pereiros220	Penela220	2163	2	3	3	6	12	19	25	30	52
Penela220	Zezere220	2164	2	2	2	3	6	9	12	13	43
Penela220	Tabua220	2168	3	3	3	4	5	7	9	10	38
Pampilhosa da Serra220	Tabua220	2169	0	0	0	0	0	0	0	0	0
Vila Cha220	Tabua220	2170	0	4	5	8	13	19	24	27	52
Pereiros220	Tabua220	2173	1	2	2	4	10	19	31	41	100
Pereiros220	Mortagua (Refer)220	2615	0	0	0	0	0	0	0	0	0
Chafariz220	Gouveia (Refer)220	2617	0	0	1	1	1	2	2	2	8
Falagueira400	Pego400	4055	0	1	3	7	13	21	28	33	64
Falagueira400	Cedillo	4056	1	2	4	9	16	23	31	35	55

Analysing Table 19 it is possible to conclude that the 10% flexibility provided by consumers, in response to real-time prices, enables a reduction in the number of congested transmission lines to two, and one line near-congested. This reduction occurs because consumers are consuming more local generation, reducing the flows of energy from the distribution to the transmission grid. Figure 42 presents the impact of demand flexibility in the load factors of the substations connecting the distribution and transmission grids.

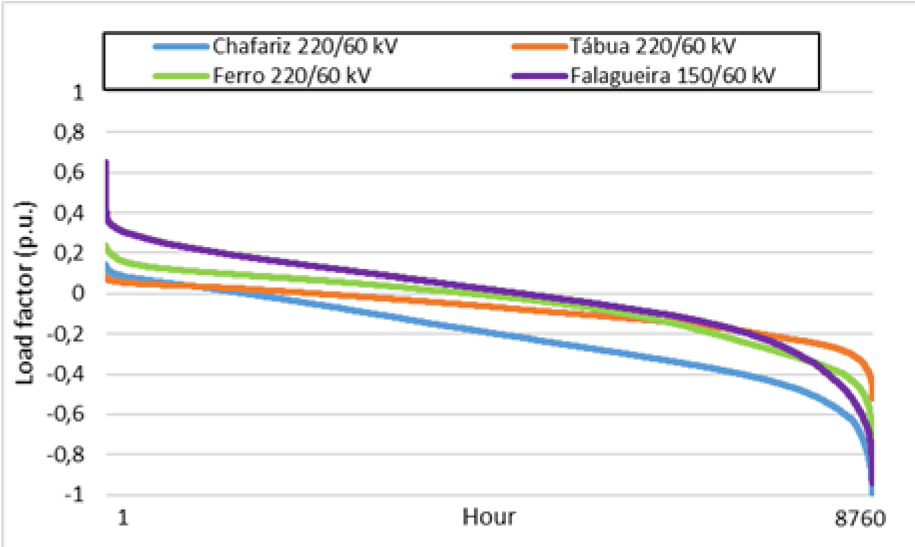


Figure 42: Substations load factors using the projected 745 MW PV and LEC flexibility in 2018.

Analysing Figure 42 it is possible to conclude that the Chafariz substation is near congested during 16 hours with an average load factor reduction of 1% in critical periods because it has a small number of members from the LEC and low benefits from their demand flexibility. On the other hand, the Falagueira substation is near congested during only 4 hours with an average load factor reduction of 6% in critical periods. Due to the flexibility of consumers, in this scenario, there are no grid congestions and curtailments of local renewable energy.

5.2.2. Economic outcomes of the different large LEC scenarios

Using the same LEC used in this work, it has been concluded that inflexible consumers can save 9% of the total costs with electrical energy by selecting the retail tariff more adequate for their consumption behaviour, 15% in the case of investing in self-consumption, 20% in the case of being part of a LEC, and if this LEC assumes cooperative self-consumption the savings can increase to 29%. The final costs of the LEC in the studied scenarios are presented in Figure 43.

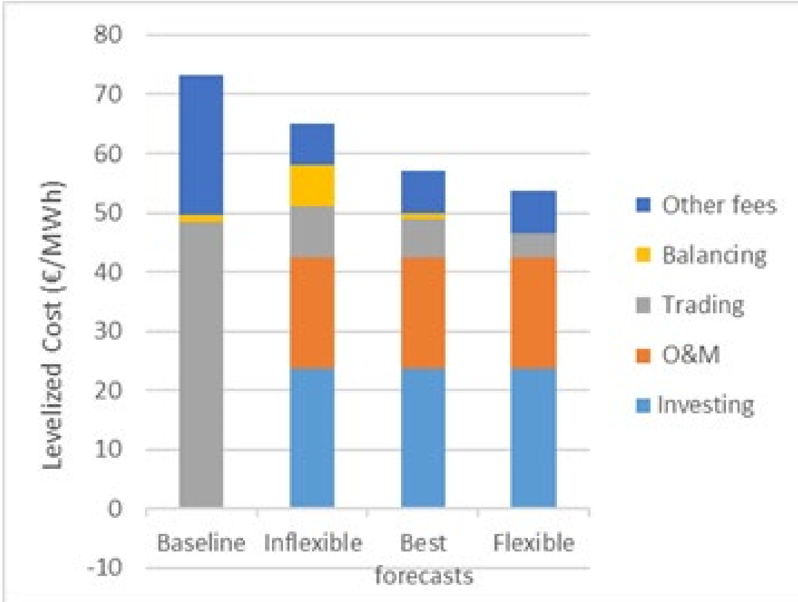


Figure 43: LMPI #3: Results of the presented scenarios. Other fees are, for instance, the grid access.

In the Baseline and Flexible scenarios, it has been considered only RTP tariffs, which are the best tariffs in those scenarios. In an RTP tariff, the LEC passes all its costs to consumers, being risk-free. In the Inflexible and Best forecasts scenarios multiple types of tariffs have been considered, such as flat, TOU, DAHP and RTP. Because of the investment in cooperative self-consumption and the inflexible consumers' behaviour, each consumer selects different tariffs among the types. Table 20 presents the computed LMPIs in each scenario.

Table 21: LMPIs of each scenario.

LMPI	Baseline	Inflexible	Best forecasts	Flexible
#1 (%)	0	87	87	87
#3 (%)	100	13	13	13
#5 (€/MWh)	73.31	65.15	59.90	53.38
#6 (5)	0	36	36	65

Using the OPF analysis is possible to identify that some of the local consumed energy is prevenient from renewable generation from non-members of the community. However, as this energy is traded in wholesale markets it was not considered in the previous scenarios, i.e., only the energy produced by members of the LEC is considered in the computation of the previous LMPIs. In the Baseline scenario all energy is transacted in wholesale markets, being the local carbon neutrality (MPI #1) and self-sufficiency (MPI #6) equal to 0% in this scenario. In the other scenarios the carbon neutrality and the import-export ratio (MPI #3) are equal because the produced energy in the community did not change. However, in the last two scenarios by triggering some demand flexibility and/or improving the forecast accuracy is possible to trade more energy in day-ahead and intraday markets, reducing real-time imbalances. Furthermore, the demand flexibility provided in the last scenario allowed to increase self-sufficiency from 36% to 65%, which impacts the import-export ratio. Although the import-export ratio is the same in all scenarios except Baseline, in the last scenario the LEC only imported 22% and exported 9% of the energy, while in the other two scenarios it imported 51% and exported 38% of the energy.

The LEC with a non-profitable behaviour can reduce their members' costs with electrical energy by 20% in the Baseline scenario. Most of its costs are in trading and others (including grid access), being balancing costs low because of the small errors of local load forecasts [26]. If it invests in cooperative self-consumption, it can reduce at least 27% of the members' costs with energy with a profit of 3%, paying a levelized price of 65.16 €/MWh in the Inflexible scenario. In this last scenario, the costs are divided by investment in local generation (36%), operation and maintenance (O&M, 29%), trading (13%), balancing (11%), and other fees (11%) related to grid access. So, a fully sustainable LEC has the potential to save more than 35% in the last three costs (trading, balancing and other fees). While investment, O&M and other fees (fixed grid access costs) are practically the same in all scenarios, balancing and trading costs reduced significantly in the last two scenarios. Indeed, balancing levelized costs are slightly negative in the Flexible scenario (-0.22 €/MWh). This means that on average the real-time LEC net load is lower than expected, receiving more money for the extra deviated energy.

By considering the improvements in the forecast accuracy of the Deliverable 4.9 methodologies, the costs of the LEC decrease to 59.90 €/MWh, with savings of 11%. Furthermore, by considering that all consumers have a flexibility of 10% using the OLST strategy [21] to shift demand and having a RTP tariff, the final costs of the LEC and the average cost of consumers are 53.38 €/MWh, being its energy sustainability index equal to 65%. Now, most of the electrical energy consumed by the LEC is produced locally. In the first and last scenarios, with an RTP tariff, the consumers save 20% and 42% regarding the best retail tariff. In the second and third scenarios, consumers may select tariffs with fixed prices, saving 27% compared with the best retail tariff. In these last two scenarios the LEC profits 3% and 11% from hedging the risk of members, respectively.

In conclusion, the presented results support the economic benefits of consumers being part of LECs. LECs may trigger the flexibility of consumers to respond to dynamic market prices with RTP tariffs, increasing local energy sustainability and grid reliability, and reducing consumption costs.

5.3 Wholesale-retail-local energy market interactions

The results of this study are divided into three subsections. In the first subsection, the personalized retail pricing scheme is evaluated to analyse the pricing strategies of the supplier, demand response of different customer groups, and the business cases of all market participants. In the second subsection, both retail buying and selling prices are analysed to evaluate both the physical and economic benefits of a local energy community. In the third section, a comparison of model-based optimization and model-based learning approaches is presented to demonstrate the effectiveness of learning approach for the P2P energy trading problem.

5.3.1. Case studies of personalized retail pricing for clustering consumers

In this experiment, a deep learning-based clustering model is implemented and tested in the trails of the European residential community 250 households, as shown in Figure 44. These 250 households are classified into three clusters, as shown in Figure 45.

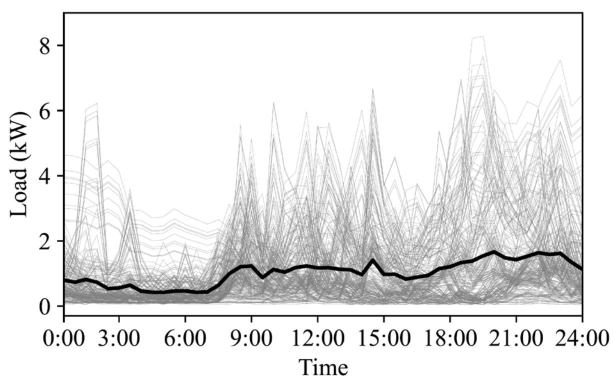


Figure 44: Daily demand profiles of European residential community 250 households.

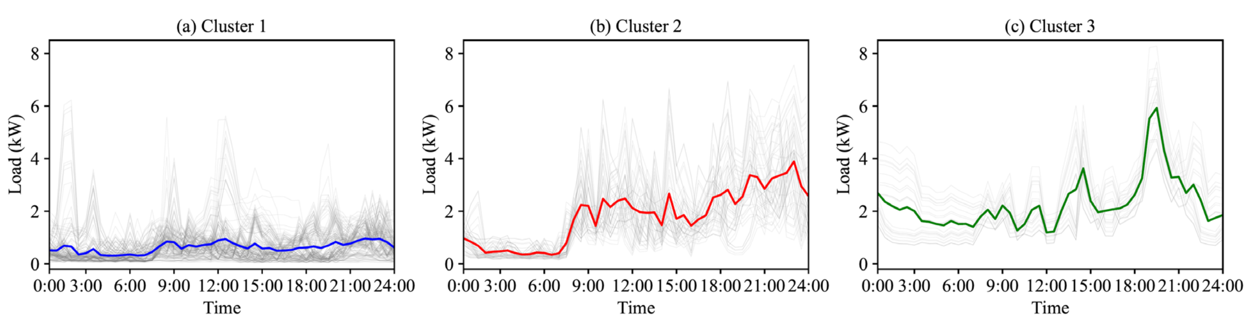


Figure 45: Clustering performance of 250 households.

After making the classification, the physical and economic benefits of the personalized retail pricing scheme will be quantified and evaluated in the analysed market. To achieve this, we utilize the traditional uniform pricing scheme as a benchmark and compare it with our proposed personalized pricing scheme. Figure 46 and Figure 47 display the daily profiles of the demand response and the strategic uniform retail price across varying flexibility levels (α = 0, 15%, and 30%). Additionally, Figure 48 - Figure 50 respectively show the daily profiles of the demand response and the strategic personalized retail prices for three clustered consumer groups for three different levels of demand flexibility.

5.3.1.1. Uniform retail pricing scheme

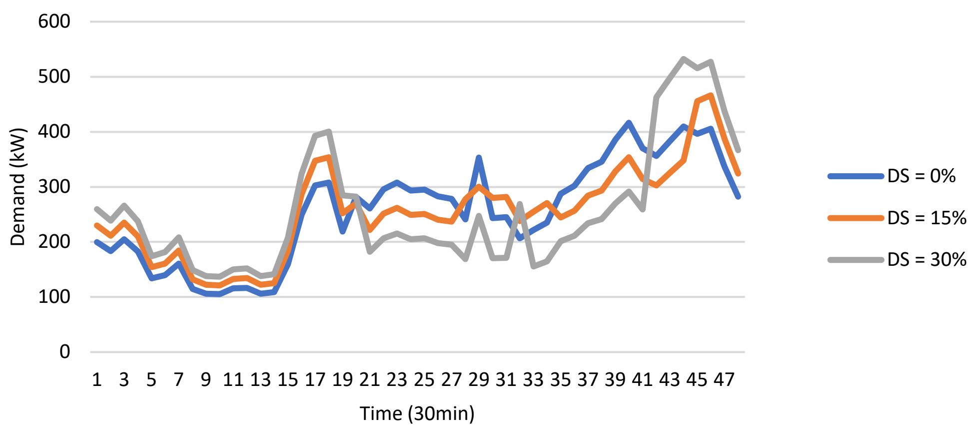


Figure 46: Demand response of 250 households' community.

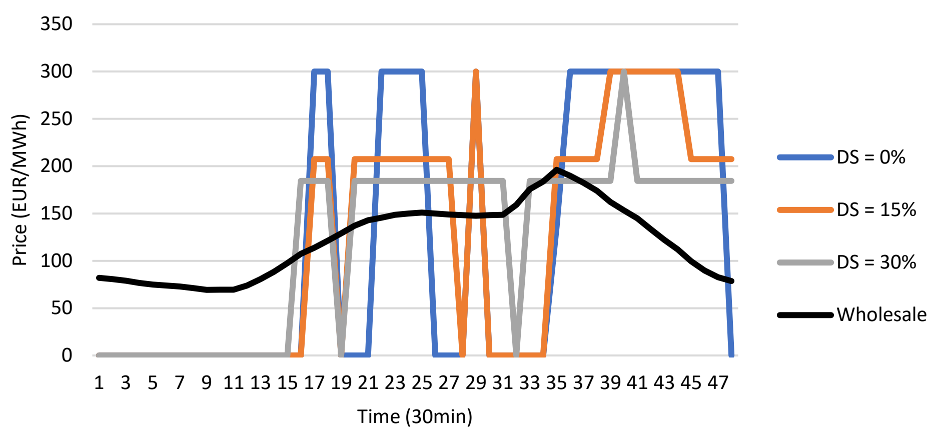


Figure 47: Uniform retail price for 250 households' community.

In Figure 46, the blue line illustrates that, in the absence of demand flexibility (α = 0), the aggregated energy consumption of consumers aligns with typical demand patterns: peak consumption at night and off-peak in the early morning. In response to this demand pattern, the strategic retailer sets the highest possible prices (200 EUR/MWh) during the nighttime peak periods and the lowest prices (0 EUR/MWh) during the early morning and daytime off-peak periods, as depicted in the blue line of Figure 47. This pricing strategy ensures the largest differential between peak and off-peak prices, thereby maximizing the supplier's daily revenue, which is calculated as the product of retail prices and demand patterns over a 24-hour period.

When consumers display some degree of demand flexibility, such as α = 15% and α = 30%, significant energy consumption shifts from peak to off-peak periods, as shown by the orange and grey lines in Figure 46. Anticipating these shifts, the strategic retailer increases off-peak prices while reducing peak prices to maintain daily revenue. The reduction in peak prices is driven by the average pricing constraint, suggesting that the strategic retailer loses its market power and cannot manipulate its served consumers through strategic pricing.

5.3.1.2. Personalized retail pricing scheme

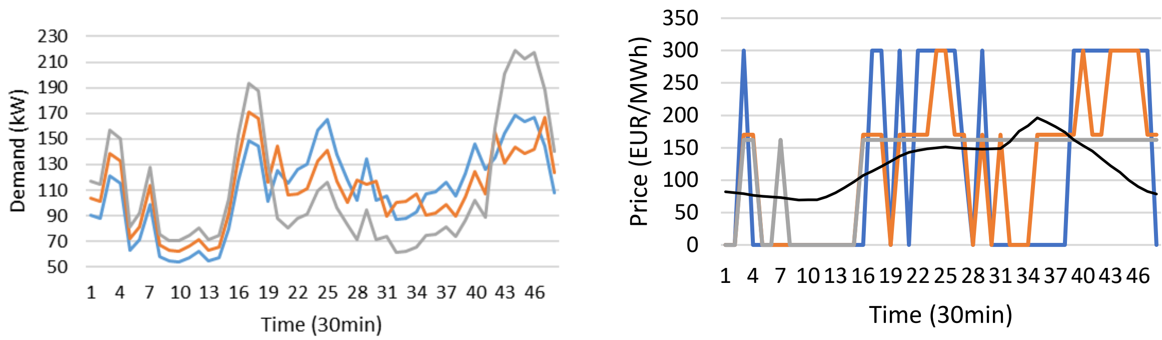


Figure 48: *Demand response and personalized retail price for cluster 1 community.*

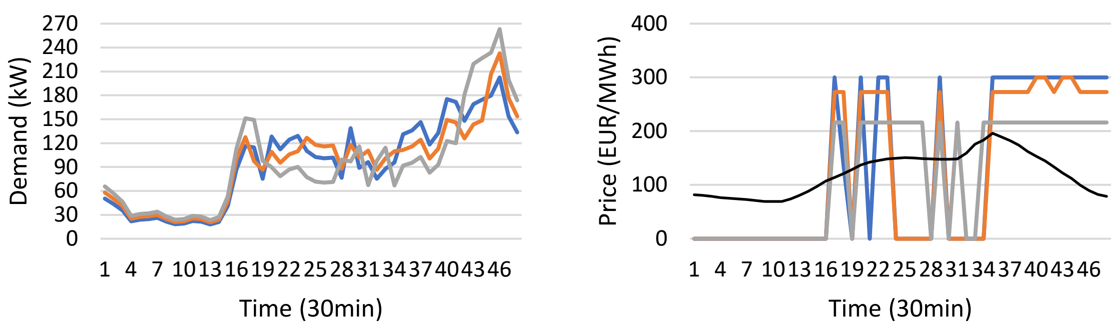


Figure 49: *Demand response and personalized retail price for cluster 2 community.*

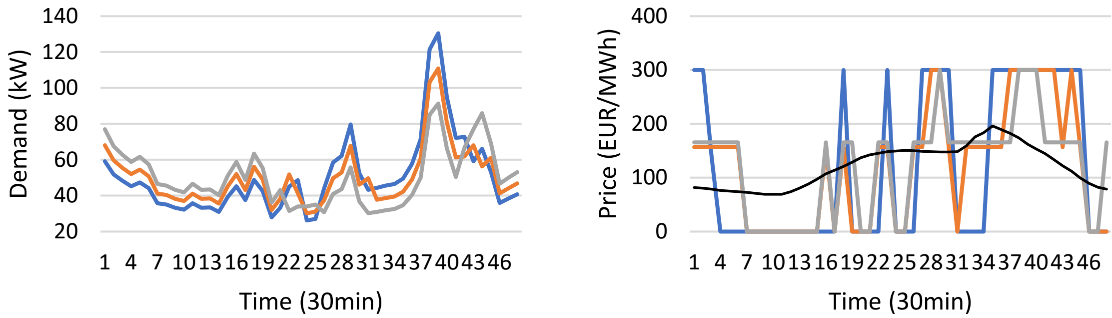


Figure 50: *Demand response and personalized retail price for cluster 2 community.*

When consumers are divided into three clusters with varying demand patterns, the strategic supplier seeks to offer personalized retail prices tailored to each cluster's characteristics. Overall, these personalized prices still align with the demand patterns of the different consumer clusters, as illustrated in the left subfigure of Figure 48 - Figure 50. This trend is consistent with the supplier's aim to maximize daily revenue, now divided into three separate segments. Consequently, the pricing strategies are more customized, depending on the unique characteristics of each cluster.

It is particularly insightful to analyse the relationship between personalized retail prices and corresponding demand responses across different clusters, as well as how consumers' demand flexibility influences these dynamics. The first observation from Figure 49 reveals that the impact of demand flexibility on retail prices and demand response is minimal for cluster 2. This is because cluster 2 consumers predominantly use energy at daytime, while refraining from consumption during the first few hours of the day. With this pattern in mind, the strategic retailer sets the highest possible price (200 EUR/MWh) consistently across varying levels of demand flexibility, as flexibility doesn't significantly affect consumption patterns, especially the first few hours of the day.

In the remaining two clusters (1 and 3), demand patterns reflect typical daily consumption, where consumers predominantly use energy during the day or night but continue to use a certain amount at other times. This provides consumers with significant flexibility to adjust their consumption patterns, leading to substantial changes in their demand profiles. As a result, the strategic retailer significantly modifies its retail pricing to maintain daily revenue, ultimately losing its market power.

5.3.1.3. Business cases of stakeholders in electricity market

After analysing the relationship between retail prices and demand response, the final subsection focuses on further examining and comparing the business cases of both consumers and suppliers, between the traditional uniform pricing scheme and the proposed personalized pricing scheme across different levels of demand flexibility. These comparisons are illustrated in Figure 51 and Figure 52. The reduction percentages of the business cases, relative to the inflexible case (α = 0), are also shown for comparative analysis in Table 21 and Table 22.

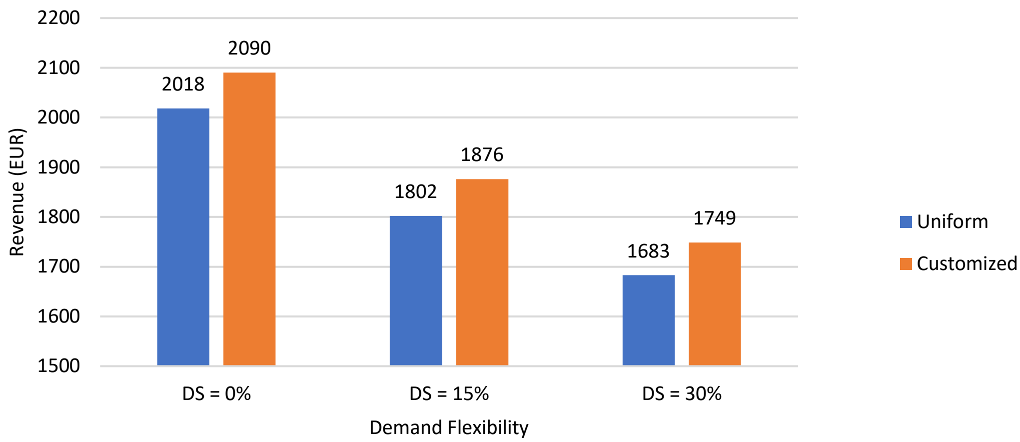


Figure 51: Daily business cases of consumers' cost for both uniform and personalized pricing schemes for different demand flexibility scenarios.

Table 22: Reductions of consumers' cost with respect to no flexibility for both uniform and personalized pricing schemes for different demand flexibility scenarios.

Consumer Cost Reduction w.r.t No Flexibility	DS = 15%	DS = 30%
Uniform	10.70%	16.60%
Customized	10.24%	16.32%

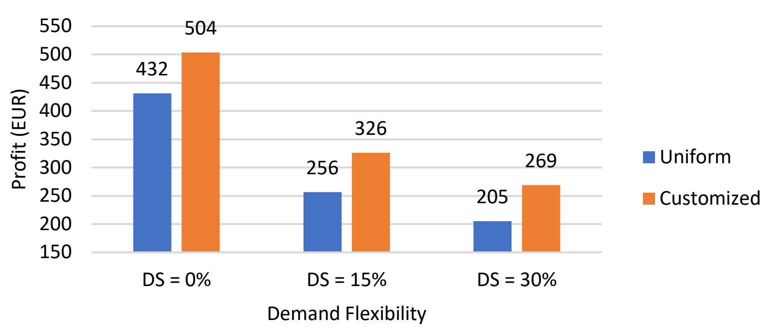


Figure 52: Daily business cases of supplier's profitability for both uniform and personalized pricing schemes for different demand flexibility scenarios.

Table 23: Reductions of supplier's profitability with respect to no flexibility for both uniform and personalised pricing schemes for different demand flexibility scenarios.

Retail Profit Reduction w.r.t No Flexibility	DS = 15%	DS = 30%
Uniform	41%	52%
Customized	35%	47%

It can be observed from Figure 51 that flexible consumers are benefiting from their demand flexibility, achieving lower energy costs as their flexibility increases. In addition, both the uniform and personalized pricing schemes demonstrate a similar flexibility benefit of cost reduction for consumers, as observed in Table 21. On the other hand, the supplier's profitability under the proposed personalized pricing scheme consistently exceeds those under the traditional uniform pricing scheme, as evidenced by Figure 52. This outcome aligns with the analyses in the previous two subsections, as the personalized pricing scheme better identifies consumer demand patterns and sets strategic retail prices accordingly. In other words, the supplier prioritizes strategies on the retail side (i.e., the personalized pricing scheme), while the wholesale side remains relatively competitive. In Table 22, it can be found that the profit reductions are less significant under the personalized pricing scheme than under the traditional uniform pricing scheme for both demand flexibility scenarios. For instance, when demand flexibility is α = 15%, profit reduction reaches 41% under the traditional uniform pricing scheme, but this decreases to 35% with the proposed personalized pricing scheme. Thus, while demand flexibility reduces the supplier's business cases, the personalized pricing scheme can alleviate this effect, ultimately benefiting the supplier's profitability.

5.3.2. Case studies of retail buy and sell pricing for local energy community

The aim of the presented case studies lies in analysing the techno-economic outcomes at the local level. Structural components related to market design considerations (e.g., structure of retail tariffs, local energy trading, flexibility procurement mechanisms) affect the interactions between the prosumers, the communities, and the aggregating entities. The effects that arise from the introduction of local trading as well as the efficiency and facilitation of the market mechanisms are the main aim of the conducted analysis.

5.3.2.1. P2G Case (Retail/Prosumer Interaction)

The peer-to-grid (P2G) case refers to the conventional market structure where the prosumers are contracted with a supplier for trading electricity according to predefined tariffs. It should be noted that this case constitutes the reference scenario, as it is assumed that there is not any local trading mechanism established, and that all the end-users interact individually with the supplier. The overall demand that is served by the supplier, i.e., the realised demand that results as a response to the buy prices is shown in Figure 53. Figure 54 shows the buy and sell prices at the Nash equilibrium. These are presented in contrast to the exogenous wholesale energy prices. It should be mentioned that the energy storage assets, in the P2G case, face the option of charging at the buy price and discharging at the sell price. The resulted buy-sell spread swifts the buy price curve at a totally higher level than the sell price curve, prohibits the ES from operating.

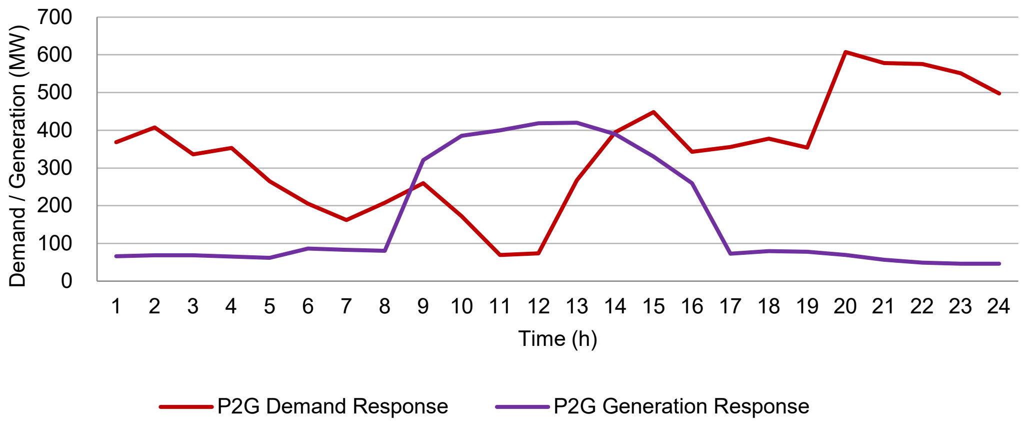


Figure 53: Demand and generation response for the P2G Case - Dynamic Tariff.

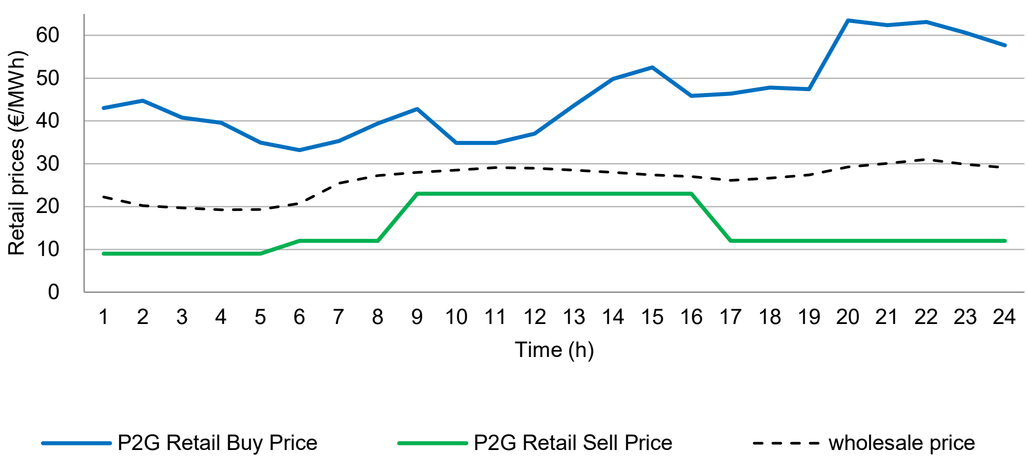


Figure 54: Buy and sell retails prices offered by the supplier in the P2G Case - Dynamic Tariff.

The self-consumption mode of the operation is very much in line with the local energy community concept and would require the integrated consideration of vRES generation and BESS. In terms of modelling implementation this would either require the alteration of the ES sub-model or the introduction of another independent player that would combine the behavioural and operational characteristics of both asset types. Finally, as the benchmark of market structure, the revenues for the supplier in P2G case turn out to be around €409.00, and the profits have been found to be €220.85. The utility of the FCs is found to be €99.97, and the profit of MGs €5.80, leading to an overall social welfare of €105.77 for the local stakeholders.

5.3.2.2. Centralised LEM (Retailer/LEM Interaction)

Figure 55 and Figure 56 illustrate the hourly profiles of overall demand and generation for customers served by the supplier. Figure 57 shows the resulting hourly net demand profiles of the LEM, including the P2G case where no LEM is established, presented for comparison. It is important to highlight that there is excess generation in the LEM before noon, resulting in negative net demand, while there is a deficit during all other hours.

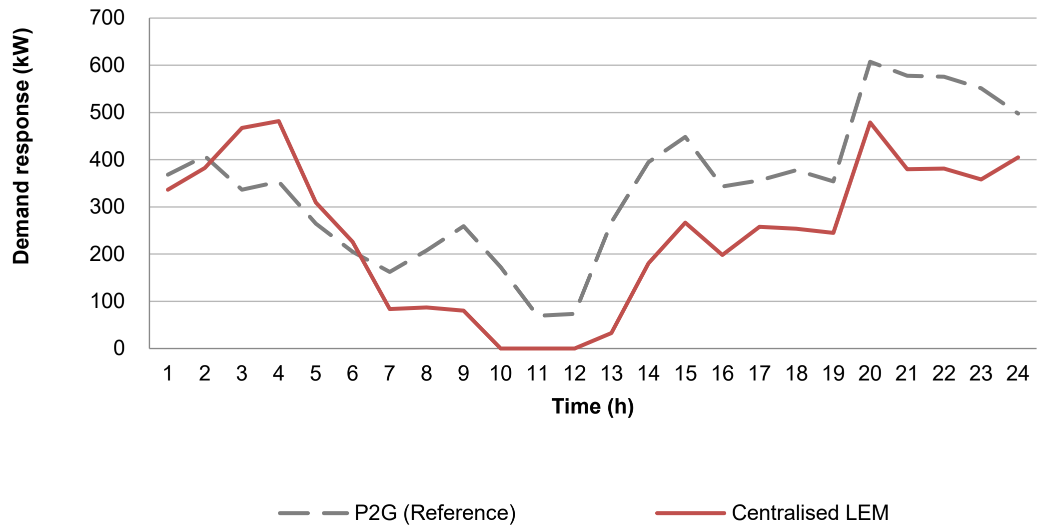


Figure 55: Total demand served by the supplier for two scenarios.

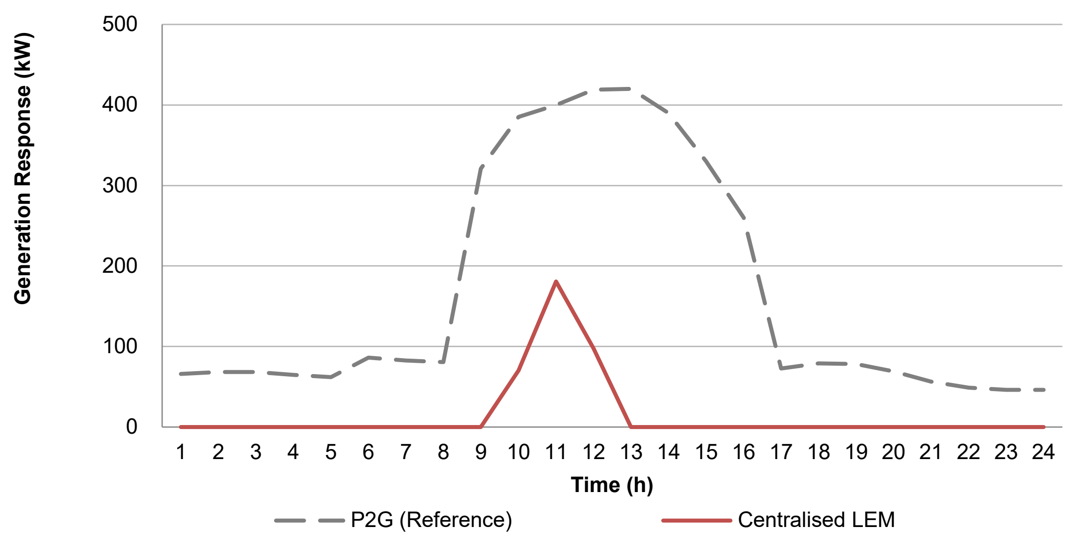


Figure 56: Total generation served by the supplier for two scenarios.

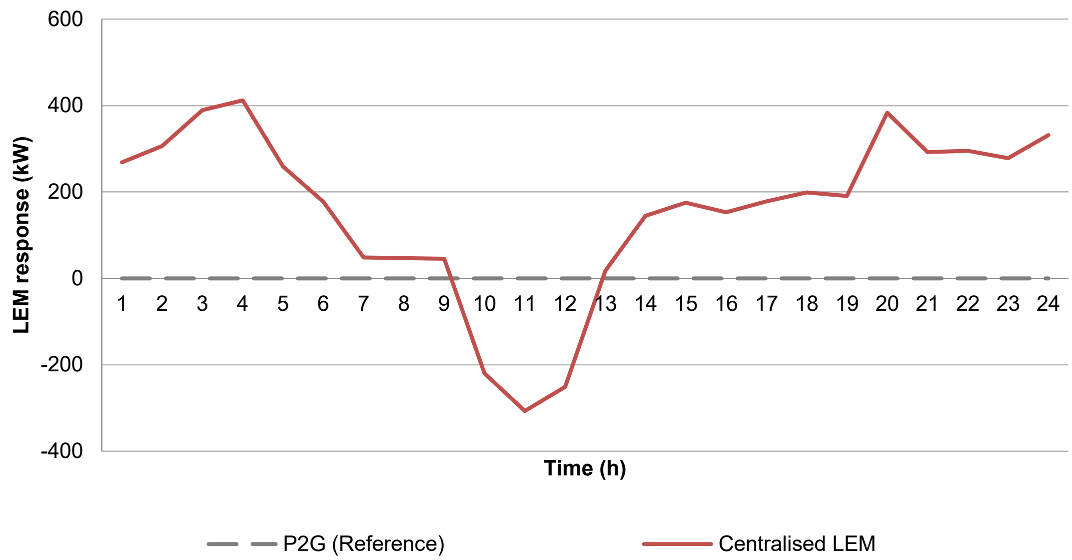


Figure 57: Net demand of LEM for two scenarios.

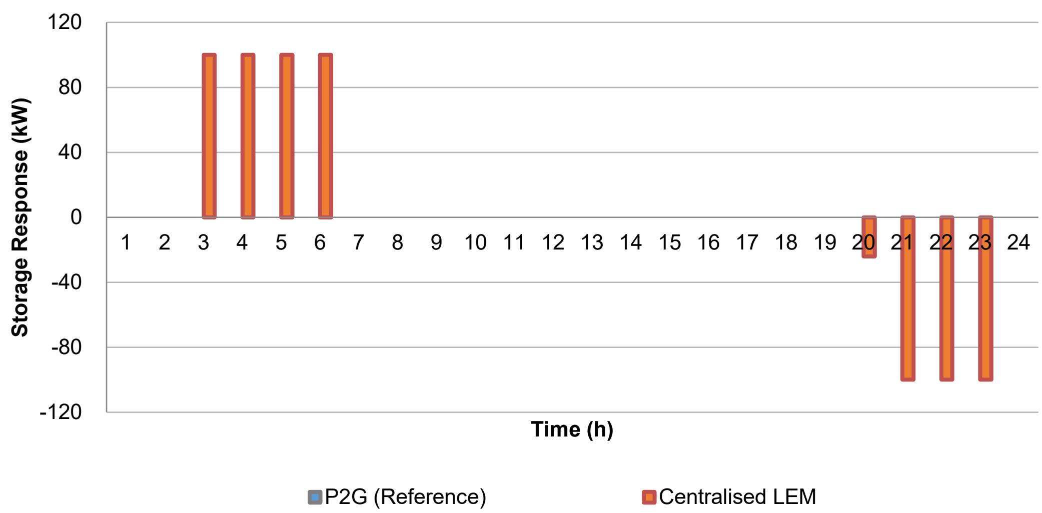


Figure 58: Aggregate charging / discharging power of ESs for two scenarios.

In the demand and generation response figures (Figure 55 and Figure 56), it is observed that the realized demand and total generation served by the supplier are highest in the P2G reference scenario across most hours. This can be attributed to the market power of the retailer operating under monopoly/monopsony conditions. In the absence of an LEM, independent end-users (FC, MG, ES) are compelled to buy and sell energy solely through the supplier. Conversely, with a centralized LEM in place, customers can engage in bilateral energy trading on more favourable terms, only resorting to the supplier for energy exceeding the local balance.

Therefore, while the LEM participants still depend on the supplier, this dependency is limited and corresponds to different marginal evaluation levels. The LEM generally buys energy from the supplier most of the day, except during hours of excess generation, and sells energy to the supplier when generation surpasses low demand requirements.

Figure 58 presents the aggregated hourly charging/discharging power actions of the two ES players, with positive values indicating charging and negative values indicating discharging. Notably, in the centralized LEM scenario, unlike the P2G reference scenario, the ESs are actively participating in the LEM rather than remaining idle. ESs engage in charging/discharging activities, benefiting both the ES players and the LEM participants representing generation and load resources. Participation in the local market provides access to favourable LEM clearing prices, which, unlike the supplier's differentiated buy and sell prices, have zero spread, enabling energy arbitrage between peak and off-peak hours. Moreover, the LEM's unified operation and controllability over all assets, along with the utilization of aggregated flexibility, provide a competitive advantage, further reducing dependency on the supplier.

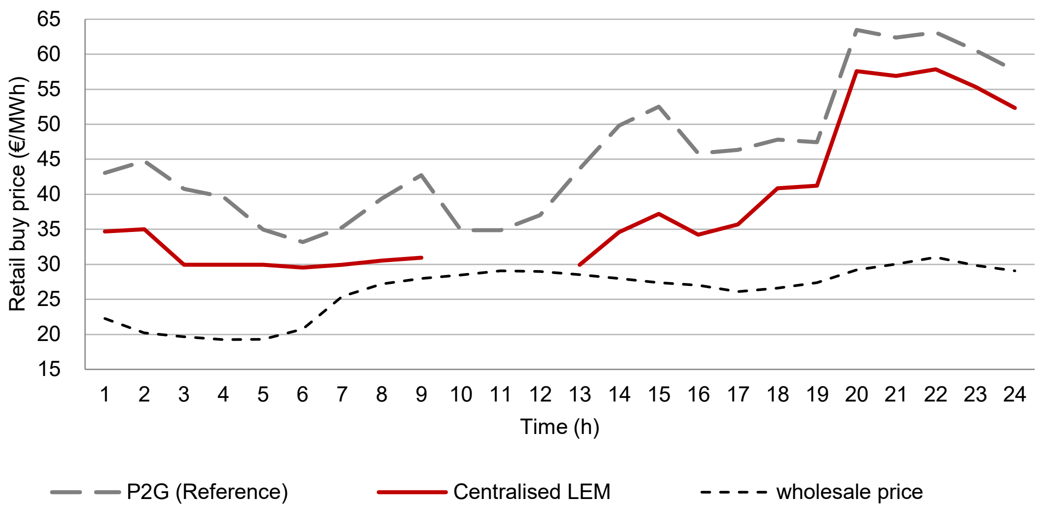


Figure 59: Buy prices offered by the supplier for two scenarios.

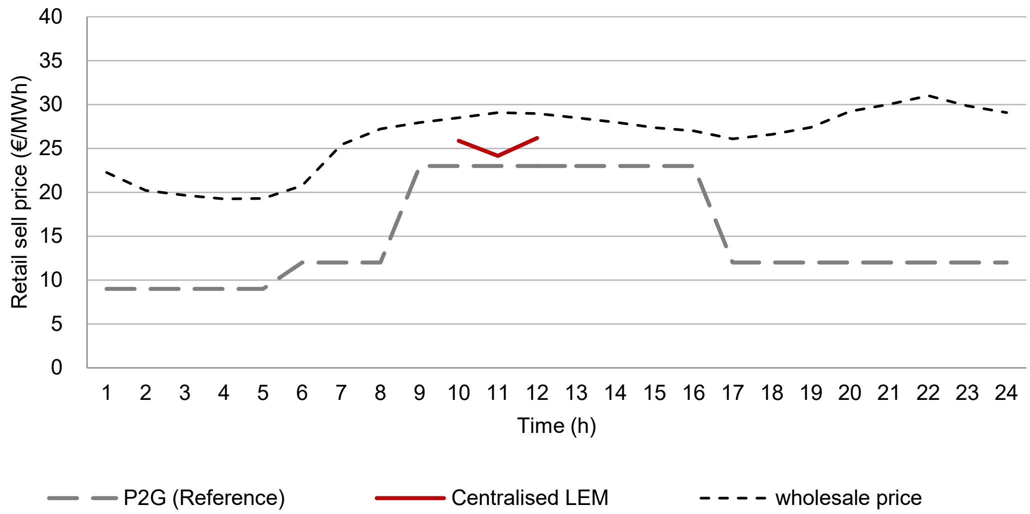


Figure 60: Sell prices offered by the supplier for two scenarios.

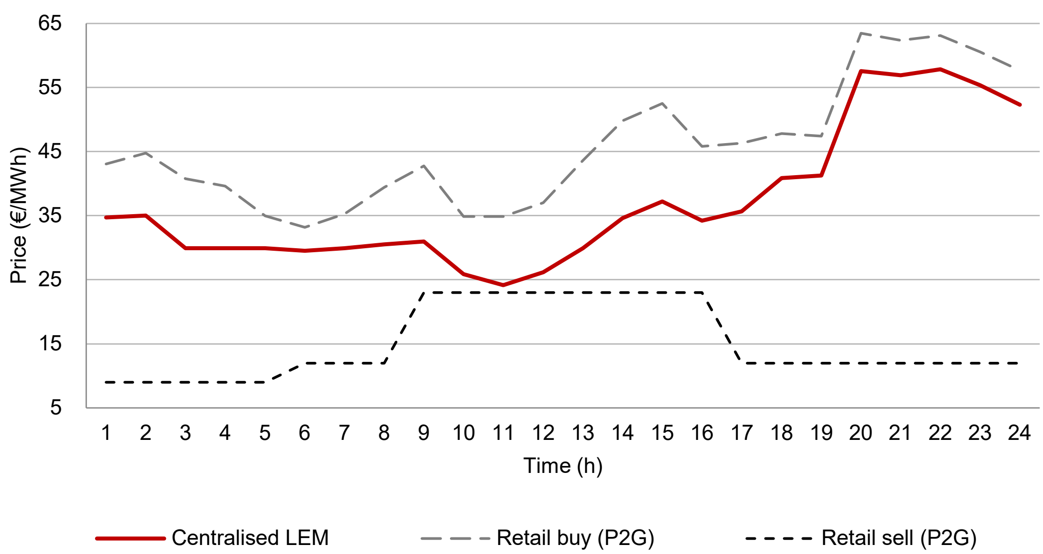


Figure 61: LEM clearing prices for two scenarios.

Regarding the economic interactions in the centralized LEM case, three distinct prices are defined: the LEM clearing price, the retail buy price, and the retail sell price. Prices are fundamentally based on the agreed monetary value for a realized transaction, meaning they are only well-defined when both bid and ask sides reach an agreement, resulting in a trade.

Figure 59 and Figure 60 display the hourly profiles of the retail buy and sell prices offered by the supplier for both the P2G reference and centralized LEM scenarios. For comparability, the wholesale prices faced by the supplier in its internal operations are also shown. Notably, in the centralized LEM case, the retail buy price is not defined during periods without buy transactions with the supplier (Figure 59), and similarly, sell prices are only defined during times when the LEM sells to the supplier (Figure 60).

Figure 61 illustrates the hourly profiles of the LEM clearing prices, which correspond to the dual variables of the balance constraint of the LEM, along with the buy and sell prices offered by the supplier in the P2G reference scenario.

In the P2G reference scenario, the strategic supplier offers very high buy prices (significantly higher than the wholesale price) to demanding customers (Figure 59) and very low sell prices (significantly lower than the wholesale price) to generating customers (Figure 60). This exploitation of market power, characterized by large differentials between buy and sell prices, supports the supplier's objective of maximizing overall operational profits.

In the centralized LEM scenario, participants (all end-users) opt to trade energy locally at LEM prices (Figure 61). due to the high buy prices and low sell prices of the supplier, making local trading mutually beneficial for all FC, MG, and ES participants. This limited dependency on the supplier significantly reduces the total demand and generation served by the supplier, leading to lower offered buy prices across most hours (1-9 & 13-24) to attract higher demand (Figure 59) and increased sell prices during hours 10-12 to attract more generation (Figure 60), compensating for the reduction caused by the LEM.

From the supplier's perspective, the introduction of the LEM limits the potential for strategic exploitation. The trends indicate that the large differentials between buy and sell prices are reduced, bringing offered prices closer to wholesale levels. Considering competition at the supplier level could further suppress prices towards wholesale values. Finally, the issue of undefined prices could be resolved by considering a generic scenario where some end-users participate in the LEM while others remain solely with the supplier, ensuring buy/sell transactions throughout the horizon.

5.3.2.3. Business cases of stakeholders in electricity market

The next step is to quantify and analyse the impact of the LEM on the economics of the supplier and its served consumers. Table 23 presents the daily revenue, retail cost, wholesale net cost, and profit of the studied supplier.

Table 24: Economics of Supplier for Two Scenarios.

Scenario	Revenue (€)	Retail cost (€)	Wholesale net cost (€)	Profit (€)
P2G Reference	409.00	79.21	108.94	220.85
Centralised LEM	242.91	8.75	139.51	94.64

As seen in Table 23, the supplier's revenue represents the largest portion of its net profit, so we begin our examination there. Specifically, the centralized LEM scenario significantly reduces this retail revenue by 68% compared to the P2G Reference scenario. This reduction is due to the lower buy prices set by the supplier (Figure 59) and the decreased overall demand it serves (Figure 55). Similarly, the centralized LEM scenario significantly lowers the supplier's cost of purchasing energy from its generating customers by 805% compared to the P2G Reference scenario.

This trend arises because, despite a slight increase in sell prices (Figure 60), the LEM dramatically reduces the total generation served by the supplier (Figure 56.

Furthermore, the centralized LEM scenario results in a 22% increase in the supplier's net cost in the wholesale market compared to the P2G Reference scenario. This trend is caused by the LEM reducing the total generation served by the supplier more than the reduction in total demand served (Figure 55 and Figure 56), necessitating additional energy purchases from the wholesale market. Overall, the introduction of the LEM significantly lowers the supplier's total profit by 133% in the centralized LEM scenario compared to the P2G Reference scenario. This substantial reduction is primarily driven by the decline in retail net revenue and the corresponding rise in wholesale net cost.

Table 25: Utility of Flexible Consumers for Different Scenarios.

Scenario	Utility of FC (€)	Profit of MG (€)	Profit of ES (€)	Social Welfare (€)
P2G Reference	99.97	5.80	-	105.77
Centralised LEM	187.88	86.27	6.46	280.61

Moving our focus to the customers, Table 24 presents the total daily economic surplus of FC, MG, and ES, as well as the customers' total social welfare. The data in Table 2 shows that the economic outcomes for all customer types, as well as the overall social welfare, are improved in the centralized LEM scenario compared to the P2G Reference scenario. This improvement is due to the customers trading energy based on the LEM clearing prices rather than the high retail buy prices and low retail sell prices.

5.3.3. Case studies of optimization and learning approaches for P2P energy trading problems

We conducted the P2P energy trading experiment using a real-world European residential community dataset comprising 250 households. Their daily energy demand and photovoltaic (PV) power generation patterns are depicted in Figure 62. Additionally, eight types of energy storage models are deployed across these 150 households to showcase their flexibility, with detailed operating parameters provided in Table 25. Grid prices consist of the Time-of-Use (ToU) tariff, which varies throughout the day as the grid buy price, and the Feed-in Tariff (FiT), which is the fixed grid sell price of 0.04 EUR/kWh for the entire day, as shown in Figure 63.

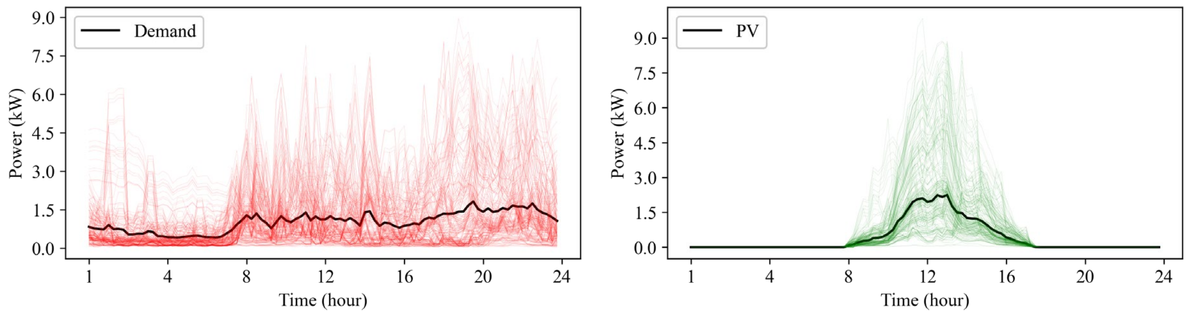


Figure 62: *Daily demand and PV power generation of European residential community 250 households.*

Table 26: Technical parameters of eight energy storage models.

Parameters	M1	M2	M3	M4	M5	M6	M7	M8
Energy capacity (kWh)	8.6	12.9	6.4	9.6	9.3	11.7	6.6	6.4
Power capacity (kW)	4.3	6.5	2	5	5	5	3.5	2
Efficiency (%)	97	96	95	97.5	95	95	94.5	95
Initial (kWh)	4.3	6.45	3.2	4.8	4.65	5.85	3.3	3.2

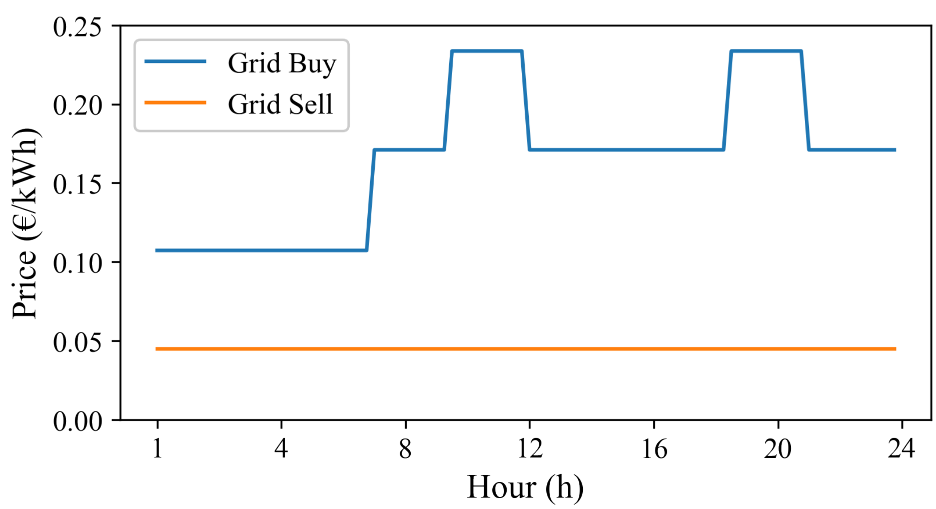


Figure 63: *Grid buy and sell prices for P2P energy trading*

5.3.3.1. Mid-Market-Rate (MMR)

This section compares the market performance of the Mid-Market Rate (MMR) pricing scheme using both traditional optimization and reinforcement learning (RL) approaches. Figure 64 shows the Local Energy Market (LEM) buy price (dashed blue line) and sell price (dashed orange line) for both optimization and RL methods, with the grid buy price (solid blue line) and grid sell price (solid orange line) included as reference levels. Figure 65 illustrates the charging (orange bars) and discharging (blue bars) power of the community's aggregated energy storage units for both approaches. Figure 66 depicts the community's net load profiles, incorporating PV power generation and storage charging and discharging flexibility. The solid black line in Figure 66 represents the baseline load level without considering storage flexibility. Lastly, Table 26 provides a summary of the operational characteristics and the community's total operational costs for both approaches.

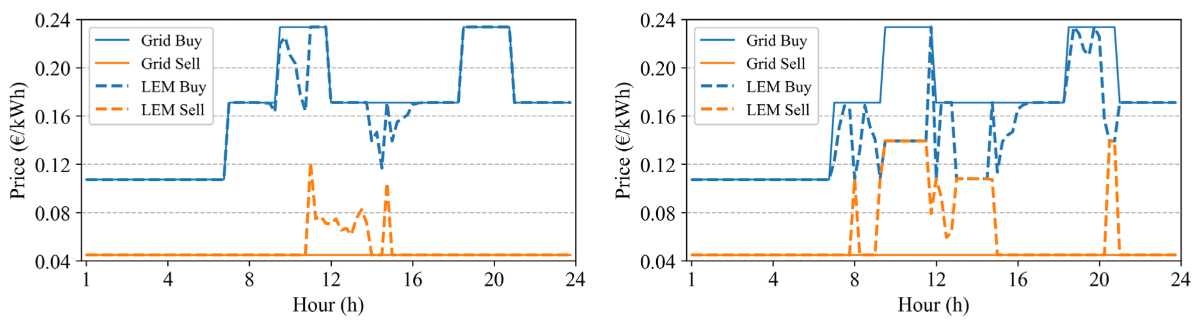


Figure 64: *Mid-market rate buy and sell prices for Optimization and RL approaches.*

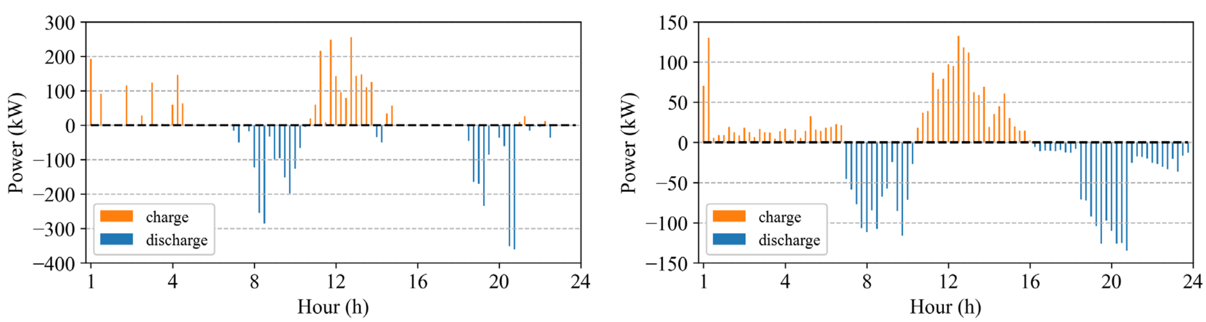


Figure 65: *Storage charging and discharging power for Optimization and RL approaches.*

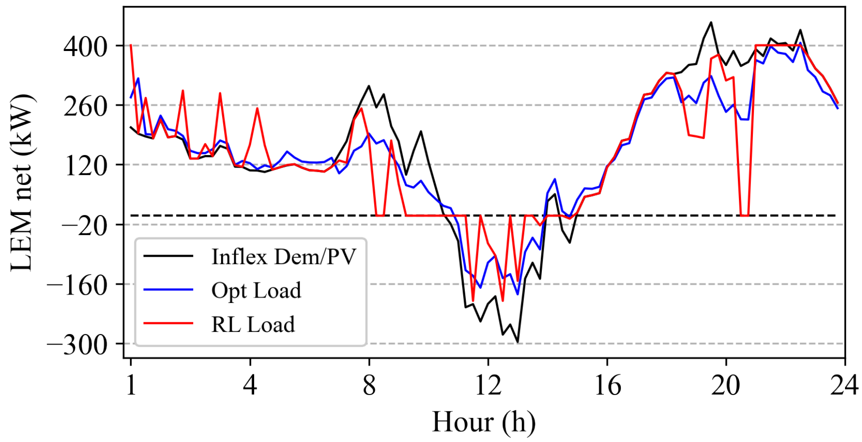


Figure 66: *Community aggregate net profiles of 250 households for Optimization and RL approaches under Mid-market rate scheme.*

Table 27: Characteristics and Community cost for Optimization and RL approaches under Mid-market rate scheme.

Case	Approach	Knowledge	Privacy	Strategy	Cost (ERU)
MMR-Opt	Optimization	Yes	No	Static	2,625
MMR-RL	Learning	No	Yes	Dynamic	2,527

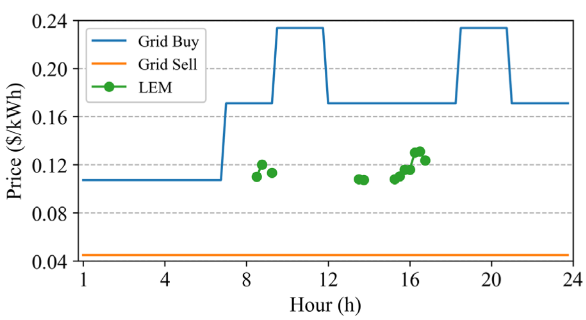
Under the optimization approach, local trading mainly occurs at midday when PV resources are abundant. This is because households using this method do not account for local market dynamics while optimizing their energy storage models individually based on fixed grid buy and sell prices determined day-ahead. As depicted in the left subfigure of Figure 65, the flexibility of energy storage models is not fully utilized, with limited charging periods during the morning (when grid buy prices are low) and at midday (when PV resources are plentiful). Discharging occurs briefly during early morning and night peak demand periods. Moreover, the left subfigure of Figure 64 shows a gap between local buy and sell prices, indicating that economic benefits are not fully maximized since local buy prices remain higher than local sell prices even during local trading.

In contrast, with the RL approach, households learn real-time charging and discharging behaviour, accounting for local trading market dynamics. This allows them to fully utilize their energy storage flexibility and coordinate with others. For example, more pronounced charging activity at midday (as shown in the left subfigure of Figure 65) helps households not only absorb their own PV resources but also charge surplus PV from neighbours, preventing curtailment or economic losses from selling excess PV back to the grid at low prices. Discharging activities are also more significant under this approach, reducing peak demand periods and maximizing energy storage flexibility. Additionally, the right subfigure of Figure 64 demonstrates that local buy and sell prices are much closer or even identical for certain periods, ensuring fairness and consistent pricing for buyers and sellers.

Examining the community's net load profiles in Figure 66 reveals that both optimization and RL approaches bring the community's net load profiles close to zero, particularly in the early morning, midday, and nighttime periods. However, the RL approach achieves more significant demand reductions during the early morning and nighttime periods. Additionally, PV absorption is more pronounced under the RL approach. Consequently, the community's overall operational cost is lower with the RL approach (EUR 2,527) compared to the optimization approach (EUR 2,625), as shown in Table 26.

5.3.3.2. Double-Auction Market (DA)

This section compares the market performance of the Double-Auction (DA) pricing scheme using both traditional optimization and reinforcement learning (RL) approaches. Figure 67 presents the Local Energy Market (LEM) trading price (green dotted line) for both optimization and RL methods, with the grid buy price (solid blue line) and grid sell price (solid orange line) included as reference benchmarks. Notably, unlike the separate local buy and sell prices under the Mid-Market Rate (MMR) pricing scheme, the DA pricing scheme uses a single, uniform local price for both buying and selling. Figure 68 illustrates the local trading quantities among the 250 households in the community for both approaches. Figure 69 displays the community's net load profiles, integrating PV power generation as well as storage charging and discharging flexibility. The solid black line in Figure 69 represents the baseline load level when storage flexibility is not considered. Finally, Table 27 summarizes the operational characteristics and the total operational costs of the community for both approaches.



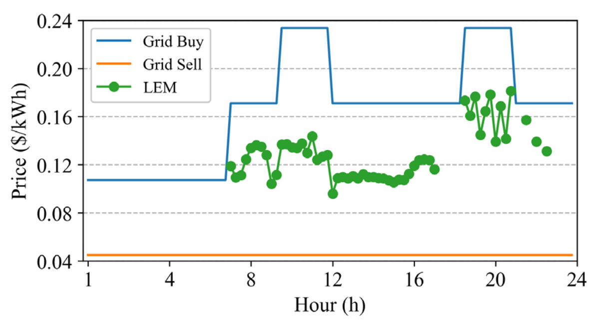


Figure 67: *Double auction buy and sell prices for Optimization and RL approaches.*

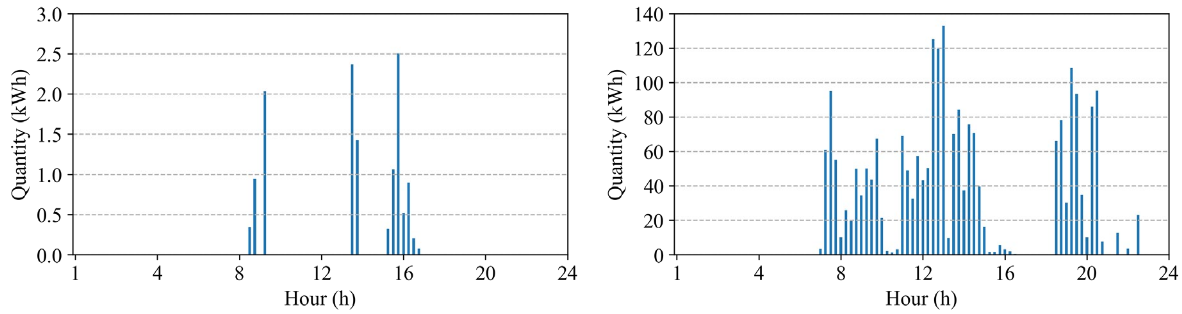


Figure 68: *Local trading quantity for Optimization and RL approaches under Double-auction scheme*

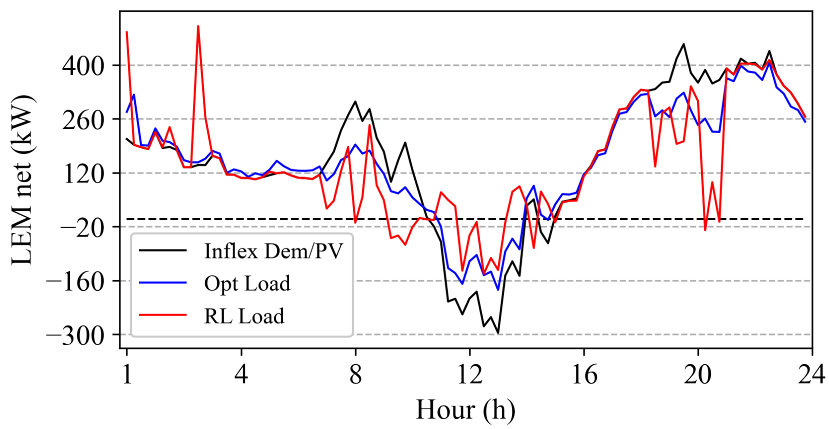


Figure 69: *Community aggregate net profiles of 250 households for Optimization and RL approaches under Double-auction scheme.*

Table 28: Characteristics and Community trading quantity and cost for Optimization and RL approaches under Double-auction scheme.

Case	Approach	Knowledge	Privacy	Strategy	Trading (kWh)	Cost (ERU)
DA-Opt	Optimization	Yes	No	Static	13	2,720
DA-RL	Learning	No	Yes	Dynamic	2,290	2,477

Similar to the Mid-Market Rate (MMR) pricing scheme, the local trading quantities under the RL approach are significantly higher than those under the optimization approach, as evidenced in Figure 67 and Figure 68 and Table 27. Additionally, Figure 69 shows that the net load profile of the community under the RL approach is much closer to zero compared to the net load profile under the optimization approach. Finally, the RL approach achieves a lower operational cost (EUR 2,477) than the optimization approach (EUR 2,720).

6. Conclusions

This report presents the critical findings, implications, and recommendations from a comprehensive assessment of market designs and trading mechanisms for Local Energy Communities (LECs). The study demonstrated substantial cost savings and enhanced energy efficiency through various market designs, including centralized optimization and decentralized peer-to-peer (P2P) trading. These findings highlight the economic, environmental, and social benefits of LECs, empowering consumers to play a central role in managing their energy production, consumption, and trading.

The implications of this study underscore the transformative potential of decentralized energy systems in promoting sustainability and resilience. The integration of advanced technologies, such as blockchain and machine learning, was shown to optimize market operations and address information asymmetry, further enhancing the effectiveness of LECs and Local Energy Markets (LEMs). However, the study also identified regulatory challenges, including variations in national policies and the evolving nature of local energy communities, which need to be addressed to fully realize the potential of LEMs.

Despite these promising results, the study encountered several limitations. The existence of many different models and levels of modelling made it difficult to compare results directly and draw strong, generalized conclusions. The diversity in methodologies and assumptions across the models created challenges in establishing a consistent evaluation framework. Additionally, the nascent stage of some technologies and varying national implementations of EU directives added complexity to the analysis and hindered the ability to make definitive policy recommendations.

Based on these findings, the report recommends strengthening regulatory frameworks to support the growth and operation of LECs, investing in innovative technologies to enhance market efficiency, and promoting active consumer participation in energy markets. These measures will facilitate the development of sustainable and autonomous energy systems, aligning with broader EU climate and energy objectives.

Future research should focus on developing standardized models and methodologies to facilitate better comparison and integration of results. It is essential to conduct long-term studies that assess the impact of regulatory changes and technological advancements on LECs and LEMs. Additionally, exploring the socio-economic impacts of decentralized energy systems on local communities will provide a more comprehensive understanding of their benefits and challenges. Collaborative efforts between policymakers, stakeholders, and communities will be crucial in implementing the recommendations and achieving sustainable energy goals.

In conclusion, this report provides a comprehensive evaluation of current and new market designs and trading mechanisms for LECs, offering valuable insights into the benefits and challenges of decentralized energy systems. The findings underscore the potential of LECs and LEMs to drive the transition towards a more sustainable, efficient, and resilient energy future. By addressing regulatory challenges, standardizing evaluation methodologies, and leveraging advanced technologies, significant progress can be made in the energy sector, fostering a cleaner and more equitable energy landscape.

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Annex A - Local market performance indicators (LMPIs)

In addition to the Market Performance Indicators (MPIs) presented in D5.1, additional Local Market Performance Indicators (LMPIs) are computed for this task. This annex presents each of the LMPIs computed in a consistent way using the following descriptors:

- Name (and acronym): Identification of the MPI and (when applicable) an acronym is provided.
- Detailed description: Detailed description of the MPI, indicating its objective and motivation to be analysed in the project. When applicable bibliographic references and common/reference values mentioned in the literature are also provided.
- Measuring the MPI/Unit: Indication how the MPI can be measured. When applicable the units of the MPI are also presented.
- Mathematical formulation: Identification of the mathematical formulation to compute the MPI.
- Target and optimal value (when applicable): Indicate the target and optimal value of the MPI. In this case, the information can be generic (e.g., increase the annual share of vRES generation). When applicable the optimal value will be provided.
- Case studies: Pre-identification of the case studies where the indicator will be used.

Table 28 presents the LMPIs:

Table 29 Overview of LMPIs

LMPI #1	
Name	Local Energy Neutrality
Detailed description	The ratio of local energy production regarding the consumption. Total production/consumption ratio over a period of time
Measuring the MPI/Unit	Percentage (%)
Mathematical formulation	$\frac{\sum_{t=1}^{T}\sum_{i=1}^{N} P_{i,t}^{Gen}}{\sum_{t=1}^{T}\sum_{i=1}^{N} P_{i,t}^{Dem}}$ where $P_{i,t}^{Gen}$ and $P_{i,t}^{Dem}$ is the power generated and demanded in node i at time t
Target and optimal value (when applicable)	Close to 1
Case studies	Local case studies
Domain	Technical / economic / environmental / social.

LMPI #2	
Name	Nodal consumption
Detailed description	Real time demand covered by local or prosumer renewable generation
Measuring the MPI/Unit	Percentage (%)
Mathematical formulation	$\frac{\sum_{t=1}^{T}\sum_{i=1}^{N}\frac{P_{i,t}^{Gen}}{P_{i,t}^{Dem}}}{T\cdot N}$ where $P_{i,t}^{Gen}$ and $P_{i,t}^{Dem}$ is the power generated and demanded in node i at time t
Target and optimal value (when applicable)	Close to 1
Case studies	
Domain	Technical / economic / environmental / social.

LMPI #3	
Name	Import-export ratio
Detailed description	The import minus export relative balance of energy
Measuring the MPI/Unit	Percentage (%)
Mathematical formulation	$\frac{\sum_{t=1}^{T}\sum_{i=1}^{N}P_{i,t}^{Imports}}{\sum_{t=1}^{T}\sum_{i=1}^{N}P_{i,t}^{Exports}}$ if well defined where $P_{i,t}^{Imports}=\max\left(0,\ P_{i,t}^{Dem}-P_{i,t}^{Gen}\right)$ and $P_{i,t}^{Exports}=\max\left(0,\ P_{i,t}^{Gen}-P_{i,t}^{Dem}\right)$
Target and optimal value (when applicable)	
Case studies	
Domain	Technical / economic / environmental / social.

LMPI #4	
Name	Total local costs (adapted from MPI #26 to local markets)
Detailed description	This MPI represents the local power system costs, including its investments and operation.
Measuring the MPI/Unit	€
Mathematical formulation	Total local Costs= Investment costs + O&M costs + trading costs + fuel costs + load shedding costs
Target and optimal value (when applicable)	
Case studies	LEC
Domain	Economic

LMPI #5	
Name	Levelized local costs (adapted from MPI #26 to local markets)
Detailed description	Cost per consumed energy
Measuring the MPI/Unit	€/MWh
Mathematical formulation	Levelized local costs=Total local Costs/ Local consumption
Target and optimal value (when applicable)	Compare results with reference tariffs/costs
Case studies	LEC
Domain	Economic

LMPI #6	
Name	Local Autarky (self-sufficiency)
Detailed description	The ratio of consumption satisfied by local production without exports and imports.
Measuring the MPI/Unit	Percentage (%)
Mathematical formulation	$$\overline{LAI} = \sum_{y,t} \frac{\min\left[\sum_i\left(P_{i,y,t}^{Gen}\right), \sum_i\left(P_{i,y,t}^{Dem}\right)\right]}{\sum_i\left(P_{i,y,t}^{Dem}\right)} \quad (13)$$ where $$P_{i,y,t}^{Gen} = P_{i,y,t}^{PV} + D_{i,y,t}^{ES} \quad (14)$$ $$P_{i,y,t}^{Dem} = P_{i,y,t}^{L} + P_{i,y,t}^{HVAC} + C_{i,y,t}^{ES} \quad (15)$$
Target and optimal value (when applicable)	Close to 1
Case studies	Local case studies
Domain	Technical / economic / environmental / social.