Design, Development and Validation of Centralised Two-Stage P2P Energy Community Market

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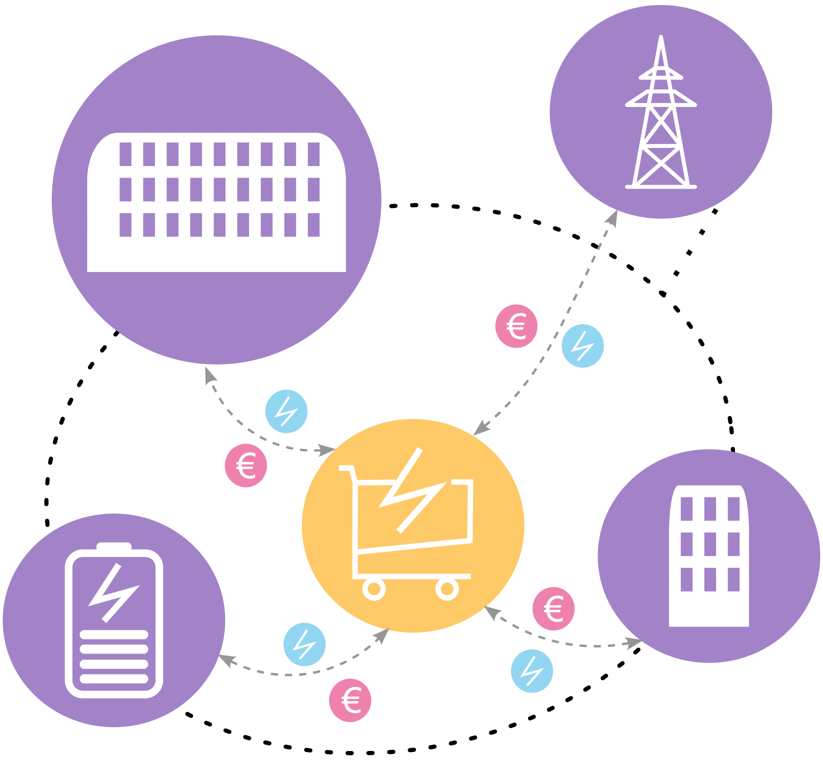

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If you know you are on the right track,
if you have this inner knowledge,
then nobody can turn you off...
no matter what they say.
— Barbara McClintock [1]

[1] The first woman to be awarded the Nobel Prize for Physiology or Medicine in 1983 and the only woman to have received the Nobel Prize in this discipline as the sole recipient.

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I'm free in salt water. Embrace the deep and leave everything. It was just a dream.[2]

Depresio larria eta antsietate orokortua diagnostikatu zizkidan psikologoak. Gorputzak eta, batez ere nire garunak, gelditzea eskatu zidaten. Hilabete gogor eta luze horietan, nire burua eta gustuko nuena auzian jarri nituen; tartean tesia. Lana geldirik egon zen lau hilabete horietan oso serioki baloratu nuen bertan behera uztea.

Ondo ezagutzen nauzuenok badakizue nire ikasketak bokazio direla, energia berriztagarrietan eta autokontsumoan sutsuki sinisten baitut. Nire inguruko batzuek ikasketak uztera animatzen ninduzuen, nire barne-sufrimenduarengatik. Nire barnean, banekien zeintzuk ziren nire errailak, eta hemen nauzue, bidaiaren azken geldialdian. Medikazioa, terapia —eskerrik asko María por la caja de herramientas que construímos y llenamos—eta lan pertsonal asko eta gero, depresioaren zulo hori tapatuta dago eta bertan oinarriak eraikita ditut.

Suntsitu nazazu ahalbazu, erreinu bat daukat eraikita zugandik salbu.[3]

Bidea ez da erraza izan; horregatik, bide honetan nire aldamenean egon zareten guztioi eskerrak eman nahi dizkizuet.

[2]Ed Sheeran, "Salt Water" (2023)
[3]IZARO, "x eta besteak" (2023)

Eskerrak eman nahi dizkiot, lehenik, Haizea Gaztañagari, IKERLANetik lan hau egiteko nigan konfiantza izan zuelako. Ez tesiarekin bakarrik, GRALetik nigan konfiantza izateagatik, eskerrik asko ia zortzi urte hauetan zehar emandako aukerengatik. Eskerrak baita ere tesiko tutore izan diren Aitor Milo eta Elvira Fernandezi, aparteko gidariak izan zarete arlo teknikoan. Gainera, pertsonalki, osasun fisiko eta mentaleko arazoak izaterakoan babesa eskaini didazue. Eskerrik asko nire lan-tresna (garuna) zaindu behar dudala ulertzeagatik eta, behar nuen guztietan, nire espazioa emateagatik.

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Nire kuadrilarekin igaro dudan momentu orori. Independiente garen adina maite zaituztet eta zuekin igaro ditudan momentu guztiak eskertzen dizuet. Tesia egiten nuen ahala, aldamenean hazi gara: ikasketen amaierak, etxe erosketak, ezkontzak eta umeak. Bakoitza bere ibilbidearekin eta adiskidetasuna elkargune. Eskerrik asko gosari, hamaiketako, bazkari, medienda, afari eta juerga bakoitzarengatik. Eta noski, nire *malaletxe* momentuak pairatzeagatik.

Jenio txarreko momentu horiek pairatu dituzten gehiengoa Aita eta Ama izan dira. Eta tesiarengatik botatako izerdi eta negar-malkoen lekuko nagusiak ere. Zuek bai dakizuela zeinen gogorra egin zaidan. Bai gaixorik nengoenean eta baita amaier-ako maratoiean. Baina hemen dago, helmugan, nire liburutxoa zuen liburutegian egoteko zain. Ez dut hitzik eskertzeko zuek eman didazuen guztia.

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Emakume feminista haiei, emakumeon berdintasuna aldarrikatu izanagatik. Beste hainbat erreibindikazioren artean, emakumeon ikasketak eskatzeagatik. Emakume zientzialariei, bidea ireki zuten emakume haiei eta jarraitu dutenei. Zuei esker nire bidea jarraitu dut trabarik gabe. Inspirazio zarete niretzat.

Eta, azkenik, nire buruari eskerrak eman nahi dizkiot. Psikologoak erakutsi zidan bezala, norbera da norberaren bizitzako pertsonarik garrantzisuena, eta ikasketa hori nire tesian islatu nahi dut. Eskerrak eman nahi dizkiot nire buruari momenturik zailenetan zulotik ateratzeko eduki nuen indarragatik eta egin nuen lanarengatik. Doktoretzak antsietatearekin pultsua egiten zuen momentuak kudeatu izanagatik eta bideko errailen barne mantendu naizelako.

Eskerrik asko denoi, bihotzez

Abstract

Title: Design, Development, and Validation of Centralised Two-Stage P2P Energy Community Market.

The European Union has set ambitious targets to fight climate change and reduce greenhouse gas emissions, including a target of 32 % of final energy consumption coming from renewable sources by 2030. In meeting these targets, the European Union emphasises the importance of distributed generation, particularly small renewable energy producers, which can play an essential role in reducing emissions, particularly in the residential sector. Distributed generation can contribute to the local economy, reduce energy losses during distribution, and empower end-users to participate actively in energy management by utilising nearby energy resources.

Digitalisation has enabled two-way energy distribution and changed end-users' roles from passive consumers to active participants in the energy market. This has strengthened various low voltage structures, such as microgrids, virtual power plants and energy communities. Energy communities enable peer-to-peer energy trading and decentralised energy management, promoting sustainable energy practices by allowing the end-users to prioritise their social, economic, environmental and energy efficiency preferences.

Energy communities can be limited to only consuming renewable energy sources, whose intermittent nature and fluctuating demand patterns pose challenges to effectively managing energy within community limits. Addressing forecasting errors in energy demand and consumption is fundamental to ensuring the reliability and efficiency of energy community operations.

The PhD thesis aims to design, develop, and validate a centralised two-stage peer-to-peer energy community market, addressing forecasting errors, developing new price-settlement methodologies, establishing business models incorporating energy storage, and creating energy management strategies aligned with energy community participants' preferences.

A novel two-stage energy-sharing market was proposed, rooted in a centralised management to optimise the energy trading (energy volume and price) for a peer-to-peer market. A methodology was employed to evaluate the functioning of the proposed energy-sharing market. The first stage, long-term, assumes an ideal scenario where different energy-sharing markets are compared. Then, in the second stage, diverse storage solutions are contrasted to cope with prediction errors in a short-term. The research contributes to advancing the understanding and implementation of sustainable energy practices, paving the way for a more efficient and resilient energy future.

In summary, the thesis explores the integration of energy communities, addresses challenges such as forecasting errors, proposes innovative solutions to optimise energy management, and introduces novel storage solutions to the research community.

Key words: Renewable energy community, Local Energy Market, Energy forecast, Energy Management Strategy, Battery-as-a-Service, Stationary battery, Mixed-Integer Linear Programming, Gradient Boosting Regression Tree.

Laburpena

Izenburua: Bi etapako P2P energia-merkatu zentralizatuaren diseinua, garapena eta balioztatzea.

Europar Batasunak asmo handiko helburuak ezarri ditu klima-aldaketaren aurka borrokatzeko eta berotegi-efektuko gasen emisioa murrizteko, besteak beste, 2030erako energia kontsumoaren % 32 iturri berriztagarrietan jatorria izatea. Helburu horiek betetzeko, Europar Batasunak sorkuntza banatuaren garrantzia azpimarratzen du, bereziki energia berriztagarriak eskala txikian ekoiztearena, emisioak murriztu baititzake, batez ere, bizitegi-sektorean. Sorkuntza banatuak, tokiko energia baliabideak erabiliz, lekuko ekonomia areagotu dezake, energia-galerak murriztu ditzake, eta azken kontsumitzaileei energiaren kudeaketan aktiboki parte hartzeko ahalmena eman diezaieke.

Digitalizazioak bi norabideko energia-banaketa ahalbidetu du, azken erabiltzaileen rolak aldatuz: energia-merkatuko kontsumitzaile pasiboak izatetik partehartzaile aktiboak izatera igaro daitezke. Ezaugarri horrek behe-tentsioko hainbat egitura indartu ditu, hala nola mikrosareak, zentral elektriko birtualak eta energia komunitateak. Energia komunitateetan parekoen arteko (peer-to-peer) energia-merkatua ahalbideratzen dute, non energia-kudeaketa deszentralizatua posiblea den. Parekoen arteko merkatu horiek, energia-praktika jasangarriak sustatzen dituzte, azken erabiltzaileei beren lehentasun sozialak, ekonomikoak, ingurumenekoak eta energia-efizientzia lehenesteko aukera emanez.

Energia komunitateetan energia-iturriak iturri berriztagarrietara mugatu daitezke. Energia berriztagarrien meteorologiarekiko dependentziak eta sorkuntzako aldakortasunak energia komunitateko mugen energia kudeaketa eraginkorra izateko erronkak sortu dituzte. Energia eskarian eta kontsumoan aurreikuspenen erroreak kudeatzea funtsezkoa da, denbora-errealeko funtzionamenduan fidagarritasuna eta eraginkortasuna bermatzeko.

Abstract

Doktorego-tesi honen helburua peer-to-peer energia-merkatu zentralizatuaren diseinua, garapena eta balioztatzea da, aurreikuspen-erroreei aurre eginez. Tesi honetan, energia komunitate barneko transakzioen prezioak finkatzeko metodologia berriak garatzen dira, biltegiratze energetikoa muina duen negozio-eredua proposatzen da, eta energia-komunitateko parte-hartzaileen lehentasunekin lerrokatutako energia-kudeaketako estrategiak sortzen dira.

Energia banatzeko bi etapako tokiko merkatu berri bat proposatzen da, kudeaketa zentralizatu batean oinarrituta, zeinean peer-to-peer merkatu baterako energiaren salerosketak optimizatzen diren (energia bolumena eta prezioa). Proposatutako energia tokiko merkatuaren funtzionamendua balioztatzeko metodologia bat erabili da. Lehen etapan, balizko egoera ideal bat analizatzen da, non proposatutako tokiko merkatua energia-banaketako egitura desberdinekin alderatzen den. Gero, iragarpen akatsei aurre egiteko, biltegiratze soluzio desberdinak konparatzen dira. Ikerketak energia-praktika jasangarriak ulertzen eta aplikatzen laguntzen du, etorkizun energetiko eraginkorrago eta erresistenteago baterako bidea erraztuz.

Laburbilduz, tesi honek komunitate energetikoen integrazioa aztertzen du eta hainbat erronka jorratzen ditu, hala nola, aurreikuspen erroreak lantzen ditu, energia kudeaketarako optimizazio soluzio berritzaileak.

Hitz-gakoak: Energia Komunitate Berriztagarria, Tokiko Energia-Merkatua, Energia igarpena, Energia Kudeaketa Estrategia, Battery-as-a-Service, Bateria estazionarioa, Programazio Oso Mistoa, Gradient Boosting Erregresio-Zuhaitza.

Resumen

Título: Diseño, Desarrollo y Validación de un Comercio P2P Centralizado de Dos Etapas.

La Unión Europea ha establecido objetivos ambiciosos para combatir el cambio climático y reducir las emisiones de gases de efecto invernadero, incluyendo un objetivo del 32 % del consumo final de energía proveniente de fuentes renovables para 2030. Para cumplir estos objetivos, la Unión Europea enfatiza en la importancia de la generación distribuida, especialmente en los pequeños productores de energía renovable, quienes pueden desempeñar un papel esencial en la reducción de emisiones, especialmente en el sector residencial. La generación distribuida puede contribuir a la economía local, reducir las pérdidas de energía durante la distribución y capacitar a los usuarios finales para participar activamente en la gestión energética mediante la utilización de recursos energéticos cercanos.

La digitalización ha permitido la distribución bidireccional de la energía y ha cambiado los roles de los usuarios finales, convirtiéndose los consumidores pasivos en participantes activos en el mercado energético. Esto ha fortalecido varias estructuras en baja tensión, tales como las microrredes, plantas de energía virtual y comunidades energéticas. Las comunidades energéticas permiten el comercio de energía entre pares (peer-to-peer) y la gestión descentralizada de la energía, promoviendo prácticas energéticas sostenibles al permitir que los usuarios finales prioricen sus preferencias sociales, económicas, ambientales y de eficiencia energética.

Las comunidades energéticas pueden estar limitadas a consumir solo fuentes de energía renovable, cuya naturaleza intermitente, junto con los patrones fluctuantes de demanda, plantean desafíos para gestionar eficazmente la energía dentro de los límites de la comunidad. Abordar los errores de predicción en la generación y el consumo de energía es fundamental para garantizar la fiabilidad y eficiencia de las operaciones de las comunidades energéticas.

La tesis doctoral tiene como objetivo diseñar, desarrollar y validar un comercio centralizado peer-to-peer de dos etapas en una comunidad energética, abordando los errores de predicción, desarrollando nuevas metodologías de fijación de precios, estableciendo modelos de negocio que incorporen almacenamiento de energía y creando estrategias de gestión energética alineadas con las preferencias de los participantes de la comunidad.

Se propone un nuevo comercio local de intercambio de energía de dos etapas, basado en una gestión centralizada para optimizar el intercambio de energía (volumen y precio) para un comercio peer-to-peer. Se emplea una metodología para evaluar el funcionamiento del comercio propuesto. En la primera etapa se asume un escenario ideal donde se compara el comercio y la estrategia propuesta con diferentes estructuras de reparto de energía. En la segunda etapa, se contrastan diversas soluciones de almacenamiento para hacer frente a los errores de predicción. La investigación contribuye a avanzar en la comprensión e implementación de prácticas energéticas sostenibles, abriendo el camino hacia un futuro energético más eficiente y resiliente.

En resumen, la tesis explora la integración de las comunidades energéticas, aborda desafíos como los errores de pronóstico, propone soluciones innovadoras para optimizar la gestión de energía e introduce soluciones de almacenamiento novedosas a la comunidad investigadora.

Palabras clave: Comunidad de Energía Renovable, Comercio Energético Local, Predicción energética, Estrategia de Gestión Energética, Batería como Servicio, Batería estacionaria, Programaciéo Lineal de Enteros Mixtos, Árbol de Regresión con Gradient Boosting.

Contents

General introduction

In recent years, climate change, high greenhouse gas emissions and Europe's high energy dependency have prompted the European Union (EU) to develop various proposals to reduce their environmental impact. Among those initiatives, the EU has established that 32 % of the final energy consumption's raw material must be renewable by 2030 [1]. In this context, the EU encourages the use of distributed generation [2].

Distributed renewable generators can be large, medium, or small scale. The promotion of small-scale generators is fundamental as these technologies can be applied in the residential sector, tackling the greenhouse gas emissions associated with this sector (concretely 17.9 % in 2023 [3]) and contributing to global decarbonisation. Exploiting nearby energy resources allows consumption in a decentralised way, where it could contribute to the local economy and reduce losses in energy transport and distribution.

Thanks to digitalisation, the possibility of bidirectional energy distribution has enabled end-users to change their role from passive to active. To this end, the EU has strengthened several Low Voltage (LV) structures: micro-grids, virtual power plants, and Energy Communities (ECs) [2]. The summit-level of preferences taken by end-consumers is achieved in ECs, where their active role is translated to considering their social, economic, environmental, and energy efficiency preferences.

Together with the bidirectional distribution, digital developments enable the Local Energy Markets (LEMs) in ECs. Digital advances have resulted in secure and immutable energy trading between peers and without intermediaries, known as Peer-to-Peer (P2P) energy trading. P2P trading can range from decentralised to centralised energy management [4]. By definition, ECs assess not only economic, environmental, and energy efficiency criteria but also the social component, where a collective benefit would be the most social. A centralised P2P follows the common good, which could be translated as the analogue of ECs. A centrally managed EC that follows collective preferences becomes complex energy management.

In addition, ECs based on renewable energy suffer from weather dependency due to the intermittent production of renewable resources. Similarly, as daily life activities can change throughout the day, end-user demand patterns can also vary. This variability in supply and load makes energy management more complex. It is, therefore, of interest to consider the management of forecasting errors.

In conclusion, the LEM models are identified as essential concepts or tools for deploying ECs and fostering the local economy. Additionally, coping with forecasting errors is a key factor for implementing Renewable Energy Communities (RECs). For these reasons, the objective of this dissertation is the:

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Besides the main goal, other targets have been established:

- To **consider forecasting errors of energy generation and consumption of the consumers/prosumers** community members.
- To **develop a new price-settlement methodology for LEMs**.
- To **develop a new business model rooted in storage**.
- To **develop EMSs and new local market rules that fulfil EC participants preferences**.

To address all that, the document has been organised as follows:

The state-of-the-art review of ECs is presented in the **first chapter**, where a thorough examination of the definitions, EU member states regulations, participating agents, LEMs, energy generation and consumption forecasting management is done. Based on that information, LEMs are emphasised as they have been identified as the key factor for developing ECs and empowering end-consumers. Here, gaps found in the literature, which has served as the baseline of the thesis, are introduced.

The **second chapter** introduces the proposed energy-sharing market and the associated LEM design. Firstly, the market is described, and the agent's participation is defined. Secondly, the methodology for evaluating the viability of the proposal is outlined. The three blocks (scenario definition, LEM design and performance evaluation) composing the methodology are described. The LEM design is detailed, where the steps for the market clearing are explained: the preliminary prediction module and the two-stage management (planning and operation). The description includes figures illustrating the information, energy, and money fluxes. Finally, the Key Performance Indicators (KPIs) employed for evaluating the performance is presented. Among them, local Batteries (BTs) and Community Energy Storage System (CESS) ageing is also considered; the ageing is mainly included to discuss any need for BT shortage and contemplate replacements.

In the **third chapter**, the EC agent's assets are mathematically modelled, and the control associated with each agent is detailed. Concerning the control, Residential Buildings (RBs) and Large Tertiary Buildings (LTBs) short-term management is explained. More precisely, their performance capability towards the BTs and CESS employment. Regarding Local Energy Market Operator (LEMO) control, its central optimisation is presented, where the optimisation objective function is detailed. Moreover, the LEMO established pricing for EC's internal LEM and external operations (grid support) is also explained, noting a novel community-based P2P price formulation.

The **fourth chapter** details the centralised optimisation algorithm design and selection employed by the LEMO. First, the problem is identified, resulting in a linear problem. Subsequently, the design variables are described. Their lower and upper limits and the interactions (equalities and inequalities) are explained. The matrices built to orchestrate the LEM fluxes are also given. Finally, the algorithm selection and application are outlined. Due to the necessity of including binary variables, the algorithm selected was the Mixed Integer Linear Programming (MILP), and the application in MATLAB environment is specified.

In the **fifth chapter**, the proposed centralised P2P price and energy-sharing market is evaluated. First, the scenario employed for assessing both proposals is detailed. Then, the pricing approach is compared to an adapted mean value of different electricity tariffs. Moreover, the two-stage LEM is analysed: a) contrasting the planning stage with other energy-sharing structures (collective self-consumption and full P2P) and b) contrasting different storage solutions in centralised P2P for planning and operation stages. Considering the results, a new electricity system tariff is proposed and evaluated. Finally, these results are discussed in detail, broken down by methodology step, with and without considering prediction deviations.

The **sixth chapter** gathers the sensitivity analysis carried out among the different input parameters of the proposed approach. In the first place, the different scenarios are defined, and then, the REC performance is evaluated in terms of Levelised Cost of Energy (LCOE). Finally, the conclusions obtained in the evaluation are shown.

The **seventh** and final **chapter** presents the general conclusions and the main contributions of the doctoral thesis. This chapter also suggests some possible future directions for the main topic of this thesis.

1

State of the Art

Summary

ECs are analysed in depth in this chapter. First, the definitions given to this structure are collected. The current regulatory framework of EU member states is also summarised. Then, the agents involved are presented. LEMs are also introduced, where a) the structures of energy trading are explained, b) the energy storage systems' presence is analysed, and c) the formulation and clearing are outlined. Due to the nature of renewable energies and the volatile consumption curves, the energy forecasting presence in community management is presented and predicted, where short-term error management in ECs is reviewed. Finally, the conclusions obtained for developing the thesis question are shown.

1.1 European Comission Definitions

In this structure, there are disparate concepts in the directives. **EMD II** or Directive 2019/944 [2], defines this scenario as **Citizen Energy Community (CEC)**, which members are natural persons, local authorities (including municipalities) or enterprises (micro or small). ECs do not have any technological limitations (they can use non-renewable energies) nor geographic restrictions, which enables them to form this figure between nations. Nevertheless, the activity is only limited to the electricity sector. The objectives related to RECs are economic, environmental and social instead of obtaining financial income.

RED II or Directive 2018/2001 [5] establishes the structure of **RECs**. In this case, the members can be natural persons, local authorities (including municipalities) or enterprises (micro or small) who use renewable energy technologies. A restriction is stipulated in this aspect: this participation cannot be their primary professional or commercial activity. Unlike CECs, RECs shareholders or members must be close to renewable energy projects owned and developed by the RECs. According to the activities, they can be active in all energy sectors. The main purpose of CECs is obtaining economic, environmental and social rather than acquiring financial income.

Both [6, 7] reports state that the concept of **Local Energy Community (LEC)** was employed before the CEC and REC definitions emerged. Concretely [7] states that the extended version of LECs is the CECs. The definitions given to ECs are summarised in Table 1.1.

1.2 European Member States Regulatory Framework

The European Commission established Directives 2018/2001 and 2019/944 concerning ECs, and the EU gave member states the legal authority to transpose ECs law. The directives were adapted in different tempos and frequently updated. At the beginning of this PhD thesis, most countries lacked legislation in ECs topic. Nowadays, most of the EU member states conceive a law concerning the community type, the approach, members, activities, control, market access and imbalances of responsibility. All definitions converge that the main purpose of RECs and CECs is obtaining economic, environmental, and social rather than financial income. To the authors' knowledge, the current European legislation for each Member State is available in the Energy Communities Repository from the European Commission [8]. That source was employed to address the ECs

Table 1.1: Energy Communities definitions comparison.

	LEC	CEC	REC
Membership	Associations, cooperatives, societies, non-profit organisations, or other legal entities	Natural persons, local authorities, including municipalities or small enterprises and microenterprises	Natural persons, small and medium-sized enterprises (whose participation is not their main professional or commercial activity) or local authorities, including municipalities
Participation	-	Open and voluntary	Open and voluntary
Energy Source	Neutral	Neutral	Renewable Energy
Geographic limitation	No geographic limitation, Member States can choose to allow cross-border CECs	No geographic limitation, Member States can choose to allow cross-border CECs	Near renewable energies whose owner is the legal entity or, at least, that the legal entity has developed
Purpose	Generally, value-driven rather than profit-driven, involved in distributed generation and performing activities of a distribution system operator, supplier or aggregator at the local level, including across borders	Offer environmental, economic or social benefits to the members or the location that develop the activity rather than financial profitability	Offer environmental, economic or social benefits to the members or the areas where it operates rather than financial profitability

regulatory framework and is summarised in Section 1.2. This table gathers the applicable law, the EC type that the law outlines, the approach in the electricity system, the EC members, the activities that can be carried out, the effective control, the wholesale market access and the imbalance responsibilities. The detailed information of each country can be consulted in Appendix A. Note that the Netherlands was exempt from this section due to a rule that was not clarified. Additionally, Czechia, Germany, Ireland, and Sweden were omitted, as no definition was given for these structures.

Table 1.2: European Union Member States definitions for Energy Communities.

Country	**Law**	**EC Type**		**Approach**		**Members**						**Activities**							**Control**	**Market Access**		**Imbalances Responsibility**
		REC	CEC	LV	MV	Legal persons	Natural persons	Local Authorities	Municipalities	Small Enterprises	Medium Enterprises	Production	Consumption	Energy Sharing	Aggregation	Energy Storage	EV Charging	Energy Efficiency	Members	Direct	Aggregators	
Austria	EIWOG	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-
	EAG	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	-	-	-
Belgium																						
Federal	Law of 23^{rd} October 2022		✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-
		✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	-	-	-	-
Brussels - Capital Region	Ordinance	✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
			✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-
Flemish Region	Energy Decree	✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓
			✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓
Walloon Region	Decree	✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
			✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
Croatia	Law on Renewable Energy Resources and Highly efficient cogeneration	✓	✗	-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	-
	Law on the Electricity Market	✗	✓	-	-	✓	✓	✓	-	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-

Country	Law	EC Type		Approach		Members						Activities							Control	Market Access		Imbalances Responsibility
		REC	CEC	LV	MV	Legal persons	Natural persons	Local Authorities	Municipalities	Small Enterprises	Medium Enterprises	Production	Consumption	Energy Sharing	Aggregation	Energy Storage	EV Charging	Energy Efficiency	Members	Direct	Aggregators	
Cyprus	Law 107(I)/2022	✓	✗	-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	-	✓	✗	✗	✓	✓	✓	-
	Law 130 (I)/2021	✗	✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓
Denmark	BEK 2021/1069		✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-
		✓		-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-
Estonia	Law of Obligations Act	✓	✗	-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓	✓	✓	-
Finland	Decree 2021/767		✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
		✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
France	Ordinance 2021-236		✓	-	-	✓	✓	✓	-	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		✓		-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗
Greece	Law 5037/2023		✓	-	-	✓	✓	✓	-	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		✓		-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗
Hungary	Electricity Act LXXXVI		✓	-	-	✗	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
		✓		-	-	✗	✓	✗	✗	✗	✗	✓	✓	✓	✗	✓	✗	✗	-	✗	✗	-
Italy	Legislative Decree 210/2021		✓	✓	✓	✓	✓	✓	✓	-	-	✓	✓	✓	-	✓	✓	✓	-	✓	✓	-
	Legislative Decree 199/2021	✓		✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	-	✓	✓	✓	-	✓	✓	✓

Latvia	Law of Energy (2022/137A.3)		✓	-	-	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	-	-	-
		✓		-	-	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	-	-	-
Lithuania	Law VIII-1881/2000	✗	✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	-	✓	✓	✓
	Law XI-1375	✓	✗	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	-	-	-	✗
Luxembourg	Act on the Organisation of the Electricity Market	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	-	-	-	✓	✓	-
Malta	Subsidiary Legislation 545.34		✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Subsidiary Legislation 545.35	✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗
Portugal	Decree 15/2022		✓	-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
		✓		-	-	✓	✓	✓	-	✓	✓	✓	✓	✓	✗	✓	✗	✗	-	✓	✓	✓
Romania	Ordinance 143/2021	✗	✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ordinance 163/2022	✓	✗	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗
Slovakia	Act 256/2022		✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓
		✓		-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	?	✓	✓	✓
Slovenia	ZOEE	✗	✓	-	-	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓
	ZAROVE	✓	✗	-	-	✓	✓	-	-	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓
Spain	Royal Decree 23/2020	✓	✗	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	-	✓	✓	-

Briefly, almost all EU members transposed at least one of the definitions given to ECs. The differences among EC types are rooted mainly in the members, activities, and imbalances of responsibility. In some member states, ECs are delimited to LV and Medium-Voltage (MV) distribution lines. Additionally, Belgium leads the legislation by considering P2P trading for community energy-sharing, see Table 1.3, even up to describing nuances of P2P trading in the Flemish region. Other countries, mainly Mediterranean countries, such as France, Italy, Slovenia, and Spain, and Luxembourg, consider that collective self-consumption has to be followed for energy sharing within community limits. All of them, except Slovenia, state that the energy allocation has to be done according to static or dynamic repartition keys. Other Member States, such as Austria, Belgium, the Flemish Region, Croatia, Finland and Portugal, determine the energy sharing without considering self-consumption schemas. Yet, Austria and Portugal do authorise energy-sharing via distribution keys. The cited laws were approved within the last three years, making the blossoming of ECs apparent.

Table 1.3: European Union Member States energy-sharing scope.

Country	**Energy Sharing allocation**				**Time-step [minutes]**
	Distribution Keys	**Individual Self-Consumption**	**Collective Self-Consumption**	**P2P**	
Austria	✓ (static or dynamic)	✗	✗	✗	15
Belgium					
Brussels-Capital	✗	✗	✗	✓	15
Flanders	✓ (N/A)	✗	✗	✓	15
Wallonia	✗	✗	✗	✓	15
Croatia	✓ (N/A)	✗	✗	✗	-
Finland	✓ (N/A)	✗	✗	✗	60
France	✗	✓	✓(static or dynamic)	✗	15
Italy	✗	✗	✓*(static or dynamic)	✗	60
Luxembourg	✗	✗	✓(static or dynamic)	✗	60
Portugal	✓(static, dynamic or hybrid)	✗	✗	✗	-
Slovenia	✗	✓	✓(N/A)	✗	-
Spain	✗	✗	✓(static or dynamic)	✗	60

1.3 Agents that can belong to an Energy Community

Besides the different concepts of ECs and regulatory aspects, ECs have similarities concerning the agents that compose them. It can be constituted by diverse agents that act to fulfil their own or collective preferences, see Figure 1.1. In this section, the definitions of the agents that can be arranged together in an EC are given [4, 7, 9, 10].

- **Generators.** This agent is in charge of generating energy for the community. According to the EU definitions, the energy generators can be of any source (CECs) or can be limited to clean resources (RECs), such as Phovoltaic (PV) generation, wind generation, etc.

- **Consumers.** This agent concerns the energy users of the community who do not have any generation source. They demand energy from the community to fulfil their electrical requirements. As stated in Austria, Italy, and Luxembourg, communities must be placed in LV or MV lines [8]. End-consumers, according to the requested power, can be the following a) residential buildings, b) commercial buildings (small, medium or large businesses, offices or business parks, shopping malls), c) industrial users (small, medium or large industrial facilities), d) farms and agricultural facilities, e) buildings related to services (schools, universities, hospitals, police stations, fire stations, post offices, etc.), and f) recreational buildings (sports centres and stadiums).

- **Prosumers.** Thanks to the advances in the energy panorama, the consumer can also produce energy in its immediations, for instance, small-scale PV on the rooftop. In recent years, consumers' and generators' figures have merged and evolved to be more empowered [10]. The prosumer name was given to a consumer that could also produce and share energy, which involves "pro" from the producer and "summer" from the consumer [10].

- **Aggregator.** This agent is the direct or indirect intermediary between the group of consumers and the wholesale market [2]. Aggregators oversee the user's objectives (ecological, economic, social, or technical) and manage their energy needs to fulfil them. There are two types of aggregators: associated with an organisation, or independent [2]. Whilst the former can be linked to consumers' retailers, the latter is not related through any other business to the supplier [2]. Additionally, it is determined that aggregators must have transparent and fair regulations together with the definition of all the products linked to energy markets, including ancillary and capacity markets [2, 9].

  If prosumers and consumers need to become more familiar with their technical needs and the market operation, the aggregator plays a vital role in the community. In the EC literature, the aggregator linked to the community management was also called **Community Manager** [4].

- **Electric Grid Operators.** This figure involves the agents traditionally in charge of the activities concerning the electric grid. Transmission System Operator (TSO), Distribution System Operator (DSO), and retailers are considered in this last agent.

- **Digital service providers.** The correct functioning of ECs depends on digital service providers. The Energy Community Repository developed by the European Commission published a report addressing the tools regarding this topic [11]. The services provided can be the following:

  - Community internal management and communications.

  - P2P trading enabler.

  - Forecasting services.

  - Energy monitoring services.

  Additionally, a digital platform can facilitate participation in a) flexibility services, e.g. taking part in demand response activities, and b) electric mobility services, e.g. car-sharing solutions [11].

New agents emerged in the energy panorama: prosumers and aggregators. The similarity between them is that the consumer is their central focus. In both, end-consumers can actively establish their own preferences (ecological, economic, social, or technical) regarding their electricity consumption.

Note that the EC agents (generators, consumers, prosumers, aggregators, TSOs, DSOs, retailers and digital service providers) can be associated in diverse ways and can share energy when conforming ECs, varying from individual self-consumers to more generalised approaches that offer flexible services to the grid. One interesting area of research in energy sharing is the LEMs [12]. These markets enhance the local economy by enabling monetary and energy exchange among community participants [13]. Depending on the LEM structure, it can even optimise local resources to meet community needs (ecological, economic, social, or technical) [4, 14, 15]. Therefore, this thesis focuses on LEM integration on ECs. In the next section, LEMs are presented in detail, where the structures of energy trading, the role of Energy Storage Systems (ESSs) and market formulation and clearing

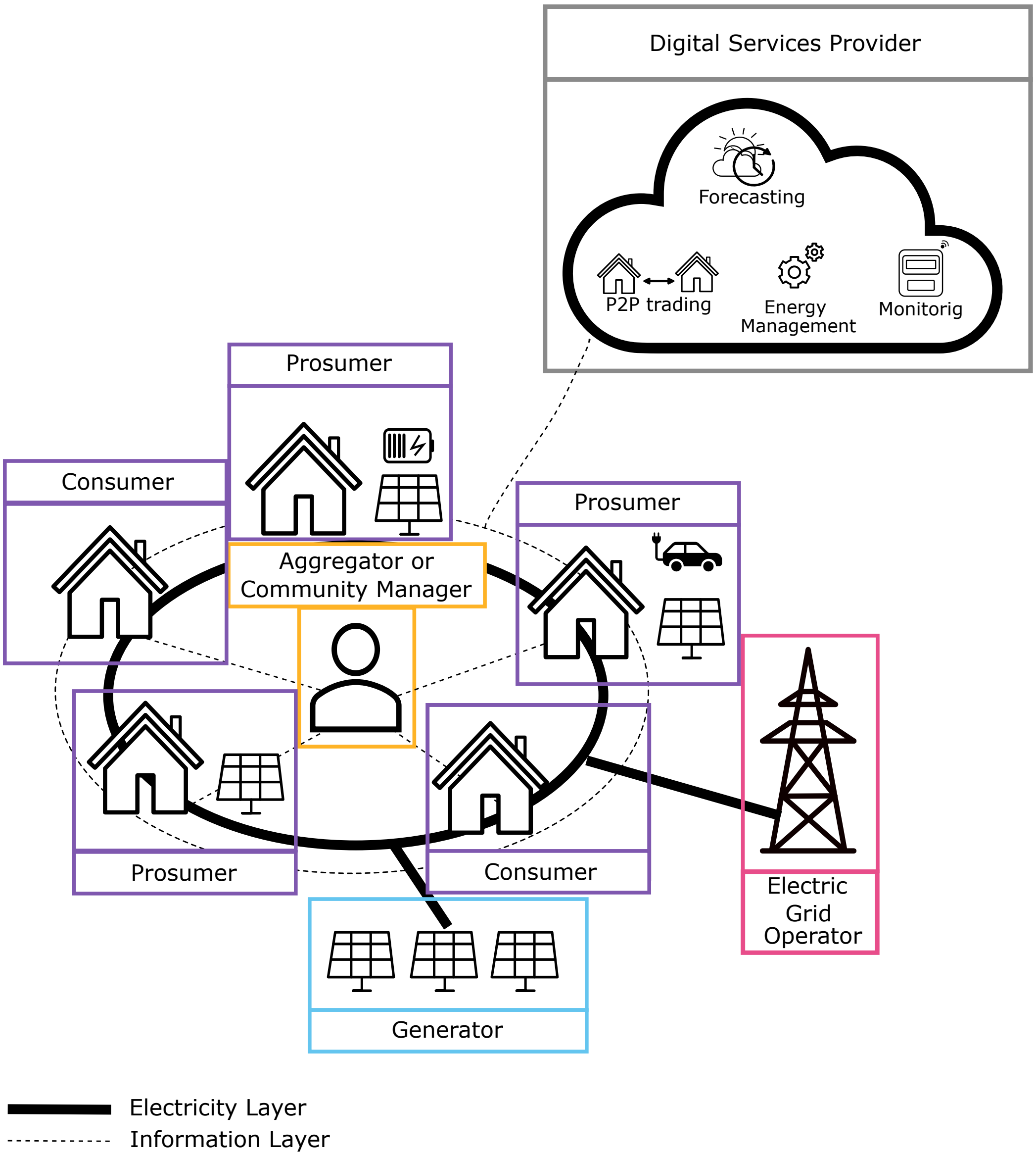

Figure 1.1: Energy Community, with the agents composing it in detail.

methods are presented.

1.4 Local Energy Markets

Alongside consumer empowerment, one of the key features of a LEM is the promotion of local economies. Together with energy decentralisation and digitalisation efforts, the concept of a LEM has been on the rise in the literature. A LEM is a market where local consumers, produces, prosumers and storage can trade independently or centrally in a local distribution network [12]. Additionally, energy can be traded between the LEMs and the wholesale market or other LEMs [12].

For the design and implementation of LEMs it is essential to define the energy trading structure [4, 12, 16, 17], formulation [18, 19] and clearing method [18, 19].

1.4.1 Structures for energy trading

Thanks to the development of Distributed Ledger Technologies (DLTs), it is possible to trade energy in a fully decentralised way among the members of the microgrid, the term stands for P2P energy trading. The P2P energy trading is performed between the community participants according to the user's preferences [4, 16]. The preferences can range from complete individualist to collective [4, 16]. Depending on the preferences set within a particular community, a kind of P2P market emerges. Three types of P2P markets have been defined in the literature [4, 16, 17]: full P2P, community-based P2P and hybrid, see Fig. 1.2. In this way, a LEM can trade energy and money in a decentralised, centralised or hybrid fashion.

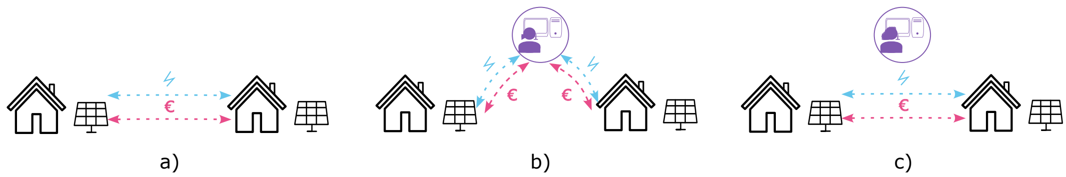

Figure 1.2: P2P markets: a) full P2P, b) community-based, and c) hybrid P2P.

1.4.1.1 Decentralised management or Full P2P

As the name indicates, energy and currency trading takes place between peers in the community without the need for a third party or intermediary [4, 16, 17]. The peers decide on the volume of energy to be traded and the price for it. The trading among the community is certified by energy bids and bilateral agreements [16, 17]. Therefore peers with energy needs select their supplier in accordance with their preferences (economic, environmental, technical or social) [4]. The main disadvantages of this structure are scalability and heavy computational burden when a large number of players participate in the P2P market [4].

1.4.1.2 Centralised management or Community-based P2P

This market is a design where a group of end-users (local organisations, micro-grids, neighbourhoods or communities) that share common interests or goals join for energy sharing [4, 16, 17]. An agent or central unit coordinates the operation of the community in the most efficient manner [4, 16]. The primary goal is to optimise energy production and consumption based on the collective preferences (technical, economic, environmental or social). For that, community members exchange information with the central coordinator, meaning there is no need to share information between peers [4]. In addition, in the presence of energy shortages or surpluses, energy is collectively exchanged with the grid, with the central entity trading on behalf of the EC members.

The advantages achieved are the result of the cooperation of the participants, and therefore, the revenues are jointly shared [4]. In addition, this P2P type has a lower computational cost than a full P2P [4]. Nonetheless, this configuration's management works for the common interest, disregarding the preferences of some members [4].

1.4.1.3 Hybrid P2P

It is a combination of the two markets described earlier; energy can be traded among centrally managed groups with other energy groups and/or peers [4, 16]. All trading is under the supervision of a central manager [4, 16]. Consequently, this energy-sharing structure empowers agents and increases cooperation. The complexity of this structure resides in energy trading, as a higher layer of coordination is required [4, 16].

Table 1.4 summarises the P2P market structures.

Table 1.4: Existing P2P market designs summary

	Full P2P	**Community-based P2P**	**Hybrid P2P**
Participants	Individual prosumers and consumers	Joint group of end-users	Nested end-users
Preferences	Individual	Collective, individual preferences are set aside	Both individual and collective, where the equilibrium that fit both preferences is sought
Coordination	Totally decentralised. Direct trading (bidding) between peers without the need of intermediaries	Totally centralised. An intermediary (CM) between peers is the decision maker	Partially independent. Peers trade (bid) between each other supervised by an intermediary (CM)
Strengths	End-users preferences are fulfilled	Easier to manage.	Cooperativity between end-users and CM
Weaknesses	Scalability problem and heavy computational burden.	Disregard some consumers preferences.	Heavy computational burden, but less than full P2P

1.4.2 Energy Storage Systems role in Local Energy Markets

The amount of energy traded in the community may be insufficient or excessive to meet the needs of the ECs. This energy mismatch can be addressed in two ways: a) buying/selling to the network as a whole or/and b) charging/discharging ESSs as in the case of [20–24]. It should be noted that when ESSs is mentioned in this thesis, it refers to lithium-ion batteries.

The deployment of ESSs, mainly batteries, at the domestic level is nowadays a reality. A storage-based solution individual [23–27] or community [20, 22, 25, 26, 28–30] ESSs. In the literature, storage was considered physical [20, 23–28] or virtual [22, 26, 30, 31]. These physical or virtual solutions can include stationary batteries [20–24, 26, 29], vehicles [30] or a mixture of both [32]. In the case of using Electric Vehicles (EVs), the recharging of the vehicles should be managed to provide energy to the community [32].

ESSs in any form (physical or virtual, batteries and/or EVs) provide flexibility to the user; prosumers can consume from the storage system whenever there is a lack of energy generated within the microgrid or when the electricity price is high. In those cases, storage systems reduce the electricity bill [20, 24, 27–29]. However, these technologies can also serve as a source of income for community users (by selling part of the battery capacity to other LEM users) [23, 31–33] or aggregators (third-party ownership that does business by selling part of the capacity of the ESS in a LEM) [22].

In the literature, the works presented in [20, 24, 27–29] **ESSs** were employed **as cost-saving method**. The work presented in [20] explored using a central battery to reduce the cost of an industrial site (five industrial buildings). This research analysed the benefits of including shared storage in the community-P2P structure, demonstrating that shared storage was up to 11 % beneficial to the community. However, the work lacked any forecasting errors. Another study, [24], considered a twenty prosumer community based on P2P structure. Each is equipped with PV and individual BTs, where the energy management was designed to decrease the community costs. This work was limited to ideal data, not acknowledging real-time or short-term management in case of forecasting miscalculations. Reference [28] considered a P2P structure with a scenario composed of consumers and prosumers that utilised a shared ESS to reduce the consumers' energy and P2P imports. EC participants were divided between buyers and sellers. It was proven that up to 10.85 % individual benefit was obtained. Nevertheless, the shared storage use was reduced to consumers, where prosumers were confined to selling the electricity to buyers or the grid; their energy could not be stored. In [29], a REC composed of five households, a rooftop PV generation and central ESS was studied, where the ESS was used to save community costs. This study employed prosumers' storage systems to reduce community bill in predicted (24-hour-ahead) and real-time (1-minute) scenarios. It was considered that the battery followed a price strategy to charge and discharge, meaning that it was discharged when the grid price was low and charged when it was high to maximise the revenues. The limit of this work is that the P2P market is not conceived. In [27], a hybrid P2P market was analysed, where LEM participants were equipped with individual BTs to reduce their LEM needs. Four communities were simulated where individual and collective benefits were sought, meaning this archipelago did not seek the global optimal. Additionally, prediction errors were not contemplated.

The research promoting the **ESS as a source of income was also studied**. Between the articles identified in the literature, in [22], each community handled their energy excess or needs. An aggregator scheduled and coordinated a central virtual battery to supply each participant with excess or surplus. The aggregator balanced members' energy fluxes, and, in case the battery capacity was scarce, it purchased the remaining energy from the grid. Prosumers followed purely individualistic management; individual preferences were sought, disregarding a collective benefit. Additionally, perfect predictions were considered, neglecting any short-term management. In [23], individually owned physical BTs traded the available capacity with other smart grid users. Also, individual preferences were appraised, where an auction-based market was simulated. Another limitation of the work was that prediction errors were not considered. In [32], a community of residential, industrial and business consumers was contemplated, where each community member-owned a BT. In this community, EVs were also members. A community-based P2P trading was done between prosumers and EVs. Collective cost minimisation was proposed, yet forecasting mismanagement was not assessed. Research in [33] introduced a LEM composed of prosumers and consumers with individual storage systems - only consumers had storage in their domain. In this case, a full P2P schema was followed, and electricity flows were limited: prosumers could only sell energy to consumers and vice versa. Here, forecasting mismatching was not evaluated. Additionally, a market solution nowadays is [31], a software that centrally manages the batteries of the members, sonnenBatteries, of a joint group of BT users named sonnenCommunity. In sonnenCommunity, the capacities of the sonnenBatteries are joined, resulting in virtual storage. In this case, sonnenBatteries can be found all around Germany. Thus, the weather between locations and the energy production of each geographical point may vary. The electricity supplied by the BTs (to other sonnenCommunity users or the grid) is economically compensated.

However, the presented works still need to address the possibility of outsourcing local storage from which community participants can obtain energy support. This can be named Battery-as-a-Service (BaaS), a concept widely used in electric vehicle jargon. The BaaS concept incorporation in ECs would be a very interesting approach as community participants would avoid the storage investment, operation and maintenance of the storage. In this PhD thesis, that gap was covered as a new EC participant was considered: an **agent that owned the BaaS asset**.

Their degradation is an interesting aspect to consider in BTs. If there is overuse or underuse, it can significantly impact the installation's energy cost or amortisation. If the BTs are employed as cost-saving methods, BTs are used to reduce the electricity bill and their use is squeezed. By contrast, the ESS employed as a source of income must consider the degradation as the owner of the BT wants to recover its inversion. Among the cited works, only reference [22] includes a unit cost of charge and discharge to the BT use.

In summary, LEMs permit diverse ways of energy and ESS capacity trading between users, where participants' preferences are considered individually or collectively. Thus, each structure's energy management is different— assessing the necessary community energy through storage systems results in even more complicated management. Consequently, correctly managing generation, consumption, and storage is vital to maximising local energy, enhancing the local economy, and reducing energy losses. It is essential to know the formulation of this management and the posterior clearing to manage the community's assets, which are explained in the following section.

1.4.3 Formulation

Formulation is referred to the mathematical models for the operation of LEMs [34]. As seen in Section 1.4.1, the market can range from following a completely selfish to a completely collaborative strategy. Therefore, a key aspect of managing local resources is the market formulation. Literature reviews [18, 19] are the basis of this section.

1.4.3.1 Centralised optimisation model

A centralised model is coordinated by a central entity (integrated or independent aggregator). Community users rely on that central entity to manage the energy they generate and consume. In this case, each user sends the energy needs to the central entity. Then, the central entity allocates the energy. The work in [18] claims that the model, although easy to implement, has scalability limitations regarding communication and computation costs. Energy orchestration is usually rooted in technical and/or economic constraints. Centralised optimisation can be aimed at maximising social welfare or minimising operating costs.

- **Social welfare maximisation** involves favouring and acting for market participants. Concretely, the research in [35] presented a local flexibility market operated by an agent to efficiently dispatch the trading between prosumers.

- **Operational costs minimisation** aims to reduce the operational costs of the system as a whole, like in [20, 21, 24, 29, 36]. Particularly, [36] analysed the effects of LEMs and centrally orchestrated P2Ps markets on LV networks. Another paper [21] also used central optimisation to compare distributed and centrally located batteries in the same LEM scenario. Research in [20] used centralised optimisation to evaluate an industrial facility scenario both with and in the absence of a central battery. Reference [24] followed the collective cost reduction of a community using local batteries. This research was expanded by including EVs as an energy provision vector in the participants' problem. In [29], a central optimisation was employed for scheduling central storage to pursue the minimum operating costs of a REC.

1.4.3.2 Game theory-based models

These are mathematical models based on game theory that aim to represent the competition between all market participants. There are several game types; however, in the markets presented in ECs context, cooperative/non-cooperative were mainly employed according to [18, 19].

- In a **cooperative game**, the model is built to follow for the common good. For this to happen, community users must share their preferences openly in order to achieve the most appropriate match for all participants. Reference [37] uses cooperative game theory to design the local market of a EC.

- In a **non-cooperative game**, individual interests are pursued and players compete with each other. It does not involve coordinating or communicating between users. In reference [38], the P2P market taking place in a micro-grid is simulated as a non-cooperative game based. The research in [23] is based on a non-cooperative Stackelberg game, with the auctioneer as the market leader and the housing units as the followers. Reference [28] also conceived the full P2P structure as a non-cooperative game. The study in [25] addressed residential community based on a non-cooperative game.

The major strength of game-theoretic models is the multiple player's participation. However, due to the assumed rational behaviours of the players, these models may not mimic real-world dynamics accurately. In addition, in certain situations, multiple equilibria (multiple winners' result) can occur, further distancing from reality.

1.4.3.3 Auction-based

An auction is a sale of goods to the highest bidder, usually by an auctioneer, and is a type of sale in which the goods are the subject of a bid. Auctions can be **single-sided**, where a) all the buyers are competing to get the good, or b) all the sellers are competing to sell their good. Or **double sided**, in which the buyer and the seller bid in an open (all participants can see all the bids) or closed (the bidding is done blindly) manner for a good or a service that they wish to acquire [39], [40]. Reference, [41] followed an open auction and [42, 43] had blind auctions. In [43], the auction mechanism was celebrated an hour ahead. In [23], individually owned physical batteries auctioned the available capacity with other smart grid users.

Auctions should include the elements of equity, transparency, objectivity, non-discrimination, a time-based process, efficient price discovery, clearly understood information and avoidance of delays, amongst others, to appeal local energy market participants [39]. Trading may be conducted for short, medium and long periods of time. In LEMs, the auctions are held in a short-term period, ranging from fifteen-minute bids [44] to a period of one hour [43].

1.4.3.4 Multi-agent models

In the multi-agent model, several agents interact dynamically with one another [18]. In [18], it is pointed out that any participant can be regarded as an agent. This allows for a more flexible environment in which agents can contemplate their strategies. In this respect, the multi-agent model allows each individual agent to conduct its strategy, which may be merged with a central entity. It can also be scaled to local flexibility markets, where the TSO, DSO, Balance Responsible Party, local flexibility market operator and participant represent a single agent. A scenario can also address agents representatives of a set of elements (e.g. the aggregator is on behalf of the portfolio of generation and consumption they oversee) and participate in the LEM, which can follow a centralised model. The ability to combine multiple models increases both complexity and computational burden. In the literature, [27] proposed a hybrid P2P marketplace in which a number of ECs were able to trade with each other (using distinct intra-community prices for energy) and with the wholesale market.

Figure 1.3 summarises LEM formulation methods.

1.4.4 Clearing methods

Market clearing is an economic concept regarding the equilibrium between goods quantity and demand [45]. In LEMs, a clearing method refers to the process

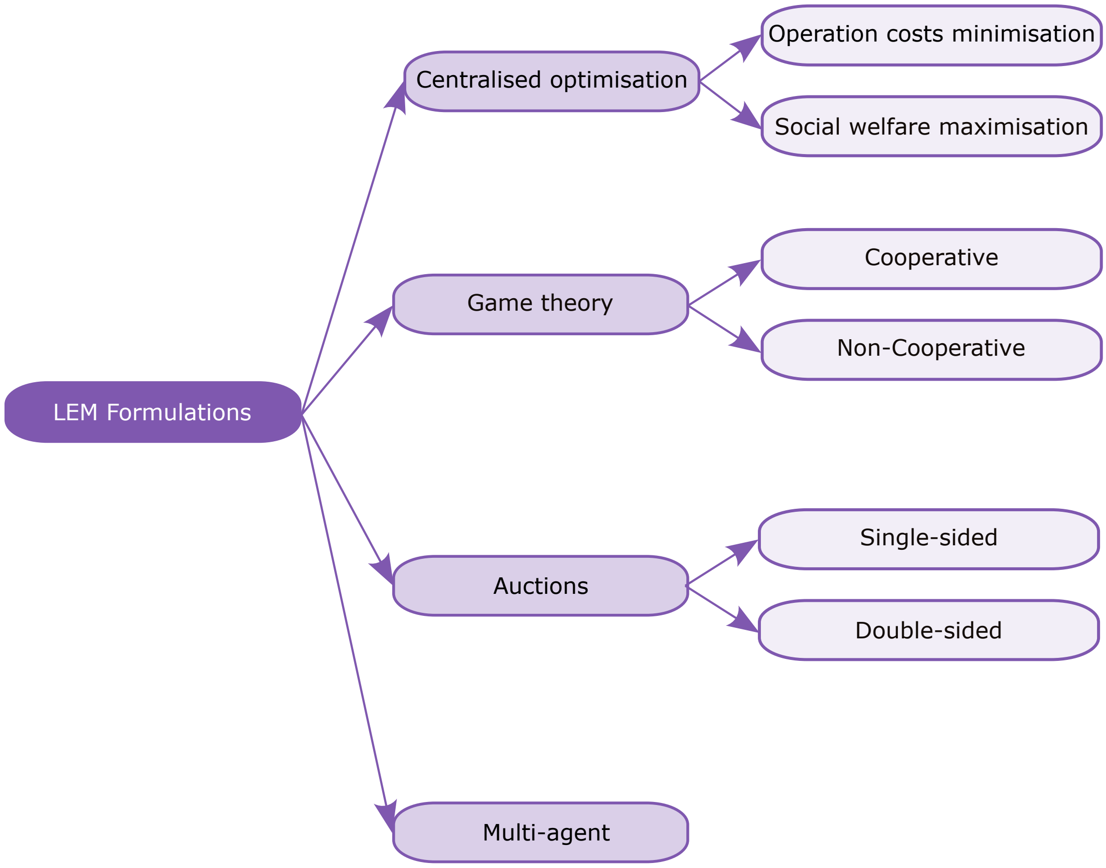

Figure 1.3: LEMs formulation

used to settle energy transactions between market participants, determining the energy amount each participant buys or sells, the associated price, and the sink (buyer) and source (seller) elements [18]. Depending on the trading structure selected, the market clearing is done in different ways. Clearing methods include centralised optimisation, decomposition methods, networked optimisation, auction mechanisms and multi-level optimisation. They are explained in the following subsections and are based on references [18, 19, 34, 39].

1.4.4.1 Centralised optimisation algorithms

Centralised market clearing optimisation algorithms involve direct, indirect or based on metaheuristics [18, 34] and are selected based on the mathematical features of the algorithms.

- **Direct algorithms** output can be directly calculated by a solver [18]. The solving algorithms involve Linear Programming (LP), MILP, Non-Linear Programming (NLP), Mixed Integer Non-Linear Programming (MINLP), Quadratic Programming (QP) and Mixed Integer Quadratic Programming

(MIQP) [18]. The main drawback is the computational cost for large systems [18].

Reference [20] used LP for an industrial site energy allocation, based on community P2P structure. Another research [21] also scoped centralised management based on multi-period LP to minimise the costs of the community. In [46] a LP algorithm minimised the cost of scheduling the flexibility assets. Centralised management was carried out using LP in [36]. In [24] MILP was used to manage the individual assets (PV generation, consumption and local BTs) of an EC. In [29] MILP was employed for scheduling central storage to pursue the minimum operating costs of a REC.

- **Indirect algorithms**. By contrast to direct algorithms, indirect algorithms cannot be solved directly due to the resolution complexity [18]. These problems are solved by metaheuristic algorithms, employing randomness or heuristics for coping with the non-convex nature [18]. Reference [18] illustrated that quadratically constrained quadratic programming could solve problem-based in alternating current optimal power flow.

- **Metaheuristic algorithms** are paradigms rooted in computational intelligence [34]. The strengths are subjected to acceptable computational times and reduced memory and processing costs [34]. Metaheuristic algorithms do not obtain an optimal result as they do not require mathematical formulation [34]. This type of algorithms include Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Simulated Annealing (SA), Artificial Bee Colony (ABC), and Teaching Learning-Based Optimisation (TLBO) [18, 34]. In [47] a multi-agent neighbourhood management was simulated, where each agent employed GA algorithm to optimise their household appliances and managed the collective energy surplus or deficit with an aggregator.

1.4.4.2 Decomposition methods

Decomposition methods break down the primary problem into a set of subproblems [18]. A summary of the main decomposition methods for local markets can be found below:

- **Augmented Lagrangian relaxation-based**. As its name states, these methods are based on Lagrangian Relaxation. Augmented Lagrangian differs from Lagrangian relaxation due to its intrinsic penalty function, allowing it to compute the optimal solution. The algorithms are: Alternating Direction Method of Multipliers (ADMM), Analytical Target Cascading (ATC), Proximal Message Passing (PMP) and Auxiliary Problem Principle (APP) [18]. The study in [15] ADMM was employed to meet the individual preferences of prosumers in a LEM. Research in [48] employed ADMM to solve a central market. The prosumers sent their bids to the auctioneer, and this central entity set the price via ADMM, according to the energy classes defined in the case study. A full-P2P market was addressed in [33] where fast ADMM was employed for energy trading.

- **Karush-Kuhn-Tucker (KKT) conditions**. The problem solution is computed by employing KKT conditions. The Optimality Condition Descomposition (OCD) is predominantly used to solve KKT conditions [18]. Relaxed consensus and innovation were used to address a full P2P structure formulated via KKT conditions in [49]. To achieve gain equilibrium, the reference [28] used KKT conditions.

Decomposition methods require less computation than optimisation algorithms, therefore decomposition methods are used in the literature to solve large markets [18]. Although good quality solutions are obtained, the optimum is not reached [34].

1.4.4.3 Auction mechanisms

Markets formulated as auctions are cleared using auction mechanisms. Auction theory is not a mathematical model; it is an ”economic allocation of resources”, as stated in [18]. The benefit of using auctions to model the market is that, in addition to allowing scalability (a large number of players), it achieves rapid market equilibrium at a relatively low computational cost. Nevertheless, if the auction is very competitive, high price spikes may occur, which may lead to rejections. There are three ways to determine the price of an auction [39, 40]:

- **English or ascending-bid auction**. Participants compete against each other, knowing how much each other wants to bid. Bids continue to rise until a unique bid wins. The paper [41] examined English auctions for a market where smart controllers bid as a representative of each user.

- **Dutch or Descending-Bid auction**. In these auctions, sellers bid openly against a price set by the auctioneer for a given amount of energy. The auctioneer will set a lower price and restart the auction if the amount to be sold exceeds the amount set. This auction involves multiple bidding rounds in a given period, matching energy and price. **Simultaneous descending**

clock auctions of non-identical products are also included in this type of auction. In summary, the auctioneer requests a price for a certain quantity of a good and the price is lowered until a bidder accepts it. In this auction, the competence level grows as the number of participants rises. This auction is also held in an open form.

The advantage of this auction lies in its efficiency, since all bidders are aware of the price and can make adjustments [39, 40]. It is also considered to be an easy auction to implement [39, 40]. It is also less prone to corruption due to the transparency [39, 40]. The disadvantages, however, are that competition is not strong and that it should be well planned and coordinated [39, 40].

- **Sealed-bid auctions**. In this type of auction, buyers and sellers simultaneously bid the price and the quantity of the good to an auctioneer in a closed (blind) way. There are different sub-types regarding the way it is bid and the clearance.

  - First-price sealed-bid auction. In this type of auction, buyers and sellers bid simultaneously for the good and the price to an auctioneer in a closed (blind) fashion. The highest bid results in the winner [39, 40]. There are distinct sub-types in terms of the way bids are made and the way they are cleared. Concretely, in [42], it follows this type of auction with private information in a neighbourhood-distributed network, where the winning bid is higher than the order. In [43], a distributed market was studied in which the auction mechanism blindly occurred one hour in advance. The price was the mean of the reserve price (the minimum price the seller would accept) and the bids. Additionally, subscription fees were paid for the usage of the distribution network.

  - Pay-as-bid or discriminatory auction. The price and quantity of the goods to be sold is bid by each buyer. To do this, costs and quantities are planned. A clearing process occurs in which the production and consumption patterns are matched. When supply meets demand, the clearing price is reached. Buyers who offer less than the clearing price are the winners of the auction [39, 40].

  - Uniform Price sealed-bid auction. The price is determined in the same way as in pay-as-bid; all bids under the clearing price are winning bids. In this case, however, the clearing price is a single price and all winners pay the identical amount, independently of the bid amount. It is important to note that this auction is considered a fair trade, as all bidders are paid the same sum [39, 40].

In overall, sealed-bid auctions are regarded as well-known, solid and straightforward [39]. However, relying on a single bid leaves the buyer with uncertainty about the outcome. All are trusted to a single request, which cannot be adjusted. Having a single bid per buyer makes this type of auction lack competence and efficiency [39, 40].

Second-price sealed-bid or Vickrey auction. In this auction where the highest bid wins, but the second highest offer is paid. In [23] the Vickrey auction is used to allocate battery capacity.

- **Hybrid**. This auction is a combination of diverse auction types. As mentioned in [39], hybrid auctions in the energy sector are a combination of sealed bids and descending clock [39]. The main advantage of a hybrid auction is that it combines all the benefits of both auction types. However, the auction is more complicated.

- **Combinatorial auctions**. Buyers bid on a combination of goods in this auction. These products can be set by the bidder or the auctioneer. Different pricing rules are applied depending on the product package. The major virtue of a combinatorial auction is that it avoids the exposure problem. Nevertheless, the complexity is higher and there is only one chance for the package to be sold (assigned) [39, 40].

The advantage of using auctions to model a LEM is that it achieves rapid market equilibrium at moderately low computational cost in addition to allowing scalability. However, if a highly competitive auction is run, high price spikes can occur, leading to rejection.

1.4.4.4 Multi-level optimisation

Multi-agent formulations optimise a good at each management hierarchy layer. The optimisation of the upper agents depends on the optimisations of the lower agents. The lower-level optimisations are constraints on the upper-level optimisations, being a cascade optimisations.

In the literature, reference [50] studied a multi-level optimisation in a community, combining ADMM and alternating current optimal power flow. In [27], at a lower level, communities were orchestrated separately, maximising their local energy dispatch. At a higher level, energy flows amidst communities were managed. In [25], prosumers coordinated with multi-objective LP their smart home devices and traded their energy surplus/shortage with a central aggregator. The central aggregator then managed all the assets (community PV generation and ESS) along with the data provided by the prosumers (optimised values at a lower level) using a non-cooperative Stackelberg game.

In the following figure, Figure 1.4, LEM clearing methods are summarised.

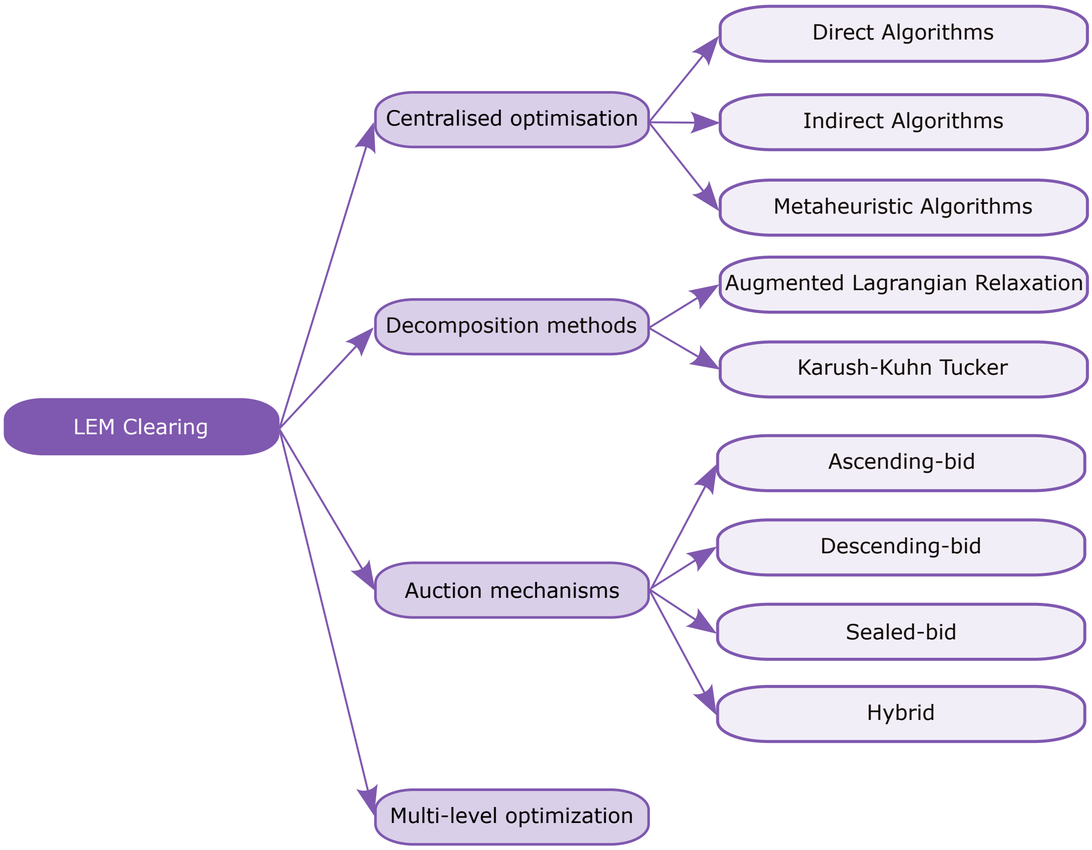

Figure 1.4: LEMs clearing

The control signals obtained from LEMs formulation and clearing methods may vary in a short-term scenario, where the three factors that drive the LEM (production and demand) are intermittent variables that may not follow a pattern in real-time. On the one hand, energy production is seasonal and weather-dependent, i.e., a cloud passing through the sky varies the irradiance beaming on the PV generation panel. On the other hand, consumption curves can fluctuate depending on the season, the weather and the vacation period. For instance, a consumer may be out of home, and the household demand may be the minimum. Another example is that depending on the weather, air conditioning or heating system switching may vary. Hence, forecasting error management in ECs is another topic to analyse and is done in the following section.

The literature review concerning LEMs was presented in a review article, in [51].

1.5 Generation and Consumption Forecasting in Community Management

In LEMs, a certain quantity of the energy produced by a generator or a prosumer is sold to another prosumer or consumer at a determined price. Three aspects come into play: energy generation, consumption, and price. Energy production depends on weather or atmospheric conditions in ECs supported by mainly renewable energies. The weather dependency derives to a variable energy pattern translated to unpredictability in energy production. The same happens with energy consumption. In the community outline, domestic consumption is also variable, which results in uncertainties in each user's energy demand. Regarding the energy price, the spot market values for the next day can be extracted from the wholesale market database. In the particular case of Spain, the following day's spot market price can be found on the grid operator (Operador del Mercado Ibérico de Energía (OMIE) in Spain) webpage [52].

Therefore, if an EC is considered in Spain, the variability is linked to consumption and generation patterns. To cope with both uncertainties and to obtain an efficient match between supply and demand, reliable forecasting models are required for energy generation and consumption. It can be concluded that it is important to rely on predictions to obtain the best matching (best trade among EC participants in terms of energy quantity and price). Then, error management is challenging as the energy deviation impacts the community electricity billing. Thus, in this section, EC short-term management literature review is done.

1.5.1 Forecasting error management

The prediction errors in electrical energy are considered an aspect to analyse, as the intermittency of renewable energy sources and consumption pattern variation can lead to miscalculations in short-term control. To ensure ECs' autonomy, it is necessary to cope with these uncertainties. Error management is an issue that must be considered, as the pattern modification after clearing the market impacts the community trading (energy deficit or surplus) directly related to the community electricity bill. The forecasting errors in short-term management are analysed in this subsection.

Regarding the literature, reference [47] did not perform any forecasting but did add forecasting errors. This way, the negative impact produced by the miscalculations was quantified. Nevertheless, this study did not address any error management. The research done in [29] predictions employed neural networks 24 hours in advance. Afterwards, for short-term management (1-minute steps), a battery was used and managed by decision trees. As it can be seen, table Table 1.5 scarce works have addressed LEMs with forecasting errors and their corresponding management.

Table 1.5: LEMs formulation, objective, clearing, ESS practical use and forecasting errors management in the literature.

Formulations	**Objectives**	**Clearing method's**	**Employed algorithm**	**Reference**	**ESS**		**Forecasting errors management**
					Cost-saving	**Source of income**	
Centralised optimisation	Operation cost minimisation	Direct algorithms	LP, MILP, MINLP, QP, MIQP	[20] (LP)	✓	✗	✗
				[36] (LP)	✓	✗	✗
				[24] (MILP)	✓	✗	✗
				[29] (MILP)	✓	✗	✓
				[32] (MILP)	✗	✓	✗
		Indirect algorithms					
	Social welfare maximization	Metaheuristic Algorithms	GA, PSO, DE, SA, ABC, TLBO	[47] (GA)	✗	✗	✓
Game theory	Cooperative	Augmented Lagrangian Relaxation	ADMM, ATC, PMP, APP	[15] (ADMM)	✗	✗	✗
				[33] (ADMM)	✗	✓	✗
	Non-cooperative	KKT		[49]	✗	✗	✗
				[28]	✓	✗	✗
Auctions	Open	Ascending-bid		[41]	✗	✗	✗
	Blind	Descending-bid		[42]	✗	✗	✗
		Sealed-bid	First-price	[43]	✗	✗	✗
			Pay-as-bid				
			Uniform Price				
		Second-price	[23]		✗	✓	✗
		Hybrid	Combination of auction types				
Multi-agent	-	-	Combination of clearing methods	[50] (AC-OPF+ADMM)	✗	✗	✗
				[27]	✓	✗	✗
				[25] (GA + NLP)	✓	✗	✗

1.6 Conclusions

The presented State of the Art aims to review the background information on ECs' energy trading and management topic. This chapter introduces the different definitions given by the EU to ECs and explains and compares LEMs P2P structures of energy trading.

According to the information obtained from the Energy Communities Repository, the different definitions given across Europe to CECs and RECs are patent. In some countries, Austria, Italy and Luxembourg, the law expresses the location in the electricity system: they can only be placed in LV and MV lines. The level of detail in laws development is also noticeable as some countries have also defined the energy-sharing method. More precisely, France, Italy and Spain limited the energy-sharing to collective self-consumption, giving detailed indications according to the energy distribution coefficients. In Belgium, energy trading was conceived as P2P trading in all regions. In Flanders specifically, detailed nuances of the P2P transactions are given. **This PhD thesis is focused on a Spanish scenario, and, in short, Spanish legislation currently recognises the figure of ECs under RECs' definition.** Energy surpluses generated in individual or collective self-consumption can be injected into the grid and economically rewarded. Nevertheless, **end-user empowerment and ECs objectives could be fulfilled by employing structures of P2P trading.**

P2P markets can be considered a tendency, as they permit the energy and money transactions within the limits of the ECs and are being addressed in the recent literature. **LEMs based on P2P trading are identified as the key factor in fostering the use of local renewable resources and enhancing the local economy**. Particularly, community-based P2P structure, where energy fluxes can be optimised to obtain more efficient trading, lessening electricity bills, reducing emissions, and fostering the local economy. Moreover, if these markets are located in LV lines, end-consumers can be empowered in the electricity system. Consequently, **P2P trading is investigated in the Spanish scenario.**

Another factor to consider is the assets employed in a community and the business characteristics. In this context, the integration of ESSs, where the ESSs serve as cost-saving assets or sources of income, has also been analysed. ESSs, mainly BTs, have been widely used as a cost-saving method, enhancing community self-sufficiency and reducing the associated electricity bill costs. However, the tertiary-owned BT is also seen as interesting, as it can serve as support for an EC and provide greater energy autonomy to the EC. Additionally, a gap was found concerning the combination of locally owned BTs and tertiary owned BTs. Hence, **a community composed of local BTs and an outsourced BT, employed as an energy service are considered.**

Correctly managing the assets in the LEM maximises local renewable consumption, reducing costs, emissions, and power losses. Consequently, optimal management is identified as the cornerstone for developing an EC. That is why the formulation and the clearing of LEMs were analysed. Among them, the technique that maximises the most local resources by giving the optimal solution is centralised optimisation, and the most straightforward clearing method is the direct algorithm. Thus, community-based P2P is founded on centralised optimisation that employs a direct algorithm. **As BTs are involved in the management, binary variables must be employed to avoid simultaneous charge and discharge. Then, in this, MILP optimisation is employed for energy management.**

Energy predictions play a key role in the LEMs due to prosumers' variability of generation and consumption patterns. Most works addressing ECs assume that the supply and demand profiles are previously forecasted and considered perfect without errors. However, the perfect forecasting approach goes beyond reality. In this thesis, energy generation and consumption predictions will be incorporated. Thus, one of the tasks of the thesis is to **include forecasting techniques in ECs management.**

After analysing the background of ECs, more accurately LEMs subjected to ECs, the gap in the literature regarding a LEM that combines P2P trading, local ESSs and tertiary-owned ESS is identified. Another aspect not fully considered in any LEMs is battery degradation, which can significantly impact the energy cost or the amortisation of the installation when overused or underused. **Thereby, a novel two-stage managed LEM will be addressed in this thesis. This LEM will consider local BTs and an outsourced BT as cost-saving mechanisms, and BT degradations will also be addressed in this thesis.**

2

New Energy-Sharing Market for Energy Communities

Summary

This chapter introduces a new energy-sharing market for ECs, where the key actors and interactions are described. First, the proposal is defined where the main agents are shown. In the second place, the methodology for evaluating the proposed energy-sharing market is detailed, where a) the scenario description is explained, b) the LEM designed is outlined, depicting the interdependence matrix of the agents' interactions, and c) the indicators for evaluating the proposal's performance are described. Lastly, the conclusions obtained are presented.

2.1 Proposed Energy-Sharing Market Description

Community-based P2P seeks the collective benefit of its participants [4], that can manage energy in terms of ecological, efficiency, technical (minimisation of losses) or social preferences. Hence, the energy-sharing market developed was rooted in a community-based P2P structure since it is the most similar to the EC definition. To achieve collective choices, a central entity orchestrates the community energy dispatch in this structure, maximising the use of local generation [4].

The EC analysed was a REC, where renewable energy resources were employed to fulfil the locally generated energy, and all the participants were located in the same area. Moreover, this community's LEM was centrally orchestrated. It was seen in the literature that a centrally managed LEM comprised of **different consumption patterns** would be more beneficial for community participants [53]. Buildings from different sectors (residential, industrial and tertiary) joined together in a community are beneficial to maximise the local resources [53].

Consequently, in the scenario **residential and tertiary sector**, buildings joined forces together. The tertiary sector buildings were specifically those appertaining to the local authorities. In a transversal way, the local authorities would be a key factor in reducing residential consumers' electricity bills.

In this regard, three types of agents were considered in the proposed energy-sharing market: the dwellings and tertiary building agents, BaaS storage and the central agent (energy manager). The assets and participation of each agent were the following:

- **Dwellings and tertiary building agents** encompassed a group of assets (local BTs, loads, and PV generation). Building agents were assumed to manage these assets internally and communicate their energy balance to the central entity. In short, residential building agents (RBs hereon) and the tertiary building agents (LTBs hereupon) were considered as EC prosumers.

- The **BaaS storage agent** was the unique agent containing a single asset: the physical collective BT (CESS hereafter) whose capacity was employed as a service. In other words, the agent provided the capacity to the other community participants. It was responsible for establishing the price of the energy volume. The central entity determined the energy quantity each building agent needed from this storage.

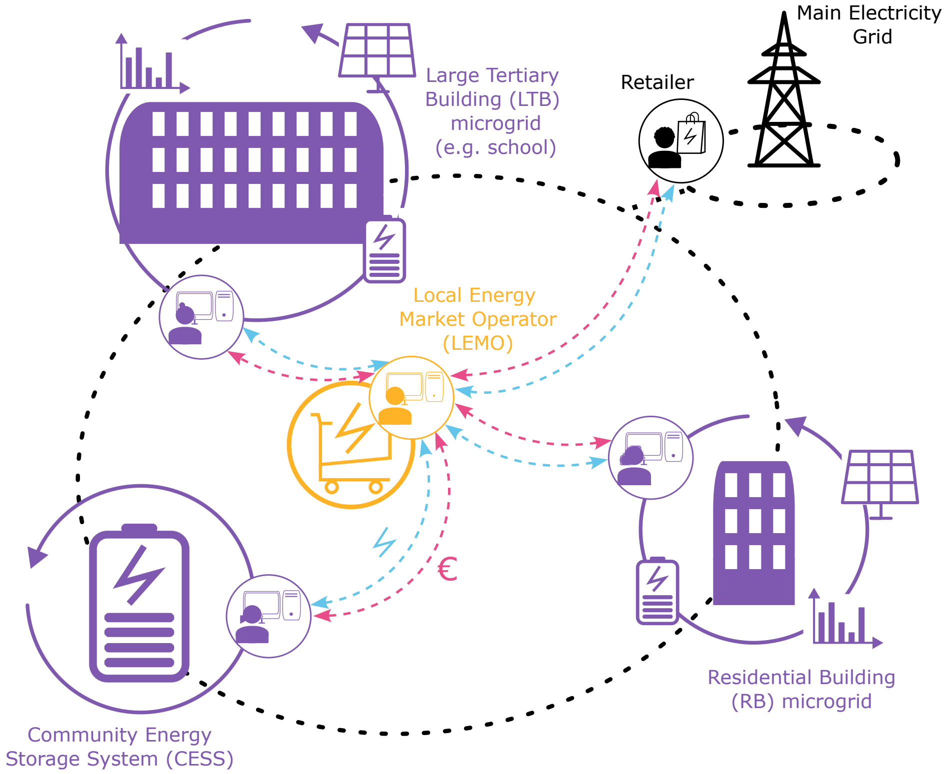

Figure 2.1: Proposed business model participants.

- The **central agent**, named LEMO, collectively coordinated all the community agents and orchestrated the energy and money trading within the community limits. Additionally, the LEMO traded with the retailer if the community had an energy deficit or surplus. All these transactions had to be charged or discounted to the community. Then, the LEMO distributed the correspondent billings to each community member. For simplicity, it was assumed that all the EC participants were linked to the same retailer.

To round off the proposed energy-sharing market, it was assumed that DLTs, such as Blockchain smart contracts, would accomplish the defined electricity and currency exchange established by the LEMO. This would address the issue of trading (data and money) cybersecurity and immutability. Nevertheless, the development of Blockchain architecture and associated smart contracts were out of the scope of this PhD thesis.

2.2 Methodology overview

The core is the LEM designed for the proposed energy-sharing market, covering the gap found in Chapter 1. A methodology was designed and implemented in

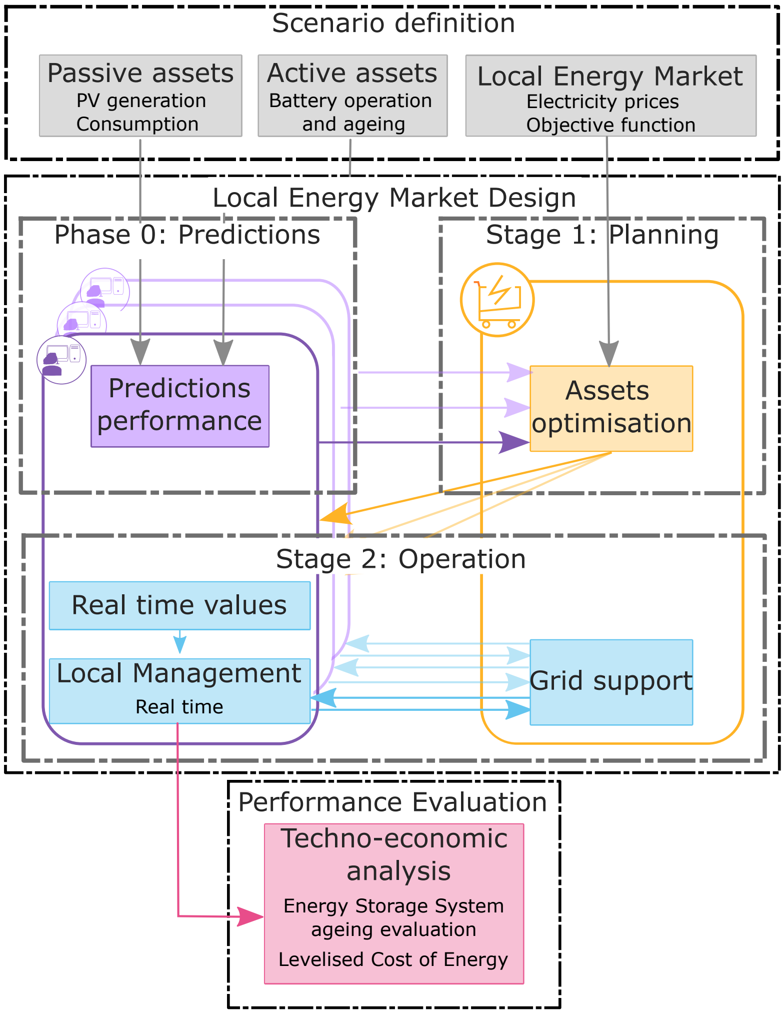

Figure 2.2: Methodology overview.

MATLAB environment (version 2022b) to guide the main research activities developed within this thesis. This methodology was employed to assess the market, address the main gaps and evaluate the proposed energy-sharing market based on three main blocks that were defined as scenario definition, LEM design and performance evaluation, as depicted in Fig. 2.2.

First, the **scenario** was defined according to the proposed energy-sharing market. The active and passive assets were characterised in line with the agents participating in the community. The main design and operation variables were defined. Market rules (gate closing times and market operation horizons) were also defined.

In the second place, the **LEM design** was applied to calculate the contribution of each building and CESS to the community dispatch. In this design, generation and consumption pattern variability were considered, as the stochasticity of these vectors brings mismanagement.

Hence, the LEM design consisted of two stages: planning and operation. In planning, each building agent sent their predicted generation and consumption curves to the LEMO to minimise the community electricity bill. Generation and consumption deposits were established to penalise the unfulfilment of predicted values. In operation, energy miscalculations were coped locally by local storage systems intending to achieve planned values. Then, each building managed prediction errors by employing CESS available capacity. The LEMO managed it with grid support if there was still an energy deficit or excess.

Finally, the LEM **performance** was **evaluated** conducting a techno-economic and environmental analysis. The techno-economic examination involved community technical aspects such as self-sufficiency, solar cover, and internal energy rate ratios. The economic analysis was subjected to the electricity bill and revenues from sharing energy in the P2P pool and injecting the excess energy into the grid. The environmental analysis was related to the CO_2 emissions.

2.2.1 Scenario overview

In the first place, the scenario was defined, characterising the building agents (RBs and LTBs), CESS agent and LEMO agent. The defined aspects were passive assets, active assets and LEM electricity prices and market clearing.

- **Passive assets** were related to inelastic patterns. The REC was located in Spain, where rooftop PV has taken force in recent years, thanks to the change in the regulatory framework of the electricity system [54]. Consequently, the buildings' generation was considered rooftop PV generation. The generation and the building's consumption could not be altered. Hence, the passive agent's data were generation and consumption patterns in predicted and real data ways.

- The **active asset** was the storage, as its operation could be changed by the corresponding agent (building or CESS). The performance of the resource was linked to its characteristics a) nominal capacity, b) initial State of Health (SOH), c) maximum charging and discharging powers, d) maximum charging and e) discharging efficiencies, and its operation ranges f) State of Charge (SOC).

- Regarding the **LEM electricity prices**, the **objective function** and the planning period were needed to execute the optimisation. Electricity prices were linked to a) the REC internal pricing, i.e. P2P price, b) external pricing, i.e. grid import and export prices and c) CESS pricing.

2.2.2 Proposed Local Energy Market Design

For determining the management design, the renewable energies generation intermittency and consumption pattern variability were considered, as the stochasticity of these vectors brings mismanagement. Data granularity is another aspect of designing a LEM. Market clearing was done in the literature from fifteen [24, 25] to hourly [20, 22, 29] timesteps. Hourly resolution was employed in this research for planning and operation phases as the historical data available for passive assets was sampled hourly, and it also corresponds to the Spanish government's energy-sharing settlement legislation, as presented in Table 1.3. This design was published in [55].

At a preliminary phase, Phase 0 in Fig. 2.2, each building carried out generation and consumption predictions. Then, two-stage LEM was held, which consisted of planning, Fig. 2.2 Stage 1, and operation, Fig. 2.2 Stage 2. First, the LEMO obtained agents' predicted data (consumption and generation) from all the community participants and gathered the wholesale market electricity prices for the next day. Through an optimisation algorithm, the LEMO planned the hourly energy dispatch on a day-ahead basis (long-term), depicted in Fig. 2.2 Stage 1. Finally, LEM operation was performed every hour (short-term). In this short-term operation, forecasting miscalculations were managed in operation employing local BTs, as shown in Fig. 2.2 Stage 2. Note that if any EC participant had any energy excess or surplus in Stage 2, it would have grid support. A detailed description of the interactions is given in the following subsections.

2.2.2.1 Phase 0: Prediction module

In this work, see Fig. 2.3, each building predicted its energy balance to decrease the computational burden of the centralised management of the LEMO. Each building employed its own historical generation (1.a) and consumption (2.a) data, downloaded from the DSO and the historical weather data gathered from local databases, and predicted the energy balance for each timestep. The building forecasted two vectors: generation and production (3.a). Finally, the predicted balance was calculated (4.a).

2.2.2.2 Stage 1: Planning

In planning, each RB or LTB entrusted the local trading agent to manage its energy deficit or surplus. Firstly, they submitted their balance based on their

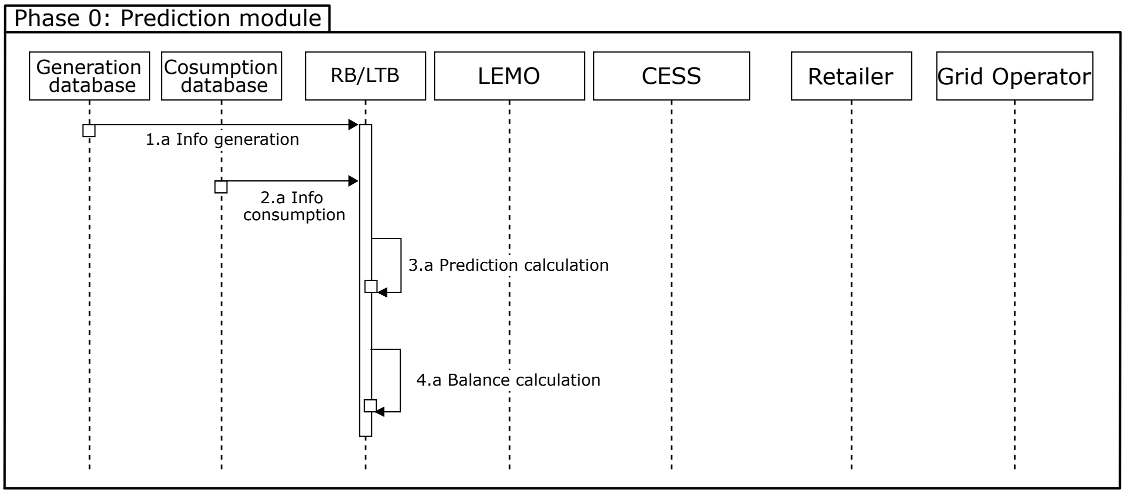

Figure 2.3: Prediction module performance.

generation and consumption predictions, the available energy of their local BTs and their operation limits, i.e. maximum and minimum charging and discharging powers and maximum and minimum SOC, step Fig. 2.4 (1.b). Also, the CESS agent provided the storage available capacity, the related physical constraints, and the operation price, as in (1.b). Secondly (2.b), the LEMO determined the energy management of the community with an optimisation algorithm based on established rules or preferences. Finally (3.b), the central agent informed each agent about the amount of energy corresponding to it at any moment.

In other words, the LEM optimised, via an algorithm and related restrictions, the energy trading within the community limits according to the expected energy balances, the CESS price and the scheduled wholesale prices for the next day. The optimisation resulted in the dispatch power allocation of each participating

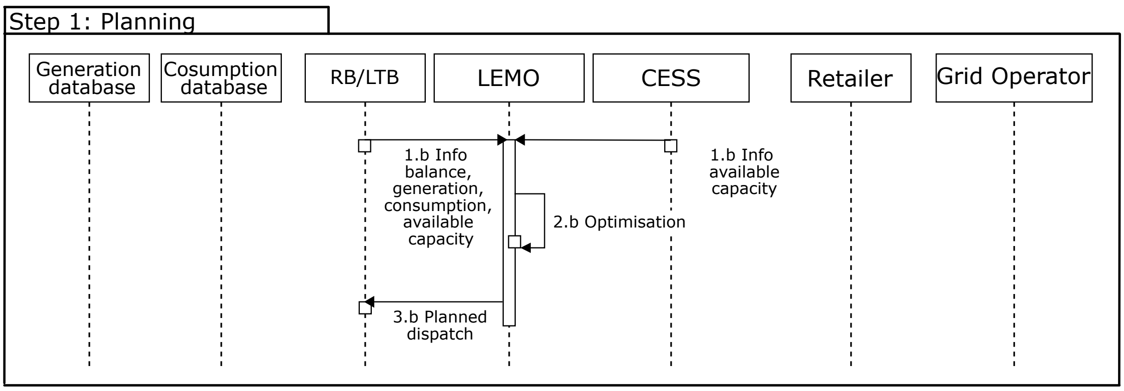

Figure 2.4: Planning performance.

agent in the community. In case a building or a group of buildings had an energy surplus, the LEMO had to manage it. In case P2P demand was covered and, if it had, the local BTs were full, and CESS was full, the community had enough energy to meet its needs. So, the LEMO would not use all the surplus energy but would feed it into the grid at the set price. Conversely, if a building or group of buildings needed energy and there was not enough P2P energy, and if they had BTs fully discharged and CESS fully discharged, the aggregation of the community resulted in collective consumption. The LEMO traded the collective demand with the retailer and bought the energy needed.

The community was remunerated or charged collectively if there were energy purchases or selling. Then, the LEMO administered the buildings' individual electricity billings. For simplicity, a unique retailer was assumed for all the community members. It was also presumed that the retailer knew and accepted all the intra-community P2P trading.

As this proposal acknowledged predicted data errors, **economic penalties** were also addressed in this LEM design. The expected plan would be altered if there were generation and consumption modifications. The LEMO would have to trade unexpected energy volumes with the retailer. Consequently, economic penalties were implemented to address energy variabilities. For that, hourly monetary deposits were applied. The **monetary deposits** were defined according to a participant's role (prosumer or consumer).

- **Generation deposit**. The deposit, $d_{r,k}^{gen}$ in [€], was designed according to the possibility of a building's inability to supply the planned energy. If a building r of the set of buildings R ($r \in R$) could not provide the allocated power in instant k of K ($k \in K$) for a time frame Δk, the community had to buy it from the grid. The predicted value could be the maximum the PV installation could administer. For grid security and quality reasons, the maximum installed PV power was limited to the buildings' contracted power.

  Because of the stochastic nature of generation and consumption, prosumers could play a different role than expected. Buildings could be predicted as prosumers and, in short-term, be consumers or vice versa. This role shift was supervised by designing the generation deposit to cope with the predicted generated energy and the real quantity the participant could consume. Consequently, the deposit was sized according to the maximum power the participant r could consume, P_r^{contr} in [€$/kW$], as expressed in Eq. (2.1).

$$d_{r,k}^{gen} = \lambda_{r,k}^{imp,grid} \cdot \left(P_r^{contr} + P_{r,k}^{PV,pred}\right) \cdot \Delta k \tag{2.1}$$

being $\lambda_{r,k}^{imp,grid}$ in [€/W] the grid price of a building r at timestep k, and $P_{r,k}^{PV,pred}$ in [W] the predicted PV generation of participant r timestep k and Δk the time frame where the energy dispatch occurs.

- **Consumption deposit**. This deposit, $d_{r,k}^{cons}$ in [€], addressed the variation between the real and predicted consumption data. A building could consume more or less than the predicted data. If a building demanded more energy than expected, the community had to fulfil it from the grid. The maximum value that a building could need was the contracted power. Suppose the prosumer role was shifted from consumer to generator. In that case, the full deposit would be returned to the participant, and the excess energy would be injected into the grid. Thus, the consumption deposit was sized according to the variation among the contracted and the predicted power, as in Eq. (2.2).

$$d_{r,k}^{cons} = \lambda_{r,k}^{imp,grid} \cdot \left(P_r^{contr} - P_{r,k}^{cons,pred}\right) \cdot \Delta k \tag{2.2}$$

where $P_{r,k}^{cons,pred}$ in [W] was the predicted consumption of a building r at sample k.

Finally, this LEM would end in a real application with the generation of energy contracts, (4.b). For instance, these contracts could be Blockchain technology smart contracts, as in [50, 56, 57]. These smart contracts would register each participant's energy volume, economic obligations, and correspondent deposits. As aforementioned, the development of smart contracts is out of the scope of this PhD thesis.

2.2.2.3 Stage 2: Operation

In operation, predicted data and real data miscalculation management were carried out in short-term. The short-term stage was also considered as hourly timesteps. In this case, the local storage units were managed individually. Short-term BT management determined whether there was sufficient energy to meet the requirements or whether energy was fed into or purchased from the grid.

- Deposits were refunded if BT physical limits were not surpassed and there was sufficient BT capacity.

- Penalties were applied if a) BT physical limits were surpassed and the capacity that could be employed was insufficient or b) if the remaining BT energy was not enough to meet energy needs. The energy that the BT could not provide or collect was discounted or paid from the deposit. If any deposits remained, they were returned to the respective participant.

The steps of the operation are described in Fig. 2.5. First (1.c), each community participant calculated the energy deviations and, in case they had local BTs, tried to cope with the deviations with the storage in their domain (2.c). Afterwards, the community participants tried to manage their deviations with the CESS (3.c). The energy was allocated if any energy storage was left (4.c). Next, each building agent calculated the grid needs (5.c) and sent their energy readings to the local trading agent (6.c). In this way, the LEMO managed the energy deviation against the data previously obtained in planning. The LEMO calculated the grid needs (7.c) and informed the retailer (8.c). The retailer managed the sell or purchase information with the grid operator by informing the operator (9.c) and obtaining support from it (10.c). Afterwards, the retailer sent the energy charge or revenue to the LEMO (11.c). Once the LEMO obtained the necessary energy, it sent the corresponding energy to each participant (12.c). Finally, in case of an energy deficit, the LEMO penalised deviations employing the data gathered in the energy contracts (13.c).

The summary of the activities and communications of the proposed energy-sharing market are gathered in a summarised way in the following Fig. 2.6.

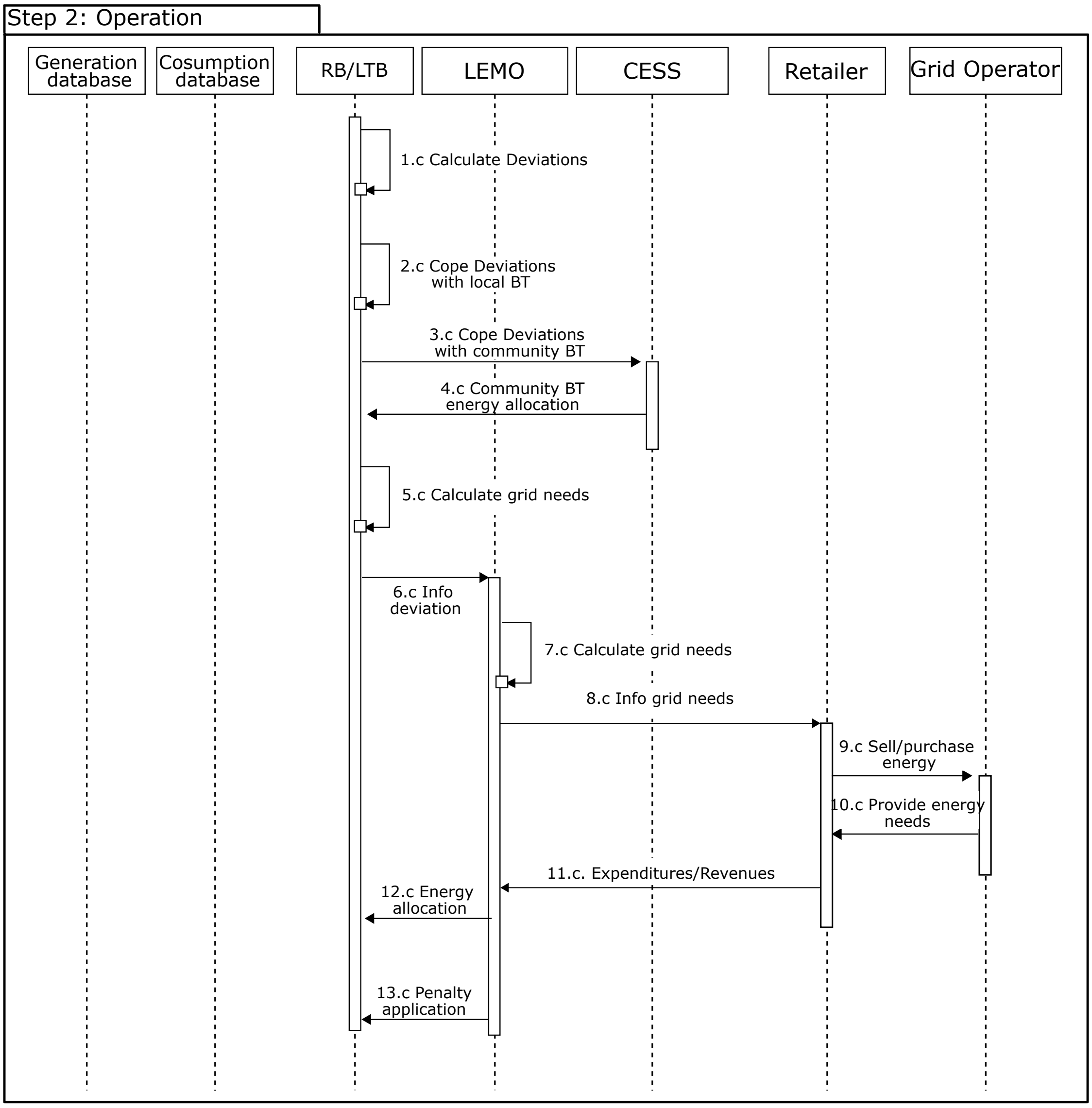

Figure 2.5: Operation performance.

2.2.3 Performance evaluation

The methodology finalised with the evaluation of the proposed energy-sharing market. A series of KPIs related to technical, economic and environmental aspects were employed for this analysis. Additionally, the BTs and CESS operations were studied in terms of ageing.

2.2.3.1 Technical Analysis

The technical aspects were analysed in terms of **self-consumption** and **solar cover** rates. The former refers to the proportion of the PV energy employed to cover the community's requirements, see Eq. (2.3). In this case, the PV en-

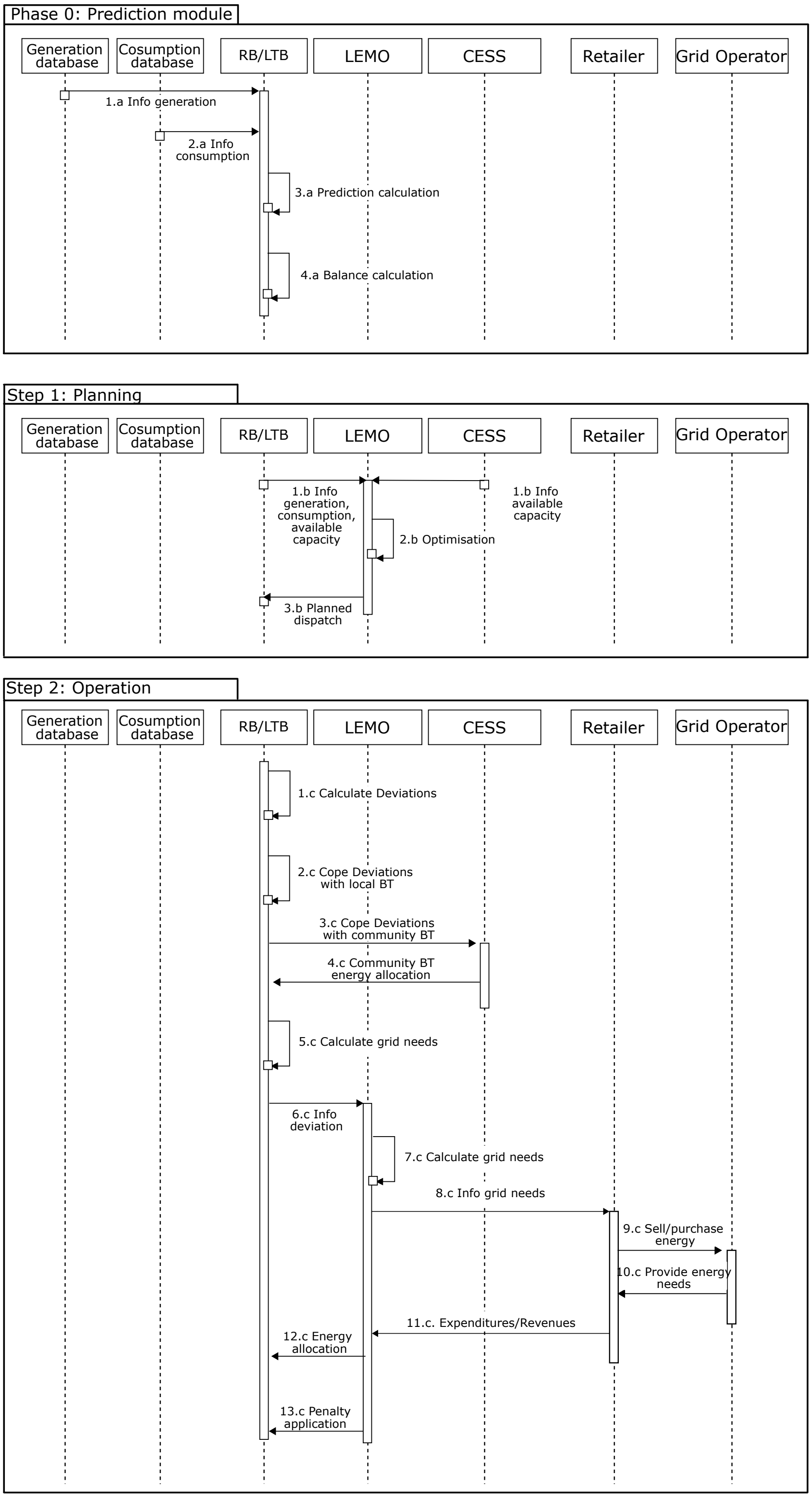

Figure 2.6: General overview of the two-stage management.

ergy that was employed for community self-consumption purposes was the PV generation used to satisfy the demand of the building r where it was installed ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow loads} \cdot \Delta k$ in $[kWh]$) and traded in the P2P pool for other participants ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow P2P} \cdot \Delta k$ in $[kWh]$). This ratio was calculated for the whole community generation ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV} \cdot \Delta k$ in $[kWh]$).

$$\text{Self-Consumption} = \frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{PV\rightarrow loads} + P_{r,k}^{PV\rightarrow P2P}) \cdot \Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV} \cdot \Delta k} \cdot 100 \tag{2.3}$$

The solar cover indicates the rate at which PV energy fulfils the community needs Eq. (2.4). For that, the PV generation used to satisfy the demand of the building where it was installed ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow loads} \cdot \Delta k$ in $[kWh]$) and traded in the P2P pool for other participants ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow P2P} \cdot \Delta k$ in $[kWh]$) were employed. The ratio was calculated with respect to the whole community demand ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{loads} \cdot \Delta k$ in $[kWh]$).

$$\text{Solar Cover} = \frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{PV\rightarrow \text{loads}} + P_{r,k}^{PV\rightarrow P2P}) \cdot \Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{loads} \cdot \Delta k} \cdot 100 \tag{2.4}$$

Moreover, this PhD introduced a rate for measuring the energy traded within the community limits called **Internal Energy Trade**, presented in [55], expressed in Eq. (2.5). This indicator was related to the PV energy traded locally in the P2P pool ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow P2P} \cdot \Delta k$ in $[kWh]$) and all the PV energy generated in the community ($\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV} \cdot \Delta k$ in $[kWh]$).

$$\text{Internal Energy Trade} = \frac{\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV\rightarrow P2P} \cdot \Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R} P_{r,k}^{PV} \cdot \Delta k} \cdot 100 \tag{2.5}$$

2.2.3.2 Economic Analysis

The economic evaluation was done in terms of collective electricity bill (C^{bill} in [€]), which was the sum of all the participants' electricity bills ($\sum_{r=1}^{R} C_r^{bill}$ in [€]), as in Eq. (2.6).

$$C^{bill} = \sum_{r=1}^{R} C_r^{bill} \tag{2.6}$$

The spanish electricity bill is calculated according to power ($\sum_{k=1}^{K} C_{r,k}^{power}$ in [€]) and energy ($\sum_{k=1}^{K} C_{r,k}^{energy}$ in [€]) term costs, which are detailed in the following Chapter 3. These costs are summed with a discount rate called *Bono Social* [58] (C^{BS} in [€]) and the equipment rental (C^{ER} in [€]). Finally, the electricity tax (tax^{elec} in [%]) and the Value Added Tax (VAT) (VAT^{elec} in [%]) are included in the term, resulting in the following equation:

$$C_r^{bill} = \left(\sum_{k=1}^{K} C_{r,k}^{power} + \sum_{k=1}^{K} C_{r,k}^{energy} + C^{BS} + C^{ER} \right) \cdot \left(1 + tax^{elec} + VAT^{elec} \right) \quad (2.7)$$

Hence, the collective bill is as expressed in Eq. (2.8).

$$C^{bill} = \sum_{r=1}^{R} \left(\sum_{k=1}^{K} \left(C_{r,k}^{power} + C_{r,k}^{energy} + C^{BS} + C^{ER} \right) \cdot \left(1 + tax^{elec} + VAT^{elec} \right) \right) \quad (2.8)$$

2.2.3.3 Environmental Analysis

The environmental aspect was examined regarding equivalent tonnes of CO_2. It is a widely used environmental indicator representing the proportion of CO_2 emitted corresponding to consuming non-renewable energy [59]. This proportion was calculated according to a) the sum energy consumed by all r participants from the grid ($\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow grid} \cdot \Delta k$ in $[kWh]$), as it is the only source with non-sustainable energy, b) a factor correlating the equivalent CO_2 with the consumed energy (ϵ in $[kgCO_2/kWh]$) and c) the energy mix at k instant of K time frame (ζ_k), as represented in Eq. (2.9).

$$\text{CO}_2 \text{ Emissions} = \frac{\sum_{k=1}^{K} \left(\sum_{r=1}^{R} P_{r,k}^{grid \rightarrow loads} \cdot \Delta k \cdot \epsilon \right) \cdot \zeta_k}{1000} \quad (2.9)$$

where ϵ is 0.331 $[kgCO_2/kWh]$ [1], as specified by the Spanish Government [60]. The variable ζ_k was determined according to the record done by the Spanish TSO. The register employed was from the year 2021 [61].

[1] ϵ depends on the installation location. Lasarte belongs to the constant specified for the Spanish peninsula - different values are employed for islands (Canary or Balearic islands) and autonomous cities (Ceuta and Melilla).

2.2.3.4 Batteries operation analysis

Another aspect to consider in the techno-economic analysis is the ESS degradation, which is also called ESS ageing. The ESS degradation depends on the storage operation and over time. The storage per se has a wear just for its existence, and the more a ESS is used, the more it deteriorates. The storage performance can be known by the SOC curve registered during the whole performance.

State-of-Charge (z_k) A storage system SOC refers to the available capacity at a specific step k concerning the nominal capacity. The SOC is a non-measurable factor that can impact battery health and safety through the years. The SOC is estimated according to the ESS chemistry and condition and can be directly measured or estimated. Direct measurements are uncommon due to their difficulty accessing ESS internal components and expansiveness. Hence, an indirect measurement was employed. In this context, the commonly used Coulomb Counting method was applied to calculate the SOC. This method computes cumulatively the current inflow at the delimited time (I_k in $[A]$) charged or discharged to the ESS, as in Eq. (2.10).

$$z_k = z_{k-1} + \int_{k-1}^{k} \frac{I_k}{Q^{nom}} \cdot dk \tag{2.10}$$

being z_k the SOC at the desired instant k in $[\%]$, z_{k-1} the storage SOC at the previosu step $k-1$ in $[\%]$, and Q^{nom} the storage nominal capacity in $[Ah]$.

In this thesis, the Coulomb Counting method was modified, where the current inflow was substituted by the fraction of the energy charged and discharged from the battery, as in Eq. (2.11). To make the optimisation more realistic, storage efficiency and the inverter efficiency—from which the storage is linked to the installation—were considered in the modified Coulomb Counting.

$$z_k = z_{k-1} + \left(\frac{P_k^{cha} \cdot \Delta k \cdot \eta^{cha} \cdot \eta^{inv}}{E^{nom}} - \frac{P_k^{dcha} \cdot \Delta k}{E^{nom} \cdot \eta^{dcha} \cdot \eta^{inv}} \right) \cdot 100 \tag{2.11}$$

where P_k^{cha} and P_k^{dcha} are, respectively, the power charged and discharged into/from the storage in k instant, and E^{nom} is the storage nominal energy in $[Ah]$, η^{cha} and η^{dcha} are the storage charging and discharging efficiencies and η^{inv} is the inverter efficiency.

Ageing (γ) A BT capacity can be degraded over time or use. The former is called calendar ageing (γ^{cal} in $[years]$), which is directly related to the capacity loss that a BT would suffer regardless of usage. The latter is named cycling ageing (γ^{cyc} in $[years]$), which is associated with the BT capacity worsening as a matter of use - linked to the SOC pattern. Hence, calendar ageing determines the BT wear, as estimated in Eq. (2.12).

$$\gamma = f(\gamma^{cal}, \gamma^{cyc}) \tag{2.12}$$

The lifespan of a BT is based on the capacity fade; it is measured by the SOH rate (SOH in [%]), which divides the available capacity ($Q^{available}$ in $[Ah]$) with the nominal capacity (Q^{nom} in $[Ah]$), as in Eq. (2.13). Knowing that the capacity loss is related to cycling and calendar ageing factors, the capacity decade (ΔSOH in [%]) is calculated by adding both calendar (ΔSOH^{cal} in [%]) and cycling (ΔSOH^{cyc} in [%]) decade terms, as expressed in Eq. (2.14) [62].

$$SOH = \frac{Q^{available}}{Q^{nom}} \cdot 100 \tag{2.13}$$

$$\Delta SOH = \Delta SOH^{cal} + \Delta SOH^{cyc} \tag{2.14}$$

It is to highlight that the manufacturer provides calendar degradation (expected lifespan years) and Full Equivalent Cycle (FEC) [2][62].

- **Calendar Estimation**. The calendar capacity decade was considered a linear degradation over time, as reflected in reference [62]. Following that assumption, the linear wear was contemplated as the rate between the calendar ageing and the installation project lifespan (γ^{proj} in $[years]$).

$$\Delta SOH^{cal} = \frac{\gamma^{cal}}{\gamma^{proj}} \tag{2.15}$$

- **Cycling Estimation**. In the literature, various ageing models were proposed with different degrees of complexity and accuracy: physical, math-

[2] A complete battery cycle is considered as charging or discharging all the available battery capacity, disregarding the quantity of the battery capacity values [63].

ematical or fatigue-based models [64]. Among these models, the Wöhler curve-based method,—a fatigue analysis method—is frequently employed for BT ageing evaluation since it has low computational burden [64]. The Wöhler method employs the Depth of Discharge (DOD)[3] parameter to estimate the BT wear [65]. DOD counting can be done by algorithms, and, in this case, the Rainflow cycle counting algorithm was employed.

- **Wöhler curve-based ageing**. The concept of Wöhler curve-based ageing mathematical model, detailed in Eq. (2.16), calculates the lifetime lost (LL_{ievt}) according to the ratio between the number of events and the maximum number of events. This represents the lifetime lost by the fraction of the number of DODs (NE_{ievt}) to the maximum number of DODs that the BT can tolerate (NE_{ievt}^{max}). The Wöhler curve varies depending on the BT chemistry.

$$LL_{ievt} = \frac{NE_{ievt}}{NE_{ievt}^{max}} \tag{2.16}$$

- **Rainflow cycle counting algorithm**. The Rainflow cycle counting algorithm determines the DOD counting utilised in the Wöhler curve-based ageing [62]. This algorithm tracks the number of cycles at various DODs, as depicted in Fig. 2.7. This method analyses the SOC operation profile (black curve) during charging (purple curves) and discharging (blue curves). Firstly, the algorithm identifies and enumerates the highest charge cycle (number 1 purple curve) and discharge cycle (number 1 blue curve). Subsequently, semi-cycles are counted without overlapping the previously numbered cycles. This assessment finishes once all the valleys are included.

Finally, cycling is estimated as the inverse of the total lifetime lost, as in Eq. (2.17).

$$\gamma^{cyc} = \frac{1}{\sum_{100}^{ievt=1} \left(\frac{NE_{ievt}}{NE_{ievt}^{max}} \right)} \tag{2.17}$$

[3]The DOD is an indicator that estimates the used capacity in a specific step k. It is the reverse of SOC parameter, being DOD = 1 − SOC. The unit is [%]

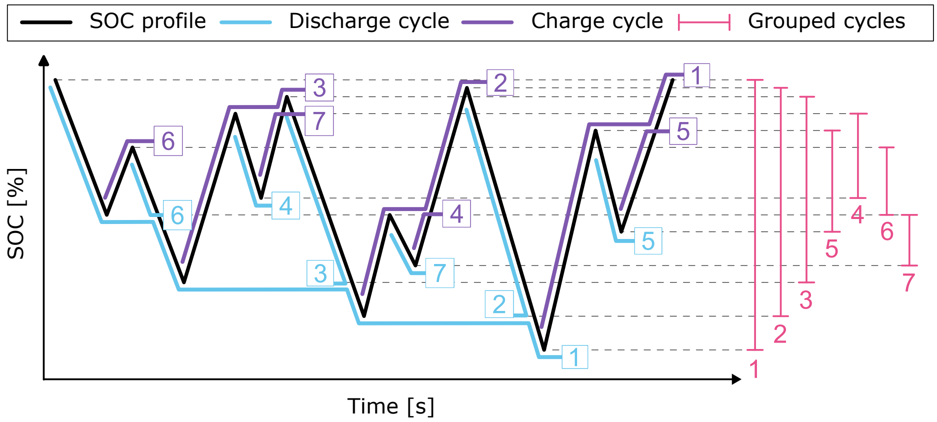

Figure 2.7: Rainflow charging/discharging cycle counting algorithm [62].

2.3 Conclusions

An **energy-sharing market** was proposed, **and the associated LEM design**, based on two-stage energy management, **were introduced** in this chapter. A novel energy-sharing market based on the BaaS concept was presented: a third agent, namely CESS, owned physical storage that provided capacity fractions to the community users. This aspect allowed community users to have another energy source with a competitive price towards the grid. Additionally, community participants strengthened their energy autarchy by consuming energy from the CESS.

In the second section, the **methodology overview for evaluating the LEM viability** was described. It was composed of three blocks: scenario overview, LEM design and performance evaluation. **The first block** details the **operation characteristics** of the active and passive assets belonging to community participants **and the objective function and electricity prices** employed in the LEM.

The steps for the market clearing were defined in the **second block**. A prediction module was introduced as input in the preliminary phase. Then, the two-stage management (planning and operation) was explained. The first stage outlined an ex-ante optimisation for the planning phase. In this phase, monetary deposits and applicable penalisations were also applied and explained. Furthermore, short-term operation management was described, where local and community BTs dealt with prediction errors. In this regard, **a gap in the literature was covered where a LEM that considered prediction errors, their latter management, and penalisations for energy deviations was proposed.**

In the **third block**, the proposed energy-sharing market **performance evalu-**

ation was introduced. That evaluation was **linked to the simulation output techno-economic, environmental, and the community ESSs ageing** analysis were outlined.

3

Energy Community agents assets modelling and control

Summary

In this chapter, the agents participating in the EC are defined, where the mathematical expressions and physics employed for modelling their passive (generation and consumption) and active (storage) assets are described. The pricing established for EC's internal and external operations was also detailed, highlighting a novel P2P price establishment. Finally, each agent control over the active agent is detailed, the LEMO agent optimisation objective is specified, and RBs and LTBs short-term management are outlined.

3.1 Energy community agents modelling

Three different agents were defined: building agents, CESS agent and LEMO agent see Fig. 2.1. The assets of each agent were passive and active. Passive assets were the rooftop solar PV installation as an inelastic renewable energy generation source and the building inelastic demand. The active asset was some participants' battery ESS that served as a buffer.

3.2 Building agents

3.2.1 Passive assets

3.2.1.1 PV generation

The instantaneous PV generation ($P_{r,k}^{PV}$ in $[kW]$) of each building r of a set of buildings R ($r \in R$) was calculated from the correlation between the PV installed power ($P_r^{PV,inst}$ in $[kW]$), the instantaneous irradiance (G_k in $[W/m^2]$) at each sample k of K time horizon ($k \in K$), and cell temperature (T_k^{cell} in $[°C]$) at each sample k, as in Eq. (3.1) extracted from [66].

$$P_{r,k}^{PV} = P_r^{PV,inst} \cdot \left\{ \frac{G_k}{1000} \cdot (1 + \iota \; (T_k^{cell} - 25) \right\} \tag{3.1}$$

being ι the PV panel temperature coefficient in $[\%/°C]$, given at each PV panel datasheet.

Installed Power The installed PV power was determined according to the contracted power of each building, as defined in Eq. (3.2), since each building's node and the related electrical safeguards are subjected to a specific power to ensure the electrical line safety and grid quality.

$$P_r^{PV,inst} = \max \left(P_{r,k}^{loads} \right) \tag{3.2}$$

Irradiance The instantaneous irradiance incident to the PV panel depends on the location of the installation [67]. The EC addressed is classified as a REC, where all the participants are located in the same geographical point. Hence, the irradiance value incident in the community was assumed to be the same for all the participants (disregarding possible surrounding shadows).

The total irradiance arriving at the panel is composed of the direct, reflected and diffuse components of the irradiance, as depicted in Fig. 3.1. The irradiance can be measured by a pyranometer [1], a pyrheliometer [2], a photodiode [3] or by satellite-based methods [4] [68]. Pyranometers, pyrheliometers and photodiodes can be installed directly in the PV panel location, which is unusual in small-scale installations [68]. Thus, it was considered that there was no measurement in the community, and due to the participants' location, the irradiance value was downloaded from the local database. The REC under study was located in Lasarte, a town in Gipuzkoa region in the north of Spain. The required data was obtained from Euskalmet [69] local database.

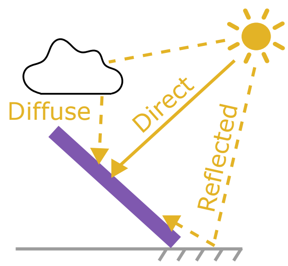

Figure 3.1: Irradiance components.

Knowing which irradiance component is employed for calculating the solar penetration is essential. The gadget used in Lasarte's meteorology station to measure the irradiance is a pyranometer [69], which measures the horizontal surface component of irradiance, differing from the one striking the solar panel, as in Fig. 3.2. Trigonometry was employed to calculate the irradiance factor, based on the relation of the solar height (α in [°]) and the panel inclination (β in [°]), as expressed in Eq. (3.3).

$$G_k = \frac{G_k^{horizontal} \cdot \sin(\alpha + \beta)}{\sin \alpha} \tag{3.3}$$

The parameter α is dynamic, as the sun's position changes within the year de-

[1]It is a high-precision sensor that measures the solar irradiance on a horizontal surface. This gadget comprises two semi-spheric capsules, a black-coloured metallic absorption surface, a thermocouple beneath the metal surface and a white-coloured metallic surface. The absorption surface heats up once the sun's rays strike the gadget. This temperature change is directly proportional to the irradiance and is evidenced by the voltage difference in the thermocouple [68].

[2]A pyrheliometer is employed to measure uniquely the direct component of the irradiance and the orientation is changed with a tracking system to position the gadget directly to the sunlight. It is a metal tube that, at the end, has a thermocouple to measure the voltage variations [68].

[3]The gadget has a small PV cell and measures the electrical signal at the output. This sensor is less accurate than a pyranometer since it has less wavelength spectrum sensitivity [68].

[4]The irradiance is calculated according to the cloud images obtained from a satellite, which is not considered an accurate measurement [68].

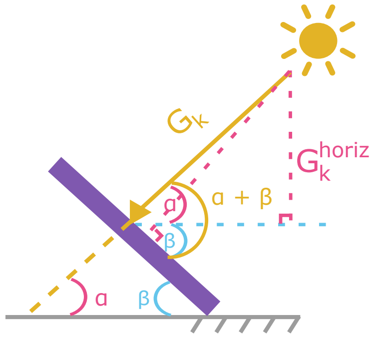

Figure 3.2: Solar irradiance for a tilted surface.

pending on the latitude (ϕ in [°]) and solar declination concerning the vertical axis of the Earth (δ in [°]). β is a static parameter since it is a value intrinsic in the PV panel installation. The α angle change within the year is represented in Eq. (3.4), all in [°].

$$\alpha = 90 - \phi + \delta \tag{3.4}$$

At the same time, the solar declination is seasonally dynamic, as Earth's rotation plane around the sun changes within the year, see Fig. 3.3. The solar declination is calculated in Cooper's formula [70], as expressed in Eq. (3.5).

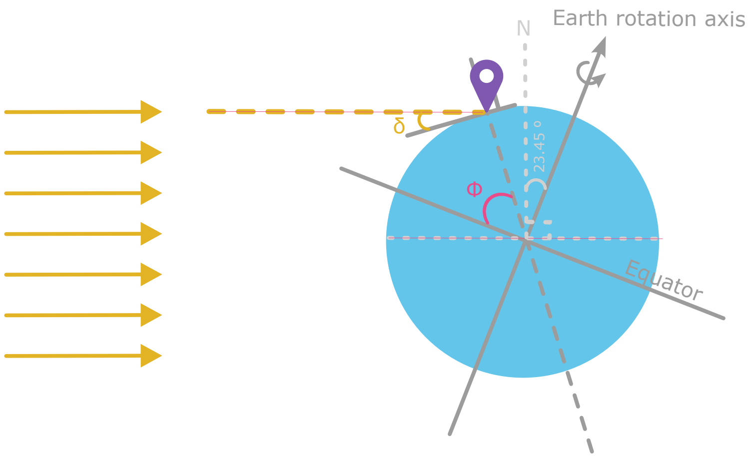

Figure 3.3: Solar declination.

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284 + D}{365}\right) \tag{3.5}$$

where 23.45 ° corresponds to the Earth's rotation axis angle to the Earth's elliptic orbit, assuming that the elliptic orbit is a flat circular surface. The day number is converted to their correspondent position in the orbit by the fraction 360/365. D is the day of the year. The 1^{st} of January, D is equivalent to 1 and 31^{st} of December is equivalent to 365.

Cell Temperature Like the local meteorological station, a small-scale installation rarely has a cell temperature sensor. Another approximation was made for obtaining this variable based on reference [66]. The cell temperature is correlated with the ambient temperature (T_k^{amb} in [$°C$]), the irradiance and the temperature at Normal Operating Cell Temperature (NOCT) conditions (T^{NOCT} in [$°C$]). The cell temperature at sample time k was calculated from the formula expressed in (3.6).

$$T_k^{cell} = T_k^{amb} + \left(\frac{T^{NOCT} - 20}{800}\right) \cdot G_k \tag{3.6}$$

3.2.1.2 Consumption

The REC participants considered were residential and tertiary buildings (school and fire station). In the absence of data, the consumption curves of both buildings' were modelled as follows:

- **RBs:** The residential buildings employed for this study were multi-apartment dwellings with ten households. This choice pretended to represent the typical Spanish residential set-up, where dwelling consumers live in apartment blocks [71]. According to the National Statistics Institute, in the year 2019, 68 % of residential buildings were recorded as multi-apartment buildings; among them, 69.3 % were of equal or more than ten households [71]. Thereby, multi-apartment buildings were of 10 households. The demand data was generated by randomly scaling and upscaling five consumption patterns from 2017, which are available in IKERLAN's database.

- **LTBs**: The daily **school** consumption pattern was obtained from [72]. Then, this pattern was replicated for each school day in the Gipuzkoa region. The vacation periods and weekends were considered, and the lowest power value was considered for those days. Concerning the **fire station** was extracted from [73]. The pattern was maintained by transforming it into a per-unit shape. Afterwards, the pattern was scaled to the maximum consumption of a fire station in the Gipuzkoa region [74].

3.2.2 Active assets

3.2.2.1 Storage

The last asset of the model was the storage system. The SOC parameter determined the operation of the BTs. Another important parameter to consider was the ageing since these characteristics indicate the degradation of the storage within the system's lifespan.

State-of-Charge The Coulomb Counting method was employed to calculate the SOC of residential storage systems as in Eq. (2.10). As aforementioned in Chapter 2, the Coulomb Counting method was modified, where the current inflow was substituted by the fraction of the energy charged and discharged from the battery, as in Eq. (2.11). More precisely, Eq. (3.7) was used to calculate residential buildings' SOC ($z_{r,k}^{BT}$ in [%]).

$$z_{r,k}^{BT} = z_{r,k-1}^{BT} + \left(\frac{P_{r,k}^{BT,cha} \cdot \Delta k \cdot \eta_r^{BT,cha} \cdot \eta_r^{inv,BT}}{E_r^{BT,nom}} - \frac{P_{r,k}^{BT,dcha} \cdot \Delta k}{E_r^{BT,nom} \cdot \eta_r^{BT,dcha} \cdot \eta_r^{inv,BT}} \right) \cdot 100 \tag{3.7}$$

being $z_{r,k-1}^{BT}$ in [%] the previous step, $k-1$ step, SOC. $P_{r,k}^{BT,cha}$ and $P_{r,k}^{BT,dcha}$ in $[kW]$, respectively, the power charged and discharged of r building of the set of buildings R storage in k instant of Δk time frame. E_r^{nom} is r buildings' storage nominal capacity in $[kWh]$, η_r^{cha} and η_r^{dcha} are the storage charging and discharging efficiencies and $\eta_r^{inv,BT}$ is the inverter efficiency of is r buildings' storage.

Ageing The ageing model was previously explained in Chapter 2. For local storage, Eq. (3.8) was used to calculate residential building r BT ageing (γ_r^{BT} in $[years]$). All the related variables to calculate the calendar and cycling parameters depended on each building's BT, calendar and cycling wear.

$$\gamma_r^{BT} = f\left(\gamma_r^{cal,BT}, \gamma_r^{cyc,BT}\right) \tag{3.8}$$

where $\gamma_r^{cal,BT}$ and $\gamma_r^{cyc,BT}$ in $[years]$ are, respectively, the calendar and cycling ageing of each building r storage.

Each building's SOH (SOH_r^{BT} in [%]) and lifetime lost, ($LL_{ievt,r}^{BT}$ in $[years]$) are expressed in Eqs. (3.9) and (3.12).

$$SOH_r^{BT} = \frac{Q_r^{available,BT}}{Q_r^{nom,BT}} \cdot 100 \tag{3.9}$$

where $Q_r^{available,BT}$ in $[Ah]$ and $Q_r^{nom,BT}$ in $[Ah]$ are, apiece, the available and nominal capacity of each building r storage.

Each buildings' BT capacity decade, ΔSOH_r^{BT}, was calculated according to Eq. (3.10).

$$\Delta SOH_r^{BT} = \Delta SOH_r^{cyc,BT} + \Delta SOH_r^{cal,BT} \tag{3.10}$$

being $\Delta SOH_r^{cyc,BT}$ and $\Delta SOH_r^{cal,BT}$, respectively, r building's local BT cycling and calendar decades. All in [%].

The lifetime lost by cycling degradation was related to the DOD counting, for which Wöhler curve-based method was employed, as expressed in Eq. (3.11).

$$LL_{ievt,r}^{BT} = \frac{NE_{ievt,r}^{BT}}{NE_{ievt,r}^{max,BT}} \tag{3.11}$$

where $LL_{ievt,r}^{BT}$ is the lifetime lost of building r storage, $NE_{ievt,r}^{BT}$ is the number of DODs of storage r, and $NE_{ievt,r}^{BT,max}$ is the maximum number of DODs in storage r.

The sum of all the number of DODs ($\sum_{ievt} LL_{ievt,r}^{BT}$) is the total lifetime lost (LL_r^{BT}) of the building, as in Eq. (3.12).

$$LL_r^{BT} = \sum_{ievt} LL_{ievt,r}^{BT} \tag{3.12}$$

Finally, the cycling wear of each r building's BT is computed as in the following Eq. (3.13).

$$\gamma_r^{cyc,BT} = \frac{1}{\sum_{ievt=1}^{100} \left(\frac{NE_{ievt,r}^{BT}}{NE_{ievt,r}^{BT,max}} \right)} \tag{3.13}$$

3.2.3 Short-term control

Since the data employed for planning was predicted data and renewable energy resources generation and consumption patterns were stochastic, in operation, the values could be different from reference values established by the LEMO. Hence, in this second stage, each participant managed their prediction errors, employing, in case they had, the BT in their domain to deliver/receive the energy reference determined in the planning stage.

Firstly, each building analysed the power request in short-term ($P_{r,k}^{real}$ in $[kW]$). The power deviation was calculated according to short-term role (consumer or generator) and the participant's predicted role.

- In short-term the participant had generator role ($P_{r,k}^{real} > 0$), the BT operation was determined as in Eq. (3.14).
  - If it was predicted as a generator ($P_{r,k}^{PV,pred} > 0$), the power quantity predicted and metered established the deviation.
    - If more power quantity, i.e. more generation, was metered than the predicted ($P_{r,k}^{real} > P_{r,k}^{PV,pred}$), the deviation was positive ($Dev > 0$) and BT charging set point was decided.
    - If less power quantity, i.e. less generation, was metered than the predicted ($P_{r,k}^{real} < P_{r,k}^{PV,pred}$), the participant would need to deliver the planned supply value. Hence, the deviation was negative ($Dev < 0$) and BT discharging set point was determined.
  - If it was predicted as a consumer ($P_{r,k}^{cons,pred} < 0$), more power quantity was metered than the predicted ($P_{r,k}^{real} > P_{r,k}^{cons,pred}$), the predicted role was changed having an energy surplus, being the deviation positive ($Dev > 0$) and BT charging set point was chosen.

$$P_{r,k}^{real} > 0 \begin{cases} P_{r,k}^{real} > P_{r,k}^{PV,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} - P_{r,k}^{PV,pred} \Rightarrow Dev > 0 \\ P_{r,k}^{real} < P_{r,k}^{PV,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} - P_{r,k}^{PV,pred} \Rightarrow Dev < 0 \\ P_{r,k}^{real} > P_{r,k}^{cons,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} + P_{r,k}^{cons,pred} \Rightarrow Dev > 0 \end{cases} \tag{3.14}$$

- In short-term the participant had consumer role ($P_{r,k}^{real} < 0$), the BT operation is expressed in Eq. (3.15).

- If it was predicted as a generator ($P_{r,k}^{PV,pred} > 0$), less power quantity was metered than the predicted ($P_{r,k}^{real} < P_{r,k}^{PV,pred}$), the deviation was negative ($Dev < 0$), it would have to deliver the predicted generation and fulfil the demand, hence, BT discharging set point was determined.

- If it was predicted as a consumer ($P_{r,k}^{cons,pred} < 0$), the power quantity predicted and metered established the deviation.

  * If more power quantity, i.e. more consumption, was metered than the predicted ($P_{r,k}^{real} < P_{r,k}^{cons,pred}$), the planned consumption would be excessive, being the deviation negative ($Dev < 0$) and BT discharging set point was decided.

  * If less power quantity, i.e. less consumption, was metered than the predicted ($P_{r,k}^{real} > P_{r,k}^{cons,pred}$), the deviation was positive ($Dev > 0$) and BT charging set point was determined.

$$\begin{cases} P_{r,k}^{real} < P_{r,k}^{PV,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} - P_{r,k}^{PV,pred} \Rightarrow Dev < 0 \\ P_{r,k}^{real} < P_{r,k}^{cons,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} - P_{r,k}^{cons,pred} \Rightarrow Dev < 0 \\ P_{r,k}^{real} > P_{r,k}^{cons,pred} \Rightarrow P_{r,k}^{dev} = P_{r,k}^{real} - P_{r,k}^{cons,pred} \Rightarrow Dev > 0 \end{cases} \tag{3.15}$$

As depicted in Fig. 3.4, firstly, the BTs' physical limits were checked. If energy was requested ($Dev < 0$), minimum SOC ($\underline{z_r^{BT}}$) and maximum discharging power ($\overline{P_r^{cha,BT}}$) were checked. If energy was injected ($Dev > 0$), maximum SOC ($\overline{z_r^{BT}}$) and maximum charging power were checked ($\overline{P_r^{dcha,BT}}$). If the energy need was within the limits, the BT was charged or discharged, and any penalties were applied. However, if any BT limit exceeded the requested energy volume, the participant would use the physical maximum that the BT could charge or discharge. The remaining energy would be subjected to economic penalties in the energy contract.

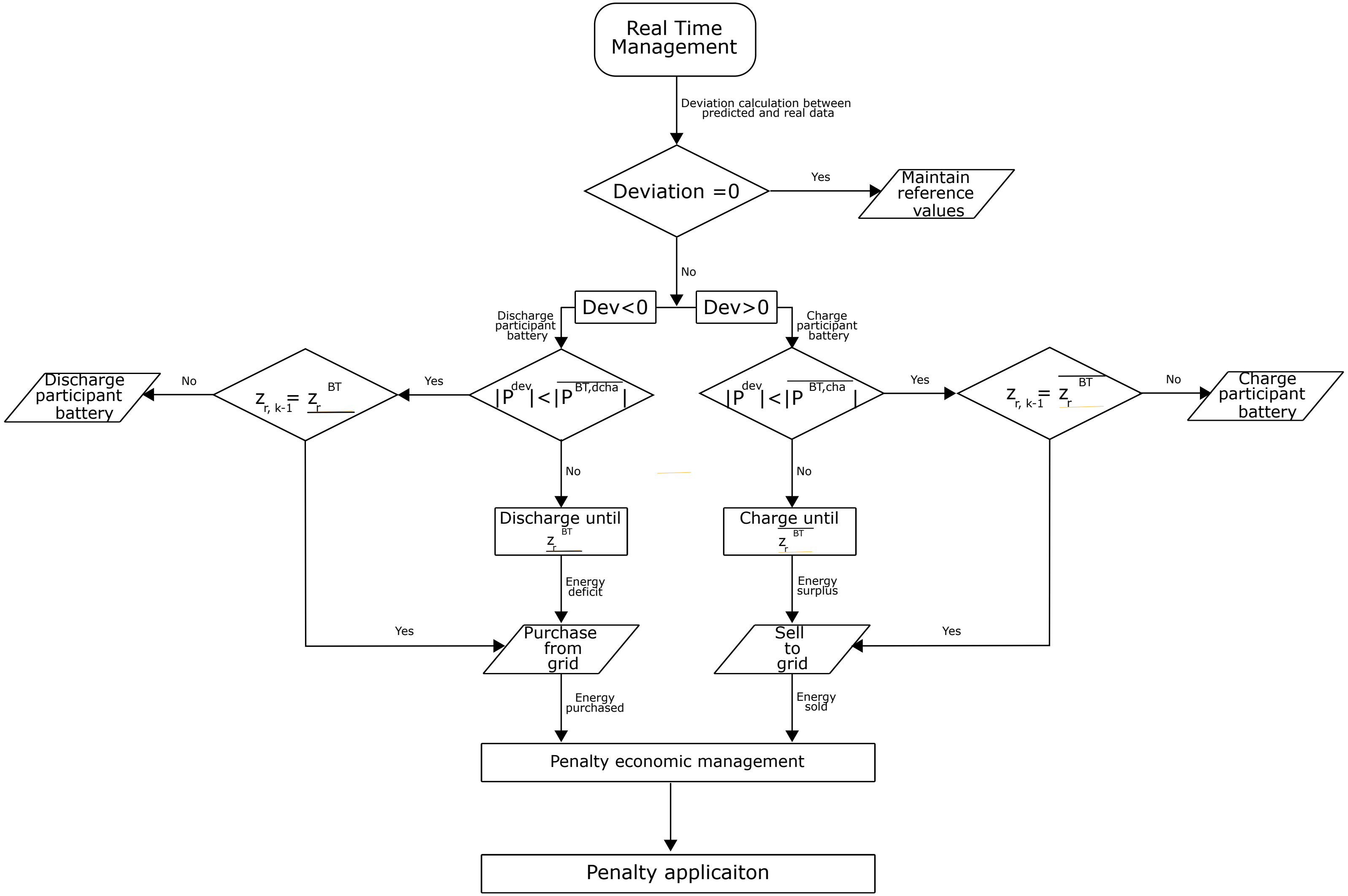

Figure 3.4: Local BT management flowchart.

3.3 Community Energy Storage System agent

The CESS was the unique REC agent with a single asset in its domain. It was the owner of the community storage that followed the BaaS model; the agent provided energy to participants as a buffer.

3.3.1 Active asset

Similarly to building storage systems, SOC and ageing parameters were determined for CESS agent.

3.3.1.1 State of charge

The SOC equation that describes the CESS behaviour is in Eq. (3.16).

$$z_k^{CESS} = z_{k-1}^{CESS} + \left(\frac{\sum_{r=1}^{R} P_k^{CESS \leftarrow PV} \cdot \Delta k \cdot \eta^{CESS,cha} \cdot \eta^{inv,CESS}}{E^{CESS,nom}} - \frac{\sum_{r=1}^{R} P_k^{loads \leftarrow CESS} \cdot \Delta k}{\eta^{CESS,dcha} \cdot E^{CESS,nom} \cdot \eta^{inv,CESS}} \right) \cdot 100 \tag{3.16}$$

being z_k^{CESS} in [%] the CESS the SOC value in k timestep and $z_{r,k-1}^{CESS}$ in [%] the SOC value in the previous timestep $k-1$ of the CESS. $\sum_{r=1}^{R} P_{r,k}^{CESS \leftarrow PV}$ and $\sum_{r=1}^{R} P_{k,r}^{loads \leftarrow CESS}$ are the power charged from r building generated PV and discharged to fulfil the demand in $[kW]$ at Δk time frame. $\eta^{CESS,cha}$ and $\eta^{CESS,dcha}$ are CESS storage charging and discharging efficiencies. Also, inverter efficiencies were considered, being $\eta^{inv,CESS}$ CESS inverter efficiency. Finally, $E^{CESS,nom}$ is the nominal energy of CESS in $[kWh]$.

3.3.1.2 Ageing

The CESS ageing parameters were modelled indentically to participants' BTs, see Eqs. (3.17) to (3.22).

$$\gamma^{CESS} = f\left(\gamma^{cal,CESS}, \gamma_r^{cyc,CESS}\right) \tag{3.17}$$

where γ^{CESS} is CESS ageing and $\gamma^{cal,CESS}$ and $\gamma^{cyc,CESS}$ are, respectively, the calendar and cycling ageing of CESS. All of them in $[years]$.

Community storage SOH (SOH^{CESS} in [%]), and lifetime lost, (LL_{ievt}^{CESS} in $[years]$), were adapted to Eqs. (3.18) and (3.21).

$$SOH^{CESS} = \frac{Q^{available,CESS}}{Q^{nom,CESS}} \cdot 100 \tag{3.18}$$

being $Q^{available,CESS}$ in $[Ah]$ and $Q^{nom,CESS}$ in $[Ah]$, apiece, the available capacity and nominal capacity of CESS.

The capacity decade (ΔSOH^{CESS} in [%]) is linked to the cycling ($\Delta SOH^{cyc,CESS}$ in [%]) and ($\Delta SOH^{cal,CESS}$ in [%]) calendar decades. All in [%].

$$\Delta SOH^{CESS} = \Delta SOH^{cyc,CESS} + \Delta SOH^{cal,CESS} \tag{3.19}$$

Concerning the lifetime lost, the DOD counting was carried out, as in Eq. (3.20).

$$LL_{ievt}^{CESS} = \frac{NE_{ievt}^{CESS}}{NE_{ievt}^{max,CESS}} \tag{3.20}$$

where NE_{ievt}^{CESS} are the number of DODs and $NE_{ievt}^{max,CESS}$ the maximum number of DODs in CESS.

The total lifetime lost (LL^{CESS}) was computed as the sum of the lifetime lost.

$$LL^{CESS} = \sum_{ievt} LL_{ievt}^{CESS} \tag{3.21}$$

Lastly, the CESS cycling ageing was calculated as the reverse of the total lifetime lost.

$$\gamma_{cyc}^{CESS} = \frac{1}{\sum_{ievt=1}^{100} \left(\frac{NE_{ievt}^{CESS}}{NE_{ievt,r}^{max,CESS}} \right)} \tag{3.22}$$

3.3.2 Community Energy Storage System import and export price

The CESS agent business model sought community users to use its storage as a buffer. The main CESS competitor was the energy provided by the community outside, i.e., the retailer. Additionally, CESS wanted to benefit from the business model. For that, energy import ($\lambda_{r,k}^{imp,CESS}$ in [€/kWh]) and export ($\lambda_{r,k}^{exp,CESS}$ in [€/kWh]) prices were determined, as expressed in Eq. (3.23).

$$\begin{cases} C_{r,k}^{imp,CESS} = \lambda_{r,k}^{imp,CESS} \cdot P_{r,k}^{imp,CESS} \cdot \Delta k; \\ \quad C_{r,k}^{imp,CESS} = \lambda_{r,k}^{imp,CESS} \cdot P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k \\ C_{r,k}^{exp,CESS} = \lambda_{r,k}^{exp,CESS} \cdot P_{r,k}^{exp,CESS} \cdot \Delta k; \\ \quad C_{r,k}^{exp,CESS} = \lambda_{r,k}^{exp,CESS} \cdot P_{r,k}^{CESS \leftarrow PV} \cdot \Delta k \end{cases} \tag{3.23}$$

being $C_{r,k}^{imp,CESS}$ in [€] the cost that a building r paid for purchasing energy from the CESS and $C_{r,k}^{exp,CESS}$ in [€] the revenue a building r obtained for exporting energy to the CESS. $P_{r,k}^{imp,CESS}$ in [kWh] is the power puchased in instant k, which was transtaled to the power purchased for fulfiling r building demand, $P_{r,k}^{loads \leftarrow CESS}$ in [kWh]. $P_{r,k}^{exp,CESS}$ in [kWh] is the power injected at step k, which was transtaled to the excess r building PV power injected in the CESS, $P_{r,k}^{CESS \leftarrow PV}$ in [kWh].

In this research, CESS prices were established as 1 % less for importing energy and 1 % more for exporting energy, as reflected in Eq. (3.24).

$$\begin{cases} \lambda_{r,k}^{imp,CESS} = 0.99 \cdot \lambda_{r,k}^{imp,grid} \\ \lambda_{r,k}^{exp,CESS} = 1.01 \cdot \lambda_{r,k}^{exp,grid} \end{cases} \tag{3.24}$$

3.4 Control agent: Local Energy Market Operator

The LEMO was in charge of the REC's centralised management, establishing the energy pricing employed for the price within the community limits (P2P pool pricing). Extra-community prices and prices for grid interactions (imports and exports) were defined in line with the current Spanish framework.

3.4.1 Extra-community prices

The prices were divided according to the source they were purchased from or sold to in case of interactions with the grid: the grid import and export prices.

Grid import price This study was developed in the Spanish context, where the cost of the energy purchased from the grid ($C_{r,k}^{imp,grid}$ in [€]) is linked to the energy cost ($C_{r,k}^{energy}$ in [€]) and the power cost ($C_{r,k}^{power}$ in [€]), as in Eq. (3.25).

$$C_{r,k}^{imp,grid} = C_{r,k}^{energy} + C_{r,k}^{power} \tag{3.25}$$

Each term is linked to a different price: the energy term is related to the energy volumetric price ($\lambda_{r,k}^{imp,grid}$ in [€$/kWh$]) and the power term belongs to the contracted power cost ($\lambda_{r,k}^{power}$ in [€$/kW$]), as expressed in Eq. (3.26)

$$C_{r,k}^{imp,grid} = \lambda_{r,k}^{imp,grid} \cdot P_{r,k}^{imp,grid} \cdot \Delta k + \lambda_{r,k}^{power} \cdot P_{r,k}^{contr} \tag{3.26}$$

where $P_{r,k}^{imp,grid}$ in $[kW]$ is the power purchased from the grid in Δk time-frame of each building r of a set of buildings R ($r \in R$).

The volumetric energy price, is composed of a set of prices: the spot market price (λ_k^{spot}), the grid toll ($\lambda_{r,k}^{energy,toll}$), and the grid access charges ($\lambda_{r,k}^{energy,charges}$), see Eq. (3.27). The power term, is constituted of the toll ($\lambda_{r,k}^{power,toll}$), and the grid access charges ($\lambda_{r,k}^{power,charges}$), as in Eq. (3.27). All the energy prices are in [€$/kWh$] and power prices in [€$/kW$].

$$\begin{split} C_{r,k}^{imp,grid} = (\lambda_k^{spot} + \lambda_{r,k}^{energy,toll} + \lambda_{r,k}^{energy,charges}) \cdot P_{r,k}^{imp,grid} \cdot \Delta k + \\ (\lambda_{r,k}^{power,toll} + \lambda_{r,k}^{power,charges}) \cdot P_{r,k}^{contr} \end{split} \tag{3.27}$$

As mentioned in the previous chapter, Chapter 2, the energy imported from the grid is solely used to fulfil participants' demands ($P_{r,k}^{loads \leftarrow grid}$ in $[kW]$). Hence, Eq. (3.27) transforms to Eq. (3.28).

$$\begin{split} C_{r,k}^{imp,grid} = (\lambda_k^{spot} + \lambda_{r,k}^{energy,toll} + \lambda_{r,k}^{energy,charges}) \cdot P_{r,k}^{loads \leftarrow grid} \cdot \Delta k + \\ (\lambda_{r,k}^{power,toll} + \lambda_{r,k}^{power,charges}) \cdot P_{r,k}^{contr} \end{split} \tag{3.28}$$

Grid export price In the Spanish electricity system framework, according to Article 4 of the Royal Decree 144/2019 [75], the volumetric energy injected into the grid can be remunerated ($\lambda_{r,k}^{exp,grid}$ in [€$/kWh$]) in two ways: subjected to compensation or not subjected to compensation. The former relates to a payment at a fixed amount previously arranged with the retailer [75]. The latter is linked to reimbursement at the spot price [75]. In this PhD thesis, the revenue at spot price was considered, as reflected in Eq. (3.29).

$$C_{r,k}^{exp,grid} = \lambda_{r,k}^{exp,grid} \cdot P_{r,k}^{exp,grid} \cdot \Delta k = \lambda_{k}^{spot} \cdot P_{r,k}^{exp,grid} \cdot \Delta k \tag{3.29}$$

where $C_{r,k}^{exp,grid}$ in [€] is the revenue obtained by r building at step k.

As previously stated in Chapter 2, the PV excess could be only injected into the grid ($P_{r,k}^{PV\rightarrow grid}$ in $[kW]$). Thus, Eq. (3.29) becomes Eq. (3.30).

$$C_{r,k}^{exp,grid} = \lambda_{r,k}^{spot} \cdot P_{r,k}^{PV\rightarrow grid} \cdot \Delta k \tag{3.30}$$

3.4.2 Local Energy Market prices establishment

PV generators and local BTs prices were disregarded because the buildings owned them, and it was assumed that participants' priority was to employ the resources at their domain. In this research, the LEMO determined P2P import and export prices.

P2P import and export price An ideal energy trading was considered, where the energy losses for using the community LV power lines were disregarded. Thereby, as a) there was no physical restriction consideration for the P2P trading due to the proximity of REC participants and b) no distinctions were made between energy buyers and sellers, the same P2P price was contemplated for P2P selling and P2P purchasing ($\lambda_{r,k}^{P2P}$ in $[€/kWh]$), as defined in Eq. (3.31).

$$\begin{cases} C_{r,k}^{imp,P2P} = \lambda_{r,k}^{P2P} \cdot P_{r,k}^{imp,P2P} \cdot \Delta k \\ C_{r,k}^{exp,P2P} = \lambda_{r,k}^{P2P} \cdot P_{r,k}^{exp,P2P} \cdot \Delta k \end{cases} \tag{3.31}$$

being $C_{r,k}^{imp,P2P}$ and $C_{r,k}^{exp,P2P}$ in [€] the P2P pool import cost and export revenues, respectively, for each building r at step k. $P_{r,k}^{imp,P2P}$ and $P_{r,k}^{exp,P2P}$ in $[kW]$, correspondingly, the power purchased from and exported to the P2P pool at step k.

P2P price could be the mean value between the price for energy imports from the grid and the revenue for exporting into the grid, as in reference [24], the resulting equation was Eq. (3.32). In that case, the grid import price was considered the same for all the community participants.

$$\lambda_{r,k}^{P2P,mean} = \frac{\lambda_{r,k}^{imp,grid} + \lambda_{r,k}^{exp,grid}}{2} \tag{3.32}$$

Diverse tariff regimes were paid for grid energy supply by the buildings of different sectors in this PhD thesis. The excesses were remunerated at the spot price. Hence, Eq. (3.32) would be translated to (3.33) as the mean value of the different electricity tariffs.

$$\lambda_{r,k}^{P2P,mean} = \frac{\left(\frac{\sum_{r}^{R} \lambda_{r,k}^{imp,grid}}{R}\right) + \lambda_{r,k}^{exp,grid}}{2} \tag{3.33}$$

Nevertheless, a novel P2P price was established in this PhD thesis ($\lambda_{r,k}^{P2P,strategy}$ in [€/kWh]) to maximise the employment of locally generated energy, introduced in [76]. This price-setting strategy gave the real energy value at each timestep as analysed in [76]. Accordingly, the price-setting equation was determined according to two parameters: a) the ratio associated with the generation quantity towards the total community energy (p_k), and b) the prosumer demand rate ($q_{r,k}$).

Essentially, the p_k rate weighted the community's generation ($\sum_{r=1}^{R} P_{r,k}^{PV}$ in [kW]) against the energy requested by the community (generation and demand ($\sum_{r=1}^{R} P_{r,k}^{loads}$ in [kW])), see Eq. (3.34). $q_{r,k}$ rate pondered the imports requested by each participant with the total community imports. This last was employed to tip the rate to the most influencing imports part at that k timestep, as in Eq. (3.35). The resulting established P2P price is expressed in Eq. (3.36).

$$p_k = \frac{\sum_{r=1}^{R} P_{r,k}^{PV}}{\sum_{r=1}^{R} P_{r,k}^{loads} + \sum_{r=1}^{R} P_{r,k}^{PV}} \in \ (0,1) \tag{3.34}$$

$$q_{r,k} = \frac{P_{r,k}^{loads}}{\sum_{r=1}^{R} P_{r,k}^{loads}} \in \ (0,1) \tag{3.35}$$

$$\lambda_{r,k}^{P2P,strategy} = \sum_{r=1}^{R} (\lambda_{r,k}^{imp,grid} \cdot q_{r,k}) \cdot (1-p_k) + \lambda_{r,k}^{exp,grid} \cdot p_k \in \left(\lambda_{k}^{exp,grid}, \max \lambda_{r,k}^{imp,grid}\right)$$

(3.36)

All the data and equations established for modelling the assets were employed by a) the agents for simulating their energy generation and consumption predictions and their short-term management and b) the LEMO for orchestrating the energy dispatch and applying short-term penalisations.

3.4.3 Optimisation objective definition

The LEMO's main objective was to reduce the community operation cost, maximising the use of the community's local energy resources. Accordingly, the LEMO balanced the energy among the community participants and prioritised employing local renewable resources. In other words, the LEMO aimed to cover the community energy needs through local excess PV generation. If more energy was needed, the LEMO relied on the CESS to fulfil the energy needs. If all these energy sources were insufficient, energy was consumed from the grid. By contrast, if local PV generation was excessive for community needs, the LEMO charged the surplus in the CESS. The LEMO injected the leftovers into the grid if the community storage was full.

The optimisation was designed to minimise the community energy bill. The objective function is detailed in Eq. (3.37).

$$\begin{aligned} \min Cost_{EC} = & \\ & \min \left(\sum_{R}^{r=1} \left(\sum_{K}^{k=1} \left(C_{r,k}^{imp,grid} + C_{r,k}^{imp,P2P} + C_{r,k}^{imp,CESS} \right.\right.\right. \\ & \left.\left.\left. - C_{r,k}^{exp,grid} - C_{r,k}^{exp,P2P} - C_{r,k}^{exp,CESS} \right) \right) \right) \end{aligned} \tag{3.37}$$

Note that power losses in community distribution lines were neglected due to the proximity of the agents. Hence, in this work, the energy volume sold in the P2P market had to be the same as the energy volume purchased. And, as the same P2P trading price was considered for buying and selling, the P2P costs got cancelled out, as in Eq. (3.38), and is reflected in Eq. (3.39).

$$\sum_{r=1}^{R} P_{r,k}^{imp,P2P} = - \sum_{r=1}^{R} P_{r,k}^{exp,P2P} \tag{3.38}$$

$$\min Cost_{EC} = \min\left(\sum_{R}^{r=1}\left(\sum_{K}^{k=1}\left(C_{r,k}^{imp,grid} + C_{r,k}^{imp,CESS} - C_{r,k}^{exp,grid} - C_{r,k}^{exp,CESS}\right)\right)\right) \tag{3.39}$$

As a unique objective was followed, the optimisation problem had a single property; this optimisation was categorised as a **single objective optimisation**. The optimisation linked to the design was presented also in [55].

3.5 Conclusions

This chapter introduced the mathematical expressions employed for modelling the assets of EC participants. The electrical models of the assets integrated into each participant's domain were introduced in the first part. **Basic models were employed to reduce the computational burden in the optimisation process**.

Secondly, cost models were implemented to assess community operational costs, determining EC external trading prices (i.e., grid imports and exports prices), internal trading prices (i.e., P2P prices), and CESS prices. In this regard, **an equation for establishing a price in a community-based P2P schema with participants attached to different electricity tariffs was introduced**. Two ratios were included in the proposed mathematical expression: a) the ratio of the generation of the total energy of the community and b) the prosumer consumption rate.

For a long-term evaluation, BT's ageing was modelled. The degradation behaviour observed during operation is valuable data to determine the profitability of the CESS business model. Ageing is directly linked to the future necessity for replacements, which is translated to the economic investment of the agent. This information can then be utilised for CESS agent decision-making at the design stage, ensuring the appropriate sizing to obtain the desired economic viability.

Furthermore, in this chapter, the control of each agent was detailed. In planning, **the LEMO followed a centralised optimisation to minimise the energy community cost and maximise the local resources.** Also, **building agents** were directly **linked to the operation phase**, where they could use the BT in their domain (if they had one) to cope with energy deviation. If they lacked BT or had insufficient capacity, they could employ the CESS by purchasing energy or selling to it. If both storages were insufficient, buildings would have to pay for their deviations with the deposit money.

4

Local Energy Market Operator optimisation algorithm design and selection

Summary

The planning stage was rooted in an optimisation algorithm, which sought the optimal result of a mathematic problem. This chapter introduces the steps followed in selecting the optimisation algorithm. An optimisation problem is composed of the problem identification, the desired objective function—presented in the previous chapter—, the optimisation design variables, the related constraints, and the optimisation algorithm selected for solving. All these aspects are explained in detail in this subsection: choosing the variables and mathematically defining the lower and upper limits, related constraints, and matrices.

4.1 Problem identification

The optimisation problem was designed to minimise operation costs. Minimising grid support, employing the maximum local resources and maximising the EC's autarchy. The LEMO had as inputs agents predicted balances, agents' physical limits, participants' local BT physical and operation limits, CESS physical and operation limits, CESS volumetric energy price, P2P operation constraints, and spot market price.

As seen in the state-of-the-art, Chapter 1, community-based P2P markets can be solved by centralised optimisation models or game theory-based models. Direct optimisation algorithms include, among others, those based on a) LP or its side MILP, b) NLP or its side MINLP, and c) QP or its side MIQP. In this research, the optimisation of the community did not include discontinuities (non-linear programming) or quadratic equations. Hence, **algorithms based on linear programming were chosen**.

A linear programming optimisation is mathematically represented as follows:

$$\min_{x} f(x) \quad \text{subject to} \quad \begin{cases} A \cdot x & \leq b, \\ Aeq \cdot x & = beq, \\ lb & \leq x \leq ub. \end{cases} \tag{4.1}$$

being x the design variables vector, $f(x)$ the objective function, A and Aeq constraint matrices, and b, beq, lb and ub coinstaint vectors. All these elements are explained in the following lines. Note that the detailed description of the optimisation design variables, lower and upper limits, optimisation constraints (equalities and inequalities) and algorithm selection and application were also introduced in the reference mentioned above [55].

4.2 Optimisation design variables

The optimisation variables were established according to the energy demand, generation and individual and community storage operation of each EC building.

- **Energy requests**. In the case of the loads, the demand was fulfilled by local PV generation ($P_{r,k}^{loads \leftarrow PV}$), local BT capacity ($P_{r,k}^{loads \leftarrow BT}$), CESS ($P_{r,k}^{loads \leftarrow CESS}$), the energy available in the P2P pool ($P_{r,k}^{loads \leftarrow P2P}$) and the grid ($P_{r,k}^{loads \leftarrow grid}$).

- **Energy generation**. The energy generated by the local PV generation was used for covering the local demand ($P_{r,k}^{loads \leftarrow PV}$, as aforementioned) charging the battery ($P_{r,k}^{BT \leftarrow PV}$), sold in the P2P market ($P_{r,k}^{PV \rightarrow P2P}$), stored in the CESS ($P_{r,k}^{PV \rightarrow CESS}$), and sold to the grid ($P_{r,k}^{PV \rightarrow grid}$).

- **Local BT**.

  - **Charge**. The local BT was charged from local PV generation ($P_{r,k}^{BT \leftarrow PV}$, as aforestated).

  - **Discharge**. The local BT was discharged, as aforesaid, to deliver energy for fulfilling the demand ($P_{r,k}^{loads \leftarrow BT}$, as previously mentioned).

  - **SOC**. The LEMO optimised the energy requested from the local BTs. Therefore, the operation limits were also considered and optimised ($z_{r,k}^{BT}$).

- **CESS**.

  - **Charge**. The CESS was charged from local PV generation ($P_{r,k}^{CESS \leftarrow PV}$, as aforesaid).

  - **Discharge**. The CESS energy was requested from the loads ($P_{r,k}^{loads \leftarrow CESS}$, as aforestated).

  - **SOC**. The LEMO optimised the CESS operation; for that, the operation limits were also considered and optimised (z_{k}^{CESS}).

In the proposed approach, the LEMO received each participant's energy predictions (energy deficit or surplus) and matched the needs with the most convenient energy source (in case of energy deficit) or sink (in case of excess). Energy importation and exportation to the same source/sink were not possible simultaneously. For that, binary variables were defined to avoid concurrent a) charging/discharging of local storage ($u_{r,k}^{BT,cha}$ and $u_{r,k}^{BT,dcha}$), b) purchase/selling in the P2P market ($u_{r,k}^{P2P,imp}$ and $u_{r,k}^{P2P,exp}$), c) charging/discharging of CESS ($u_{k}^{CESS,cha}$ and $u_{k}^{CESS,dcha}$), and d) imports/exports into the grid ($u_{r,k}^{grid,imp}$ and $u_{r,k}^{grid,exp}$).

The design variables defined are gathered in the following table, see Table 4.1.

Table 4.1: Optimisation design variables

Design variable	Unit	Description	Type
$P_{r,k}^{loads \leftarrow PV}$	W	Instantaneous load demand fulfilled by the instantaneous power generated in the local PV generation	Continuous
$P_{r,k}^{loads \leftarrow BT}$	W	Instantaneous load demand fulfilled by the instantaneous power available in the local BT	Continuous
$P_{r,k}^{loads \leftarrow CESS}$	W	Instantaneous load demand fulfilled by the instantaneous power available in the CESS	Continuous
$P_{r,k}^{loads \leftarrow P2P}$	W	Instantaneous load demand fulfilled by the instantaneous power available in the P2P pool	Continuous
$P_{r,k}^{loads \leftarrow grid}$	W	Instantaneous load demand fulfilled by the grid	Continuous
$P_{r,k}^{BT \leftarrow PV}$	W	Instantaneous BT charge by the instantaneous power generated in the local PV generation	Continuous
$P_{r,k}^{PV \rightarrow P2P}$	W	Instantaneous local PV generation injected into the P2P pool	Continuous
$P_{r,k}^{PV \rightarrow CESS}$	W	Instantaneous local PV generation injected into the CESS	Continuous
$P_{r,k}^{PV \rightarrow grid}$	W	Instantaneous local PV generation injected into the grid	Continuous
$u_{r,k}^{BT,cha}$	-	Charging of local BT	Integer
$u_{r,k}^{BT,dcha}$	-	Discharging of local BT	Integer
$u_{r,k}^{P2P,imp}$	-	Purchase in the P2P pool	Integer
$u_{r,k}^{P2P,exp}$	-	Selling in the P2P pool	Integer
$u_{k}^{CESS,cha}$	-	Charging of CESS	Integer
$u_{k}^{CESS,dcha}$	-	Discharging of CESS	Integer
$u_{r,k}^{grid,imp}$	-	Imports from the grid	Integer
$u_{r,k}^{grid,exp}$	-	Exports into the grid	Integer
$z_{r,k}^{BT}$	%	Local BT SOC parameter	Continuous
z_{k}^{CESS}	%	CESS SOC parameter	Continuous

The design variables were defined for each r building of the set of buildings R inside the community ($r \in R$), except CESS SOC —a single physical storage system—. Thus, the variables to optimise were linked to the total number of community buildings. The resulting general overview of the x parameter is shown in Eq. (4.2). The matrix size was according to the number of design variables and the quantity of participants.

Specifically, each participant r of the set of buildings R was related to the set of assets in their domain. Also, each optimisation variable consisted of *length* variables according to the market closing time. Hence, a total of $R \cdot length \times 1$ array was employed for nine design variables that were determined for source and sink ($P_{r,k}^{loads \leftarrow PV}$, $P_{r,k}^{loads \leftarrow BT}$, $P_{r,k}^{loads \leftarrow CESS}$, $P_{r,k}^{loads \leftarrow P2P}$, $P_{r,k}^{loads \leftarrow grid}$, $P_{r,k}^{BT \leftarrow PV}$, $P_{r,k}^{PV \rightarrow P2P}$, $P_{r,k}^{PV \rightarrow CESS}$, and $P_{r,k}^{PV \rightarrow grid}$). Also, another continuous variable was determined for each r building local storage ($z_{r,k}^{BT}$), which size was $R \cdot length \times 1$. Additionally, integer variables were defined to avoid local BTs ($u_{r,k}^{BT,cha}$ and $u_{r,k}^{BT,dcha}$), which integer size was $R \cdot length \times 1$ for the set of buildings R.

In the case of the CESS, the operation was delimited by the SOC variable (z_k^{CESS}). In this case, it was limited to a unique element, making the array size $length \times 1$, and simultaneous charge and discharge were eschewed by employing integer variables ($u_k^{CESS,cha}$ and $u_k^{CESS,dcha}$). The P2P purchase and selling co-occurrence was avoided by establishing integer variables ($u_{r,k}^{P2P,imp}$ and $u_{r,k}^{P2P,exp}$) of size $R \cdot length \times 1$, in accordance with each r participant. The simultaneousness of grid imports and exports ($u_{r,k}^{grid,imp}$ and $u_{r,k}^{grid,exp}$) of each building r was prevented with $R \cdot length \times 1$ size integer parameter.

All this resulted in a set of sixteen parameters of $R \cdot length \times 1$, relating to the interactions of r buildings with source and sink elements continuous and integer variables. And three parameters associated to the CESS operation; the integer variables linked to the avoidance of the simultaneous charge and discharge and the SOC.

$$x_{(16\cdot R\cdot length+3\cdot length)\times 1} = \begin{pmatrix} P^{loads\leftarrow PV}_{r,k_{R\cdot length\times 1}} \\ P^{loads\leftarrow BT}_{r,k_{R\cdot length\times 1}} \\ P^{loads\leftarrow CESS}_{r,k_{R\cdot length\times 1}} \\ P^{loads\leftarrow P2P}_{r,k_{R\cdot length\times 1}} \\ P^{loads\leftarrow grid}_{r,k_{R\cdot length\times 1}} \\ P^{BT\leftarrow PV}_{r,k_{R\cdot length\times 1}} \\ P^{PV\rightarrow P2P}_{r,k_{R\cdot length\times 1}} \\ P^{PV\rightarrow CESS}_{r,k_{R\cdot length\times 1}} \\ P^{PV\rightarrow grid}_{r,k_{R\cdot length\times 1}} \\ u^{BT,cha}_{r,k_{R\cdot length\times 1}} \\ u^{BT,dcha}_{r,k_{R\cdot length\times 1}} \\ u^{P2P,imp}_{r,k_{R\cdot length\times 1}} \\ u^{P2P,exp}_{r,k_{R\cdot length\times 1}} \\ u^{CESS,cha}_{k_{length\times 1}} \\ u^{CESS,dcha}_{k_{length\times 1}} \\ u^{grid,imp}_{r,k_{R\cdot length\times 1}} \\ u^{grid,exp}_{r,k_{R\cdot length\times 1}} \\ z^{BT}_{r,k_{R\cdot length\times 1}} \\ z^{CESS}_{k_{length\times 1}} \end{pmatrix} \tag{4.2}$$

The optimisation was carried out on a long-term, a daily basis with an hourly timestep, thus, the length employed for each hour ($length = 24$). The presented variables optimisation is scalable up to R number of buildings, as expressed in Eq. (4.3). However, the optimisation can be calculated for a shorter period of time, e.g. 10 minutes ($length = 144$), as in Eq. (4.4). For instance, if optimisation is requested for a set of 15 buildings ($R = 15$) and with a time step of 10 minutes ($length = 144$), it would result in a $x_{34992\times 1}$ as in Eq. (4.5).

$$length = 24h \cdot \frac{1sample}{1h} = 24 \Rightarrow x_{(16\cdot R\cdot 24+3\cdot 24)\times 1} \Rightarrow x_{(384\cdot R+72)\times 1} \tag{4.3}$$

$$length = 24h\cdot \frac{60min}{1h}\frac{1sample}{10min} = 144 \quad \Rightarrow x_{(16\cdot R\cdot 144+3\cdot 144)\times 1} \Rightarrow x_{(2304\cdot R+432)\times 1} \tag{4.4}$$

$$length = 24h\cdot \frac{60min}{1h}\frac{1sample}{10min} = 144 \quad and \quad R = 15 \Rightarrow x_{(16\cdot 15\cdot 144+3\cdot 144)\times 1} \Rightarrow x_{34992\times 1} \tag{4.5}$$

4.2.1 Lower and upper limits

The upper and lower bounds of each optimisation variable depended on a) the type (continuous or integer) and, in case they were continuous variables, b) the element to which energy was directed (loads, PV generation or storage). On the one hand, the integer values were delimited to binary values. In this case, the minimum value was 0, and the maximum was 1. On the other hand, continuous variables were linked to their physical limits:

- The minimum load of a building was the lack of demand, and the maximum was the building contracted power (P_r^{contr}).
- PV generation minimum value was the absence of generation (a null value), and the maximum was the installed power of the PV generation (P_r^{PVinst}).
- The storage systems were restricted by their maximum charging ($\overline{P_r^{cha,BT}}$ and $\overline{P^{cha,CESS}}$) and discharging ($\overline{P_r^{dcha,BT}}$ and $\overline{P^{dcha,CESS}}$) powers, and minimum and maximum SOC established for operation ($\underline{z_r^{BT}}$ and $\overline{z_r^{BT}}$ for local BTs, and $\underline{z^{CESS}}$ and $\overline{z^{CESS}}$ for CESS).

Continuous optimisation variables were defined according to source and sink elements and ESSs operation. In cases involving source and sink elements, the lower and upper bounds were limited to the lowest value that both elements could provide or subtract. All the employed values are gathered in expressions Eqs. (4.6) and (4.7). Particularly, each participant r is related to the set of assets in their domain, making nine lower and upper bounds of $R \cdot length \times 1$ for the group of buildings R, from row 1 to 9 of expressions Eqs. (4.6) and (4.7). Additionally, binary variables were defined to avoid local BTs and CESS simultaneous charge and discharge. In the former, two lower and upper limits were restricted for each r building, making $R \cdot length \times 1$. Two bounds were delimited in the latter, with $length \times 1$ size, linked to CESS simultaneous charge and discharge avoidance related binary integers. More precisely, rows 10 and 11 for local BTs and rows 14 and 15 for CESS in expressions Eqs. (4.6) and (4.7). Additionally, The P2P purchase and selling co-occurrence was avoided by establishing two binary variables for each r building trading, being the size $R \cdot length \times 1$, correspondent to rows 12 and 13 in expressions Eqs. (4.6) and (4.7). The simultaneousness of grid exports and imports was prevented with two $R \cdot length \times 1$ size binary parameter linked to the variables set in rows 16 and 17 of expressions Eqs. (4.6) and (4.7). The SOC upper and lower limits of local BTs were addressed in row 18 of expressions Eqs. (4.6) and (4.7). The SOC upper and lower limits of the CESS were addressed in row

19 of expressions in expressions Eqs. (4.6) and (4.7). Consequently, the outcome was sixteen parameters of $R \cdot length \times 1$ (related to buildings' interactions between themselves, the grid and their local storage). And three parameters linked to the CESS (operation, the binary variables and the SOC) of $length \times 1$ were detailed.

For instance, the variable $P_{r,k}^{BT \leftarrow PV}$ was linked to building r's PV energy that was injected in the local BT in a k step, line 6 of Eq. (4.2). Hence, the lower bound variable was delimited by both BT minimum charging power and minimum PV power delivery, in a null value, as expressed in line 6 of Eq. (4.6). The upper bound of the variable was delimited by both BT maximum charging power and maximum PV power delivery, which was translated to the PV installed power. Then, the resulting upper bound was the minimum value between the BT maximum charging power and installed PV, as expressed in line 6 of Eq. (4.7).

$$lb_{(16 \cdot R \cdot length + 3 \cdot length) \times 1} = \begin{pmatrix} 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{length \times 1} \\ 0_{length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ \underline{z_r^{BT}}_{R \cdot length \times 1} \\ \underline{z^{CESS}}_{length \times 1} \end{pmatrix} \tag{4.6}$$

$$ub_{(16\cdot R\cdot\text{length}+3\cdot\text{length})\times 1} = \begin{pmatrix} \min(P_r^{contr}, \overline{P_r^{PVinst}})_{R\cdot\text{length}\times 1} \\ \min(P_r^{contr}, \overline{P_r^{dcha,BT}})_{R\cdot\text{length}\times 1} \\ \min(P_r^{contr}, \overline{P^{dcha,CESS}})_{R\cdot\text{length}\times 1} \\ \min(P_r^{contr}, \sum_{s=1}^{S} P_s^{PVinst})_{R\cdot\text{length}\times 1} \\ {P_{r,k}^{contr}}_{R\cdot\text{length}\times 1} \\ \min(\overline{P_r^{cha,BT}}, P_r^{PVinst})_{R\cdot\text{length}\times 1} \\ {P^{PVinst}_r}_{R\cdot\text{length}\times 1} \\ \min(P_r^{PVinst}, \overline{P_r^{cha,CESS}})_{R\cdot\text{length}\times 1} \\ {P^{PVinst}_r}_{R\cdot\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ 1_{\text{length}\times 1} \\ 1_{\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ 1_{R\cdot\text{length}\times 1} \\ \overline{z_r^{BT}}_{R\cdot\text{length}\times 1} \\ \overline{z^{CESS}}_{\text{length}\times 1} \end{pmatrix} \tag{4.7}$$

where $\sum_{s=1}^{S} P_s^{PVinst}$ is the installed PV value of s peer of a set of S peers ($s \in S$).

4.2.2 Optimisation constraints

In the following lines, the constraints employed for addressing the physical and operation limits are detailed:

4.2.2.1 Equalities

The equalities considered for this EC were linked to the demand fulfilment, community energy balance, P2P trading energy balance, local BTs, and CESS SOC.

Demand Fulfilment The demand requested by the loads of a building ($P_{r,k}^{loads} \cdot \Delta k$) was covered by the local PV ($P_{r,k}^{loads\leftarrow PV} \cdot \Delta k$), local storage ($P_{r,k}^{loads\leftarrow BT} \cdot \Delta k$), CESS ($P_{r,k}^{loads\leftarrow CESS} \cdot \Delta k$), P2P trading ($P_{r,k}^{loads\leftarrow P2P} \cdot \Delta k$) and the energy imported from the grid ($P_{r,k}^{loads\leftarrow grid} \cdot \Delta k$), as expressed in Eq. (4.8).

$$\begin{aligned} &P_{r,k}^{loads} \cdot \Delta k = P_{r,k}^{loads\leftarrow PV} \cdot \Delta k + P_{r,k}^{loads\leftarrow grid} \cdot \Delta k + P_{r,k}^{loads\leftarrow P2P} \cdot \Delta k + \\ &P_{r,k}^{loads\leftarrow BT} \cdot \Delta k + P_{r,k}^{loads\leftarrow CESS} \cdot \Delta k \end{aligned} \tag{4.8}$$

PV generation The PV generation of each building r was employed to fulfil the requested demand by r building's loads ($P_{r,k}^{loads \leftarrow PV} \cdot \Delta k$), sold in the P2P pool ($P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k$), stored in local BT ($P_{r,k}^{BT \leftarrow PV} \cdot \Delta k$) and/or CESS ($P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k$), and injected to the grid ($P_{r,k}^{PV \rightarrow grid} \cdot \Delta k$), as detailed in Eq. (4.9).

$$\begin{aligned} P_{r,k}^{PV} \cdot \Delta k = P_{r,k}^{loads \leftarrow PV} \cdot \Delta k + P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k + P_{r,k}^{BT \leftarrow PV} \cdot \Delta k + \\ P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k + P_{r,k}^{PV \rightarrow grid} \cdot \Delta k \end{aligned} \tag{4.9}$$

Community energy balance To achieve the community energy balance, the energy bought by all the peers to the grid ($\sum_{r=1}^{R} P_{r,k}^{imp,grid} \cdot \Delta k$), all the energy purchased from the P2P market ($\sum_{r=1}^{R} P_{r,k}^{imp,P2P} \cdot \Delta k$), the energy discharged from the local BT from ($\sum_{r=1}^{R} P_{r,k}^{imp,BT} \cdot \Delta k$), and the energy imported from the CESS ($\sum_{r=1}^{R} P_{r,k}^{imp,CESS} \cdot \Delta k$) had to be equal to the energy injected by all the peers to the grid ($\sum_{r=1}^{R} P_{r,k}^{exp,grid} \cdot \Delta k$), the energy sold in the P2P market ($\sum_{r=1}^{R} P_{r,k}^{exp,P2P} \cdot \Delta k$), the energy charged to the local BTs ($\sum_{r=1}^{R} P_{r,k}^{exp,BT} \cdot \Delta k$), and the energy exported to the CESS ($\sum_{r=1}^{R} P_{r,k}^{exp,CESS} \cdot \Delta k$). This energy balance is reflected in Eq. (4.10).

$$\begin{aligned} \sum_{r=1}^{R} P_{r,k}^{imp,grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{imp,P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{imp,BT} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{imp,CESS} \cdot \Delta k = \\ \sum_{r=1}^{R} P_{r,k}^{exp,grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{exp,P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{exp,BT} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{exp,CESS} \cdot \Delta k \end{aligned} \tag{4.10}$$

- **Grid imports**. The energy imported from the grid could be employed to fulfil the energy demanded by the community loads ($\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow grid} \cdot \Delta k$) and charge the local BTs ($\sum_{r=1}^{R} P_{r,k}^{BT \rightarrow grid} \cdot \Delta k$) at cheap periods. However, local BTs were not charged from the grid in this research. They could only be charged from their corresponding local PV generation installation, as expressed in Eq. (4.11).

$$\sum_{r=1}^{R} P_{r,k}^{imp,grid} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow grid} \cdot \Delta k \tag{4.11}$$

- **P2P imports**. The energy imported from the P2P pool was employed to supply the energy demanded by the community loads ($\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k$), as in Eq. (4.12).

$$\sum_{r=1}^{R} P_{r,k}^{imp,P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k \tag{4.12}$$

- **BT imports**. The energy loads imported from the BT were discharged from the local storage. ($\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow BT} \cdot \Delta k$), as in Eq. (4.13).

$$\sum_{r=1}^{R} P_{r,k}^{imp,BT} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow BT} \cdot \Delta k \tag{4.13}$$

- **CESS imports**. The energy imported from the CESS was the energy discharged from the community storage to fulfil k building's demand ($\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k$), as in Eq. (4.14).

$$\sum_{r=1}^{R} P_{r,k}^{imp,CESS} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k \tag{4.14}$$

- **Grid exports**. The energy injected from the community to the grid was the sum of the excess generated by local PV generation installations ($\sum_{r=1}^{R} P_{r,k}^{PV \rightarrow grid} \cdot \Delta k$), as in Eq. (4.15).

$$\sum_{r=1}^{R} P_{r,k}^{exp,grid} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow grid} \cdot \Delta k \tag{4.15}$$

- **P2P exports**. The energy exported to the community P2P pool was the sum of the excess PV generated in the community buildings ($\sum_{r=1}^{R} P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k$), as in Eq. (4.16).

$$\sum_{r=1}^{R} P_{r,k}^{exp,P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k \tag{4.16}$$

- **BT exports**. The energy exported to the BT was local PV excess that charged into the local battery ($\sum_{r=1}^{R} P_{r,k}^{BT \leftarrow PV} \cdot \Delta k$), as in Eq. (4.17).

$$\sum_{r=1}^{R} P_{r,k}^{exp,BT} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{BT \leftarrow PV} \cdot \Delta k \tag{4.17}$$

- **CESS exports**. The energy exported to the CESS was the excess PV energy employed to charge the community storage ($\sum_{r=1}^{R} P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k$), as in Eq. (4.18).

$$\sum_{r=1}^{R} P_{r,k}^{exp,CESS} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k \tag{4.18}$$

Substituting the expression in Eq. (4.10) with the energy fluxes between the community elements, the equations presented in Eqs. (4.11), (4.12) and (4.14) to (4.18), resulting in Eq. (4.19).

$$\begin{aligned}&\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow BT} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k = \\ &\sum_{r=1}^{R} P_{r,k}^{PV \rightarrow grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{BT \leftarrow PV} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k\end{aligned} \tag{4.19}$$

Optimisation variables constituted this equality and had to be be rewritten to be incorporated in the optimisation process, as expressed in Eq. (4.20).

$$\begin{aligned}&\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow BT} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k \\ &- \left(\sum_{r=1}^{R} P_{r,k}^{PV \rightarrow grid} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{BT \leftarrow PV} \cdot \Delta k + \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow CESS} \cdot \Delta k \right) = 0\end{aligned} \tag{4.20}$$

P2P trading balance To maximise the local resources, it was considered that a P2P buyer ($P_{r,k}^{imp,P2P} \cdot \Delta k$) could acquire energy from various sellers, ($\sum_{r=1}^{R} P_{r,k}^{exp,P2P} \cdot \Delta k$), as in Eq. (4.21). And vice versa, a P2P seller ($P_{r,k}^{exp,P2P} \cdot \Delta k$) could provide energy to different buyers ($\sum_{r=1}^{R} P_{r,k}^{imp,P2P} \cdot \Delta k$). All these variables were substituted with the fluxes between community elements (PV generator, P2P pool and loads), previously detailed in Eqs. (4.12) and (4.16). The equations are the consecutive Eqs. (4.21) and (4.22), respectively.

$$P_{r,k}^{imp,P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{exp,P2P} \cdot \Delta k; \quad P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k \tag{4.21}$$

$$P_{r,k}^{exp,P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{imp,P2P} \cdot \Delta k; \quad P_{r,k}^{PV \to P2P} \cdot \Delta k = \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k \quad (4.22)$$

All elements involved in the equation were optimisation variables, and an optimisation variable could noy be part of the result. Therefore, the equations were transformed to Eqs. (4.23) and (4.24), so it can be included in the optimisation process.

$$P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k - \sum_{r=1}^{R} P_{r,k}^{PV \to P2P} \cdot \Delta k = 0 \quad (4.23)$$

$$P_{r,k}^{PV \to P2P} \cdot \Delta k - \sum_{r=1}^{R} P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k = 0 \quad (4.24)$$

Local BT and CESS State of Charge The operation limits of local BT and CESS limits were considered for planning the community energy dispatch. The limits addressed were done regarding battery SOC. The SOC was modelled according to a modified Coulomb Counting method, as in Chapter 3. The SOC for local BTs and CESS is expressed in Eqs. (3.7) and (3.16).

The optimisation problem was designed to define the energy flux from one element to another, so the storage systems' charge and discharge were considered disaggregated. In the local BTs case, Eq. (4.25) and Eq. (4.26) refer to the charge and discharge behaviour. Similarly, CESS charge and discharge were separated in Eq. (4.27) and Eq. (4.28).

$$z_{r,k}^{BT,cha} = z_{r,k-1}^{BT} + \left(\frac{P_{r,k}^{BT \leftarrow PV} \cdot \Delta k \cdot \eta_r^{BT,cha} \cdot \eta_r^{inv,BT}}{E_r^{BT,nom}} \right) \cdot 100 \quad (4.25)$$

$$z_{r,k}^{BT,dcha} = z_{r,k-1}^{BT} - \left(\frac{P_{r,k}^{loads \leftarrow BT} \cdot \Delta k}{\eta_r^{BT,dcha} \cdot E_r^{BT,nom} \cdot \eta_r^{inv,BT}} \right) \cdot 100 \quad (4.26)$$

$$z_k^{CESS,cha} = z_{k-1}^{CESS} + \left(\frac{\sum_{r=1}^{R} P_{r,k}^{PV \to CESS} \cdot \Delta k \cdot \eta^{CESS,cha} \cdot \eta^{inv,CESS}}{E^{CESS,nom}} \right) \cdot 100 \quad (4.27)$$

$$z_k^{CESS,dcha} = z_{k-1}^{CESS} - \left(\frac{\sum_{r=1}^{R} P_{r,k}^{loads \leftarrow CESS} \cdot \Delta k}{\eta^{CESS,dcha} \cdot E^{CESS,nom} \cdot \eta^{inv,CESS}} \right) \cdot 100 \tag{4.28}$$

These equalities composed the *Aeq* matrix and *beq* vectors shown in Eqs. (4.59) and (4.64). The equalities were implemented in the optimisation in this way:

- 1^{st} row: Equality represented in Eq. (4.8) that refered to the demand fulfilment with $[R \cdot length \times 1]$ size.
- 2^{nd} row: Equality represented in Eq. (4.9) that refered to the PV generation dispatch with $[R \cdot length \times 1]$ size.
- 3^{rd} row: Equality defined in Eq. (4.20) that corresponded to the community balance with $[length \times 1]$ size.
- 4^{th} row: Equality described in Eq. (4.23) that was assigned to the P2P trading balance with $[length \times 1]$ size.
- 5^{th} row: Equality described in Eq. (4.24) that was assigned to the P2P trading balance with $[length \times 1]$ size.
- 6^{th} row: Equality expressed in Eq. (4.25) that specified the local BTs charge with $[R \cdot length \times 1]$ size.
- 7^{th} row: Equality in Eq. (4.27) that denoted the CESS charge with $[length \times 1]$ size.
- 8^{th} row: Equality represented in Eq. (4.26) that determined the local BTs discharge with $[R \cdot length \times 1]$ size.
- 9^{th} row: Equality shown in Eq. (4.28) attributed to the CESS discharge with $[length \times 1]$ size.

4.2.2.2 Inequalities

The inequalities defined were linked to the physical limits of PV generation, grid imports and exports, P2P trading and storage. Additionally, to prevent simultaneities on battery charging/discharging, P2P importing/exporting, and grid energy purchasing/selling, binary variables were included in the optimisation problem. All of them are detailed consecutively.

Binary variables As mentioned above, the battery (local or community) charge/discharge, P2P energy acquisition and selling, and grid energy supply or injection could not co-occur. The concurrencies were avoided using binary integer variables, where the value could only be null or unitary. Limiting the binary variables delimited to each source or sink element to one was the way to prevent simultaneities, as in Eqs. (4.29) to (4.32).

$$u_{r,k}^{BT,cha} + u_{r,k}^{BT,dcha} \leq 1 \tag{4.29}$$

$$u_{k}^{CESS,cha} + u_{k}^{CESS,dcha} \leq 1 \tag{4.30}$$

$$u_{r,k}^{grid,imp} + u_{r,k}^{grid,exp} \leq 1 \tag{4.31}$$

$$u_{r,k}^{P2P,imp} + u_{r,k}^{P2P,exp} \leq 1 \tag{4.32}$$

Grid imports and exports simultaneity On the one hand, the energy imported from the grid could not be higher than the sum of the demand, as in Eq. (4.33). On the other hand, the exported energy could not be above the PV generation, as in Eq. (4.34). It is to highlight that, to avoid grid imports and exports simultaneity, the respective binary variables were employed with the respective operating limits.

$$P_{r,k}^{loads\leftarrow grid} \cdot \Delta k \leq P_{r,k}^{loads} \cdot \Delta k \cdot u_{r,k}^{grid,imp}; \quad u_{r,k}^{grid,imp} = \{1(imp), 0(exp)\} \tag{4.33}$$

$$P_{r,k}^{PV\rightarrow grid} \cdot \Delta k \leq P_{r,k}^{PV} \cdot \Delta k \cdot u_{r,k}^{grid,exp}; \quad u_{r,k}^{grid,exp} = \{0(imp), 1(exp)\} \tag{4.34}$$

Both sides of the inequality were composed of optimisation variables. Therefore, the inequalities were rewritten to the following Eqs. (4.35) and (4.36).

$$P_{r,k}^{loads\leftarrow grid} \cdot \Delta k - P_{r,k}^{loads} \cdot \Delta k \cdot u_{r,k}^{grid,imp} \leq 0; \quad u_{r,k}^{grid,imp} = \{1(imp), 0(exp)\} \tag{4.35}$$

$$P_{r,k}^{PV\rightarrow grid} \cdot \Delta k - P_{r,k}^{PV} \cdot \Delta k \cdot u_{r,k}^{grid,exp} \leq 0; \quad u_{r,k}^{grid,exp} = \{0(imp), 1(exp)\} \tag{4.36}$$

P2P trading simultaneity and operation The energy consumed was limited to the available energy at the P2P pool at sample k, as in Eq. (4.37). The exported energy to the P2P pool could not be superior to the energy generated by the PV system, as in Eq. (4.38). Concurrent P2P buying and selling was avoided using the binary variables linked to P2P trading.

$$P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k \leq P_{r,k}^{loads} \cdot \Delta k \cdot u_{r,k}^{P2P,imp}; \quad u_{r,k}^{P2P,imp} = \{1(imp), 0(exp)\} \tag{4.37}$$

$$P_{r,k}^{PV} \cdot \Delta k \cdot u_{r,k}^{P2P,exp} \geq P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k; \quad u_{r,k}^{P2P,exp} = \{0(imp), 1(exp)\} \tag{4.38}$$

Once again, the inequalities included optimisation variables and were transformed into the subsequent Eqs. (4.39) and (4.40).

$$P_{r,k}^{loads \leftarrow P2P} \cdot \Delta k - P_{r,k}^{loads} \cdot \Delta k \cdot u_{r,k}^{P2P,imp} \leq 0; \quad u_{r,k}^{P2P,imp} = \{1(imp), 0(exp)\} \tag{4.39}$$

$$P_{r,k}^{PV} \cdot \Delta k \cdot u_{r,k}^{P2P,exp} - P_{r,k}^{PV \rightarrow P2P} \cdot \Delta k \geq 0; \quad u_{r,k}^{P2P,exp} = \{0(imp), 1(exp)\} \tag{4.40}$$

Another aspect to consider was determining the number of participants with which the energy buyer and seller could share energy. It was determined that an energy exporter ($u_{r,k}^{P2P,exp}$) could export energy to various importers ($\sum_{r=1}^{R} u_{r,k}^{P2P,imp}$) up to R number of buildings, as in Eq. (4.41), and vice versa; an energy buyer ($u_{r,k}^{P2P,imp}$) could purchase energy from different sellers ($\sum_{r=1}^{R} u_{r,k}^{P2P,exp}$) to a limit of R buildings, as in Eq. (4.42), to maximise the energy flux inside the community.

$$u_{r,k}^{P2P,exp} + \sum_{r=1}^{R} u_{r,k}^{P2P,imp} \leq R \tag{4.41}$$

$$u_{r,k}^{P2P,imp} + \sum_{r=1}^{R} u_{r,k}^{P2P,exp} \leq R \tag{4.42}$$

Local BTs and CESS simultaneity and operation The BT per se has safe operating ranges established by the manufacturer, which allow secure BT operation. These limits are related to the BT's **maximum charge and discharge powers**. Binary variables were applied to avoid simultaneous charge and discharge of the BTs. The equations related to the physical limits of local BTs are shown in Eqs. (4.43) and (4.44) and those linked to CESS in Eqs. (4.45) and (4.46).

$$|P_{r,k}^{BT\leftarrow PV}| \cdot \Delta k \leq |\overline{P_r^{cha,BT}}| \cdot \Delta k \cdot u_{r,k}^{BT,cha}; \quad u_{r,k}^{BT,cha} = \{1(cha), 0(dcha)\} \quad (4.43)$$

$$|P_{r,k}^{loads\leftarrow BT}| \cdot \Delta k \leq |\overline{P_r^{dcha,BT}}| \cdot \Delta k \cdot u_{r,k}^{BT,dcha}; u_{r,k}^{BT,dcha} = \{1(dcha), 0(cha)\} \quad (4.44)$$

$$|\sum_{r=1}^{R} P_k^{PV\rightarrow CESS}| \cdot \Delta k \leq |\overline{P^{cha,CESS}}| \cdot \Delta k \cdot u_k^{CESS,cha}; u_k^{CESS,cha} = \{1(cha), 0(dcha)\} \quad (4.45)$$

$$|\sum_{r=1}^{R} P_k^{loads\leftarrow CESS}| \cdot \Delta k \leq |\overline{P^{dcha,CESS}}| \cdot \Delta k \cdot u_k^{CESS,dcha}; u_k^{CESS,dcha} = \{1(dcha), 0(cha)\} \quad (4.46)$$

Once again, the inequalities were composed of optimisation variables, and mathematically, the optimisation problem could not be computed this way. The equations were transformed to Eqs. (4.47) and (4.48) in the case of local BTs and Eqs. (4.49) and (4.50) in the case of CESS.

$$|P_{r,k}^{BT\leftarrow PV}| \cdot \Delta k - |\overline{P_r^{cha,BT}}| \cdot \Delta k \cdot u_{r,k}^{BT,cha} \leq 0; \quad u_{r,k}^{BT,cha} = \{1(cha), 0(dcha)\} \quad (4.47)$$

$$|P_{r,k}^{loads\leftarrow BT}| \cdot \Delta k - |\overline{P_r^{dcha,BT}}| \cdot \Delta k \cdot u_{r,k}^{BT,dcha} \leq 0; \quad u_{r,k}^{BT,dcha} = \{1(dcha), 0(cha)\} \quad (4.48)$$

$$\begin{aligned} &|\sum_{r=1}^{R} P_k^{PV\rightarrow CESS}| \cdot \Delta k - |\overline{P^{cha,CESS}}| \cdot \Delta k \cdot u_k^{CESS,cha} \leq 0; \\ &u_k^{CESS,cha} = \{1(cha), 0(dcha)\} \end{aligned} \quad (4.49)$$

$$\begin{aligned} &|\sum_{r=1}^{R} P_k^{loads\leftarrow CESS}| \cdot \Delta k - |\overline{P^{dcha,CESS}}| \cdot \Delta k \cdot u_k^{CESS,dcha} \leq 0; \\ &u_k^{CESS,dcha} = \{1(dcha), 0(cha)\} \end{aligned} \quad (4.50)$$

Besides, **maximum and minimum SOC** values were limited for battery operation, which were used to set the minimum and maximum energy limits. In Eqs. (4.51) and (4.52), the SOC operation range of each local BT and CESS, apiece, are shown.

$$\underline{z_r^{BT}} \cdot E_r^{BT,nom} \leq z_{r,k}^{BT} \cdot E_r^{BT,nom} \leq \overline{z_r^{BT}} \cdot E_r^{BT,nom} \tag{4.51}$$

$$\underline{z^{CESS}} \cdot E^{CESS,nom} \leq z_k^{CESS} \cdot E^{CESS,nom} \leq \overline{z^{CESS}} \cdot E^{CESS,nom} \tag{4.52}$$

Both SOC limit equations were disaggregated as the optimisation calculates the charge and discharge powers separately. The minimum SOC is related to the battery discharge; see Eq. (4.53) for local BT and Eq. (4.54) for the CESS. The maximum charge is related to the maximum SOC, as in Eq. (4.55) for local BTs and Eq. (4.56) for CESS.

$$\underline{z_r^{BT}} \cdot E_r^{BT,nom} \leq z_{r,k}^{BT} \cdot E_r^{BT,nom} \tag{4.53}$$

$$\underline{z^{CESS}} \cdot E^{CESS,nom} \leq z_k^{CESS} \cdot E^{CESS,nom} \tag{4.54}$$

$$z_{r,k}^{BT} \cdot E_r^{BT,nom} \leq \overline{z_r^{BT}} \cdot E_r^{BT,nom} \tag{4.55}$$

$$z_k^{CESS} \cdot E^{CESS,nom} \leq \overline{z^{CESS}} \cdot E^{CESS,nom} \tag{4.56}$$

Both charging inequalities Eqs. (4.53) and (4.54) sign had to coincide with the inequation stated Eq. (4.1), thus, were transformed to the following Eqs. (4.57) and (4.58).

$$-z_{r,k}^{BT} \cdot E_r^{BT,nom} \leq -\underline{z_r^{BT}} \cdot E_r^{BT,nom} \tag{4.57}$$

$$-z_k^{CESS} \cdot E^{CESS,nom} \leq -\underline{z^{CESS}} \cdot E^{CESS,nom} \tag{4.58}$$

The inequalities defined constructed the A matrix and b vector, respectively, Eqs. (4.65) and (4.74). The inequalities expressed included in the optimisation problem in this fashion:

- 1st row: Inequality represented in Eq. (4.29) that refered to the avoidance of the simultaneous local BTs charge ($u_{r,k}^{BT,cha}$) and discharge ($u_{r,k}^{BT,dcha}$) with $[R \cdot length \times 1]$ size.

- 2nd row: Inequality detailed in Eq. (4.30) that pertained to preventing the concurrent CESS charge ($u_{r,k}^{CESS,cha}$) and discharge ($u_{r,k}^{CESS,dcha}$) with $[length \times 1]$ size.

- 3rd row: Inequality defined in Eq. (4.31) that corresponded to inhibit the grid imports ($u_{r,k}^{grid,imp}$) and exports ($u_{r,k}^{grid,exp}$) at the same time with $[R \cdot length \times 1]$ size.

- 4th row: Inequality described in Eq. (4.32) that was assigned to avoid co-ocurring P2P buying ($u_{r,k}^{P2P,imp}$) and selling ($u_{r,k}^{P2P,exp}$) with $[R \cdot length \times 1]$ size.

- 5th row: Inequality in Eq. (4.35) that represented the grid import limit, where the binary variable was employed to dodge the simultaneous grid imports, considering the imports limit, with $[R \cdot length \times 1]$ size.

- 6th row: Inequality expressed in Eq. (4.36) that described grid exports and its limit with $[R \cdot length \times 1]$ size.

- 7th row: Inequality in Eq. (4.39) that denoted P2P import limit with the correspondent binary variable with $[R \cdot length \times 1]$ size.

- 8th row: Inquality represented in Eq. (4.40) that determined the maximum a participant could export to the P2P pool with its linked binary variable with $[R \cdot length \times 1]$ size.

- 9th row: Inequality shown in Eq. (4.41) that addressed the possibility of a peer selling energy to various peers with $[length \times 1]$ size.

- 10th row: Inequality expressed in Eq. (4.42) that regarded the possibility of a participant purchasing energy from different participants with $[length \times 1]$ size.

- 11th row: Inequality detailed in Eq. (4.47) that represented the maximum charge of each local BT, where the binary variable was employed to avoid the simultaneous charge and discharge imports, with $[R \cdot length \times 1]$ size.

- 12th row: Inequality described in Eq. (4.48) that expressed maximum discharge of each local BT, where the binary variable was employed to avoid the simultaneous charge and discharge imports, with $[R \cdot length \times 1]$ size.

- 13th row: Inequality in Eq. (4.49) that described maximum charge of the CESS, where the binary variable was employed to avoid the simultaneous charge and discharge imports, with $[length \times 1]$ size.

- 14th row: Inequality detailed in Eq. (4.50) that expressed maximum discharge of CESS, where the binary variable was employed to avoid the simultaneous charge and discharge imports, with $[length \times 1]$ size.

- 15th row: Inequality represented in Eq. (4.57) indicated the minimum operation of the local BT, with $[R \cdot length \times 1]$ size.

- 16th row: Inequality described in Eq. (4.58) determined the minimum operation of the CESS, with $[length \times 1]$ size.

- 17th row: Inequality in Eq. (4.55) defined the maximum operation of the BT, with $[R \cdot length \times 1]$size.

- 18th row: Inequality in Eq. (4.56) showed the maximum operation of the CESS, with $[length \times 1]$ size.

Additionally, auxiliary matrices were employed:

- U: It was a single column matrix constituted of ones of $[R \times 1]$ size, as in Eq. (4.75), that was employed to represent the sum of all the participants in a determined k timestep.

- I: The identity matrix, see Eq. (4.76), was used to illustrate a unique matrix element with $[length \times length]$ size.

- T: It was a square matrix of $[length \times length]$ size, see Eq. (4.77), where the diagonal comprised of ones and the lower bidiagonal of minus ones. This was utilised to subtract a specific value from its preceding one.

$$Aeq_{(4\cdot R\cdot \text{length}+5\cdot \text{length})\times(16\cdot R\cdot \text{length}+3\cdot \text{length})} =$$

$$\begin{pmatrix}
I\cdot\Delta k & I\cdot\Delta k & I\cdot\Delta k & I\cdot\Delta k & I\cdot\Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
I\cdot\Delta k & 0 & 0 & 0 & 0 & I\cdot\Delta k & I\cdot\Delta k & I\cdot\Delta k & I\cdot\Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & U\cdot\Delta k & U\cdot\Delta k & U\cdot\Delta k & U\cdot\Delta k & -U\cdot\Delta k & -U\cdot\Delta k & -U\cdot\Delta k & -U\cdot\Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & I\cdot\Delta k & 0 & 0 & -U\cdot\Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & -U\cdot\Delta k & 0 & 0 & I\cdot\Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & A1\cdot I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & A2\cdot U & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T\\
0 & -A3\cdot I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T & 0\\
0 & 0 & -A4\cdot U & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T
\end{pmatrix} \tag{4.59}$$

$$A1 = \left(\frac{\Delta k\cdot \eta_r^{BT,cha}\cdot \eta_r^{inv,BT}}{E_r^{BT,nom}}\right)\cdot 100 \tag{4.60}$$

$$A2 = \left(\frac{\Delta k\cdot \eta^{CESS,cha}\cdot \eta^{inv,CESS}}{E^{CESS,nom}}\right)\cdot 100 \tag{4.61}$$

$$A3 = \left(\frac{\Delta k\cdot \eta_r^{BT,dcha}\cdot \eta_r^{inv,BT}}{E_r^{BT,nom}}\right)\cdot 100 \tag{4.62}$$

$$A4 = \left(\frac{\Delta k \cdot \eta^{CESS,dcha} \cdot \eta^{inv,CESS}}{E^{CESS,nom}} \right) \cdot 100 \tag{4.63}$$

$$beq_{(4 \cdot R \cdot length + 5 \cdot length) \times 1} = \begin{pmatrix} P^{loads}_{r_{R \cdot length \times 1}} \\ P^{PV}_{r_{R \cdot length \times 1}} \\ 0^{CommunityBalance}_{length \times 1} \\ 0^{P2PBalance}_{length \times 1} \\ 0^{P2PBalance}_{length \times 1} \\ 0^{BT}_{r_{R \cdot length \times 1}} \\ 0^{CESS}_{length \times 1} \\ 0^{BT}_{r_{R \cdot length \times 1}} \\ 0^{CESS}_{length \times 1} \end{pmatrix} \tag{4.64}$$

$$A_{(11 \cdot R \cdot \text{length}+7 \cdot \text{length}) \times (16 \cdot R \cdot \text{length}+3 \cdot \text{length})} =$$

$$\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & I & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & I & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & I \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A5 \cdot I & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A6 \cdot I & 0 & 0 \\
0 & 0 & 0 & I \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A5 \cdot I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -I \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & A6 \cdot I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & U & I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & U & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & I \cdot \Delta k & 0 & 0 & 0 & A7 \cdot I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & I \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A8 \cdot I & & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & U \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & A9 \cdot I & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & U \cdot \Delta k & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A10 \cdot I & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -A11 \cdot I & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -A12 \cdot I \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A11 \cdot I & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A12 \cdot I
\end{pmatrix} \tag{4.65}$$

$$A5 = -P_{r,k}^{loads} \cdot \Delta k \tag{4.66}$$

$$A6 = -P_{r,k}^{PV} \cdot \Delta k \tag{4.67}$$

$$A7 = -|\overline{P_r^{cha,BT}}| \cdot \Delta k \tag{4.68}$$

$$A8 = -|\overline{P_r^{dcha,BT}}| \cdot \Delta k \tag{4.69}$$

$$A9 = -|\overline{P^{cha,CESS}}| \cdot \Delta k \tag{4.70}$$

$$A10 = -|\overline{P^{dcha,CESS}}| \cdot \Delta k \tag{4.71}$$

$$A11 = E_r^{BT,nom} \tag{4.72}$$

$$A12 = E^{CESS,nom} \tag{4.73}$$

$$b_{(11 \cdot R \cdot length + 7 \cdot length) \times 1} = \begin{pmatrix} 1_{R \cdot length \times 1} \\ 1_{length \times 1} \\ 1_{R \cdot length \times 1} \\ 1_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ R_{length \times 1} \\ R_{length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{R \cdot length \times 1} \\ 0_{length \times 1} \\ 0_{length \times 1} \\ \left(-\underline{z_r^{BT}} \cdot E_r^{BT,nom}\right)_{R \cdot \text{length} \times 1} \\ \left(-\underline{z^{CESS}} \cdot E^{CESS,nom}\right)_{length \times 1} \\ \left(\overline{z_r^{BT}} \cdot E_r^{BT,nom}\right)_{R \cdot \text{length} \times 1} \\ \left(\overline{z^{CESS}} \cdot E^{CESS,nom}\right)_{length \times 1} \end{pmatrix} \tag{4.74}$$

$$U_{R \times 1} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \tag{4.75}$$

$$I_{length \times length} = \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{pmatrix} \tag{4.76}$$

$$T_{length \times length} = \begin{pmatrix} 1 & 0 & 0 & \cdots & \cdots & 0 \\ -1 & 1 & 0 & \cdots & \cdots & \vdots \\ 0 & -1 & 0 & \cdots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \ddots & -1 & 1 & 0 \\ 0 & \cdots & \cdots & 0 & -1 & 1 \end{pmatrix} \tag{4.77}$$

4.3 Algorithm selection and application

The addition of binary variables to the linear optimisation problem resulted in using MILP as the optimisation algorithm for this case since it allows the use of integers. Briefly, this method was used because of the following reasons:

- Linear equations were used to describe energy flows and their corresponding limits.
- Binary variables were applied to avoid the following simultaneities:
  - BTs (local or CESS) charge and discharge.
  - Grid buying and selling.
  - Buying and selling from/to a peer.

The optimisation was executed by the function *intlinprog* [77] of MATLAB *Optimizaiton Toolbox* [78] with the default properties, as detailed in [77].

- $Dual - simplex$ algorithm was determined as the **solver**.
- **Heuristics** were used to find the feasible points. MALTAB gives as option with a a) starting heuristic, or b) improvement heuristic. The former assists the solver in finding an initial or new feasible integer solution. The latter starts from a feasible integer value and seeks an improved achievable integer

value.

The default option was *basic*. In that option, the solver executes the rounding heuristic twice with different values and the diving heuristic two times with differing values. Then, it searches near the current optimal feasible integer solution value (if any) to determine a new and improved solution and employs local branching to find feasible integer results. The solver will not run further heuristics if the previous has produced a sufficiently good feasible integer solution.

- The solution convergence was obtained via the **branch-and-bound method**. This involves constructing a set of subproblems that seek to converge to solve the MILP. The default rule is *reliability*, which selects the fractional variable with the maximum pseudocost.

- The **maximum nodes** employed for branch and bound were $1 \cdot 10^7$.

- **Absolute gap tolerance** was the stopping command. The remaining amount is among the calculated upper and lower limits on the objective function ($UpperLimit - LowerLimit \leqslant AbsoluteGapTolerance$). The default value is delimited to 0.

- **Relative gap tolerance** is another stopping command related to the relative difference between the upper and lower limits computed internally in the objective function. That relative difference must be equal or lower than the relative gap tolerance ($(UpperLimit - LowerLimit)/(|UpperLimit| + 1) \leqslant RelativeGapTolerance$). The value was delimited to $1 \cdot 10^{-4}$.

- The **linear programming optimality tolerance** is the discrepancy between costs, defined as 1^{-7}, that serve the algorithm to incorporate the variable into the basis.

- The **contraints tolerance**is linked to lineal restrictions maximum discrepancy and considers that discrepancy is acceptable for the solution. This value was delimited to $1 \cdot 10^{-4}$.

- The **integer tolerance** is linked to the maximum discrepancy that the integer variable solution has concerning an integer value and is acceptable for considering it as an integer. This value was $1 \cdot 10^{-5}$.

- The **maximum feasible point** are linked to the maximum possible integer solutions that can be found, which were Inf.

- The **maximum executing time** was 7200 seconds.

4.4 Conclusions

This chapter presented the clearing of the designed LEM. Firstly, the mathematical representation of a linear programming optimisation was presented, explaining the relation between the minimisation of the objective function and the design variables, the constraint matrices and vectors.

The second section summarised the optimisation design variables, detailing the breakdown variables for source or sink functioning. Energy requests were limited to sink functioning, and energy generation was delimited to source elements. That is to say, energy requests could only be received, and energy generation could only be delivered. Local BTs and CESS functioned as a buffer, charging or discharging the received or delivered energy. For optimising the operation of community ESSs solutions, a variable was established for each local BT and another for the CESS. Additionally, simultaneities were addressed by defining binary variables. Two related binary variables were designed to avoid each building's simultaneous a) P2P imports and exports, b) simultaneous local BT charge and discharge, and c) grid imports and exports. Another binary variable was modelled for avoiding community charge and discharge from the CESS, making a total of 16 variables per building at each optimisation, considering P2P transactions, BT operation and grid interaction, and three variables for CESS.

Among the second section, on the one hand, the lower and upper limits of each design variable, optimisation constraints related to equalities in a) demand fulfilment, b) P2P trading balance, c) local BTs SOC, and d) CESS SOC were detailed. Source and sink elements interactions, i.e. PV generation, community energy balance, grid imports and exports, P2P imports and exports, BT charge and discharge, CESS charge and discharge, were mathematically associated. On the other hand, inequalities linked to a) binary variables and the involved operation simultaneities avoidance (maximum and minimum 1) grid imports and exports, 2) P2P trading, 3) local BTs operation and 4) CESS operation), b) local BTs maximum and minimum SOC, and c) CESS maximum and minimum SOC were mathematically expressed. The matrixes corresponding to the linear programming optimisation expression were also detailed in this subsection.

Local Energy Market Operator optimisation algorithm design and selection

Finally, on one side, the reasons for selecting the MILP algorithm to carry out the optimisation were presented. The linearity of the equations used and the binary variables to avoid simultaneities in the operation were emphasised. Conversely, the detailed nuances of the properties used in the *intlinprog* function of the MATLAB *Optimization Toolbox* were given.

5

Simulation results

Summary

In this chapter, the proposed two-stage energy-sharing market performance is evaluated. Firstly, the introduced centralised LEM or community-based P2P price is analysed with the adapted mean price derived from the literature. Then, the designed LEM is compared with other energy-sharing structures (collective self-consumption and decentralised LEM or full-P2P) in techno-economic and environmental terms at the planning stage. Afterwards, for stage two, different storage solutions were contrasted with the proposed BaaS business model. Finally, a new electricity system tariff is proposed for the BaaS business model viability.

5.1 Scenario definition

The EC analysed in this PhD thesis was a REC, where renewable energy resources were employed to fulfil the locally generated energy, and all the participants were located in the same area. Buildings from different sectors (residential, industrial and tertiary) joined together in a community are beneficial to maximise the local resources. Consequently, residential and tertiary sector buildings joined forces in the scenario. The tertiary sector buildings were specifically those appertaining to the local authorities (school and fire station). In a transversal way, the local authorities would be a key factor in reducing residential consumers' electricity bills.

The **consumption patterns** were obtained as detailed in Section 3.1. The participants selected for this PhD thesis included eight residential buildings (RB1, RB2, RB3, RB4, RB5, RB6, RB7 and RB8) along with two large tertiary buildings: a school (LTB1) and a fire station (LTB2) that were regarded as prosumers. The consumption curves used for evaluating the proposal are shown in Fig. 5.1. The depicted data only shows the generation related to a week in January.

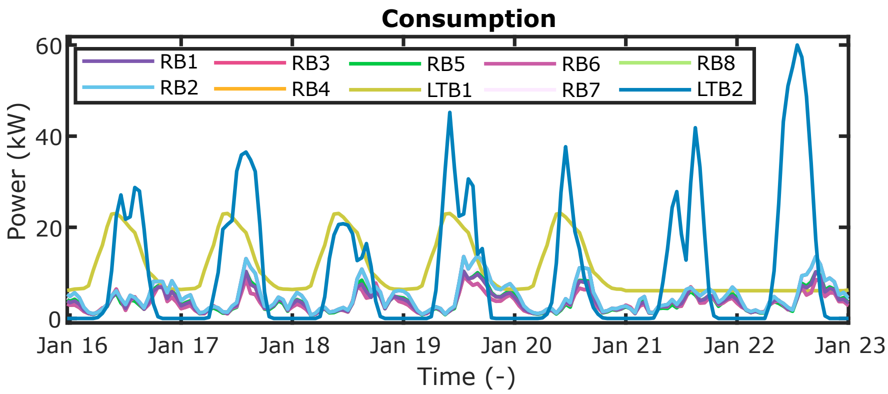

Figure 5.1: REC consumption patterns for a week in January.

Regarding the **generation patterns** for each building, grid quality and security were considered so that the renewable energy installation of each building was not higher than the contracted power. This was an assumption made to establish that the protections of the analysed system would work properly without any security issues and stability preservation of each node. The patterns were generated according to Section 3.1, and the PV panel employed for the simulations had - 0.45 [%/°C] temperature coefficient (ι = - 0.45 [%/°C]) [79]. The buildings' curves related to a specific week of January are illustrated in Fig. 5.2.

All the buildings covered partly or fully their demand needs by participating in

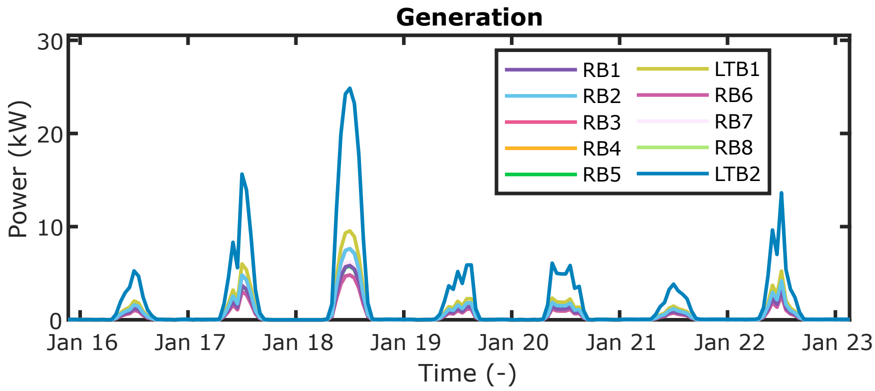

Figure 5.2: REC generation patterns for a week in January.

the LEM. It was also considered that **RB3 and RB7 participants had a BT in their domain** to reduce their electricity bill. Moreover, **A third-party-owned storage system conjointly participated in the community** with the building assets. It was determined that RB3 and RB7 had Cegasa's eBick Ultra 100 Lithium Iron Phosphate (LFP) BTs of 17.2 kWh nominal capacity [80]. CESS storage was an eBick Ultra 175 LFP storage with a nominal capacity of 54 kWh [81]. Both storage solutions characteristics are gathered in Table 5.1. The cycling degradation data was extracted from the Wöhler in [82] and the employed data is summarised in Table 5.2.

Table 5.1: Local BTs and CESS characteristics, extracted from [80, 81].

Storage	**Capacity [kWh]**	**Nominal Voltage [V]**	**Continuous current charge [A]**	**Continuous current discharge [A]**	**Reference**
Local BTs	17.2	48	190	190	[80]
CESS	54	48	475	475	[81]

Table 5.2: LFP chemistry cycles according to the DOD, extracted from [82].

DOD [%]	**Cycles [-]**	**DOD [%]**	**Cycles [-]**
0	9,507,700	60	8,900
10	438,500	70	5,900
20	97,600	80	4,400
30	39,800	90	3,400
40	21,000	100	2,700
50	13,100		

Concerning electricity prices, in Spain, the **grid imports** are subject to various energy and power grid charges and tolls that are structured according to the voltage level to which the consumer is connected. The REC under study was located in LV. In 2022, the electricity tariffs suffered a reform according to the late incorporation of BOE-A-2020-1066 [83] that introduced two time-discriminating Transmission and Distribution (TD) tariffs applicable to LV buildings: 2.0 TD and 3.0 TD. The former was available for consumers with a contracted power of less than 15 kW and the latter for those with a contracted power equal to 15 kW or more. Grid toll and charges vary between tariff segments and are applied according to established periods (P1, P2, P3, P4, P5, P6) [84].

The six-period time differentiation divides the hours of the year into six periods (P1 to P6) according to the season, day of the week and time of day [84]. Five days were classified: Type A, Type B, Type B1, Type C and Type D [84]. These days are not the same for all the Spanish territories; a distinction is made according to the place where the energy consumption took place (Iberian Peninsula, Canary Islands, Balearic Islands, Autonomous City of Ceuta or Autonomous City of Melilla) [84].

For tariff 3.0 TD, P1, P2, P3, P4, P5 and P6 are determined for energy and power terms tolls and charges [84]. P6 is the only period that is constant in the whole year [84]. It is the valley period—the lowest pricing time window—from midnight to 8 a.m. on weekdays and for the whole day on national holidays [84]. The REC under study was located in the Iberian Peninsula, where a) January, February, July and December corresponded to high season, b) March and November linked to mid-high season, c) June, August and September characterised as mid-season, and d) April, May and October as low-season [84].

- Type A: from Monday to Friday in high season, i.e. January, February, July and December, excluding holidays.
- Type B: from Monday to Friday in mid-high season, i.e. March and November, excluding holidays.
- Type B1: from Monday to Friday in mid-season, i.e. June, August and September, excluding holidays.
- Type C: from Monday to Friday in low-season, i.e. April, May and October, excluding holidays.
- Type D: Saturdays, Sundays, and national holidays.

The detailed nuances are given in table Table 5.3.

Tariff 2.0 TD is the exception; P1, P2 and P3 are only established for the energy term tolls and charges. P1 stands for the peak period—the highest pricing time

Table 5.3: Tariff 3.0 TD periods for grid energy and power terms tolls and charges.

Time frame	Day type				
	Type A	Type B	Type B1	Type C	Type D
P1	9 a.m. to 2 p.m. and 6 p.m. to 10 p.m.	-	-	-	-
P2	8 a.m. to 9 a.m., 2 p.m. to 6 p.m. and 10 p.m. to 12 a.m.	9 a.m. to 2 p.m. and 6 p.m. to 10 p.m.	-	-	-
P3	-	8 a.m. to 9 a.m., 2 p.m. to 6 p.m. and 10 p.m. to 12 a.m.	9 a.m. to 2 p.m. and 6 p.m. to 10 p.m.	-	-
P4	-	-	8 a.m. to 9 a.m., 2 p.m. to 6 p.m. and 10 p.m. to 12 a.m.	9 a.m. to 2 p.m. and 6 p.m. to 10 p.m.	-
P5	-	-	-	8 a.m. to 9 a.m., 2 p.m. to 6 p.m. and 10 p.m. to 12 a.m.	-
P6	12 a.m. to 8 a.m.	12 a.m. to 8 a.m.	12 a.m. to 8 a.m.	12 a.m. to 8 a.m.	All hours

window—, P2 for the shallow period and P3 for the valley period—the lowest pricing time window—[84]. The Iberian Peninsula stands for a) P1 is determined for weekdays from 10 a.m. to 2 p.m. and 6 p.m. to 10 p.m., b) P2 is established for weekdays from 8 a.m. to 10 a.m., from 2 p.m. to 6 p.m. and from 10 p.m. to midnight and c) P3 is regulated for weekdays from midnight to 8 a.m. and the whole 24 hours in every weekday and national holiday [84]. Note that the power term tolls and charges from 2.0 TD is divided into two periods: a) peak period (P1) gathers energy term P1 and P2, from 8 a.m. to 12 a.m. on weekdays, and b) valley period (P2) corresponds to energy P3, from 12 a.m. to 8 a.m. in weekdays, in weekends and national holiday. [84]. All these periods are gathered in Table 5.4.

Table 5.4: Tariff 2.0 TD periods for energy and power terms tolls and charges.

Periods for energy tolls and charges		
	Weekdays	**Weekends and national holiday**
P1	10 a.m. to 2 p.m. and 6 p.m. to 10 a.m.	-
P2	8 a.m. to 10 p.m., 2 p.m. to 6 p.m. and 10 p.m. to 12 a.m.	-
P3	12 a.m. to 8 a.m.	All hours
Periods for power tolls and charges		
	Weekdays	**Weekends and national holiday**
P1	8 a.m. to 12 a.m.	-
P2	12 a.m. to 8 a.m.	All hours

- The **grid charges** employed for evaluating the proposed energy-sharing market were those related to 2022, defined in BOE-A-2021-21794 [85]. The corresponding pricing for each tariff is detailed in Table 5.5. Note that tariff 2.0 TD has only three time periods (P1, P2, P3) defined for energy term charges and two time periods (P1 and P2) for power term charges.

Table 5.5: Grid power and energy charges.

Tariff Segment	Energy term charges [€/kWh] 10^{-3}					
	P1	P2	P3	P4	P5	P6
2.0 TD	72.9	14.594	3.648	-	-	-
3.0 TD	40.678	30.119	16.271	8.136	5.215	3.254
Tariff Segment	**Power term charges** [€/kW year]					
	P1	P2	P3	P4	P5	P6
2.0 TD	4.970	0.319	-	-	-	-
3.0 TD	6.176	3.090	2.245	2.245	2.245	1.029

- Concerning **grid tolls**, the values employed were related to BOE-A-2021-21208 [86]; see Table 5.6, which corresponded to the year 2022. It is to highlight that in toll terms, three time periods (P1, P2, and P3) were defined for the 2.0 TD tariff and two time periods (P1 and P2) for the power term.

Table 5.6: Energy and power term toll.

Tariff Segment	Energy term toll [€/kWh] 10^{-3}					
	P1	P2	P3	P4	P5	P6
2.0 TD	27.778	19.146	0.703	-	-	-
3.0 TD	17.752	14.567	7.955	5.361	0.321	0.321
Tariff Segment	**Power term toll** [€/kW year]					
	P1	P2	P3	P4	P5	P6
2.0 TD	22.988	0.938	-	-	-	-
3.0 TD	10.493	9.152	3.688	2.802	1.122	1.122

- Finally, the **spot market price** is the same for buyers linked to any electricity tariff, and in this research, values from 2021 were employed [87]. At the moment of the simulation, 2022 spot market price values were unavailable. Hence, the latest record was used: 2021 spot market price.

Data for each building (tariff segment, contracted power, annual consumption, installed PV, annual generation and battery capacity) and CESS capacity are summarised in Table 5.7.

5.2 P2P price-setting mechanism evaluation

First, the rates defined were analysed for opposite seasons, winter and summer. The results are presented over a week of simulations. This REC was located in the northern hemisphere; hence, for the winter season, the week of 16 th to 23 rd

Table 5.7: Case study data.

Building	**Tariff Segment**	**Contracted Power [kW]**	**Consumption [MWh/year]**	**Installed PV [kWp]**	**Generation [MWh/year]**	**Battery capacity [kWh]**
RB1	3.0 TD	15.1	28.03	15.1	16.43	-
RB2	2.0 TD	11.7	24.37	11.7	12.64	-
RB3	2.0 TD	14	26.43	14	15.32	17.2
RB4	3.0 TD	18.5	31.96	18.5	20.06	-
RB5	2.0 TD	13.9	25.51	13.9	15.14	-
RB6	2.0 TD	11.6	24.37	11.6	12.64	-
RB7	2.0 TD	14	26.43	14	15.32	17.2
RB8	3.0 TD	18.5	31.96	18.5	20.06	-
LTB1	3.0 TD	23	82.42	23	65.36	-
LTB2	3.0 TD	60	90.85	60	25.09	
CESS	-	-	-	-	-	54

January is shown, and for the summer season, the week of 3 rd to 10 th July are presented.

Both generation (p_k) and consumption ($q_{r,k}$) ratios were evaluated. The former (p_k) was directly related to PV generation. The ratio was null either winter, Fig. 5.3 a), or summer, Fig. 5.3 b), at nighttime. During the daytime, this rate fluctuated according to the meteorological conditions that produced stochasticity in renewable generation in winter, Fig. 5.3 a), or summer, Fig. 5.3 b). This REC had the highest solar incidence in summer due to its location in northern hemisphere, see Fig. 5.3 b), up to 0.73 rate at peak hours. By contrast, the solar height reduced significantly in winter, registering up to 0.18, as reflected in Fig. 5.3 a).

The consumption ratio, ($q_{r,k}$), is also depicted for winter, Fig. 5.4 a), and summer seasons, Fig. 5.4 b). Residential and tertiary buildings participated in this REC, where different energy volumes were consumed. LTB1 and LTB2 obtained the highest ratios, up to 0.58 and 0.73, respectively, because of the energy volume consumption of tertiary buildings. Residential buildings scored in a 0.02 and 0.14 rate interval. It is to highlight that, in this PhD study, the school—LTB1—closing was considered for weekends and holidays. The school consumption ratio in summer decreased to 0.46 due to the higher solar penetration.

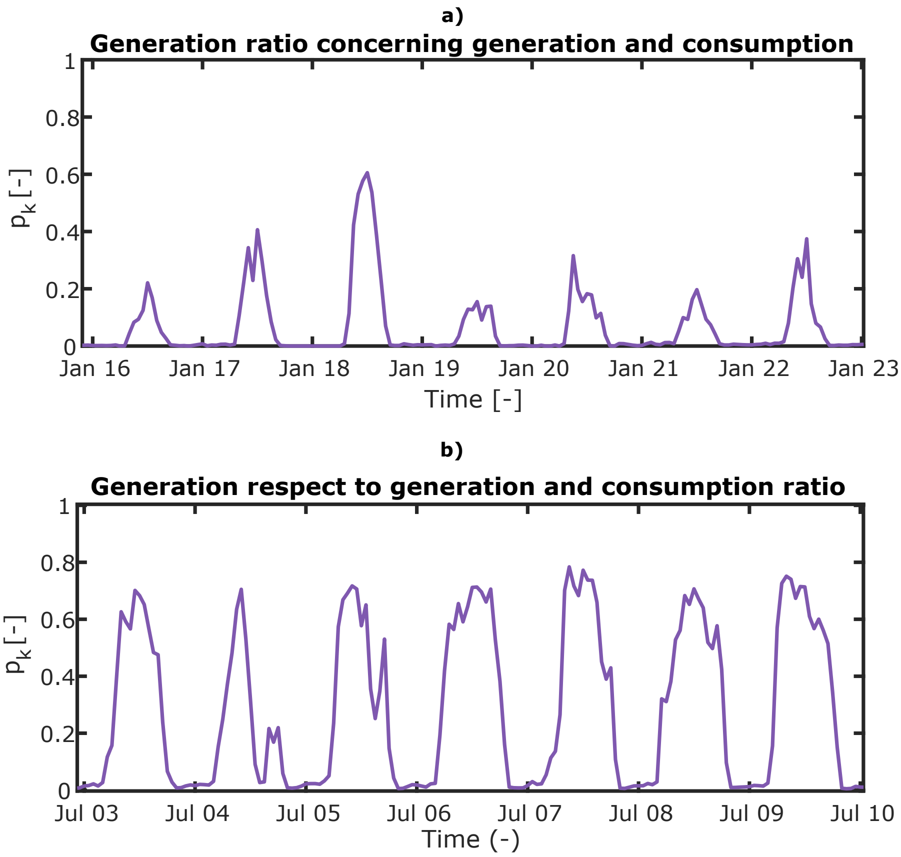

Figure 5.3: Generation ratio, p_k, in a week, a) for a week in winter and b) for a week in summer.

As expressed previously in Eq. (3.36), both ratios composed the P2P energy price ($\lambda_{r,k}^{P2P}$), where the P2P price for purchasing and selling energy was the same. Regarding the consumption ratio ($q_{r,k}$), it impacted the P2P import price due to the different electricity tariffs that the REC participants employed, see Fig 5.5. The generation ratio (p_k) influenced the price weight to a cheaper or more expensive value. The P2P import price was closer to the export value if there was more community generation than consumption, as shown in Fig. 5.5. And vice versa, the P2P import price was closer to the import prices due to the simultaneous consumption of residential and tertiary buildings (previously computed with $q_{r,k}$), as in Fig. 5.5.

The P2P price ($\lambda_{r,k}^{P2P}$) was obtained by employing the proposed equation, Eq. (3.36). The P2P import and export prices were pondered, and the results are depicted in Fig. 5.6. First, it can be seen that the P2P price converged between import and export prices. Second, it can be observed that the P2P price superimposed the P2P import price due to the lack of energy generation at night-

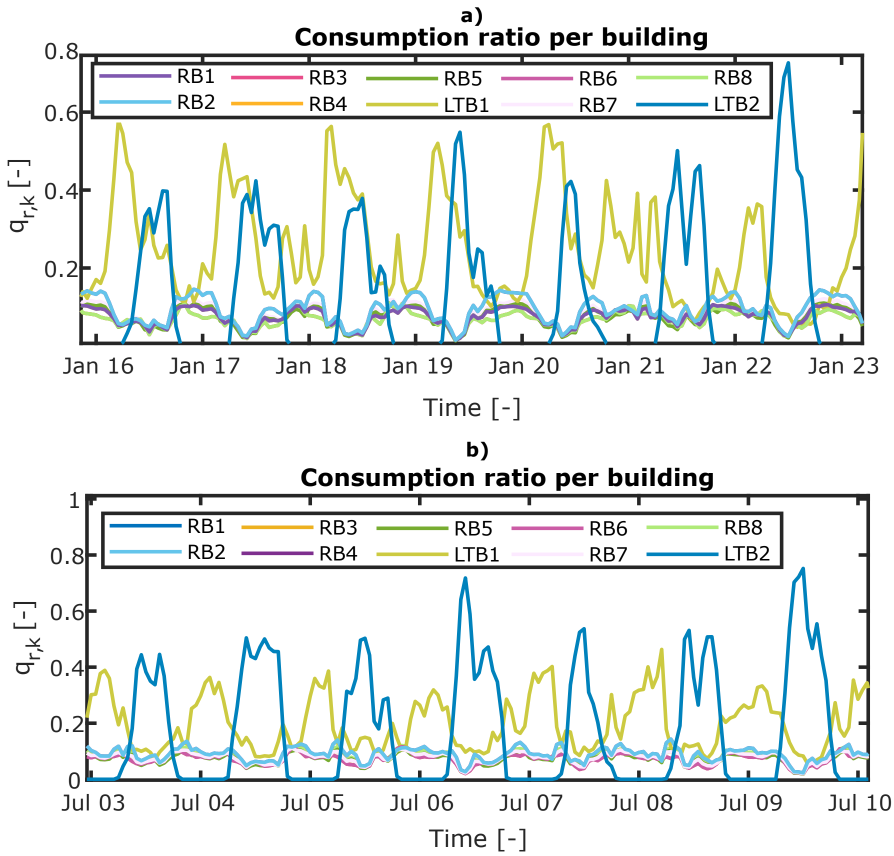

Figure 5.4: Consumption ratio per building, $q_{r,k}$, in a week, a) for a week in winter and b) for a week in summer.

time. Third, comparing the winter (Fig. 5.6 a)) and summer (Fig. 5.6 b)) seasons, P2P price patterns got lower in summer, which was caused by the higher solar penetration.

5.2.1 Analysis per electricity tariff

The P2P price ($\lambda_{r,k}^{P2P}$) was analysed from the particularity of each electricity tariff. The benchmark of this evaluation was the adapted mean price, as reflected in Eq. (3.33). In hours with low energy consumption and high solar generation, i.e. at noon, the proposed P2P price obtained a lower volumetric price than the benchmark for both tariffs (2.0 TD and 3.0 TD). More precisely, see Fig. 5.7, 2.0 TD tariff achieved up to 33.3 % price reduction with the proposed price against up to 25.3 % diminishment with the adapted mean price. The 3.0 TD tariff also decreased; up to 19.9 % depreciation was recorded with the proposed equation, and up to 10.2 % was obtained by using the adapted mean value. Hence, the proposed price-setting equation contributed to tipping the price within the community limits to the export price.

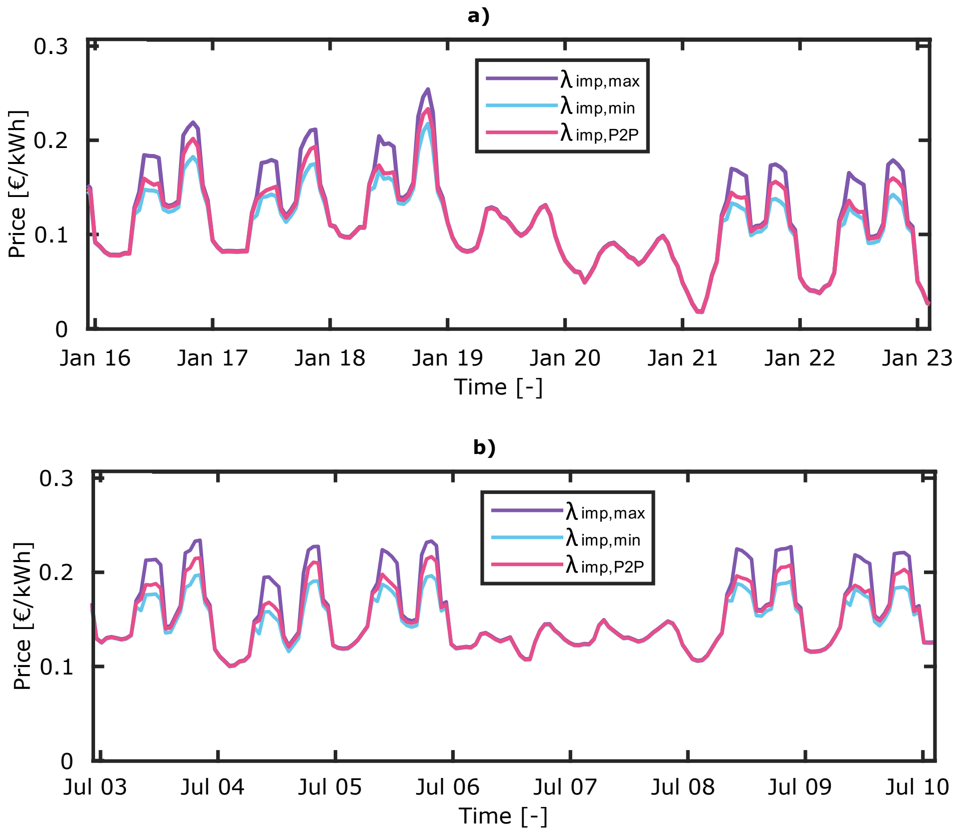

Figure 5.5: P2P import price, $\lambda_{r,k}^{P2P,imp}$, evolution in a) a week of winter and b) a week of summer.

In hours with high energy demand and low solar penetration, i.e. at 9 pm, our approach showed benefits for 2.0 TD users; the values recorded with the adapted mean value were more elevated than the 3.0 TD price. Concretely, 2.0 TD tariff users recorded up to 8.8 % discount with the price-setting strategy, far from the 24.4 % achieved with the adapted mean price. Users of the 3.0 TD tariff up to 8.7 % price increase was obtained with the proposed equation, and up to 9.8 % decrease was recorded from the adapted mean price.

Furthermore, as depicted in Fig. 5.7, buildings with greater consumption had cheaper electricity tariffs (3.0 TD) than buildings with lower tariffs (2.0 TD). Consequently, the proposed equation benefited the energy generator and benefited small consumers by reducing electricity prices at expensive hours, where cheaper tariffs (3.0 TD) helped smaller consumers.

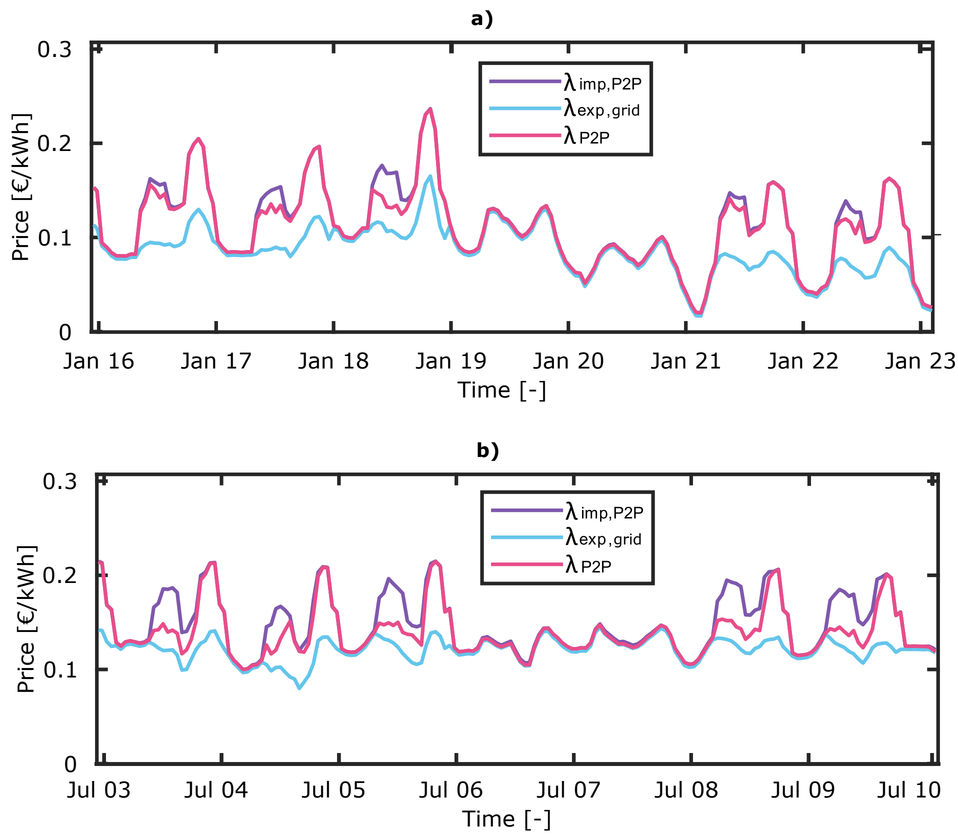

Figure 5.6: P2P import price, $\lambda_{r,k}^{P2P}$in a) a week of winter and b) a week of summer.

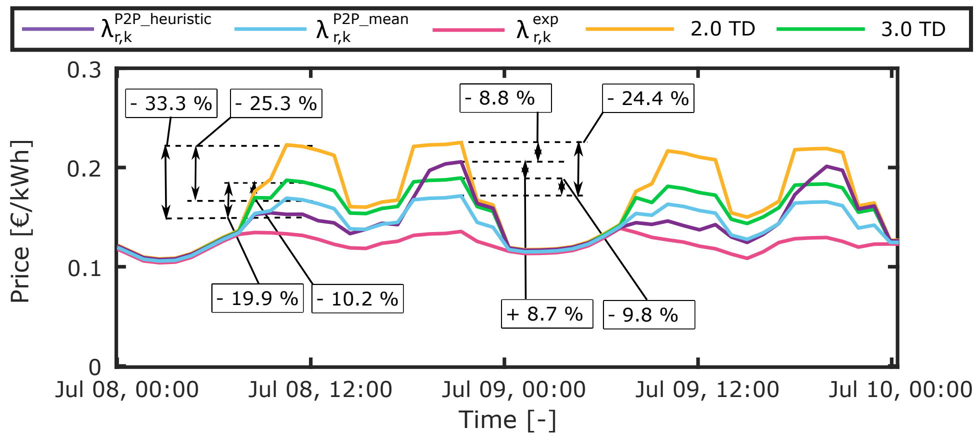

Figure 5.7: Proposed P2P price compared to the mean adapted price, the exports price and 2.0 TD and 3.0 TD tariff.

5.2.2 Analysis per building

The proposed P2P price was also analysed at the community level. The community's buildings were examined in terms of constituting a) a tertiary sector community consisting of only LTB participants, b) a community composed of residential buildings where only RB participated and c) a community where tertiary and residential buildings joined their forces. As depicted in Fig. 5.8, if participants of different sectors were involved in a community by up to 3.8 % and 2.0 %, the electricity bill was reduced for tertiary and residential buildings, respectively. Thus, joining their forces in a REC was more interesting for both buildings.

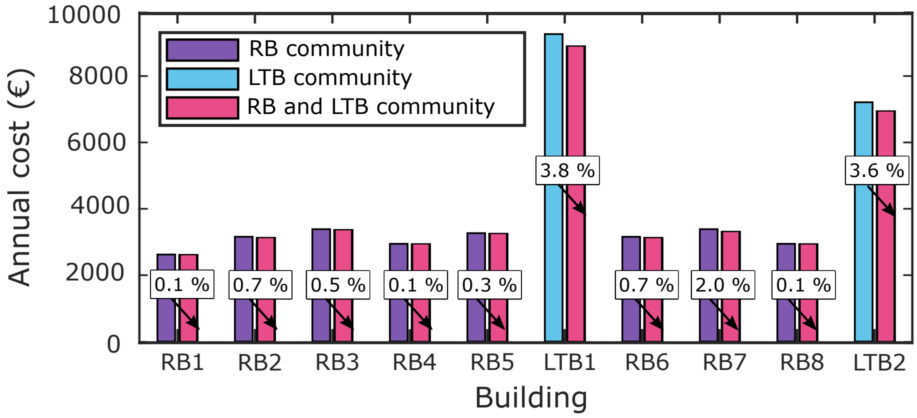

Figure 5.8: Comparison of the electricity bill of each building by joining a community of their same sector (residential or tertiary) and joint sectors community.

It is to highlight that the novel P2P price-setting mechanism evaluation was also presented in [76].

5.3 Proposed Local Energy Market one-stage performance evaluation (without considering deviation management)

First, the energy-sharing market proposed was contrasted with other LV energy-sharing structures to study its viability. That comparison was subjected to technical (self-consumption and solar cover rates), economic (community annual electricity bill) and environmental (equivalent CO_2 tons) KPIs. The energy-sharing structures used in simulations are listed below:

- **Grid-dependent (GRID)**: The community had no local generation, and all the consumption was grid-dependent. This structure was employed as the benchmark.

- **Collective Self-Consumption (CSC)**: The energy was shared between the households of the multi-apartment buildings and the energy generated in tertiary buildings was only consumed by themselves. There was no energy trading between buildings.

- **Full P2P (F-P2P)**: There was a LEM inside the community limits, where participants (i.e. buildings) with energy surplus could sell their energy to others with energy deficiency. The F-P2P followed a first-price sealed-bid auction, where the highest buyer won. In other words, an individual benefit was pursued without regard to social aspects; whoever offered the highest price got the energy. Note that the energy excess was injected into the grid at the spot market price. This LEM was part of the development of this thesis and was also presented in conference proceedings and can be consulted on [88].

- **Community-based P2P (C-P2P)**: The LEM was centrally managed by the LEMO which employed part of the proposed energy management and associated constraints. In this case, collective benefits were sought following the optimisation minimising the collective bill, as expressed previously in Eq. (3.39). Note that solely the planning phase of the proposed two-stage management algorithm was evaluated. In this last case, a LEM took place where energy trading between participants was possible.

All the structures were tested with the same conditions. This first section presents the comparison made with the influence of predictions in the planning stage. The predictions were carried out with the Gradient Boosting Regression Trees technique, and it is further explained in Appendix B. The REC was simulated in an i7-1185G7 CPU with 3.00GHz and 16.0 GB for a year with the four energy-sharing structures, resulting in a five hour simulation. The evaluation followed the KPIs defined in Chapter 2: technical (self-consumption and solar rate), economic (annual electricity bill) and environmental (equivalent tons of CO_2).

5.3.1 Energy analysis

All structures' energetic performance is depicted below in Fig. 5.10. In the first place, **prediction errors** were analysed. Predicted data resulted in higher grid imports concerning real data in the GRID case, addressing a 6.9 % reduction. By contrast, the LV structures increased their energy purchase from the grid in the real case, with CSC and F-P2P scoring 2.5 % more energy to fulfil from the grid and C-P2P obtaining 2.4 % above the real value.

Regarding **grid imports**, the C-P2P structure outperformed, recording 43.5 % and 37.9 % reductions concerning GRID for predicted and real data. It was followed by F-P2P, achieving up to 42.0 % and 36.1 % diminishments with predictions

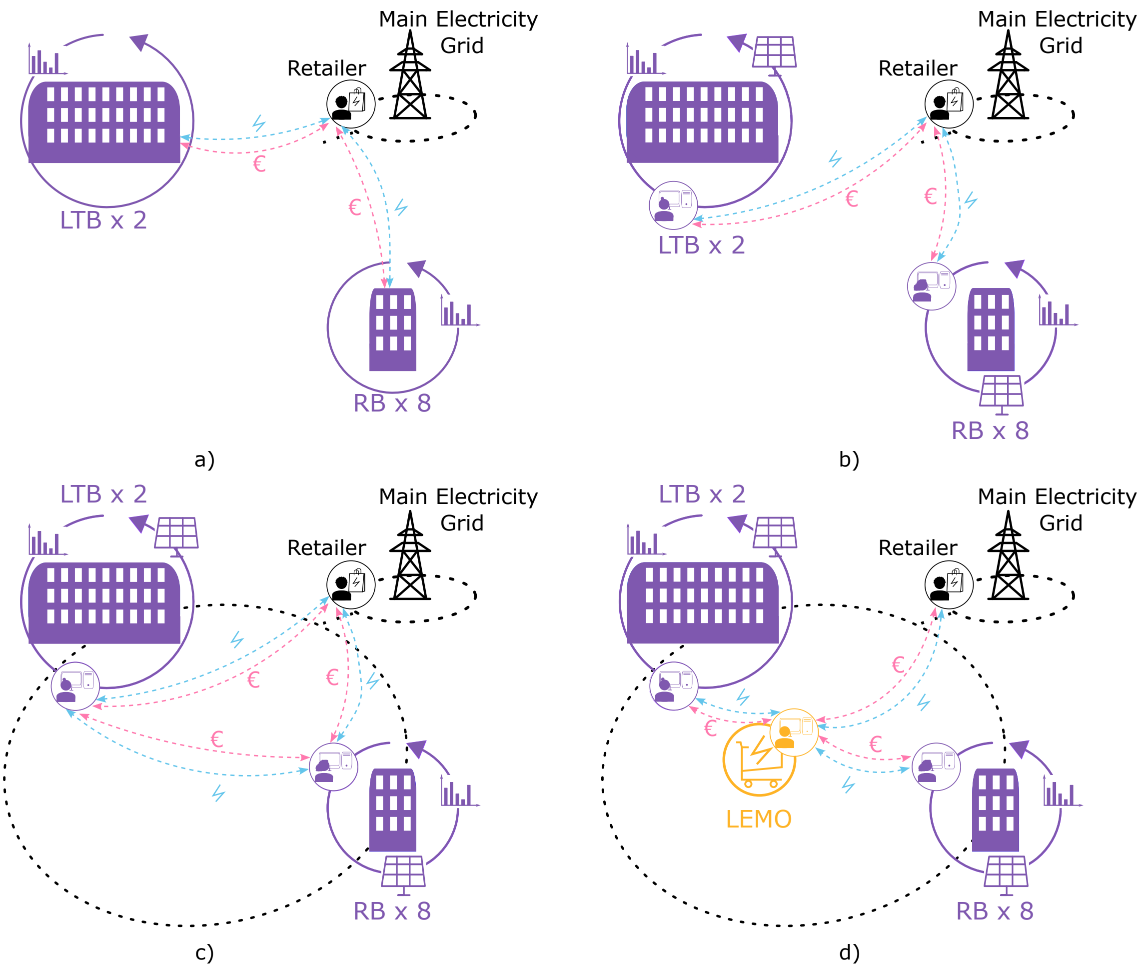

Figure 5.9: Scenarios analysed: a) grid-dependent, b) collective self-consumption, c) full P2P and d) community-based P2P.

and real data. Finally, CSC obtained 40.8 % and 34.9 % lessening by employing predicted and real data, respectively.

CSC was a baseline for the **energy injected** into the grid. Again, C-P2P performed best, addressing 15.5% and 14.7 % fewer energy exports by employing predicted and real scenarios correspondingly. In the case of F-P2P, 6.5 % less energy was sold to the grid with predicted values and 6 % was incremented when utilising real values. The increment of utilising real values in F-P2P happened due to the variability of auctions. That is to say, the energy balance variability impacted in auctions matching. Moreover, the C-P2P structure also improved **internal trading**, which corresponds to the energy quantity traded within REC limits. C-P2P recorded 136.2 % more energy traded within the community limits with predicted data, and 144.6 % more was transacted in the P2P market with real values comparing it to F-P2P structure.

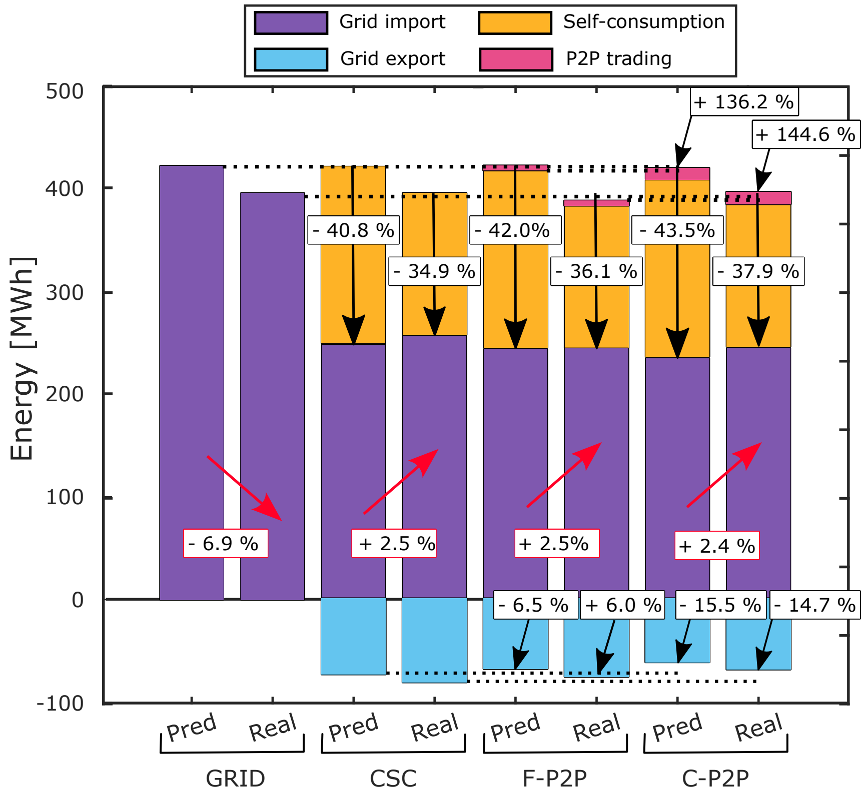

Figure 5.10: Energy results for GRID, CSC, F-P2P and C-P2P with and without predictions and without deviations management.

5.3.2 Economic analysis

The economic evaluation of the REC was done in terms of electricity bill, and the results are depicted in Fig. 5.11. The **prediction errors** meant a 6.6 % billing reduction for the real scenario in the GRID case. However, for the other structures, CSC was the most affected by entailing a 2.9 % bill increase, followed by a 2.1 % increment for C-P2P and a rise of 1.5 % for F-P2P.

C-P2P recorded the best results, diminishing by 51.1 % and 46.6 % the **electricity bill** in the predicted and real cases with respect to the GRID. The following structure was F-P2P, which rated 50.7 % and 46.4 % decreases in the predicted and real cases having the GRID as the benchmark. Regarding CSC, up to 50.1 % and 46.0 % discounts were obtained with the predicted and real data comparing it to GRID. In the current Spanish context, P2P structures proved effective regarding electricity bills, particularly C-P2P, with F-P2P closely behind.

The **revenues from injecting the energy exports** into the grid were also analysed. In this case, CSC was taken as a benchmark, and F-P2P earned more with predicted and real values, addressing, respectively, 0.5 % and 2.9 %. By contrast, the C-P2P structure reduced the income from injecting energy excesses; more precisely, 2.3 % and 3.1 % less were recorded with predicted and real data. The variation regarding export income arised from C-P2P optimising the energy flows within the community and prioritising energy trading within the community. This was reflected by analysing the **P2P trading**, taking F-P2P as a reference, C-P2P registered 390.6 % and 303.8% P2P increase, with predicted and real values, respectively. This meant the local economy was fostered: C-P2P almost quadrupled with predicted data and tripled in the real case.

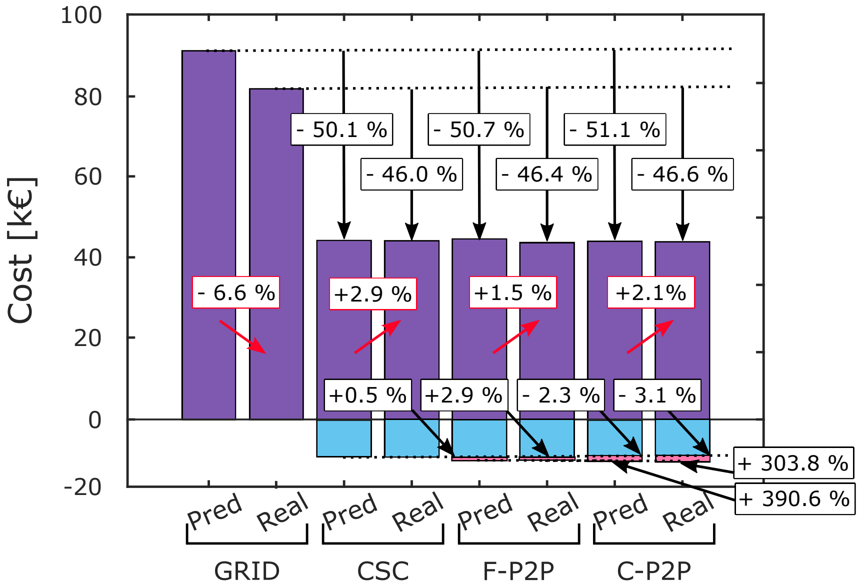

Figure 5.11: Billing results for GRID, CSC, F-P2P and C-P2P with and without predictions and without deviations management.

5.3.3 Technical analysis

The technical results obtained are gathered in Table 5.8, where C-P2P outperformed among energy-sharing structures, recording up to 42.8 %, 36.5 % and 5.5 % of annual self-consumption, solar cover and internal energy trade rates, respectively, for the real case. In the case of CSC, the lowest values were achieved. With real data, 37.3 % and 31.8 % were recorded for annual self-consumption and solar cover rates. These results were followed by the F-P2P structure, obtaining 39.5 %, 33.7 % and 2.2 % for annual self-consumption rate, annual solar cover rate and annual internal energy trade rates, correspondingly, for real data.

In the predicted case, C-P2P values lowered to 34.7 % for the self-consumption rate, 34.3 % for solar cover and 4.7 % for internal energy rates. In the case of

F-P2P, the values also diminished, accordingly, to 32.0 %, 31.6 % and 1.9 %. CSC registered, respectively, 30.1 % and 29.7 % rates for predicted data.

Table 5.8: Technical results for GRID, CSC, F-P2P, and C-P2P in terms of self-consumption rate, solar cover rate, and internal energy trade rate.

Structures	**Predictions**	**Annual Self-Consumption Rate [%]**	**Annual Solar Cover Rate [%]**	**Annual Internal Energy Trade Rate [%]**
GRID	✗	0	0	0
	✓	0	0	0
CSC	✗	37.3	31.8	0
	✓	30.1	29.7	0
F-P2P	✗	39.5	33.7	2.2
	✓	32.0	31.6	1.9
C-P2P	✗	42.8	36.5	5.5
	✓	34.7	34.3	4.7

5.3.4 Environmental analysis

The results obtained are shown in Table 5.9, where C-P2P structure performed best, registering the least emissions, reducing up to 40.9 % and 36.0 % with predicted and real data apiece, concerning GRID. It was followed by F-P2P that addressed up to 39.3 % and 34.2 % cutback for predicted and real values. Lastly, CSC diminished up to 38.1 % with predicted and 33.0 % with real values.

Table 5.9: Equivalent CO_2 results comparison.

Config.	**Predictions**	**Greenhouse gas emissions [teqCO_2]**	**Emissions difference [%]**
GRID	✗	63.6	-
	✓	69.0	-
CSC	✗	42.6	- 33.0
	✓	42.7	- 38.1
F-P2P	✗	41.8	- 34.2
	✓	41.9	- 39.3
C-P2P	✗	40.7	- 36.0
	✓	40.8	- 40.9

The one-stage performance evaluation was published in [55].

5.4 Proposed Local Energy Market two-stage performance evaluation (considering deviation management)

The proposed central optimisation, C-P2P, exceeded other energy-sharing structures with real data and regression tree predictions regarding technical, economic and environmental KPIs. Another analysis was done regarding the LEM designed in this PhD thesis (with deviation management): different storage structures were evaluated. The steps below were followed in this evaluation:

- Phase 0: All the buildings carried out their demand and generation predictions employing the Gradient Boosting Regression Tree method. The Gradient Boosting predictions are detailed in Appendix B.

- Stage 1: The predicted data and the spot market price were employed to optimise the REC energy trading dispatch. In this stage, energy volume and price were established. The trading was determined in a day-ahead manner on an hourly basis.

- Stage 2: The real data was assumed to be read from the building smart meters in operation, and the deviation module actuated in case there were forecasting miscalculations. In the first place, each building would try to manage the variation with local BT. Then, with CESS and finally, penalisations were applied if the participant could not employ any storage. This stage performance was held in an hourly time slot.

The analysis of the proposed LEM was extended by making a comparison with the same scenario used previously to study the best energy-sharing structure. In this case, the evaluation benchmark was the centralised structure, i.e. C-P2P, with ideal data and any storage system. The objective of these comparisons was to analyse the advantages/disadvantages of including storage individually (in each participant) and in the community and considering the prediction errors. In total, four scenarios were investigated:

- **Case 0**: Centralised management with persistence predictions (perfect predictions) and any storage (neither local nor community).

- **Case 1**: Centralised management with predictions without storage (neither local nor community).

- **Case 2**: Centralised management with predictions and local storage (without community storage).

- **Case 3**: Centralised management with predictions, local and community storage.

The analysis conducted was analogous to the KPIs defined in Chapter 2: technical (self-consumption rate and solar rate), economic (annual electricity billing) and environmental (equivalent tons of CO_2). Additionally, to evaluate the incorporation of ESSs, the factors related to battery charge and discharge were included in these KPIs.

Concerning the self-consumption rate, the terms energy excess of PV generation injected into the BT ($P_{r,k}^{BT\leftarrow PV}$) and CESS ($P_{r,k}^{PV\rightarrow CESS}$) were added to Eq. (5.1). Regarding the solar cover rate, the energy discharged from the BT was disregarded due to the stored energy capacity that the battery had before its usage, which could also be employed to supply the energy demand.

$$\begin{aligned}&\text{Self-Consumption} = \\ &\frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{loads\leftarrow PV} + P_{r,k}^{PV\rightarrow P2P} + P_{r,k}^{BT\leftarrow PV} - P_{r,k}^{loads\leftarrow BT})\cdot\Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R}P_{r,k}^{PV}\cdot\Delta k}\cdot 100 \\ &+\frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{PV\rightarrow CESS} - P_{r,k}^{loads\leftarrow CESS})\cdot\Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R}P_{r,k}^{PV}\cdot\Delta k}\cdot 100\end{aligned} \tag{5.1}$$

$$\begin{aligned}&\text{Solar Cover} = \\ &\frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{loads\leftarrow PV} + P_{r,k}^{PV\rightarrow P2P} + P_{r,k}^{BT\leftarrow PV})\cdot\Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R}P_{r,k}^{loads}\cdot\Delta k}\cdot 100 - \\ &\frac{\sum_{k=1}^{K}\sum_{r=1}^{R}(P_{r,k}^{loads\leftarrow BT} + P_{r,k}^{PV\rightarrow CESS} - P_{r,k}^{loads\leftarrow CESS})\cdot\Delta k}{\sum_{k=1}^{K}\sum_{r=1}^{R}P_{r,k}^{loads}\cdot\Delta k}\cdot 100\end{aligned} \tag{5.2}$$

5.4.1 Energy analysis

First, the variations introduced by prediction miscalculations were assessed in terms of energy. Comparing all the cases to predictions error-free case (Case 0), the most significant savings were achieved with Case 3 addressing up to 6.2 % grid consumption decrease, 27.0 % fewer grid exports and increasing P2P trading up to 15.1 %. This meant less energy was requested and sold to the grid by enhancing local P2P trading and using local ESSs solutions, fostering the local economy. This was thanks to the annual 1.9 MWh stored in local and CESS storage systems. Case 2 also highlighted the importance of local storage by minimising 3.5 % grid consumption, decreasing 14.7 % grid exports, and increasing 8.4 % P2P trading by storing 0.9 MWh in a year simulation. Case 1 obtained 2.3 %, 9.6 %, and 4.2 % less grid consumption, grid exports and P2P trading, respectively, contrasting it to Case 0.

Table 5.10: Yearly energy results for different C-P2P structures.

Scenario	Individual Storage	Community Storage	Predictions	Grid Imports [MWh]	Self-consumed energy [MWh]	Grid Exports [MWh]	P2P trading [MWh]	Energy Stored [MWh]	Grid Consumption difference [%]	Grid Exports difference [%]	P2P Trading difference [%]
Case 0	✗	✗	✗	243.5	136.7	69.3	11.9	-	-	-	-
Case 1	✗	✗	✓	237.8	172.2	62.6	11.4	-	- 2.3	- 9.6	- 4.2
Case 2	✓	✗	✓	235.1	174.3	59.1	12.9	0.9	- 3.5	- 14.7	+ 8.4
Case 3	✓	✓	✓	228.5	165.4	50.6	13.7	1.9	- 6.2	- 27.0	+ 15.1

5.4.2 Economic analysis

The electricity bill costs and retributions are summarised in Table 5.11. Case 3 achieved the lowest grid imports against Case 0, lessening grid consumption by up to 9.8 %, followed by Case 2 with up to 5.7 % decrease and Case 2 with up to 3.3 % diminishment. Grid exports were reduced by 2.2 % for Case 1 and Case 2, and Case 3 was reduced by up to 3.2 % compared to the benchmark. The energy saved from injecting it into the grid was employed for P2P trading purposes and, in case they had batteries available, for storing it. P2P trading was increased up to 16.7 % by Case 3 (storing energy in CESS and local BTs), up to 11.1 % by Case 2 (storing energy in local BTs), and 5.5 % was diminished in Case 1 (any energy storage). Regarding penalisation, Case 1 was taken as a benchmark. Case 3 evidenced the least penalisations with up to 59.0 %, and Case 2 recorded a 1.0 % diminishment. The difference between Case 3 and Case 2 was due to the CESS integration. CESS cost was 2,800 € and revenues were 2,700 € with an annual 100 € payment to CESS agent, that together with all the other economic benefits obtained by Case 3, made it worthwhile for participants.

The economic viability of the BaaS business model was analysed from the CESS point of view regarding amortisation. In case the CESS was a second-life ESS, the investment was envisioned as 150 €/kWh with a useful life of 10 years [89]. In case the CESS desired an amortisation in 5 years, the CESS needed a minimum gain of 1620 €/year, as reflected in Eq. (5.3), far from the simulated 100 € gain. Hence, a new tariff system would need to be in force to have an interesting BaaS business model. Therefore, a new tariff system would need to be implemented to create an attractive BaaS business model.

$$\text{Amortisation} = \frac{\text{Investment}}{\text{Desired years}} = \frac{150\,€/\text{kWh} \cdot 54\,\text{kWh}}{5\,\text{years}} = 1620\,€/\text{year} \quad (5.3)$$

Table 5.11: Yearly electricity bill costs and retributions for different C-P2P structures.

Scenario	Individual Storage	Community Storage	Predictions	Grid Imports [k€]	Grid Exports [k€]	P2P trading [k€]	CESS cost [k€]	CESS revenues [k€]	Penalisation [k€]	Grid Consumption difference [%]	Grid Exports difference [%]	P2P Trading difference [%]	Penalisation difference [%]
Case 0	✗	✗	✗	45.7	9.3	1.8	-	-	-	-	-	-	-
Case 1	✗	✗	✓	44.2	9.1	1.7	-	-	10.0	- 3.3	- 2.2	- 5.5	-
Case 2	✓	✗	✓	43.1	9.1	2.0	-	-	9.9	- 5.7	- 2.2	+ 11.1	- 1.0
Case 3	✓	✓	✓	41.2	9.0	2.1	2.8	2.7	4.1	- 9.8	- 3.2	+ 16.7	- 59.0

5.4.3 Technical analysis

The technical KPIs were analysed in terms of self-consumption rate, solar cover rate and internal energy rate. The results gathered in Table 5.12 show that the higher the storage capacity in the community was, the better results were obtained, where Case 3 outperformed, evidencing BT's and CESS key role in EC structure. However, the recorded values were far from the benchmark. Case 3 addressed up to 36.8 % annual self-consumption rate, 36.3 % annual solar cover rate, and 5.6 % annual internal energy trade rate. It was followed by Case 2, achieving, correspondingly, up to 35.4 %, 34.9 % and 5.3 % annual self-consumption, solar cover, and internal energy trade rates. Finally, Case 1 registered up to 34.7 %, 34.3 % and 4.7 % annual self-consumption, solar cover, and internal energy trade rates, respectively.

Table 5.12: Technical results for different C-P2P structures concerning self-consumption rate, solar cover rate, and internal energy trade rate.

Scenario	Individual Storage	Community Storage	Predictions	Annual Self-Consumption Rate [%]	Annual Solar Cover Rate [%]	Annual Internal Energy Trade Rate [%]
Case 0	✗	✗	✗	42.8	36.5	5.5
Case 1	✗	✗	✓	34.7	34.3	4.7
Case 2	✓	✗	✓	35.4	34.9	5.3
Case 3	✓	✓	✓	36.8	36.3	5.6

5.4.4 Environmental analysis

Finally, the environmental analysis was conducted, and the results are collected in Table 5.13. Case 3, again, obtained the best results, registering the least emissions, reducing up to 4.4 % of emissions registered in Case 0. It was followed by Case 2, with up to 1.2 % decrement. In Case 1, CO_2 emissions increased due to the higher energy imports caused by the deviations recording up to 0.2 % emissions gain.

Table 5.13: Equivalent yearly CO_2 results for different C-P2P structures.

Scenario	**Individual Storage**	**Community Storage**	**Predictions**	**Greenhouse gas emissions [teqCO_2]**	**Emissions difference [%]**
Case 0	✗	✗	✗	40.7	-
Case 1	✗	✗	✓	40.8	+ 0.2
Case 2	✓	✗	✓	40.2	- 1.2
Case 3	✓	✓	✓	38.9	- 4.4

The two-stage performance evaluation was also presented in [55].

5.5 New electricity system tariff proposal

This last subsection introduces a new tariff system to generate an attractive scenario for BaaS deployment. Currently, the end-consumers electricity bill, apart from electricity tax and VAT, is composed of four terms:

- **Power term**. The power term is a payment for energy availability in the grid. The maximum power availability of an end-consumer, i.e., community participant, is its contracted power.

- **Energy term**. The energy term refers to the instantaneous energy being consumed.

- **Discount rate**. The cost term added per day is inherent in the Spanish electricity bill.

- **Equipment rental**. This term refers to the rental paid for electricity metering elements.

In the current electricity bill, power term, discount rate, and equipment rental are cost terms that remain fixed each month, being the unique variable term for energy. Nowadays, in Spain, individual and collective self-consumption energy-sharing schemes are enabled with excess electricity injection into the grid and correspondent remuneration. The energy covered by self-consumption is subtracted from the energy consumption, and the surplus revenues are discounted in terms of energy. Although the end-consumer does not require grid services due to self-consumption or excess energy, it pays for grid availability at any time for power terms.

In the current context where network availability is paid for, the BaaS was not a profitable business model in a community scenario, as demonstrated in Section 5.4.2. This work also evaluated the BaaS business model in a context where the community participant is exempt from paying for the entire power term. The LEMs was located in LV and was assumed to use local power lines, traditionally used for distribution. In this study, a reduced power term has been proposed. The power term for intra-community energy trading was set at half of the power term for transport and distribution lines, saving the costs associated with using large transport and distribution lines that the participant would pay for the availability of the grid. The energy, economic, technical, and environmental analysis was done.

Simulations were carried out with Case 3 (local BTs and CESS with predictions with current tariff), previously defined in Section 5.4.2, attached to the novel electricity tariff and was named Case 4. Previous Case 0 (no storage solutions, without predictions, and current tariff) and Case 1 (no storage solutions with predictions and current tariff) were taken as benchmarks to analyse the benefits of the proposed new electricity system tariff.

5.5.1 Energy analysis

Results were gathered in Table 5.14, where it is shown that Case 4 diminished grid consumption up to 10.3 % and grid exports up to 35.8 % comparing it to Case 0. This was due to the major CESS use. Note that the P2P trading difference prevailed the same as in Case 3, up to 15.1 %. P2P energy trading remained the same due to the internal energy pricing, the cheapest energy to buy was for P2P trading and the most revenues were obtained with P2P trading, albeit the addition of power term.

5.5.2 Economic analysis

Regarding the economic analysis, see Table 5.15, diminishing the power term to the half implied a higher use of the CESS. It indicated that taking Case 0 as a reference, up to 12.7 % less was paid for energy coming from the grid, and up to 6.5 % less was remunerated from the grid. The results registered a higher CESS use, where up to 1800 € profit was recorded for the CESS owner, making the BaaS attractive for a third-party CESS owner. Additionally, penalisations were analysed by comparing it to Case 1 and up to 65.0 % reduction was obtained by employing

Table 5.14: Yearly energy results for different C-P2P structures, comparing them to the novel tariff proposal.

Scenario	Current tariff	Proposed tariff	Predictions	Grid Imports [MWh]	Self-consumed energy [MWh]	Grid Exports [MWh]	P2P trading [MWh]	Energy stored [MWh]	Grid Consumption difference [%]	Grid Exports difference [%]	P2P Trading difference [%]
Case 0	✓	✗	✗	243.5	136.7	69.3	11.9	-	-	-	-
Case 1	✓	✗	✓	237.8	172.2	62.6	11.4	-	- 2.3	- 9.6	- 4.2
Case 3	✓	✗	✓	228.5	165.4	50.6	13.7	1.9	- 6.2	- 27.0	+ 15.1
Case 4	✗	✓	✓	218.6	188.7	44.5	13.7	2.4	- 10.3	- 35.8	+ 15.1

Case 4. In summary, the novel tariff benefited both participants and CESS owner. This novel business model in the electricity system paradigm could be used for novel start-ups or even as a new business area for existing energy companies.

Table 5.15: Yearly electricity bill costs and retributions for different C-P2P structures, comparing them to the novel tariff proposal.

Scenario	Current tariff	Proposed tariff	Predictions	Grid Imports [k€]	Grid Exports [k€]	P2P trading [k€]	CESS cost [k€]	CESS revenues [k€]	Penalisation [k€]	Grid Consumption difference [%]	Grid Exports difference [%]	P2P Trading difference [%]	Penalisation difference [%]
Case 0	✓	✗	✗	45.7	9.3	1.8	-	-	-	-	-	-	-
Case 1	✗	✗	✓	44.2	9.1	1.7	-	-	10.0	- 3.3	-2.2	- 5.5	-
Case 3	✓	✗	✓	41.2	9.0	2.1	2.8	2.7	4.1	- 9.8	- 3.2	+ 16.7	- 59.0
Case 4	✗	✓	✓	39.9	8.7	2.1	4.2	2.4	3.5	- 12.7	- 6.5	+ 16.7	- 65.0

5.5.3 Technical analysis

Regarding the technical analysis, see Table 5.16, the major use of the CESS also impacted on technical KPIs; 36.9 % annual self-consumption, 38.7 % solar-cover and 5.6 % annual internal energy trade rates were recorded. Self-consumption and solar-cover rates increased due to the more competent pricing and higher energy stored in the CESS.

5.5.4 Environmental analysis

Finally, the environmental analysis recorded up to 18.7 % emissions difference concerning Case 0, making Case 4 the best option, as shown in Table 5.17.

Table 5.16: Technical results for different C-P2P structures concerning self-consumption rate, solar cover rate, and internal energy trade rate, comparing them to the novel tariff proposal.

Scenario	Current tariff	Poroposed tariff	Predictions	Annual Self-Consumption Rate [%]	Annual Solar Cover Rate [%]	Annual Internal Energy Trade Rate [%]
Case 0	✓	✗	✗	42.8	36.5	5.5
Case 1	✓	✗	✓	34.7	34.3	4.7
Case 3	✓	✗	✓	36.8	36.3	5.6
Case 4	✗	✓	✓	36.9	38.7	5.6

Table 5.17: Equivalent yearly CO_2 results for different C-P2P structures.

Scenario	Current tariff	Proposed tariff	Predictions	Greenhouse gas emissions [teqCO_2]	Emissions difference [%]
Case 0	✓	✗	✗	40.7	-
Case 1	✓	✗	✓	40.8	+ 0.2
Case 3	✓	✗	✓	38.9	- 4.4
Case 4	✗	✓	✓	33.1	- 18.7

5.6 Conclusions

This chapter presented the results obtained by simulating the proposed energy-sharing market in Chapter 2. In the first section, the scenario employed for the evaluation was presented. The REC participants' consumption and generation patterns were depicted. The electric (voltage ranges, charging and discharging currents, nominal capacities, among others) and physic (Wöhler curve) characteristics of the local BTs and CESS were also given. Moreover, the electricity prices related to the grid, energy tool, charges, and pool were detailed.

The second section evaluated the proposed equation to determine prices for intra-community flows of a community-based P2P system with participants with different electricity tariffs. This equation incorporated two ratios: the proportion of generation relative to the community's total energy and each participant's consumption rate. The proposed P2P price converged between grid import and export. It was evidenced that the approach provided real energy value; it offered insights into how community energy was consumed. It was concluded that the higher the energy generation, the lower the energy price proposed approach enhances the energy generation, promoting ECs' self-consumption. This empowered prosumers, allowing them to adjust their consumption pattern to lower prices and align their demand with peak energy generation hours. Consequently, the equation encouraged a more balanced community consumption while fostering renewable energy self-consumption, flattering the community demand and encouraging renewable energy penetration. Finally, it was demonstrated that the price settlement benefited both LTBs and RBs. In the former, the electricity billing was considerably reduced by joining forces with RBs. In the latter, the electricity price was advantageous, considerably reducing the purchase price in both high generation and high consumption hours.

In section three the day-ahead management techno-economic and environmental analysis was conducted by evaluating it to other energy-sharing structures (collective self-consumption and full P2P) and having a full consumption to the grid as benchmark. The proposed day-ahead community P2P approach outperformed collective self-consumption and full P2P models, considering ideal and real data. This conclusion was drawn through numerical analysis of KPIs encompassing energy (grid imports, exports, internal trading), technical (self-consumption, solar cover, internal rates), and environmental (equivalent CO_2 emissions) aspects:

- It was proved that predicted data variabilities affected all energy-sharing structures, ranging between 2.4 % and 2.5 % in energy terms. Concretely, C-P2P increased grid imports with real data by 2.4 %. It was evidenced that C-P2P obtained the best energetic results addressing up to 43.5 % and 37.9 % grid consumption reduction for predicted and real data with respect to GRID structure.

- In economic level, predictions influenced most to CSC structure (2.9 %) and the least to F-P2P (1.5 %). C-P2P obtained 2.1 % prediction variability. Although C-P2P recorded more economic deviations than C-P2P, it obtained the best results, registering up to 51.1 % and 46.6 % bill reduction for the predicted and real cases compared to GRID.

- Analysing technical results, C-P2P achieved the best results with and without predicted data against the GRID benchmark. Real data evidenced a 42.8 % annual self-consumption rate, 36.5 % annual solar cover rate and 5.5 % annual internal energy trade. Simulations with predicted data registered a 34.7 % annual self-consumption rate, 34.3 % annual solar cover rate and 4.7 % annual internal energy trade.

- Environmental analysis was carried out in equivalent CO_2 emissions, addressing up to 36.0 % and 40.9 % reductions with respect to GRID in real and predicted cases.

Section four assessed the performance of the two-stage energy-sharing market within different ESS solutions. The tests had as a benchmark the energy-sharing market with persistence predictions (Case 0). The other cases utilised the Gradient Boosting Regression Tree technique to predict consumption and generation patterns, accounting for forecasting errors. Case 1 considered any storage, Case 2 only had local BTs and Case 3 combined local BTs and CESS. Differences from the ideal case in KPI terms were observed among all scenarios, but including local storage notably reduced these disparities. The numerical contrast was further amplified by incorporating the CESS:

- In energy terms, Case 3 outperformed other ESSs solutions compared to Case 0 by reducing up to 6.2 % and 27.0 %, respectively, grid consumption and exports. It also incremented P2P trading in a 15.1 %.

- Case 3 also obtained the best results in the economic evaluation. 9.8 % and 3.2 % reductions were achieved for grid consumption and exports, apiece. Moreover, 16.7 % more revenues were recorded in Case 3 for P2P trading. Deviations were also evaluated, where Case 1 was taken as a benchmark. Case 3 outperformed, scoring up to 59.0 % penalisation reduction.

- The amortisation of CESS was analysed. The proposed solution was only beneficial for REC participants; BaaS was not profitable for the CESS owner with the current Spanish scenario. A business model for the tertiary owner as an annual benefit of 100 € was obtained, far from the 1620 € benefit that it would need to have a profitable business model.

- In technical aspects, Case 3 obtained the best results compared to the other ESS solutions considering prediction mismatch (Case 2 and Case 3). It was evidenced that a 36.8 % annual self-consumption rate, 36.3 % annual solar cover rate and 5.6 % annual internal energy trade were obtained. It is to highlight that Case 0 annual internal energy trade was slightly surpassed by Case 3.

- At the environmental level, equivalent CO_2 emissions were analysed where 4.4 % emissions reduction was recorded for Case 3 against Case 0.

The fifth section proposed a new electricity system tariff for the Spanish context. The power term is currently paid for grid availability, even though the grid is not used when self-consuming. If P2P were recognised in the current electricity panorama, the grid availability would have to be paid. Since energy was used or traded within the community without using the grid support, it was considered that only an amount for using local lines would have to be paid in a future scenario. For this reason, the proposed power term varied depending on where the energy comes from and is injected into, i.e. Case 4. The full power term was paid in the period when the electricity was traded with the outside of the REC. Nevertheless, half of the electricity term was paid when energy was traded within the community. This proposal was also numerically studied in techno-economic and environmental terms, and the results were the following:

- Regarding energetic evaluation, Case 4 lowered up to 10.3 % and 35.8 % grid imports and exports, respectively, which was obtained thanks to extensive use (2.4 MWh stored) of the CESS.

- Concerning the electricity bill, Case 4 achieved up to 12.7 % and 6.5 % fewer expenditures and revenues from the grid due to a major use of the CESS. Since PV generation and buildings' consumption remained the same, the CESS was extensively used, addressing up to 1800 € cost to the community. Penalisations were evaluated with Case 1, and the penalisations cost was reduced by up to 65%.

- BaaS business was evicended to be more interesting in this new context as the yearly amortisation was covered.

- In technical terms, the system improved its annual consumption and solar fraction by 36.9 % and 38.7 %. This was due to higher CESS usage.

- The environmental analysis showed that up to 18.7 % of CO_2 emissions could be avoided using more CESS.

6

Sensitivity Analysis

Summary

This last chapter assesses the sensitivity analysis regarding the operation of the proposed two-stage energy-sharing market. The impact of the inputs (generation and consumption estimation errors, renewable energy sources penetration, consumption quantity, local BTs sizing, CESS sizing and spot market price) on the economic results (community LCOE) are individually evaluated.

6.1 Sensitivity Analysis

The proposed LEM also underwent a sensitivity analysis to evaluate the most influential input variables. There are two types of sensitivity analysis in the literature: the local sensitivity analysis and the global sensitivity analysis. The former refers to a linear hypothesis, where one unique variable is changed while the others remain fixed [90, 91]. It is a widely used method in power systems with good identification accuracy [90]. In the latter, all the variables change randomly, to cope with non-linearities [90], which is being a trend used in recent literature. However, it is a complicated and time-consuming evaluation [90, 91]. Hence, local sensitivity analysis has been used in this thesis due to its higher accuracy and provides us with a better interpretation of the influence of each input variable on the system. The evaluated inputs, quantitative indicators and results are presented in the following subsections.

6.1.1 Analysed inputs

The input parameters to the LEMO were evaluated. The input data to Stage 1 were a) generation estimation, b) consumption estimation, c) generation energy volume, d) consumption energy volume, e) local storage capacity, f) CESS capacity, and g) spot market price. These parameters were evaluated in nine ranges, from zero to double. That is to say, each parameter was assessed from 0 % (i.e. no estimation errors case) to 200 % (i.e. double the estimation errors) in increments of 25 %. Note that consumption had only eight parameters, as a community with null consumption does not fit into the EC philosophy. The spot market price was excluded from this range as it was evaluated using real data from different years. The parameter dimension for each range is summarised in Table 6.1.

Table 6.1: Parameter ranges for the local sensitivity analysis.

Parameter \ **Range** [%]	**0**	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
Generation volume [MWh]	0	54.2	109.2	163.6	218.1	272.6	327.2	381.7	436.2
Consumption volume [MWh]	-	98.1	196.2	294.3	392.3	490.4	588.5	686.5	784.6
BT capacity [kWh]	0	8.6	17.2	25.8	34.4	43	51.6	60.2	68.8
CESS capacity[kWh]	0	13.5	27	40.5	54	67.5	81	94.5	108
Generation estimation error [%]	0	25	50	75	100	125	150	175	200
Consumption estimation error [%]	0	25	50	75	100	125	150	175	200

The Spanish spot market price has experienced price fluctuations over the last four years, as shown in Fig. 6.1. The price used to evaluate the performance of the proposed LEM was 2021, as this was the most recent value available when the simulations were carried out. As seen in the figure, the values of 2020, 2021 and

2022 were outliers, with the highest price change in 2022 and the lowest in 2020, the COVID 19 pandemic year. In addition, 2017, 2018 and 2019 showed more stable trends, a more stable price was of interest for the sensitivity analysis. The 2023 price was also studied as it is the most recent register.

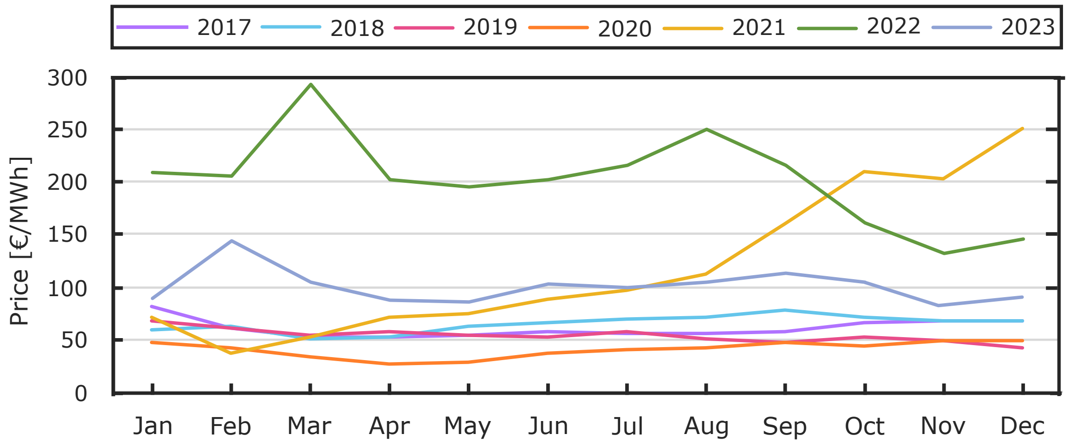

Figure 6.1: Monthly mean OMIE spot market price.

Pool price scenarios were evaluated for seven years, making seven cases. It is worth mentioning that in 2021, the electricity tariff changed in June 2021; the toll term was split into toll and charges, previously paid in a single toll term. The toll term from year 2017 to year 2021 was paid according to a price established by the retailer. Those changes were considered in this evaluation, where two scenarios were studied for 2021, with the old and new tariffs, making a total of eight price cases. Table 6.2. Therefore, fifty-four scenarios were evaluated, as expressed in Eq. (6.1).

Table 6.2: Toll and charges per year and equivalent tariffs.

Year	Charges	Toll	Tariffs in low voltage
2023	BOE-A-2022-23737	BOE-A-2022-21799	2.0 TD and 3.0 TD
2022	BOE-A-2021-21794	BOE-A-2021-21208	2.0 TD and 3.0 TD
2020	Established by the retailer		2.0 A, 2.0 DHA, 2.0 DHS, 2.1 A, 2.1 DHA, 2.01 DHS, 3.1 A
2019	Established by the retailer		2.0 A, 2.0 DHA, 2.0 DHS, 2.1 A, 2.1 DHA, 2.01 DHS, 3.1 A
2018	Established by the retailer		2.0 A, 2.0 DHA, 2.0 DHS, 2.1 A, 2.1 DHA, 2.01 DHS, 3.1 A
2017	Established by the retailer		2.0 A, 2.0 DHA, 2.0 DHS, 2.1 A, 2.1 DHA, 2.01 DHS, 3.1 A

$$\text{Total cases} = \text{Estimation error}^{cons} + \text{Estimation error}^{gen} + \text{Vol}^{cons} + \text{Vol}^{gen} + \text{Price} + \text{Cap}^{BT} + \text{Cap}^{CESS} = 8 + 8 + 7 + 7 + 8 + 8 + 8 = 54 \tag{6.1}$$

It is essential to highlight that with the 2021 reform, the tariffs in LV also changed. The tariffs 2.0 A, 2.0 DHA, 2.0 DHS 2.1 A, 2.1 DHA and 2.1 DHS were replaced by 2.0 TD tariff. 2.1 DHS was selected as the 2.0 TD tariff because it shares the number of energy segments. 3.1 A tariff was converted to 3.0 TD tariff. Additionally, as 2017 to 2021 toll pricing were determined according to retailer, in this study, Spanish retailer Goiener historical price was employed.

Table 6.3: Toll and charges per year and equivalent tariffs.

Year	Charges	Toll	Tariffs in low voltage
2023	BOE-A-2022-23737 [92]	BOE-A-2022-21799 [93]	2.0TD and 3.0TD
2022	BOE-A-2021-21794 [85]	BOE-A-2021-21208 [86]	2.0TD and 3.0TD
2021	Goiener [94]		2.1 DHS and 3.1 A
2020	Goiener [94]		2.1 DHS and 3.1 A
2019	Goiener [94]		2.1 DHS and 3.1 A
2018	Goiener [94]		2.1 DHS and 3.1 A
2017	Goiener [94]		2.1 DHS and 3.1 A

With all these variations, seven scenarios were identified per asset. All the evaluated cases are summarised in Table 6.4.

Table 6.4: Evaluated cases in the sensitivity analysis.

Scenario	Consumption estimation error [%]	Generation estimation error [%]	Generation volume [MWh]	Consumption volume [MWh]	Price year [-]	Local Storage Capacity [kWh]	CESS Capacity [kWh]	Scenario	Consumption estimation error [%]	Generation estimation error [%]	Generation volume [MWh]	Consumption volume [MWh]	Price year [-]	Local Storage Capacity [kWh]	CESS Capacity [kWh]
Case 0	0	0	218.1	392.3	2021	34.4	54	Case 24	100	100	218.1	98.1	2021	34.4	54
Case 1	0	25	218.1	392.3	2021	34.4	54	Case 25	100	100	218.1	196.2	2021	34.4	54
Case 2	0	50	218.1	392.3	2021	34.4	54	Case 26	100	100	218.1	294.3	2021	34.4	54
Case 3	0	75	218.1	392.3	2021	34.4	54	Case 27	100	100	218.1	490.4	2021	34.4	54
Case 4	0	100	218.1	392.3	2021	34.4	54	Case 28	100	100	218.1	588.5	2021	34.4	54
Case 5	0	125	218.1	392.3	2021	34.4	54	Case 29	100	100	218.1	686.5	2021	34.4	54
Case 6	0	150	218.1	392.3	2021	34.4	54	Case 30	100	100	218.1	784.6	2021	34.4	54
Case 7	0	175	218.1	392.3	2021	34.4	54	Case 31	100	100	218.1	392.3	2021	0	54
Case 8	0	200	218.1	392.3	2021	34.4	54	Case 32	100	100	218.1	392.3	2021	8.6	54
Case 9	100	100	54.2	392.3	2021	34.4	54	Case 33	100	100	218.1	392.3	2021	17.2	54
Case 10	100	100	109.2	392.3	2021	34.4	54	Case 34	100	100	218.1	392.3	2021	25.8	54
Case 11	100	100	163.6	392.3	2021	34.4	54	Case 35	100	100	218.1	392.3	2021	43	54
Case 12	100	100	272.6	392.3	2021	34.4	54	Case 36	100	100	218.1	392.3	2021	51.6	54
Case 13	100	100	327.2	392.3	2021	34.4	54	Case 37	100	100	218.1	392.3	2021	60.2	54
Case 14	100	100	381.7	392.3	2021	34.4	54	Case 38	100	100	218.1	392.3	2021	68.8	54
Case 15	100	100	436.2	392.3	2021	34.4	54	Case 39	100	100	218.1	392.3	2021	34.4	0
Case 16	25	0	218.1	392.3	2021	34.4	54	Case 40	100	100	218.1	392.3	2021	34.4	13.5
Case 17	50	0	218.1	392.3	2021	34.4	54	Case 41	100	100	218.1	392.3	2021	34.4	27
Case 18	75	0	218.1	392.3	2021	34.4	54	Case 42	100	100	218.1	392.3	2021	34.4	40.5
Case 19	100	0	218.1	392.3	2021	34.4	54	Case 43	100	100	218.1	392.3	2021	34.4	67.5
Case 20	125	0	218.1	392.3	2021	34.4	54	Case 44	100	100	218.1	392.3	2021	34.4	81
Case 21	150	0	218.1	392.3	2021	34.4	54	Case 45	100	100	218.1	392.3	2021	34.4	94.5
Case 22	175	0	218.1	392.3	2021	34.4	54	Case 46	100	100	218.1	392.3	2021	34.4	108
Case 23	200	0	218.1	392.3	2021	34.4	54	Case 47	100	100	218.1	392.3	2017	34.4	54

Table 6.5: Evaluated cases in the sensitivity analysis.

Scenario	Consumption estimation error [%]	Generation estimation error [%]	Generation volume [MWh]	Consumption volume [MWh]	Price year [-]	Local Storage Capacity [kWh]	CESS Capacity [kWh]
Case 48	100	100	218.1	392.3	2018	34.4	54
Case 49	100	100	218.1	392.3	2019	34.4	54
Case 50	100	100	218.1	392.3	2020	34.4	54
Case 51	100	100	218.1	392.3	2021-old	34.4	54
Case 52	100	100	218.1	392.3	2021-current	34.4	54
Case 53	100	100	218.1	392.3	2022	34.4	54
Case 54	100	100	218.1	392.3	2023	34.4	54

6.1.2 Quantitative indicators

The EC LCOE ($LCOE^{EC}$) quantitative indicator was used to identify the most influential inputs in the two-stage LEM proposal.

6.1.2.1 Levelized Cost of Energy

The LCOE is an economic metric widely employed to compare different generation technologies, considering the net present value of capital cost, project size, useful life, return of investment, and more [95]. In [96] it was claimed that the LCOE of a microgrid is measured as the sum of all the economic indicators linked to each asset. Reference [96] also stated that the LCOE of a microgrid is the sum of a) the LCOE related to electricity generation systems, b) the Levelised Cost of Storage (LCOS), that is linked to energy storage systems, c) the Levelised Cost of Heat (LCOH), related to thermal power technologies, d) the Levelised Cost of Cooling (LCOC) for cooling systems, and the Levelised Cost of Exergy (LCOEx), linked to the whole system exergy values. The REC under study was composed of electricity generation technologies and ESSs. Hence, the community LCOE ($LCOE^{EC}$ in €$/MWh$) is the sum of renewable energy sources and ESSs.

- The **LCOE** of electricity generators ($LCOE^{Gen}$ in [€$/MWh$]) value is calculated by dividing the total lifetime cost by the electrical energy produced [95, 96], as expressed in Eq. (6.2).

$$LCOE^{Gen} = \frac{\text{Total lifetime cost}}{\text{Electrical energy produced}} \tag{6.2}$$

In more detail, the $LCOE_r^{PV}$ relates the investment in generation technology ($Inv_{r,t}^{PV}$ in [€]), operation and maintenance costs ($M_{r,t}^{PV}$ in [€]), fuel expenditure ($F_{r,t}$ in [€]), revenue ($Rev_{r,t}^{PV}$ in [€]) and energy production ($E_{r,t}^{PV}$ in

$[MWh]$) of building r in year t over an expected project lifetime T, taking into account the discount rate i, as in Eq. (6.3) [95]. In the evaluated scenario, only PV was used as generation technology, expressed as $LCOE_r^{PV}$, as in Eq. (6.3).

$$LCOE_r^{PV} = \frac{Inv_t^{PV} + \sum_{t=1}^{T}\left(\frac{M_{r,t}^{PV}+F_{r,t}-Rev_{r,t}^{PV}}{(1+i)^t}\right)}{\sum_{t=1}^{T}\left(\frac{E_{r,t}^{PV}}{(1+i)^t}\right)} \tag{6.3}$$

In this thesis, the term associated with the generation technology was adapted due to the possibility of sharing excess PV energy in the LEM through community-based P2P trading and further reimbursement. Based on the premise of remuneration of PV surplus as grid compensation, P2P trading ($Rev_{r,t}^{P2P}$) was reflected in the equation as shown in Eq. (6.4).

$$LCOE_r^{PV with P2P} = \frac{Inv_{r,t}^{PV} + \sum_{t=1}^{T}\left(\frac{M_{r,t}^{PV}+F_{r,t}-Rev_{r,t}^{PV}-Rev_{r,t}^{P2P}}{(1+i)^t}\right)}{\sum_{t=1}^{T}\left(\frac{E_{r,t}^{PV}}{(1+i)^t}\right)} \tag{6.4}$$

- The **LCOS** is a value analogous to the LCOE used for ESSs, ranging from pumped hydro to supercapacitors. Reference [97] introduced this parameter, which relates the total lifetime cost to the total energy delivered by the storage system, as in Eq. (6.5).

$$\text{LCOS} = \frac{\text{Total lifetime cost}}{\text{Electrical energy produced}} \tag{6.5}$$

More precisely, the total lifetime cost was defined as the ESS investment (Inv_t^{ESS} in [€]), operation and maintenance cost (M_t^{ESS} in [€]), charging cost (C_t^{ESS} in [€]) and replacement cost (Rep_t^{ESS} in [€]) during the whole system lifetime, as represented in Eq. (6.6)

$$LCOS_r = \frac{Inv_t^{ESS} + \sum_{t=1}^{T}\left(\frac{M_t^{ESS}+C_t^{ESS,cha}+Rep_t^{ESS}}{(1+i)^t}\right)}{\sum_{t=1}^{T}\left(\frac{E_t^{ESS,dcha}}{(1+i)^t}\right)} \tag{6.6}$$

where $E_t^{ESS,dcha}$ in $[MWh]$ is the total energy discharged from the storage in the year t.

Battery replacement time is to be emphasised. In this thesis, the ESS replacement was calculated according to the ageing parameter detailed in Sections 3.2.2.1 and 3.3.1.2 for local BTs and CESS, respectively. After one year simulation, the SOH parameter was calculated from the cycling, i.e. SOC curve cycle counting, and the calendar ageing estimates.

In the case of the present study, the LCOS referred to the different storage systems used: the individual BTs in the building domain and the CESS used by all community users. The LCOS equation was adapted differently for each storage solution. While the individual BTs were owned, maintained and used individually by the community participants, the CESS was owned and maintained by a tertiary party, meaning that the community users only had to pay for the fuel costs over the system's lifetime. Therefore, two LCOS were defined; $LCOS_r^{BT}$ in $[€/MWh]$ for building BTs, as in Eq. (6.7), and $LCOS^{CESS}$ in $[€/MWh]$, as in Eq. (6.8), to indicate CESS usage.

$$LCOS_r^{BT} = \frac{Inv_{r,t}^{BT} + \sum_{t=1}^{T}\left(\frac{M_{r,t}^{BT} + C_{r,t}^{BT,cha} + Rep_{r,t}^{BT}}{(1+i)^t}\right)}{\sum_{t=1}^{T}\left(\frac{E_{r,t}^{BT,dcha}}{(1+i)^t}\right)} \tag{6.7}$$

being $Inv_{r,t}^{BT}$ in [€] the BT initial purchase, $M_{r,t}^{BT}$ in [€] the yearly operation and mainteinance costs, $C_{r,t}^{BT}$ in [€] the yearly charging costs, $Rep_{r,t}^{BT}$ in [€] the battery replacement cost and $E_{r,t}^{BT,dcha}$ in $[MWh]$ the energy discharged from the r building BT in a year t.

$$LCOS^{CESS} = \frac{\sum_{t=1}^{T}\left(\frac{C_t^{CESS,cha}}{(1+i)^t}\right)}{\sum_{t=1}^{T}\left(\frac{E_t^{CESS,dcha}}{(1+i)^t}\right)} \tag{6.8}$$

where C_t^{CESS} in [€] is linked to the yearly CESS dicharging cost and $E_t^{CESS,dcha}$ in $[MWh]$ to the energy dicharged from the CESS.

The $LCOE^{EC}$ term employed in this study is the sum of the PV LCOE LCOS ($LCOE^{PVwithP2P}$ in $[€/MWh]$), the individual BTs LCOS ($LCOS^{BT}$ in $[€/MWh]$) and the CESS LCOS ($LCOS^{CESS}$ in $[€/MWh]$), as expressed in

Eq. (6.9).

$$LCOE^{EC} = \sum_{r=1}^{R} \left(LCOE_r^{PVwithP2P} + LCOS_r^{BT} \right) + LCOS^{CESS} \tag{6.9}$$

Substituting all the terms, the remaining equation is Eq. (6.10).

$$\begin{aligned} &LCOE^{EC} = \\ &\sum_{r=1}^{R} \left(\frac{I_{r,t}^{PV} + \sum_{t=1}^{T} \left(\frac{M_{r,t}^{PV} + F_{r,t} - Rev_{r,t}^{PV} - Rev_{r,t}^{P2P}}{(1+i)^t} \right)}{\sum_{t=1}^{T} \left(\frac{E_{r,t}^{PV}}{(1+i)^t} \right)} + \right. \\ &\left. \frac{I_{r,t}^{BT} + \sum_{t=1}^{T} \left(\frac{M_{r,t}^{BT} + C_{r,t}^{BT,cha} + Rep_{r,t}^{BT}}{(1+i)^t} \right)}{\sum_{t=1}^{T} \left(\frac{E_{r,t}^{BT,dcha}}{(1+i)^t} \right)} + \frac{\sum_{t=1}^{T} \left(\frac{C_t^{CESS,cha}}{(1+i)^t} \right)}{\sum_{t=1}^{T} \left(\frac{E_t^{CESS,dcha}}{(1+i)^t} \right)} \right) \end{aligned} \tag{6.10}$$

6.1.3 Employed data

For determining the community LCOE the assets investment (PV installation and local BTs) and their related operation and maintenance (O&M) had to be established. Note that the BTs in buildings' domain were of first-life. The employed data for carrying out the LCOE evaluation is presented in Table 6.6.

Table 6.6: Investment and operation and maintenance prices.

Asset	**Parameter**	**Price**	**Reference**
PV installation	Investment [€/kWh]	1364.76	[98]
	O&M [€/($kWh \cdot year$)]	20	[98]
Local BT installation	Investment [€/kWh]	519.69	[99]
	O&M [€/($kWh \cdot year$)]	7.1	[99]

The BT replacements were calculated according to the ageing estimation previously described in Section 3.2.2.1 and according to that, the replacements were calculated. The local BT started at 100 % SOH and ended at 80 % SOH.

6.1.4 Results

Each asset and price were individually evaluated. In generation and consumption cases, their estimation error and volume were analysed. The results obtained in the simulation are described in this subsection.

6.1.5 Generation estimation error and volume influence

In the generation case, see Fig. 6.2, estimation errors produced up to 67.7 % LCOE increase and 46.7 % decrease concerning the baseline LCOE. In case there were only generation errors, and with the predicted values (100 % prediction errors), LCOE decreased by 8.7 %. Analysing volume influence, shown in Fig. 6.3, if the volume was downsized and consumption was maintained, up to 270.2 % was increased the LCOE, if there was a double of the generation, LCOE decreased up to 24.7 %. Note that the generation increase tended to stabilise. This was due to the oversized PV generation, P2P energy-sharing has a limit and energy is sold to the grid at a lower price, not obtaining sufficient revenues to improve the LCOE value. Hence, the proposed market was more sensitive to generation volume than generation estimation errors.

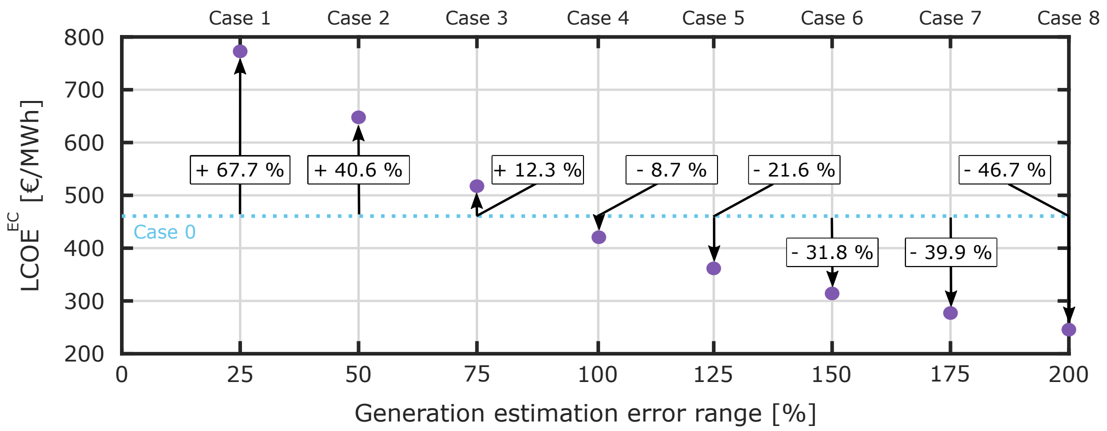

Figure 6.2: LCOE change within different generation estimation error ranges.

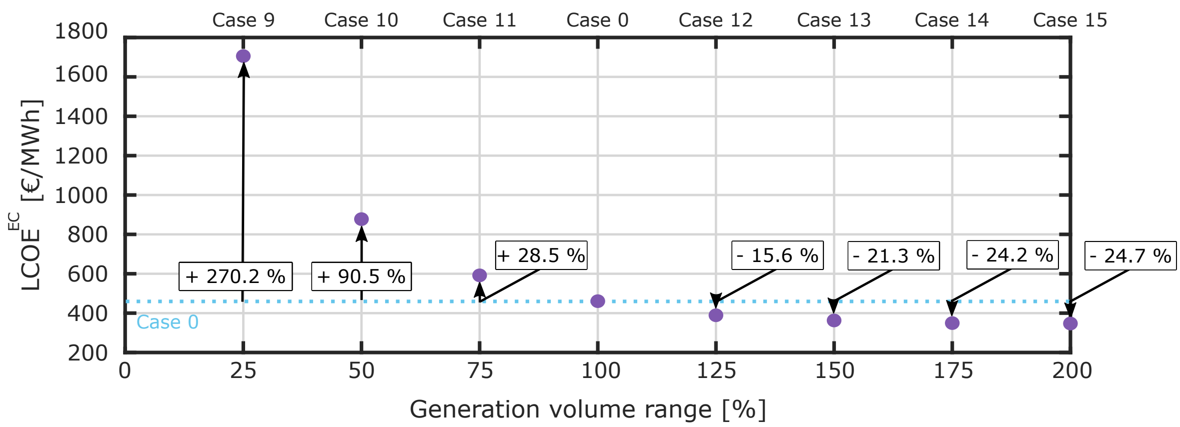

Figure 6.3: LCOE change within different generation volume ranges.

6.1.6 Consumption estimation error and volume influence

The errors produced in estimating the consumption are depicted in Fig. 6.4, where it can be seen that a linear trend was followed. The lowest estimation errors were produced at 25 % estimation errors, addressing up to 49.4 % LCOE decrease. The highest LCOE was registered when the worst estimation was done, where up to a 50.1 % increase was scored. It could be concluded that consumption errors also impacted the two-stage LEM performance but at a lower level than generation. In the case of analysing the sensitivity towards consumption volume, up to 50.4 % LCOE decrease was registered when reducing consumption volume, and up to 61.4 % was increased when doubling it. In this case, almost a linear trend was followed, and generation volume was seen as a more sensible parameter for downsizing the volume. Still, generation upsizing was concluded to be a more sensible parameter.

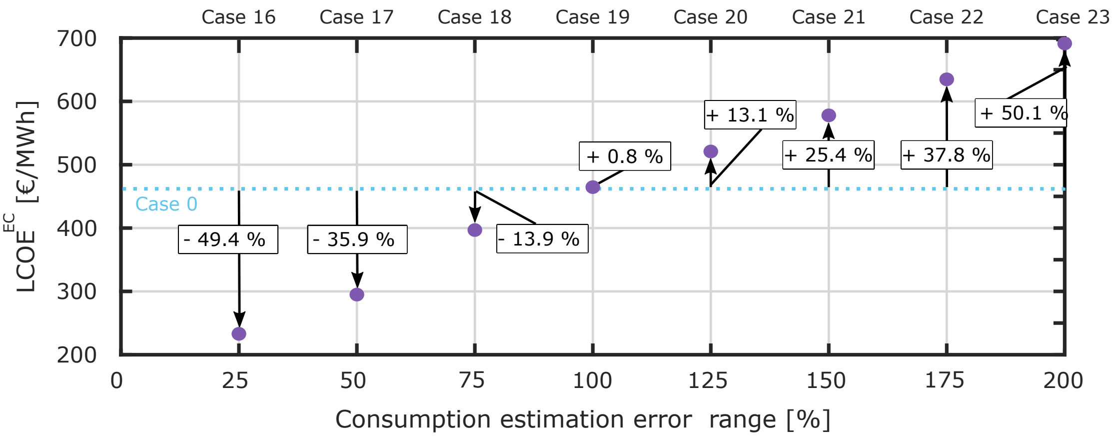

Figure 6.4: LCOE change within different consumption estimation error ranges.

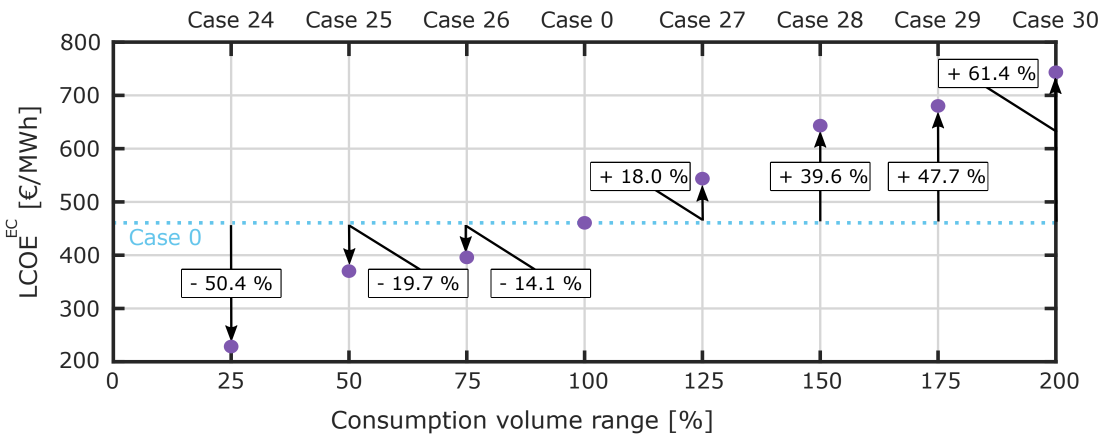

Figure 6.5: LCOE change within different consumption volume ranges.

6.1.7 Local batteries capacities influence

Local BTs capacity ranges were also analysed. This parameter had little influence compared to generation and consumption estimation errors or volume. The highest difference at downsizing the BTs was up to 5.5 % LCOE decrease, and at upsizing, the BTs, up to 4.4 % increment was obtained. This meant that omitting storage was beneficial up to 5.5 % because there was another storage system, i.e. CESS. Additionally, local BTs replacement did not affect as much as sensible as consumption and generation estimation errors of volume.

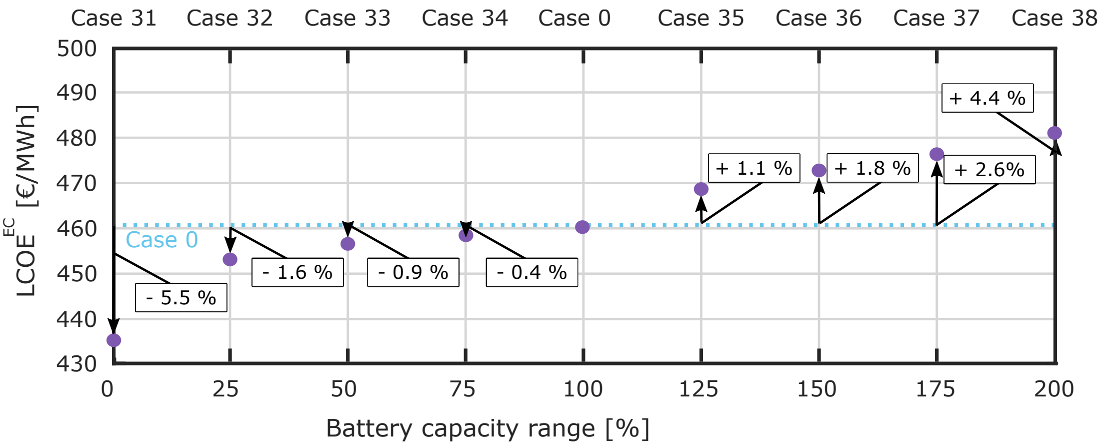

Figure 6.6: LCOE change within local BTs capacity ranges.

6.1.8 Community battery capacity influence

Concerning the CESS capacity volume, the lower the capacity was, the bigger the influence in the community LCOE it had. Without CESS, the community increased up to 6.3 %. However, if the volume of the CESS increased, the lesser grid imports were addressed, reducing up to 3.3 % the community LCOE. However, this parameter's influence was far from that evidenced by consumption and generation estimation errors and volumes.

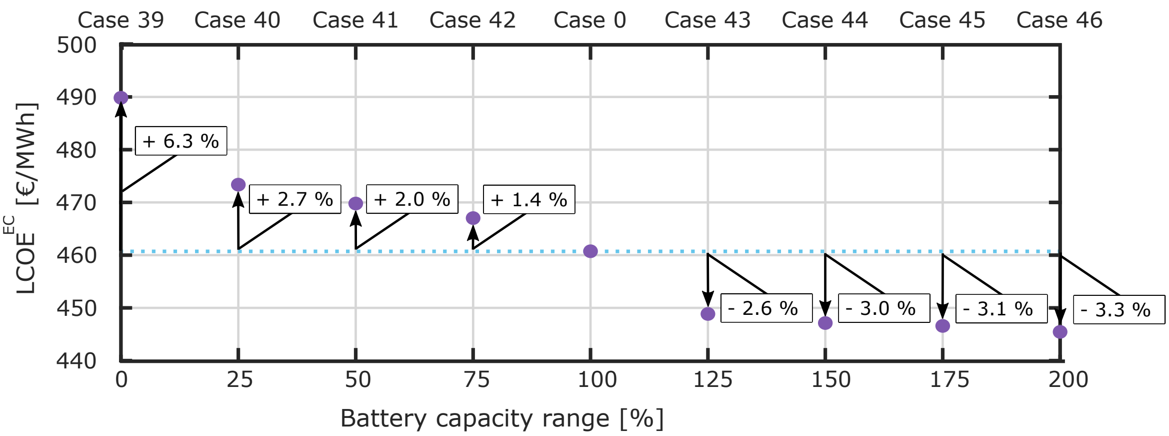

Figure 6.7: LCOE change within CESS capacity ranges.

6.1.9 Spot market price influence

The spot market price was compared with stable prices (2017 to 2020) and variable prices (from 2021 to 2023); see Fig. 6.8. 2022 was the year with the most expensive price, as evidenced in the graph, addressing up to an 8.5 % increase. The lowest scenario was in 2018, addressing up to 17.1 % decrease. This was also evidenced by the change in legislation, which analysed toll and charge value differences in 2021 between the old tariff and the new tariff system. The old tariff registered 4.7 % more expenses in LCOE, and 0.8 % was increased with the current tariff, evidencing that the community performed better with the current tariff. Additionally, if the community was constructed in 2023, up to 13.8 % would diminish the LCOE.

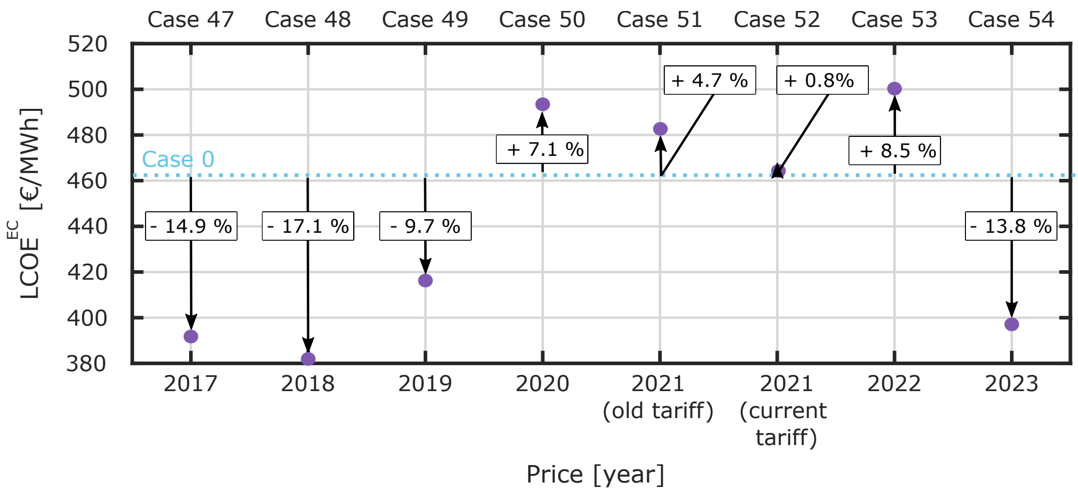

Figure 6.8: LCOE change within different spot market prices.

6.2 Conclusions

This chapter presented the sensitivity analysis of the proposed two-stage energy-sharing market in Chapter 2. The impact of the inputs (generation and consumption estimation errors, renewable energy sources penetration, consumption quantity, local BTs sizing, CESS sizing and spot market price) were individually evaluated. A total number of fiftyfour cases were analysed.

1. **Generation estimation errors and volume** greatly influenced the proposed energy-sharing market. The better the error accuracy, the higher the community LCOE was, addressing up to 67.7 %. By contrast, if the errors were the worst, the LCOE improved up to 46.7 %. The generation volume was the most impacting input. If generation volume was downsized by 25 %, the LCOE increased up to 270.2 %. However, if generation was incremented to double (i.e. 200 %), the community LCOE up to 24.7 % was downsized. In conclusion, generation volume had greater influence than the generation estimation error. It is to highlight the tendency to stabilise the LCOE as the volume increases. This was caused by the oversized PV generation, where

P2P energy-sharing reached the limit and energy was injected into the grid at a lower price, not obtaining sufficient revenues to improve the LCOE value.

2. **Consumption estimation errors and volume**. A linear trend was seen in both estimation errors and volume. At 25 % estimation errors, up to 49.4 % LCOE decrease was registered, and at 200 % estimation errors, up to 50.1 % increase. If the analysis was done regarding the consumption volume range, those values incremented. At 25 % of consumption volume, the community LCOE decreased up to 50.4 %. By contrast, at 200 % of consumption, the community LCOE increased up to 61.4 %. Hence, it can be concluded that consumption volume impacted the indicator more than the estimation error.

3. When analysing the **local BTs capacity ranges**, this parameter had little influence compared to errors in production and consumption estimates or volume. The largest difference when BTs was reduced was up to 5.5 % LCOE reduction, and when BTs was increased was up to 4.4 %. This meant that up to 5.5 %, it was advantageous to dispense with storage because there was another storage system, CESSs. In addition, local BTs substitution did not significantly affect the consumption and production estimation errors of the volume.

4. Regarding the **volume of CESS capacity**, the lower the capacity, the more it influenced the community LCOE. Without CESS, the community increased up to 6.3 %. However, if the volume of the CESS increased, the smaller grid imports were addressed, reducing the community LCOE up to 3.3 %. Nevertheless, the influence of this parameter was far from that shown by the errors in consumption and generation estimates and volumes.

5. Concerning the **spot market price**, stable prices (2017 to 2020) and variable prices (from 2021 to 2023) influence in the community LCOE was evaluated. 2022 was the year with the most expensive price, evidencing and LCOE increase of up to 8.5 %. The cheapest scenario was 2018, with a decrease of up to 17.1 %. The evaluation also evidenced by the change in legislation, which analysed the differences in toll and charge value in 2021 between the old tariff and the current tariff system. The old tariff registered 4.7 % more expenditure in the LCOE and the current tariff increased it by 0.8 %, proving that the community performed better with the current tariff. In addition, if the community were built in 2023, the LCOE would be reduced by up to 13.8 %.

7

General conclusions and future research lines

Summary

This final chapter summarises the main conclusions of the thesis. The main contribution, the design, development, and validation of a two-stage centralised P2P Energy Community Market is highlighted. Finally, some future lines of research are suggested.

7.1 Main contribution and overall conclusion

The introduction of energy supply and demand uncertainties in LEMs topic and further short-term deviation management has yet to be widely addressed in the literature. Hence, **this PhD Thesis has proposed a centralised two-stage energy community market considering renewable generation and consumption uncertainties.** Additionally, this thesis **introduced a novel business model rooted in BaaS**, where a third party provides physical storage, enhancing energy autonomy and offering competitive prices compared to the grid. Participants also benefit from being exempt from a CESS's investment, operation, and maintenance.

The state-of-the-art review of ECs background information and its energy trading and management was carried out in Chapter 1. Firstly, the definitions of ECs across Europe were explored, resulting in two different definitions: RECs and CECs. A general scope of Member States transposition was given, as the EC definition into their national legal frameworks is at different stages. ECs present new opportunities and roles in the energy landscape, such as different allocation schemes for energy sharing and the inclusion of new actors in the electricity system. LEMs are part of the allocation schemes where P2P structures for energy trading can take place. **P2P markets were observed as a trend, facilitating energy and monetary transactions within EC members**, and are addressed in recent literature.

Among P2P structures, community-based align with the philosophy of ECs, seeking collective benefits such as optimising local energy, reducing collective electricity bills, lowering emissions, and supporting the local economy. Effective asset management is important to maximise the use of local resources. The ESSs employed in LEMs are mainly BTs. When local resources are based on renewable generation, there is stochasticity. In addition, consumption patterns vary from day to day. Both supply and demand intermittency errors have to be dealt with in short-term dispatch, which was little explored in the literature. **In this context, a REC was proposed that combined P2P trading market, local BTs and a novel BaaS business model for stationary applications and considered short-term generation and consumption management.**

In Chapter 2 the innovative energy-sharing market was explained, detailing the proposed design and methodology for assessing the viability of the LEM. The energy-sharing market was a community-P2P structure that orchestrates the energy trading on a two-stage basis. The methodology for evaluating the viability of the LEM was outlined, and a detailed explanation and timeline of each methodology step was given.

1. Scenario definition. The active and passive active characterisation was done, defining their design and operation variables. The agents' participation in the REC under study were explained, **introducing the novelty of the BaaS in ECs**. Market rules were also detailed, with gate closing times on an hourly basis and market operating horizons on a daily basis.

2. LEM design. The novel two-stage proposal was described. Market clearing was outlined, involving planning (ex-ante optimisation) and operation stages. The introduction of a prediction module as input in a preliminary phase was also explained. **The LEM design covered a gap in the literature by considering prediction errors, their management, and penalties for energy deviations**.

3. Performance evaluation. The proposed energy-sharing market evaluating KPI (energy, technical, economic and environmental) and the ageing of the community energy storage system were expressed.

Chapter 3 presented the mathematical expressions used to model the assets of EC participants, their associated control and LEM prices.

1. Assets modelling. In the former, electrical models of the assets (passive and active) within each participant's domain were given, describing the main formulas and databases for obtaining the generation and consumption curves and BTs operation.

2. Control strategy. **The thesis presents an innovative two-stage control strategy.** The control strategy for each agent was detailed—each building agent was responsible for predicting its energy balance, and **the LEMO was in charge of minimising community energy costs through a centralised optimisation**. Building agents were directly involved in the operational phase, using **BTs to manage energy deviations**. They could **access the CESS when there was insufficient capacity** by buying or selling energy. **Failure to meet deviations resulted in a payment from the deposit**.

3. LEM pricing. The cost models employed for determining the REC operation were defined. The community management was under the LEMO and used

these innovative prices to plan the LEM.

- The extra-community prices (grid imports and exports prices) were defined by the current Spanish framework.

- The LEM novel prices were established depending on the influence of each participant according to their electricity tariff. Here, **a novel community-based P2P pricing was introduced, weighting each building's generation and consumption rates**. The P2P price settlement showed advantages over other modalities, which were evidenced in the simulations carried out in Chapter 5: a) encouraging community generation and b) joining different sector buildings in a same community.

Chapter 4 introduced the optimisation algorithm and explained the steps taken to select the algorithm. The design variables, the associated constraints, and the reasons for selecting the optimisation algorithm, the MILP, were detailed.

In Chapter 5, **the performance of the innovative two-stage energy-sharing market approach was evaluated**. First, the evaluation scenario was described, including the consumption and generation patterns of REC participants and the characteristics of local BTs and CESS. Additionally, electricity prices related to the grid, energy tolls, charges, and spot were detailed. Afterwards, analyses were carried out regarding the proposed P2P price, the proposed two-stage energy-sharing market and the novel tariff.

1. The proposed novel **community-based P2P** price was analysed, with the resulting P2P price **converging between grid import and export prices, providing the real value of energy, encouraging energy generation and penalising consumption**. By promoting energy generation, EC's self-consumption was encouraged. This way, participants could adjust their consumption patterns and match demand to peak energy generation hours. Moreover, this price settlement was shown to be beneficial for both LTBs and RBs. LTBs significantly diminish electricity billing when joined with RBs. RBs, especially those with lower contracted power, had an interesting price during high generation and consumption hours.

2. Then, **the proposed innovative approach was examined in techno-economic and environmental terms at each stage**. In the first stage, the community-based P2P structure was compared with other energy-sharing

structures: the full P2P and the collective self-consumption, having the traditional passive consumer as a benchmark. Real and predicted data were evaluated, where predicted data was obtained from the Gradient Boosting Regression Tree technique, aspect included in the planning stage of this PhD thesis. The proposed day-ahead community P2P approach outperformed collective self-consumption and full P2P models. This conclusion was drawn through numerical analysis of KPIs encompassing energy (grid imports, exports, internal trading), technical (self-consumption, solar cover, internal rates), and environmental (equivalent CO_2 emissions) aspects:

- In energy terms, predicted data variability affected all energy-sharing structures, ranging from 2.4 % to 2.5 %. C-P2P achieved the best results, reducing grid consumption by up to 43.5 % and 37.9 % for predicted and real data, respectively, concerning the GRID structure. The exports were reduced up to 15.5 % in predicted data case and up to 14.7 % with real data. The energy saved from exports was employed to fulfil community needs, improving up to 144.6 % of the internal trading, comparing it to the full P2P structure.

- Concerning the technical results, C-P2P performed best against the GRID benchmark with and without predicted data. With real data, up to 42.8 % annual self-consumption rate, 36.5 % annual solar cover rate and 5.5 % annual internal energy trade were recorded. With predicted data, the results reduced to 34.7 %, 34.3 % and 4.7 %, respectively.

- The environmental analysis was done in terms of equivalent CO_2 emissions, where reductions up to 36.0 % and 40.9 % were obtained with real and predicted data compared to GRID.

3. **Different ESS solutions (local storage and local storage with a novael business model based on BaaS) were analysed integrated in the REC**. The benchmark in this evaluation was the centrally orchestrated, i.e. C-P2P structure, energy-sharing market with persistence predictions (prediction and real data are the same, Case 0). Predicted data was obtained again via the Gradient Boosting Regression Tree technique for other cases. The analysis was done regarding energy (grid imports, exports, internal trading), technical (self-consumption, solar cover, internal rates), and environmental (equivalent CO_2 emissions) terms.

   - Energetically, the combination of local BTs and CESS (Case 3) outperformed other solutions, where grid consumption and exports were reduced by up to 6.2 % and 27.0 %, respectively. There was also a 15.1 % increase in P2P trade.

- Case 3 also exceeded the economic results, scoring up to 9.8 % and 3.2 % discounts grid expenditure and revenues, correspondingly. Regarding P2P trading, the local economy incremented by 16.7 %. Deviations caused by prediction variability were also analysed, where Case 1 (any storage solution and predicted data) was taken as a reference. Case 3 outperformed again, registering up to 59.0 % penalisation decrease. In this context, the BaaS viability was analysed, where it was concluded that the BaaS business model was not profitable for the CESS owner with the current Spanish scenario: an annual benefit of 100 € was obtained. The minimum benefit to have a profitable business was 1620 €.

- From a technical point of view, Case 3 achieved the best results compared to the other ESS solutions, taking into account the forecast mismatch (Case 2 and Case 3). It was demonstrated an annual self-consumption of 36.8 %, a yearly solar cover rate of 36.3 % and an annual internal energy trade of 5.6 % were achieved. It should be noted that the annual internal energy trade of Case 0 was slightly exceeded by Case 3.

- The environmental analysis registered up to 4.4 % of CO_2 emissions reduction against Case 0.

4. The fifth section introduced a **proposal for a new tariff for the electricity system to have a profitable BaaS for the CESS owner**. The power term was presented as a variable component of the electricity bill since energy was consumed or traded within the community, i.e. traded within the participants or with the CESS. The power term varied according to the source or sink of the electricity at any given time. The whole power term was paid if the electricity was traded outside the REC limits, and half of the power term was paid if the electricity was traded inside the community. In this context, **the BaaS business was profitable to CESS owner**.

The **sensitivity analysis of the proposed two-stage LEM** was done in local sensitivity analysis terms and presented in Chapter 6. The effects of each input (errors in generation and consumption estimates, renewable energy resources volume, consumption volumes, local BTs size, CESS size and spot market prices) were assessed separately. A set of fiftyfour cases were evaluated. The study was done with the community LCOE. Among all the terms, **generation volume and error estimation were the parameters that impacted most of the innovative two-stage approach, followed by consumption volume and estimation errors**.

- Generation volume and estimation errors. While downsizing generation volume to 25 %, the LCOE increased up to 270.2 %, and upsizing registered up to 24.7 %. Note that the LCOE stabilised as volumes increase. This was due to the oversized PV, with P2P energy sharing reaching its limit and energy being fed into the grid at a lower price, not generating sufficient revenue to improve LCOE. In the case of generation estimation errors, the higher the errors were, the higher the LCOE difference was, recording up to 67.7 % LCOE.

- Consumption volume and estimation errors. More precisely, consumption volume was the next parameter affecting the proposed market and was followed by the consumption volume; if the volume increased up to 200 %, the LCOE increased by 61.4 %. If the volume was diminished up to a 25 %, the LCOE decreased to 50.4 %. Regarding estimation errors, the higher the errors, the bigger the difference, where up to 61.4 % LCOE increase was obtained.

- The spot market price variability evidenced noteworthy results. The electricity reform of 2021 in Spain was noticeable, where the old tariff registered 4.7 % more LCOE expenditure, and the current tariff scored up to 0.8 % increase. Moreover, the lowest scenario was addressed in a pre-pandemic year, in 2018, addressing up to 17.1 % reduction; this was due to a very stable price registered in that year. The most expensive price was recorded for 2022, scoring up to 8.5 % LCOE increase.

- CESS volume capacity had a smaller impact, with up to 6.3 % LCOE increase in the absence of CESS. If CESS capacity was doubled, the LCOE fell by up to 3.3 %, reflecting the less energy imported from the grid.

- Local BTs absence meant a 5.5 % LCOE decrease, and the employment of a capacity 200 % higher signified an increment of 4.4 %. Thus, it could be concluded that local storage could be avoided in case there was another storage system, the CESSs.

7.2 Future research lines

A number of potential future lines of research were identified following the development of the thesis. The future research lines were identified in line with the papers developed in the literature concerning ECs topic:

- **Experimental testing**. The proposed two-stage energy-sharing market can be tested in an experimental environment, i.e. a test bench or hardware in the loop, where the emulation of the REC assets can be carried out. In that respect, the proposal can be tested with commercial equipment (inverters, protection devices, etc.), and a more realistic approach can be seen.

- **Electrical losses**. The proposed two-stage energy-sharing market can be tested in different distribution topologies, where, due to the layout, different modelling lines can be addressed and calculated. These lines can even be integrated into the optimisation algorithm for a more realistic solution.

- **Integration with DLTs**. In reality, the application of this energy-sharing market must rely on a cyber-secure and immutable environment for energy trading, avoiding tampering and guaranteeing data protection and privacy. In this line, a DLT development can be done, designing nodes composing it and the energy contracts for each participant.

- **Integration in local flexibility markets**. The REC can participate in local flexibility markets via flexible assets. In the current state of development, storage systems are unique assets, but this thesis can be expanded to address flexible demand and response to participate in those markets. Additionally, the REC can join with other communities, composing an archipelago, to participate jointly in flexibility markets.

- **Vehicle-to-Everything (V2X)**. EVs can be interesting in ECs context. EVs can be at different locations: at individual households (Vehicle-to-Home (V2H)), buildings (Vehicle-to-Building (V2B)), and at parking lots. EVs can serve as storage without any additional BT investment cost. Another advantage is that using EVs as stationary storage implies low degradation, causing low impact for the main mobility purpose. Finally, EC members could sell the BTs used in mobility functions as second-life storage to a tertiary, for instance, the BaaS agent, taking full advantage of the storage lifetime and closing the BT lifespan cycle.

Note that this thesis was developed using a theoretical framework. An amendment to the current regulation would be necessary to develop the proposed centralised P2P energy-sharing market in the Spanish scenario. Additionally, new laws should be designed where retailers had to deduct, likewise in self-consumption schemas, the energy volumes traded in the P2P taking place within community limits.

A

Appendix A

Summary

This appendix summarises the regulatory framework related to EC of each EU member state. The details regarding the following are given: a) EC type that they consider, b) the approach electricity system, c) the conceived members and activities, d) the effective control, e) the market access and f) the imbalances responsibility of the community.

A.1 Austria

Austria has a Coordination Office for ECs that supervises and assists ECs development. The EC law was introduced in mid-2021. More precisely, the Federal **Law on the Organisation in the Field of the Electricity Industry (EIWOG)** [100] defined the regulation related to CECs and RECs. A more detailed definition was given to RECs in the **Federal Law on the Expansion for Energy From Renewable Sources (EAG)** [101] in its 6^{th}*Section* .

In summary, both types of ECs participation are open and voluntary, and they need at least two members. In both cases, they can only perform under authorised DSO, in LV and MV and whose main activity is not energy. In the case of RECs, they are considered legal entities that permit energy sharing inside the community. The community comprises legal persons, associations, or cooperatives close to the generation points. These members can be natural persons, municipalities and legal entities. The activities are linked to energy production, self-consumption, storage, energy selling and energy sharing. In the case of CECs, it is extended to aggregation and energy services provision (energy efficiency and EV charging). The energy sharing is allocated by the DSO via static or dynamic coefficients. Dynamic coefficients are updated on a fifteen-minute basis. Community members or shareholders do the control. The REC must be placed in LV and MV lines, where participants can share the self-generated energy.

A.2 Belgium

Belgium is a country where the Federal Legislation and the three regions, Brussels-Capital, Flanders, and Wallonia, stipulated the energy and climate regulatory framework. Whilst Federal legislation is related to transmission and large-scale, regional laws determine renewable energy (omitting offshore sources), electricity distribution and regulation of retail markets, among other competencies. Hence, this country's regulation concerning ECs is given in federal and regional laws.

- **Federal Legislation** In the third quarter of 2022, **Law of 23rd October 2022** [102] introduced RECs and CEC. CEC comprises natural persons, local authorities, municipalities, educational institutions, associations, and other ECs, and small and medium enterprises can be community members. The activities are linked to production (renewable and non-renewable), consumption, aggregation, energy storage, energy efficiency services, EV charging services and other energy services.

  Concerning RECs, participants are natural persons, local authorities, municipalities, educational establishments, associations, other ECs and small and medium enterprises whose main economic activity is not the REC participation. The energy generation is restricted to renewable resources. The federal legislation also details that the REC has to, at least, a) produce energy in an installation of its domain or of its right of use, b) self-consume the generated energy, c) store energy, d) supply or take part in energy-services, e) supply or take part in flexibility or aggregation or f) sell produced energy to the transmission system.

- **Brussels-Capital Region** In the Brussels-Capital region, ECs legislation is described by the **Ordinance** [103]. It differentiates REC, CEC and LEC concepts. The LEC members can be any natural person, public authority or small or medium enterprise whose community participation is not their main activity. Renewable energy is produced, consumed, stored and shared between members and the assets. Energy sharing is scoped as P2P exchange and occurs every fifteen minutes. For complying with the P2P trading, each participant needs to provide contact details, role (consumer, producer or prosumer), the energy resource (renewable or non-renewable), the energy quantity and the time frame when the trading is held. Community members do effective control. In this case, the community or participants own or have the right to exploit community facilities.

  RECs are wider than LECs, they have the same members and the characteristics are broadened to the ability to participate in aggregation services and supply flexibility and energy services. They can also join energy-sharing activities via a supply contract, such as charging EVs.

  CECs are similar to RECs. The difference lies in a) the resource, which is not limited to renewables, and b) the membership; companies are delimited to small companies, whose main activity is not the energy sector and have no activity at a large scale.

- **Flemish Region** The Flemish region legislation was regulated by the **Energy Decree** [104]. Concerning RECs, community members must be near renewable generation and can be natural persons, local authorities or small and medium enterprises whose main activity is unrelated to the EC. Community participants must be connected to the electricity distribution network, local transmission or close to the distribution network. The main activities are linked to energy production, self-consumption, energy sharing, aggregation, energy storage, EV charging and providing energy efficiency services.

Each REC member has an agreement where their rights and obligations are patent for developing those activities. If there is energy sharing, the agreement also contains distribution keys. The REC control can be carried out by a third party or the REC itself. The control is also subjected to possible imbalances that REC activities may produce. Note that REC has installation property rights. Metering for the total community energy needs to be done and is distribution network duty. CEC differ concerning RECs in terms of participation, where medium enterprises cannot be part of them. Energy resources are not limited to renewable generation.

It is to highlight that the Flemish region regulates P2P trading. The minimum number of participants is limited to two, whose main activity is not energy-related. The trading is done each quarter-hour, and to take place, there is the need to have measured data, energy allocation calculation methods, reconciliation, invoicing, and adjustments.

- **Walloon Region** A **Decree** [105] regulated RECs and CECs in the Walloon region. Participants can be natural persons, local authorities and small and medium enterprises whose main activity is not the EC. In both ECs, energy can be a) self-consumed, b) stored, c) shared among participants, d) aggregated, e) employed for participating in flexibility services, f) used to provide EV charging, g) shared, and h) used for P2P trading. Energy management can be delegated. The difference between RECs and CECs is related to the energy resource employed (RECs energy resource is limited to renewable energies, and CEC resource is open). Both communities can access electricity markets directly or through aggregation and are responsible for their imbalances.

A.3 Croatia

In Croatia, the **Law on Renewable Energy Resources and Highly Efficient Cogeneration** [106] legislated the RECs and the **Law on the Electricity Market** [107] regulated CECs. Natural persons, local authorities, and enterprises can participate. More previsely, small and medium enterprises can participate in the case of RECs, and micro and small enterprises in the case of CECs. It is established that a) a community member has a vote and b) a member's shares cannot be higher than 40 %. The activities are linked to energy production, supply, consumption, sharing and storage in the case of RECs. In the case of CECs, the activities are extended to energy efficiency, EV charging, and other services. A sharing scheme (metering, distribution key, members involved) must be submitted to the DSO if energy sharing is wanted. The control of both ECs lies on shareholders or members, who cannot have more than 40 % of the shares. The regulation also stated that access to energy markets can be done directly by the community or through an aggregator.

A.4 Cyprus

Cyprus regulated ECs in two different laws. **Law 107(I)/2022** [108] leigslated RECs and **Law 130(I)/2021** [109] determined CECs. In the former, natural persons, local authorities or small and medium enterprises can participate. The activities are related to production, consumption, energy storage and selling renewable energy. The control is in the hands of shareholders and members. RECs can access electricity markets directly or through aggregators. In the latter, members are limited to natural persons, local authorities, or small businesses. The activities are delimited to energy production, distribution and supply of electricity, consumption, energy storage, energy efficiency services, EV charging services, and other energy services. Partners or members effectively controlled the community, and access to electricity markets can be done directly or through aggregators.

A.5 Denmark

RECs and CECs were regulated in the year 2021 under the **BEK 1069** [110]. It determines that natural persons, local authorities, municipalities and small and medium enterprises (only small for CECs) could be EC members. Their activities are limited to production, supply, consumption, aggregation, energy storage, energy efficiency, EV charging services, and others. If energy sharing is held, it has to be agreed upon by the energy trading company, and a price can be charged for the traded electricity. Participants or capital owners control, and ECs can access electricity markets directly or by third party.

A.6 Estonia

RECs were regulated by the **Energy Sector Organisation Act** [111] and there is any law for CECs. Natural persons, local authorities and small or medium enterprises whose main activity is not in the energy sector can be community participants. The activities are linked to energy production, consumption, storage, sharing and selling. Shareholders and members whose location is near renewable resources can control the community. Access to electricity markets can be done directly or by aggregators.

A.7 Finland

The Finnish EC regulation was determined in **Decree 2021/767** [112], where LECs and CECs were regulated. The difference between LECs and CECs is that the energy resource in LECs is limited to renewable generation. Hence, albeit in this country, the concept of RECs is not mentioned; that same definition is given as LECs. Community members can be natural persons, municipalities, local authorities and small enterprises (in LECs case, is extended to medium enterprises). Communities can produce, supply, consume, share, aggregate and store energy. The energy sharing is held hourly, and the community has to present the scheme (energy resource and consumption location, and the quantity). Additionally, they can provide energy efficiency services, EV charging and other energy services. The control relies on members or shareholders. If there are energy excesses, they can be injected into the grid or purchased by a third party. The excesses can be remunerated collectively or individually.

A.8 France

In France, RECs and CECs were legislated by **Ordinance 2021-236** [113]. Natural persons, local authorities, mixed economy companies (public and privately owned), private small and medium autonomous enterprises (only small if CECs and in both cases, their primary activity cannot be the EC participation), social entrepreneurship initiatives, associations, and solidarity enterprises of social utility can be members. The activities linked to RECs are limited to producing, consuming, storing and selling energy. In the case of CECs production, supply, aggregation, storage, selling, energy efficiency services, EV charging and other services can be provided. The control of both communities falls to shareholders or members. Energy sharing is also scoped in both communities, where it is only envisaged as a collective or individual self-consumption. Collective self-consumption is limited to a geographical energy sharing in LV lines of a 2km radius and 3 MW generation installations. If it is a rural location or a low-density population, the radius is extended to 20 km. The energy-sharing is netted every fifteen minutes and can distributed by static or dynamic distribution keys. The relevant information (distribution key, legal entity, producer and consumer participating) must be transferred to the DSO. Additionally, this CECs and RECs can access energy markets directly or through aggregation. In the particular case of CECs, they are financially responsible for the imbalances they can cause.

A.9 Greece

Greece regulated RECs and CECs under the **Law 5037/2023** [114]. In the case of RECs, members can be natural persons, legal entities, local authorities, associations, agricultural and urban cooperatives, small and medium enterprises and public or private non-profit legal entities located in LV and MV. RECs activities are linked to production, consumption, storage, energy selling and sharing. Market access can be done directly or through an aggregator.

Concerning CECs, members are linked to natural persons, local authorities and small businesses. Both ECs' control is in the hands of the members that cannot be part of another EC. CECs activity is extended to aggregation, provision or flexibility and balancing, energy efficiency services, EV charging services, and others. Particularly if energy is shared in CECs network charges and tariffs are paid. They are in charge if CECs have energy imbalances.

In both cases, the law establishes that at least 51 % of the members are near renewable resources. The minimum number of members is delimited to thirty except a) the REC located an insular municipality of less than 3,100 inhabitants, twenty members, b) joining fifteen small and medium enterprises, resulting in a community of fifteen members, and c) a community conformed by a local authority and two enterprises fully owned by local authorities, resulting in a community of three. Note that it is stated that enterprises fully owned by local authorities and agricultural cooperatives belonging to the same agricultural cooperative as other members can participate in more than one community. Moreover, members also have a cooperative share; the maximum participation is up to 20 %, and enterprises fully owned by local authorities can own 40 % of shares. A share can be transferred to another community member or third party. Regardless of the share percentage, each member has a vote. Energy sharing is charged according to network tariffs and charges. Concerning the surpluses, virtual net metering was legislated in Law 4513/2018 [115], where individual or collective self-consumption was considered. The remuneration of the surpluses is also delimited. At least 10 % of the value must be held in the community's ordinary reserve, and 70 % is withheld as a special reserve. The effective control is under community members. Market access can be done directly or through an aggregator.

A.10 Hungary

In Hungary, the Directives referred to CECs and RECs were transposed in **Electricity Act LXXXVI** in 2021 [116]. CEC structure was regulated as EC. Both communities can be composed of natural persons and non-profit companies, whose share cannot exceed 30 % of the community. The activities are energy production, consumption, storage and selling in RECs case. EC is extended to provision of distribution, flexibility services, aggregation, provision of electromobility services and electromobility charging. It is also stated that ECs can participate in electricity markets directly or through an aggregator. They are financially responsible if imbalances in CECs are produced.

A.11 Italy

Legislative Decree 199/2021 [117] regulated RECs and **Legislative Decree 210/2021** [118] legislated CECs. Concerning RECs, their members are located in LV and MV, which can be natural persons, local authorities, municipalities, research and training entities, religious entities, third sector and environmental protection associations, local administrators and small and medium enterprises whose main activity is not in the energy sector. The activities are subjected to energy production, consumption, self-consumption, storage, energy sharing, energy efficiency, EV charging services, and supply and flexibility services. The generation plants for each member are limited to 1 MW; farms are exempt from that limit. Energy sharing is envisioned as diffuse self-consumption, defined as the total electricity supplied through the interconnected points within a specific market region. The case of RECs is delimited to the connection points of the same substation. The management is in the hands of the Energy System Manager, and the sharing is hourly held via static or dynamic coefficients. The energy sharing can be done through contracts between community members or through a third party. Generated surpluses can be stored or sold directly to the market via an aggregator or power purchase agreements. A virtual regulatory model was developed in Italy to subtract ex-post from the electricity bill, the energy quantity, and the cost of the self-consumed energy.

CECs members are natural persons, local authorities, research and training entities, religious entities, third-sector and environmental protection associations, local administrators and small enterprises whose main activity was not in the energy sector. The activities are extended for flexibility and distribution purposes. Energy sharing, i.e. diffuse self-consumption, is held hourly, and storage can be used to share electricity. If any imbalance occurs, they are responsible. Their access to markets is directly done or through an aggregator.

A.12 Latvia

Latvia legislated both RECs anc CECs in the **Law of Energy (2022/137A.3)** [119]. Note that CECs is referred as Elektroenergijas Kopiena (EEC). The difference between them relies mainly on the operation area: EEC operates in the electricity sector and REC in the renewable energy sector. Their members are natural persons and small and medium enterprises. Their activities are energy production, consumption, trade, supply, storage, demand response provision, EV recharging services, energy efficiency services and other energy services. If energy sharing is held, the law establishes that storing it for later use is forbidden, but it can be sold to the community outside. Additionally, EC members sharing energy cannot participate in net settlement (financial net accounting), net accounting (energy net metering) and certificates of origin at the same time. Their control is limited to members and shareholders. It is to highlight that EECs must determine agreements with electricity traders before operations. In both cases, energy traded with the community outside is paid according to the net accounting systems.

A.13 Lithuania

Lithuanian RECs were regulated by the Law on Renewable Energy, **Law XI-1375** [120], which was updated in 2022. Community members can be natural persons, small and medium enterprises, non-profit legal entities, municipalities and enterprises and institutions managed by the municipality. The activities are limited to energy production, consumption, storage and selling. For energy selling, if internal selling, independent supplier requirements must be met and can be sold through contracts. If energy is transferred outside the community, the Law of Electricity must be applied to the billing. It also establishes that RECs are exempt from a) being financially responsible for their imbalances and b) paying compulsory production taxes.

Concerning CECs, the legislation was rooted in the Law on Electricity (**Law VIII-1881/2000** [121], updated in 2022). Natural persons, very small and small enterprises, municipalities, municipal institutions, associations, and public non-profit institutions can be community members. Their activities are energy production, consumption, sharing, demand-response, storage, energy efficiency, and EV charging services. They are paid according to Law VIII-1881/2022 if a purchase or sale is held. If energy is sold outside community limits, an agreement must be made according to the law, where the CEC has an independent supplier role if the supply is bigger than 10 MW. It is also established that they are financially responsible for their imbalances.

A.14 Luxembourg

Luxembourg only recognised RECs and was regulated by the **Act on the Organisation of the Electricity Market (AOEM)** [122] amended in 2021. Natural persons, small and medium enterprises, local authorities and municipalities can be part of a REC. Their activities are located in LV and MV and are linked to producing, consuming, storing, and selling electricity. Energy can be shared within community limits in each 15-minute step by employing station or dynamic distribution keys that can differ from the keys established for collective self-consumption in this country. The sharing can be formalised through a power purchase agreement. Surpluses can be sold directly or through a third party via power purchase agreements if the balancing responsibilities are complied with.

A.15 Malta

Maltese Government also divided RECs and CECs into two different legislations in 2021. **Subsidiary Legislation 545.35** [123] regulates RECs, whose members are natural persons, local authorities, municipalities and small and medium enterprises, whose main activity is not their participation in the community. Shareholders and members effectively control them, and their activities are rooted in producing, sharing, consuming, storing, and selling energy through power purchase agreements. Note that the DSO assists the energy transfers. Their access to markets can be done directly or through an aggregator.

The CEC is legislated through **Subsidiary Legislation 545.34** [124]. The members can be natural persons, local authorities, municipalities, and small enterprises. Members and shareholders exercise effective control. Their activity is linked to generation, distribution, supply, energy sharing, consumption, aggregation, energy storage and providing energy efficiency, EV changes and other energy services. In case there are imbalances, they are financially responsible for them. Their access to markets is done directly or via an aggregator.

A.16 Portugal

In Portugal, both RECs and CECs were legislated under the **Decree 15/2022** [125]. There are slight differences among both EC types; the main difference, as in the previous cases, is the energy resource. REC are rooted in renewable energy resources and CECs in renewable and non-renewable sources. The membership is for natural or legal persons, public or private, small and medium enterprises and local authorities. The activities are linked to producing, consuming, storing, sharing, buying and selling electricity in the case of RECs and are extended to distribution, aggregation, and services (energy efficiency, EV charging and others) for CECs. Energy sharing can be done via static, dynamic or hybrid coefficients that the management entity or hybrid management must determine. Community users are exempt from tariffs if the public network is not used internally. Members control both community types and have full responsibility for their generated deviations. Both communities can also access markets directly or through aggregation.

A.17 Romania

Romanian government regulated RECs and CECs with different laws, **Ordinance 163/2022** [126] legislated RECs and **Ordinance 143/2021** [127] determined CECs. The members in a REC can be natural persons, local authorities, municipalities and small and medium enterprises. CECs membership excludes medium enterprises. Shareholders or members effectively control both. RECs activities are limited to energy production, consumption, storage and selling, where they can jointly consume locally generated energy. CECs legislation extended the activities to distribution, aggregation and energy services (energy efficiency, EV charging and others). In both cases, access to markets is done directly by the community or through aggregators. In the case of RECs, DSOs cooperate to facilitate energy transfers. Concerning CECs, they can autonomously manage their network, and agreements must be established with DSOs and TSOs. Additionally, they are financially responsible if imbalances exist in CECs.

A.18 Slovakia

Slovakia employs different terms for RECs and CECs. The country defines them as Community producing Energy from Renewable Resources (CPER) and as ECs, respectively. Both definitions were given by **Act 256/2022** [128]. CPERs are not limited to renewable energy resources but also consider biomethane production. The community members are natural persons, local authorities, municipalities, and small enterprises. The membership is extended to medium enterprises in the case of CPERs. Their activities involve energy production, supply, sharing, storage (only renewable energy resources in the case of CPERs), aggregation, distribution, charging station operation, and other energy-related activities. The control of CPERs is limited to members with permanent residence or business headquarters in its location. It is stated that ECs can be managed by the local distribution system. In both cases, contracts must be made for energy sharing (produced or stored energy). More precisely, in CPER's case, the gas contract must be made with TSO and DSO. In CPERs, the DSO assists with energy sharing. CPERs and ECs are financially responsible if there are any imbalances. Both have access to markets directly or through aggregators.

A.19 Slovenia

Slovenia established the definition of RECs in the **Act of the Promotion of the Use of Renewable Energy Sources (ZSROVE)** [129] and CECs were regulated by the **Act on Electricity Supply (ZOEE)** [130]. The members can be legal or natural persons, where legal persons can be linked to small and medium enterprises (in CECs, medium enterprises cannot participate). The control is rooted in community members or partners. The activities are limited to energy production, consumption, storage and selling in the case of RECs. The activities for CECs are extended to aggregation, energy efficiency services, EV charging and other services. The energy selling can be done through power purchase agreements. Energy can be self-consumed individually or collectively through a contract. Access to electricity markets can be carried out directly or through aggregation. Balancing can be carried out by the community or outsourced. It is determined that the DSO has to assist in energy transfers.

A.20 Spain

The Spanish legislation of ECs is rooted in **Royal Decree 23/2020** [131], where RECs are only legislated. Members can be natural persons, local authorities, municipalities and small or medium enterprises. The activities that can be carried out are producing, consuming, storing, and selling renewable energy. The energy sharing is envisioned as an hourly dispatch through collective self-consumption, limited to a radius of 1 km. If it is a PV generation, it is extended to 2 km. A participant cannot adhere to individual and collective self-consumption simultaneously. Surpluses can be injected (self-consumption with surpluses) or not (self-consumption with anti-dump mechanism) into the grid. If they are injected, according to Article 4 of the Royal Decree 144/2019 [75], the energy excess can be reimbursed a) subjected to compensation or b) not subjected to compensation. The former pays a fixed amount agreed before with the retailer [75]. It has a criterion for being able to choose it: a) the resource must be renewable, b) the associated production facilities sum has to be less or equal to 100 kW, c) a contract of the compensation quantity must be signed, d) the producer cannot adhere to another or specific remuneration regime, e) if auxiliary production services are provided, a contract must be signed. The latter remunerates the surpluses at the spot price [75]. The access to markets can be done directly or through aggregation. CECs still need to be legislated.

B

Appendix B. Load and PV generation forecasting

Summary

This appendix introduces an overview of the forecasting methods employed for loads and PV generation. Then, a literature review is done to select the predictor for forecasting energy supply and demand patterns. Finally, the predictions done for each passive asset are shown and validated, and the obtained errors are presented.

B.1 Forecasting methods

LEMs trade energy and money between prosumer and prosumer or prosumer and consumer. Three aspects come into play: energy production, consumption, and price. The proposal of this PhD thesis is based on a REC, supported by renewable energy sources, whose production depends on weather or atmospheric conditions. The weather dependency results in a variable generation pattern, translating into energy production unpredictability. The same applies to energy consumption. Household consumption is also variable, leading to uncertainties in the energy demand of each user. As aforementioned, spot market price is a day-ahead known variable underestimated from forecasting.

Reliable forecasting models for energy production and consumption are needed to cope with both patterns' uncertainties and achieve an efficient match between supply and demand. Hence, energy generation and consumption forecasting were included in this dissertation.

The identified factors that drive the LEM (energy production and demand) are variables that are predicted according to forecasting methods that rely on the historical data of each variable. Forecasting techniques based on historical data are divided into four groups [132]: a) persistence method, b) statistical approaches, c) machine learning algorithms and d) hybrid techniques. The information in this section was based on references [132–134].

B.1.1 Presistence model

In this model, the forecasted output is assumed to be the same as the following day [132, 133]. In other words, the predicted values for the next day are the same as today. This supposition can be reliable if the weather conditions do not change significantly daily. This model is commonly used as a benchmark for comparing the accuracy of other forecasting methods.

B.1.2 Statistical approaches

Statistical approaches employ numerical analysis and statistical processing to examine numerically and extract statistical information. Those methods embrace Auto Regressive Moving Average (ARMA) models, Auto Regressive Integrated Moving Average (ARIMA), regression techniques or exponential smoothing methods [132].

- **ARMA model** is the mathematical term that combines both autoregressive ”ar” and moving average ”ma” terms. The former models the predicted variable according to the regression of the previous values. The latter indicates that the error of predicted data is a combination of diverse points in time, including the current point in time. Briefly, ARMA predicts the following value of the time series according to the previous values of that same variable and adds an error (white noise) factor.

- **ARIMA model** adds an integrated part to the ARMA model. The data has an internal structure that includes some repeatability or logic. The objective of the method is to explore the internal structure and know how the moving average of the time series' noise and the variable's linear regression combine to predict the series' evolution. The integrated term refers to differencing the time series to make it stationary. Differentiation is deducting the preceding value from the current value in a time series data set.

- **Regression analysis** employs statistical processes to establish a pattern for the relationship between a variable or a set of variables and the response. Among regression techniques, the simplest method is linear regression, which refers to a unique variable and a single response. This technique is called multivariate linear regression if more of a variable is involved. Logistic regression is used when the output of a variable or set of variables is a binary response (e.g. true or false). For instance, it can be used to predict whether a tumour is malignant or benign. Mathematically, a logistic regression can resolve a multivariate linear regression function.

- **Exponential smoothing method** refers to a method where the historical data is weighted in an exponentially decreasing way. In other words, the oldest data is given the least weight, and the newest has the highest weight.

B.1.3 Machine learning algorithms

Machine learning algorithms are artificial intelligent methods also used to forecast electric energy generation and demand [133]. The algorithms are divided into supervised learning, unsupervised learning, reinforcement learning and ensemble methods [133]. Supervised learning is a technique where a mathematical model is built according to known inputs and outputs [133]. This model is trained with previous data for obtaining reasonable prediction outputs [133]. By contrast, unsupervised learning is built according to unknown outputs. Due to the unknown outputs, patterns or intrinsic structures are searched in the available data for giving a forecasted value [133].

Supervised learning is the most suitable among machine learning techniques for this PhD thesis proposal, as LEM participants' variable assets (energy production and consumption) are parameters where historical data is available. The most used techniques in supervised learning are artificial neural networks, support vector machines, and decision trees [132, 133].

- **Artificial Neural Networks (ANNs)** method is inspired by human brain information processing. This method intends to mimic the interconnection among neurons to obtain a forecasted output. One of the main characteristics of this method is that it learns complex patterns and even automatically models non-linear relations between variables straight from data [132, 133]. The advantages of this method are the ability to learn, self-organisation, fault tolerance and flexibility to noise in the input signals [132, 133, 135].

  There is a wide range of ANNs, from the most basic architecture to more complex structures. The perceptron is the most basic architecture with an input layer, a single neuron hidden layer and an output layer [135], as depicted in Fig. B.1. First, each input is multiplied by a weight, and all the multiplications are added, resulting in a weighted sum. Then, this weighted sum is added to the bias term. Finally, the output is obtained when the result of the weighted sum with the bias term is calculated in an activation function.

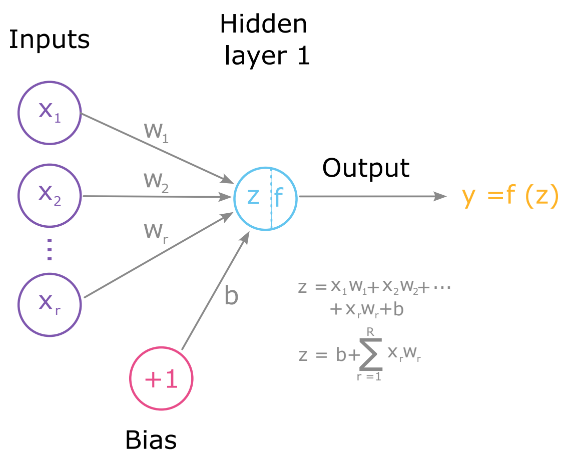

Figure B.1: Artificial Neural Network.

  An ANN is a modular method consisting of several neurons in a single hidden layer and can be scaled to several hidden layers. When the architecture consists of more than a hidden layer, it is called a multilayered perceptron. Another characteristic to consider in the architecture is whether the neural network has feedback [135]. A feedbacked ANN is called a Recurrent Neural

Network. It has a "memory", which raises the complexity and is usually employed in language or time-series data [135].

An ANN can be trained and calculated either in a feed-forward (solved in a forward way) or back-propagation (solved backwardly, employing errors to tune internal weights) way. Among ANNs, several architectures are used in the literature for prediction: multilayered perceptron, recurrent neural networks, general regression neural networks, etc [135].

The main drawback about ANNs is that they require good quality and a large amount of data for obtaining reliable forecasting [135]. Another disadvantage is that ANNs can learn from training data but performs poorly with new input data. Additionally, the lack of transparency makes it difficult to understand a decision that an ANN takes [135].

- **Decision Trees or Breiman bagging** use statistics to predict a variable from observations (branches) to target values (leaves) [133], as depicted in Fig. B.2. Firstly, the tree is constructed by dividing the data set into subsets according to the value of an input feature. The aim is to obtain the purest possible subgroups concerning the outcome (i.e. subgroups with predominantly one class label or subgroups with similar outcomes) [134].

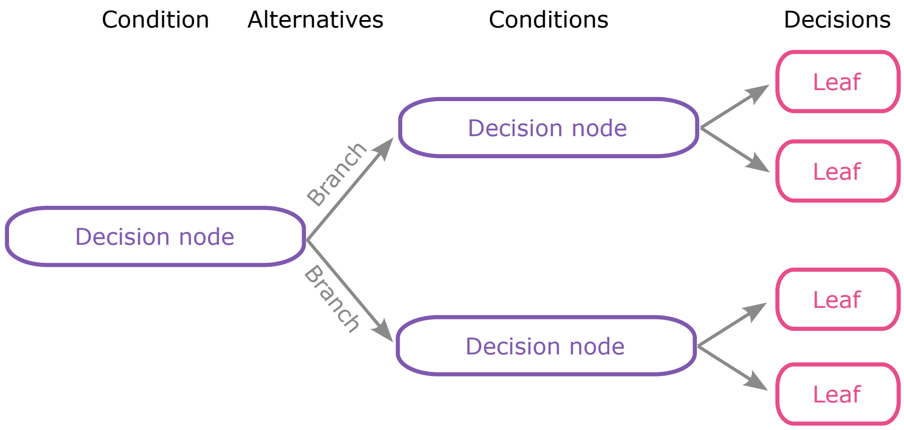

Figure B.2: Decision Tree.

This method is comprehensible, simple and accurate [133, 134]. The major disadvantage lies in overfitting, which can be resolved by establishing restrictions to the model parameters and combining nodes (pruning) to the average value between them. These models have high variance [133, 134].

Depending on the output type, there are two decision tree types: classification trees and regression trees [133]. Classification and Regression Tree (CART) is the term that refers to both. Whilst classification trees' output variable only gives categorical (e.g. true or false) responses based on the mode of the tree branches, regression trees' output is continuous (e.g. numeric) and the mean value of the observations. Despite the differences among CARTs, ensemble techniques, boosting and bootstrap aggregation (also known as bagging) are employed for solving.

  – **Boosting** is a technique that estimates the output by training sequentially a series of weak models, where each new model corrects the previous errors [133]. If decision trees are employed, a new tree is created to predict the leftovers of the previously developed ensemble tree [133], see Fig. B.3. The boosting technique with decision trees is denominated as **Gradient Boosting**. A strong and high-accuracy learner can be built by adding new models [133].

  – **Bagging** is the next step to the bootstrap method and is used to reduce the high variance of predictive models, i.e. CARTs [133]. Firstly, it randomly creates sub-samples of the available dataset. Then, the CART is trained with each created sample and obtains a predicted output likely to be the most frequent value. Predictions are performed with new datasets; the overall forecast response is the average of all the predicted outputs, for instance, for predicting the colour of a rose. Assuming there are five prediction outputs, red, red, white, red, and white, the bagged result will likely be red. **Random Forests** is a particular application of the bagging technique [133]. Firstly, input data subsets are determined, and decision trees are created. Each decision tree has randomly assigned its features at each split point and is trained with a different input data subset. If the output is continuous, the result is based on the average of the forecasting of each tree.

- **Support Vector Machines (SVMs).** This technique divides the data set into two classes via a hyperplane to minimise errors [132, 133]. Therefore, this technique can be used for classification or regression [132, 133]. In scenarios where the data is linearly separable or almost separable, SVMs are particularly effective. It is a robust technique due to its ability to handle complex data sets [132, 133]. The main drawback is that if the data points closest to the hyperplane, also known as support vectors, are changed, the hyperplane is changed, and the worst prediction is made [132]. Therefore, finding the most accurate support vectors will give a better answer for the

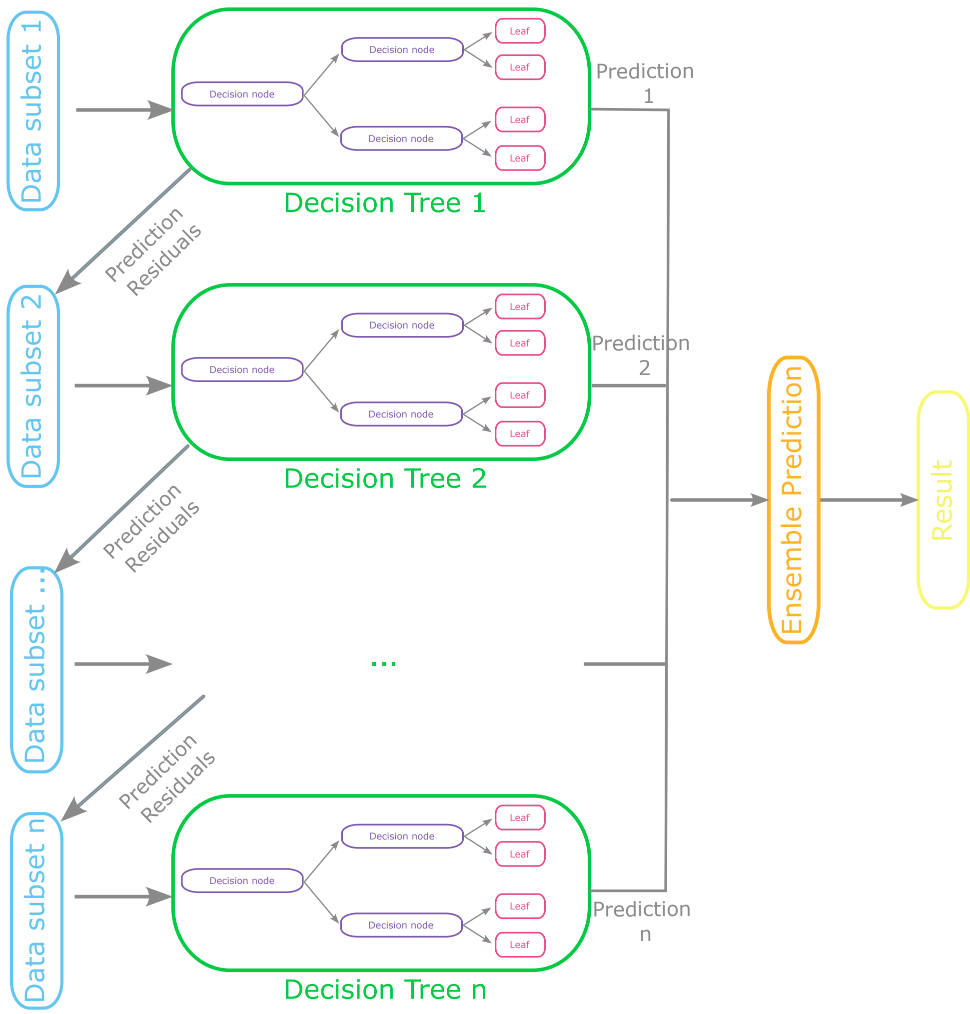

Figure B.3: Gradient Boosting.

prediction [132]. The kernel function is used to transform the data pattern into more separable data [132].

B.1.4 Hybrid technique

This category refers to combining two or more forecasting techniques [132, 133]. This field can use several combinations, such as combining ANNs with the ARIMA model [136]. It combines the linearities identification of ARIMA with the non-linearities captured by ANNs [136].

B.1.5 Literature review

Energy generation and consumption predictions are widely researched topics in the literature. Several works reviewed forecasting techniques for energy supply and demand. Concerning **PV generation forecasting**, in [132], it was stated

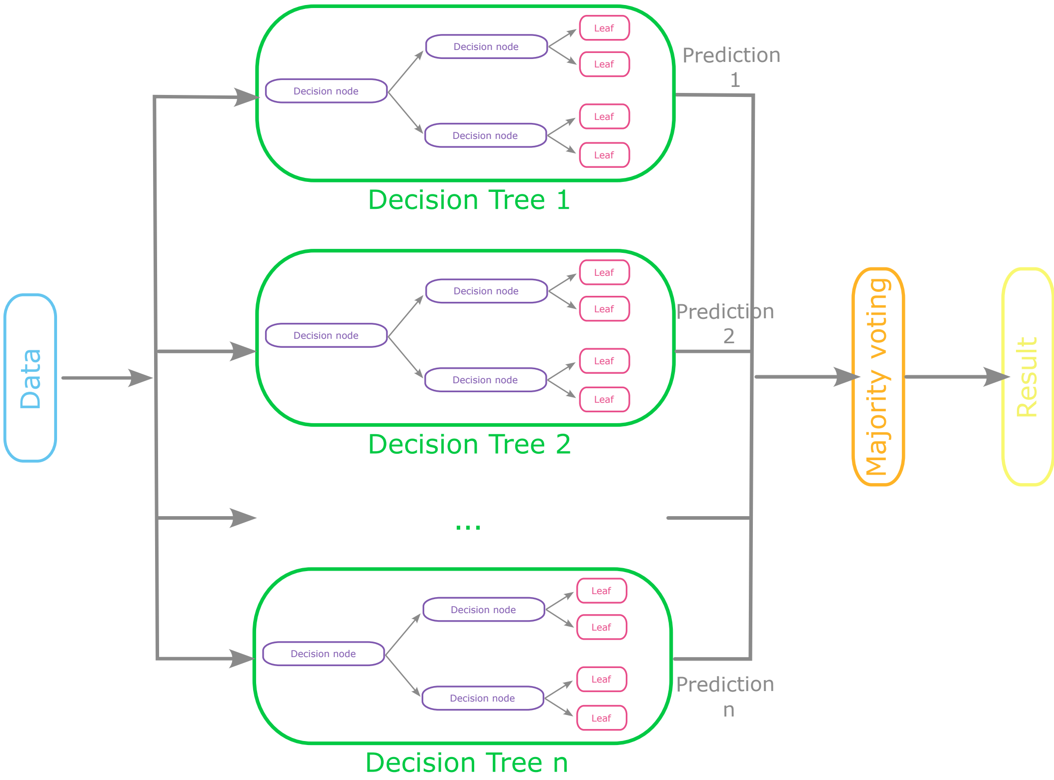

Figure B.4: Random Forest.

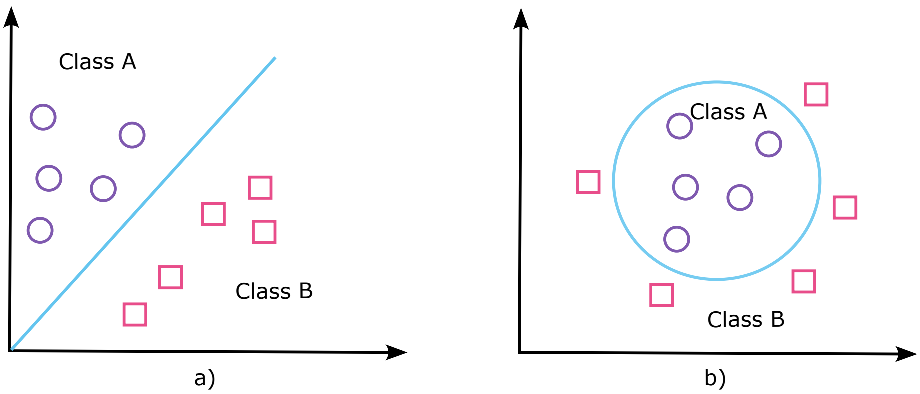

Figure B.5: Support Vector Machines, being a) linear model and b) non-linear model.

that ANNs and support vector machines perform well and make rapid predictions. In another review for solar radiation forecasting, in [133], it was evidenced that ANNs addressed most of the works, where the most used technique was the multi-layered perceptron at that time. The study compared ANNs with support vector machines, regression trees and random forests, obtaining promising results with regression trees. That is why the research foresaw a trend in using those techniques.

After that review, the same authors followed the way towards regression trees where they analysed in [137] three regression tree methods (pruned, boosted and bagged regression trees) for solar irradiation forecasting in different time horizons, obtaining that a boosted regression tree had the least errors. Furthermore, boosted regression trees outperformed in [138] compared with ANNs and support vector machines. In other work [139], ensemble learning-based models (regression trees and random forests) were compared to support vector machines and the Gaussian process for six different locations. It was concluded that although no unique method performed the best in all the locations, the ensemble method performed best.

Concerning energy **consumption forecasting**, most prediction is carried out with ANNs [140, 141]. Concretely, multilayered perceptron are the most used types of ANNs [135]. However, like energy generation, regression trees have been used in the recent literature for prediction [142]. The research in [143] demonstrated better performance for domestic consumption with decision trees than with ANNs for electricity consumption. The work in [144] proved that boosting techniques exceeded ANNs for different time windows (24-hour prediction, one-week prediction and one-month prediction). The study was done on the electricity demand in Tripura state in India. Additionally, they proposed a novel prediction combining random forest and gradient boosting, outperforming the simple boosting technique. Reference [145] studied prediction techniques for commercial building energy demand. It was evidenced that, once again, boosting technique results surpassed ANNs and other prediction techniques such as linear regression, bagging, and random forests.

As it has been reviewed, a wide range of prediction techniques can be applied in this context. ANNs have been widely used for energy production and consumption, obtaining reliable results. Nevertheless, the latest trend is to use **regression trees** due to their ease and rapid operation. Hence, this thesis forecasted energy supply and demand patterns based on regression trees.

B.2 Generation and consumption forecasting rooted in Regression Trees

Consumption and generation vectors depend on different aspects of building the energy pattern. The irradiance arrives on the Earth in a similar pattern each year due to the Earth's and the sun's position. By contrast, consumption curves may differ from one year to another. For instance, household inhabitants' numbers or habits can change in residential buildings. The same happens with prediction variables; for example, knowing the weekday is neglectable for PV generation and is indispensable for demand. Thereby, generation and consumption forecasts were carried out independently.

B.2.1 Generation forecasting

B.2.1.1 Inputs and database selection

The REC under study was located in Lasarte, a town in northern Spain. As PV is weather dependent, weather data was employed as input. The available database is Euskalmet [69], a local weather database. The accessible information in that database is ambient temperature, humidity, precipitation, wind speed, wind direction, irradiance, day, month, and hour. **Data correlation** was studied first to establish the most representative data for predicting PV generation. Irradiance factor is directly proportional to energy generation and was used to obtain the generation pattern, as expressed in Eq. (3.1) extracted from [66]. Thus, the correlation of irradiance with other meteorological data was studied.

Data from 2020 was employed for this study and was pre-processed: empty data and negative values, unrelated to any variable, were neglected and filled with interpolated values. All the data accessible went under study via *MATLAB Curve Fitting Toolbox* and the correlation was evaluated in terms of the coefficient of determination (R^2)[1]. It was concluded that the meteorological data influencing the most irradiance were the humidity and the temperature, as shown in Table B.1. In solar generation, Earth's translation also impacts the quantity of irradiance that arrives at the PV surface. Hence, day number, month number and hour were also considered for predicting PV generation. The data employed for the prediction were hour, day, month, ambient temperature, humidity, previous hour irradiance, and previous day irradiance.

Table B.1: Correlation between meteorologic variables and irradiance.

Variable	**Correlation**
Humidity	0.510
Temperature	0.362
Rainfall	0.001
Wind Direction	0.012
Wind Speed	0.069

The database selected for training the predictor was the meteorological data cor-

[1] The coefficient of determination is a statistical measure used for determining how close the variable is to the established line and explains the proportion in which the variance changes towards the variable. The measure lies between 0 and 1, the closest to 1 the best fitting.

respondent 2020 and the theoretical PV generation, obtained with Eq. (3.1) and meteorological data from 2020 because IKERLAN's PV generation did not have any meteorological station nor meteorological database in the same location.

B.2.1.2 Tree selection

The Gradient boosting technique was implemented via the *Regression Learner Application* from MATLAB [146]. The Boosting technique parameters were defined as in [147]; the minimum leaf size was 1,024, the number of regression trees was 10,000, and the learning rate was established as 0.01. The data employed for the prediction were hour, day, month, ambient temperature, humidity, previous hour irradiance, and previous day irradiance corresponding to 2020.

B.2.1.3 Results

The prediction was validated by comparing the irradiance obtained in the prediction and irradiance downloaded from the Lasarte meteorology station for the year 2020. The validation was evaluated in terms of Root-Mean-Square Error (RMSE), where RMSE is a commonly used indicator for evaluating predictions. RMSE is the root of the division between the quadratic difference among predicted and real values and the total number of observations, as expressed in Eq. (B.1). The RMSE value obtained for the prediction of the whole year is 64.73 W/m^2.

$$\text{RMSE} = \sqrt{\frac{\sum_{k=1}^{K}(\hat{y_k} - y_k)^2}{K}} \tag{B.1}$$

where $\hat{y_k}$ is the predicted value and y_k the database value, both in $[W/m^2]$.

Additionally, energy calculated by the predicted irradiance for July 2020 was compared with the energy samples gathered from the PV installation at IKERLAN's Galarreta office, located 5 km from the meteorological station, as depicted in Fig. B.6. The RMSE value obtained for this frame was 0.59 kW.

B.2.2 Consumption prediction

Consumption curves may differ from year to year; the same day of the year does not maintain the weekday, and, in residential buildings' case, household inhabitants' numbers or habits can change. That is why the accuracy of the prediction is more complex.

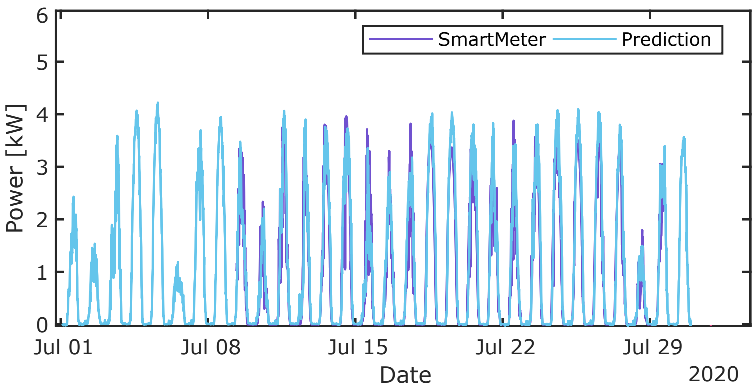

Figure B.6: PV generation obtained from predicted data compared to Smart Meter data

B.2.2.1 Inputs and database selection

Like generation prediction, the meteorological database was the local weather database Euskalmet [69]. Among the available information, ambient temperature, day, month, and hour were selected to predict buildings' load. Data from 2020 was employed for this study and was pre-processed: empty data and negative values, unrelated to any variable, were neglected and filled with interpolated values.

In demand patterns, the database chosen for training was the meteorological data correspondent 2020 [69] and the five consumption patterns available at IKERLAN's database. The most influencing factors are the day of the week, the prior day, the prior week, and whether a day is a holiday. Hence, the data employed for the prediction were hour, day, month, day of the week, ambient temperature, previous day consumption irradiance, and previous week consumption. Due to the scarcity of consumption data, 75 % of the data was employed for training the predictor, and the remaining 25 % was used for testing.

B.2.2.2 Tree selection

Again, the *Regression Learner Application* from MATLAB [146] was used to obtain the predictions. Specifically, the input data used to predict consumption were hour, day, day of the week, whether a day was a holiday, month, ambient temperature, consumption of the previous day, and consumption of the previous week. Note that, unlike generation, each prediction is based on a consumption pattern; thus, a regression tree was constructed for each consumption pattern. The Gradient Boosting technique was employed, and the parameters were defined again as in [147]; the minimum leaf size was 1,024, the number of regression trees was 10,000, and the learning rate was established as 0.01.

B.2.2.3 Results

The prediction was validated by testing the obtained output against the remaining 25 % of consumption data. The demand predicted for each building was compared with each building's real consumption. For example, the predicted and consumed data difference for RB1 is depicted in Fig. B.7, and the RMSE was 1.74 kW. The RMSE value obtained for each building consumption prediction was between 1.35 kW and 8.92 kW interval; see gathered data in Table B.2. Note that better RMSE values are obtained with residential buildings.

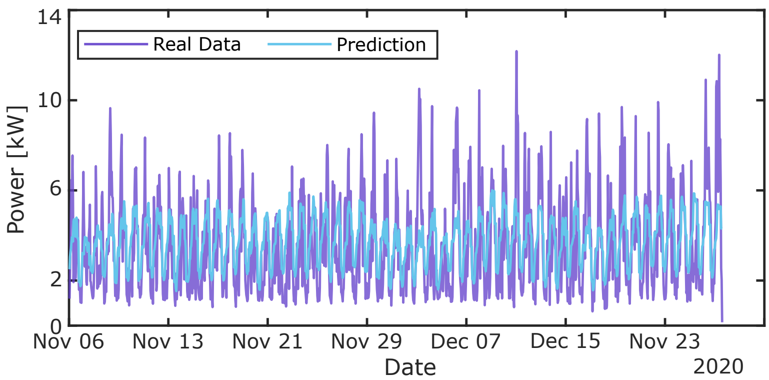

Figure B.7: 25 % of predicted consumption pattern of RB1 compared to 25 % of the real consumed data.

Table B.2: RMSE between meteorologic variables and irradiance.

Building	**RMSE [kW]**	**Building**	**RMSE [kW]**
RB1	1.74	RB6	1.35
RB2	1.41	RB7	1.65
RB3	1.68	RB8	2.21
RB4	2.22	LTB1	4.53
RB5	1.65	LTB2	8.92

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Notation

Abbreviations

ABC Artificial Bee Colony

ADMM Alternating Direction Method of Multipliers

ANN Artificial Neural Network

APP Auxiliary Problem Principle

ARMA Auto Regressive Moving Average

ARIMA Auto Regressive Integrated Moving Average

ATC Analytical Target Cascading

BaaS Battery-as-a-Service

BT Battery

CART Classification and Regression Tree

CEC Citizen Energy Community

CESS Community Energy Storage System

DE Differential Evolution

DLT Distributed Ledger Technoloy

DOD Depth of Discharge

DSO Distribution System Operator

EC Energy Community

EU European Union

ESS Energy Storage System

EV Electric Vehicle

FEC Full Equivalent Cycle

GA Genetic Algorithm

KKT Karush-Kuhn-Tucker

KPI Key Performance Indicator

LCOC Levelised Cost of Cooling

LCOE Levelised Cost of Energy

LCOEx Levelised Cost of Exergy

LCOH Levelised Cost of Heat

LCOS Levelised Cost of Storage

LEC Local Energy Community

LEM Local Energy Market

LEMO Local Energy Market Operator

LFP Lithium Iron Phosphate

LP Linear Programming

LTB Large Tertiary Building

LV Low Voltage

MILP Mixed Integer Linear Programming

MINLP Mixed Integer Non-Linear Programming

MIQP Mixed Integer Quadratic Programming

MV Medium-Voltage

NOCT Normal Operating Cell Temperature

NLP Non-Linear Programming

OCD Optimality Condition Descomposition

OMIE Operador del Mercado Ibérico de Energía

P2P Peer-to-Peer

PMP Proximal Message Passing

PSO Particle Swarm Optimization

PV Phovoltaic

QP Quadratic Programming

RB Residential Building

REC Renewable Energy Community

SA Simulated Annealing

SOC State of Charge

SOH State of Health

SVM Support Vector Machine

TD Transmission and Distribution

TLBO Teaching Learning-Based Optimisation

RMSE Root-Mean-Square Error

TSO Transmission System Operator

V2B Vehicle-to-Building

V2G Vehicle-to-Grid

V2H Vehicle-to-Home

V2X Vehicle-to-Everything

VAT Value Added Tax

Indexes

Index	Description	Unit
k	Index of time of Day-Ahead and shrot-term (k = 1, 2, ..., K)	$[h]$
r	Index of buildings (r = 1, 2, ..., R)	$[-]$
$ievt$	Index of Depth of discharge event index	$[-]$
t	Index of time of LCOE evaluation (t = 1, 2, ..., T)	$[year]$
s	Index of peer buildings (r = 1, 2, ..., S)	$[-]$

Parameters

Symbol	Description	Unit
α	Solar height	$[°]$
β	PV panel inclination	$[°]$
δ	Solar declination concerning the vertical axis of the Earth	$[°]$
Δk	Simulation time slot	$[h]$
D	Day of the year	$[-]$
ϵ	Factor correlating the equivalent CO_2 with the consumed energy	$\left[\frac{kgCO_2}{kWh}\right]$
η^{cha}	ESS charge efficiency	$[\%]$
$\eta_r^{BT,cha}$	r building BT charge efficiency	$[\%]$
$\eta_r^{BT,dcha}$	r building BT discharge efficiency	$[\%]$
$\eta_r^{CESS,cha}$	Community BT charge efficiency	$[\%]$
$\eta_r^{CESS,dcha}$	Community BT discharge efficiency	$[\%]$
η^{dcha}	Energy storage system discharge efficiency	$[\%]$
η^{inv}	Inverter efficiency	$[\%]$
$\eta^{inv,BT}$	r building BT inverter efficiency	$[\%]$
$\eta^{inv,CESS}$	CESS inverter efficiency	$[\%]$
ι	PV panel temperature coefficient	$\left[\frac{\%}{°C}\right]$
i	Discount rate	$[\%]$
Inv_r^{BT}	Building r BT investment cost	$[€]$
Inv_t^{ESS}	ESS investment cost	$[€]$
Inv_r^{PV}	Building r PV investment cost	$[€]$

Symbol	Description	Unit
$M_{r,t}^{BT}$	Building r BT operation and maintenance cost	[€]
M_{t}^{ESS}	ESS operation and maintenance cost	[€]
$M_{r,t}^{PV}$	Building r PV operation and maintenance cost	[€]
ϕ	Latitude	[°]
tax^{elec}	Electricity tax	[%]
VAT^{elec}	Value Added Tax of electricity	[%]
ζ_k	Energy mix at k instant	[%]

Variables

Symbol	Description	Unit
C^{bill}	Collective electricity bill	[€]
C_r^{bill}	r building electricity bill	[€]
C^{BS}	Discount rate cost	[€]
$C_{r,t}^{BT,cha}$	r building BT charging cost at year t	[€]
$C_t^{CESS,cha}$	CESS charging cost at year t	[€]
$C_{r,k}^{energy}$	Energy term cost of the energy imported from the grid by building r at instant k	[€]
C^{ER}	Equipment rental cost	[€]
$C_t^{ESS,cha}$	ESS charging cost at year t	[€]
$C_{r,k}^{exp,CESS}$	Revenue of the energy exported to the CESS	[€]
$C_{r,k}^{exp,grid}$	Revenue of the energy exported to the grid	[€]
$C_{r,k}^{exp,P2P}$	Cost of the energy exported to the P2P pool	[€]
$C_{r,k}^{imp,CESS}$	Cost of the energy imported from the CESS	[€]
$C_{r,k}^{imp,grid}$	Cost of the energy imported from the grid	[€]
$C_{r,k}^{imp,P2P}$	Cost of the energy imported from the P2P pool	[€]
$C_{r,k}^{power}$	Power term cost of the energy imported from the grid by building r at instant k	[€]
ΔSOH	Battery capacity decade	[%]
ΔSOH_r^{BT}	r building BT capacity decade	[%]
ΔSOH^{cal}	BT calendar capacity decade	[%]
$\Delta SOH_r^{cal,BT}$	r building BT calendar capacity decade	[%]
$\Delta SOH^{cal,CESS}$	CESS calendar capacity decade	[%]

Symbol	Description	Unit
ΔSOH^{CESS}	CESS capacity decade	[%]
ΔSOH^{cyc}	BAttery cycling capacity decade	[%]
$\Delta SOH_r^{cyc,BT}$	r building BT cycling capacity decade	[%]
$\Delta SOH^{cyc,CESS}$	CESS cycling capacity decade	[%]
$d_{r,k}^{cons}$	r building consumption deposit for step k	[€]
$d_{r,k}^{gen}$	r building generation deposit for step k	[€]
Dev	k instant power deviation binary indicator	$[-]$
E^{nom}	ESS nominal energy	$[kWh]$
$E_t^{BT,dcha}$	Energy discharged from building r local BT at year t	$[kWh]$
$E_r^{BT,nom}$	r building BT nominal energy	$[kWh]$
$E_t^{CESS,dcha}$	Energy discharged from CESS at year t	$[kWh]$
$E^{CESS,nom}$	CESS nominal energy	$[kWh]$
$E_t^{ESS,dcha}$	Energy discharged from an ESS at year t	$[kWh]$
$E_{r,t}^{PV}$	Energy discharged from building r PV installation at year t	$[kWh]$
$F_{r,t}^{PV}$	Energy cost for building r PV installation at year t	[€]
γ	Battery lifetime	$[years]$
γ_r^{BT}	r building BT lifetime	$[years]$
γ^{cal}	Battery cycling lifetime	$[years]$
$\gamma_r^{cal,BT}$	r building BT calendar ageing	$[years]$
$\gamma^{cal,CESS}$	CESS calendar ageing	$[years]$
γ^{CESS}	CESS lifetime	$[years]$

Symbol	Description	Unit
γ^{cyc}	Battery cycling lifetime	$[years]$
$\gamma^{cyc,CESS}$	CESS cyling ageing	$[years]$
$\gamma_r^{cyc,BT}$	BT cycling ageing	$[years]$
γ^{proj}	Project duration	$[years]$
G_k	Instantaneous irradiance at step k	$[W/m^2]$
$G_k^{horizontal}$	Instantaneous horizontal irradiance at step k	$[W/m^2]$
I_k	Current flow in the battery pack at isntant k	$[A]$
$\overline{I^{BT}}$	Maximum current limit of the battery pack	$[A]$
$\underline{I^{BT}}$	Minimum current limit of the battery pack	$[A]$
$\lambda_{r,k}^{energy,charges}$	Energy term charge price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{energy,toll}$	Energy term toll price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{exp,CESS}$	CESS export price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{exp,grid}$	Grid export price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{imp,CESS}$	CESS import price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{imp,grid}$	Grid import price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{P2P}$	P2P energy price	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{P2P,mean}$	P2P energy price, being this the mean value between grid imports and exports price	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{P2P,strategy}$	P2P energy price, being this the result of the strategy proposed	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{power}$	Power term total price of building r at step k	$\left[\frac{€}{kWh}\right]$
$\lambda_{r,k}^{power,charges}$	Power term charge price of building r at step k	$\left[\frac{€}{kWh}\right]$

Symbol	Description	Unit
$\lambda_{r,k}^{power,toll}$	Power term toll price of building r at step k	$\left[\frac{€}{kWh}\right]$
λ_{k}^{spot}	Sport market price at step k	$\left[\frac{€}{kWh}\right]$
$LCOE^{EC}$	Energy Community LCOE	$[€/MWh]$
$LCOE^{Gen}$	Microgrid generation technologies LCOE	$[€/MWh]$
$LCOE_{r}^{PV}$	Building r PV generation LCOE	$[€/MWh]$
$LCOE_{r}^{PV withP2P}$	Building r PV generation LCOE considering the energy sharing in the P2P market	$[€/MWh]$
$LCOS$	ESSs LCOE	$[€/MWh]$
$LCOS_{r}^{BT}$	r building local BTs LCOE	$[€/MWh]$
$LCOS^{CESS}$	CESS LCOE for the community	$[€/MWh]$
LL_{ievt}	Battery lifetime lost	$[-]$
LL_{ievt}^{CESS}	CESS lifetime lost at $ievt$	$[-]$
$LL_{ievt,r}^{BT}$	r building BT lifetime lost at $ievt$	$[-]$
LL_{r}^{BT}	r building BT total lifetime lost	$[-]$
LL^{CESS}	CESS total lifetime lost	$[-]$
NE_{ievt}	Number of depth of discharge events	$[-]$
NE_{ievt}^{CESS}	CESS number of depth of discharge events	$[-]$
$NE_{ievt,r}^{BT}$	r building BT number of depth of discharge events	$[-]$
NE_{ievt}^{max}	Number of maximum depth of discharge events	$[-]$
$NE_{ievt}^{max,CESS}$	CESS number of maximum depth of discharge events	$[-]$
$NE_{ievt,r}^{max}$	r building number of maximum depth of discharge events	$[-]$

Symbol	Description	Unit
p_k	Community generation ratio at step k	$[-]$
$P_{r,k}^{BT\rightarrow grid}$	r building's BT exports to the grid	$[kW]$
$P_{r,k}^{BT\leftarrow PV}$	Energy imported from local PV by r building at step k to local BT	$[kW]$
$P_{r,k}^{BT,cha}$	Power charged to r building BT at step k	$[W]$
$P_{r,k}^{BT,dcha}$	Power discharged from r building BT at step k	$[W]$
$P_{r,k}^{CESS\leftarrow PV}$	Energy exported from r building's PV generation to community storage at step k	$[kW]$
$P_{r,k}^{CESS,cha}$	Power charged from CESS at step k	$[W]$
$P_{r,k}^{CESS,dcha}$	Power discharged from CESS at step k	$[W]$
P_{k}^{cha}	Power charged to the energy storage system at step k	$[W]$
$\overline{P_{r}^{cha,BT}}$	Maximum r building BT charging power	$[kW]$
$\overline{P^{cha,CESS}}$	Maximum CESS charging power	$[kW]$
P_{r}^{contr}	Contracted power of r building	$[W]$
$P_{r,k}^{cons,pred}$	Building r's predicted consumption at step k	$[kW]$
P_{k}^{dcha}	Power discharged from the energy storage system at step k	$[W]$
$\overline{P_{r}^{dcha,BT}}$	Maximum r building BT discharging power	$[kW]$
$\overline{P^{dcha,CESS}}$	Maximum CESS discharging power	$[kW]$
$\overline{P_{r,k}^{dev}}$	r building ower deviation at instant k	$[kW]$
$P_{r,k}^{exp,BT}$	Power exported to local BT by r building's at step k	$[kW]$
$P_{r,k}^{exp,CESS}$	Power exported from the CESS by r building's at step k	$[kW]$
$P_{r,k}^{exp,grid}$	Power exported to the grid by building r at step k	$[kW]$

Symbol	Description	Unit
$P_{r,k}^{exp,P2P}$	Power exported to P2P pool by r building's at step k	$[kW]$
$P_{r,k}^{imp,BT}$	Power imported from BT by r building's at step k	$[kW]$
$P_{r,k}^{imp,CESS}$	Power imported from CESS by r building's at step k	$[kW]$
$P_{r,k}^{imp,grid}$	Power imported from grid by r building's at step k	$[kW]$
$P_{r,k}^{imp,P2P}$	Power imported from P2P pool by r building's at step k	$[kW]$
$P_{r,k}^{loads}$	r building demand at step k	$[kW]$
$P_{r,k}^{loads \leftarrow BT}$	Energy imported from local BT by r building at step k	$[kW]$
$P_{r,k}^{loads \leftarrow CESS}$	Energy imported from community storage by r building at step k	$[kW]$
$P_{r,k}^{loads \leftarrow grid}$	Energy imported from grid by r building at step k	$[kW]$
$P_{r,k}^{loads \leftarrow P2P}$	Energy imported from P2Ppool by r building at step k	$[kW]$
$P_{r,k}^{loads \leftarrow PV}$	Energy imported from local PV by r building at step k	$[kW]$
$P_{r,k}^{PV}$	PV power generated by r building's installation at step k	$[kW]$
$P_{r,k}^{PV \rightarrow CESS}$	Power exported to CESS by r building's PV generation at step k	$[kW]$
$P_{r,k}^{PV \rightarrow loads}$	PV power utilised by r building's lo cover the demand at step k	$[kW]$
$P_{r,k}^{PV \rightarrow grid}$	Power exported to grid by r building's PV generation at step k	$[kW]$
$P_{r,k}^{PV \rightarrow P2P}$	Power exported to P2P pool by r building's PV generation at step k	$[kW]$

Symbol	Description	Unit
$P_r^{PV,inst}$	Installed PV generation of building r at step k	$[kW]$
$P_{s,k}^{PV}$	PV power generated by s building's installation at step k	$[kW]$
$P_{r,k}^{PV,pred}$	Building r's predicted PV power at step k	$[kW]$
$P_{r,k}^{PV,real}$	Short-term PV power generated by r building's installation at step k	$[kW]$
$q_{r,k}$	r building consumption rate according to total communjity imports at step k	$[-]$
$Q^{available}$	Battery available capacity	$[Ah]$
$Q^{available,CESS}$	CESS available capacity	$[Ah]$
Q^{nom}	Battery nominal capacity	$[Ah]$
$Q^{nom,CESS}$	CESS nominal capacity	$[Ah]$
$Q_r^{available,BT}$	r building BT available capacity	$[Ah]$
$Q^{available}$	r building battery available capacity	$[Ah]$
$Q_r^{nom,BT}$	r building BT nominal capacity	$[Ah]$
$Rep_{r,t}^{BT}$	r building BT replacement at year t	$[year]$
Rep_t^{ESS}	ESS replacement at year t	$[year]$
$Rev_{r,t}^{P2P}$	r building revenues at year t for exporting energy to the community	[€]
$Rev_{r,t}^{P2P}$	r building revenues at year t for exporting energy to the grid	[€]
SOH	Battery state of health	[%]
SOH^{CESS}	CESS state of health	[%]
SOH_r^{BT}	r building local BT state of health	[%]
T_k^{amb}	Ambient temperature at step k	$[°C]$

Symbol	**Description**	**Unit**
T_k^{cell}	PV cell temperature at step k	$[°C]$
T^{NOCT}	Temperature at Normal Operating Cell Temperature conditions	$[°C]$
$u_{r,k}^{BT,cha}$	Binary variable to determine r building's local BT charge at step k	$[-]$
$u_{r,k}^{BT,dcha}$	Binary variable to determine r building's local BT discharge at step k	$[-]$
$u_{r,k}^{CESS,cha}$	Binary variable to determine CESS charge at step k	$[-]$
$u_{r,k}^{CESS,dcha}$	Binary variable to determine CESS discharge at step k	$[-]$
$u_{r,k}^{grid,exp}$	Binary variable to determine r building's grid exports at step k	$[-]$
$u_{r,k}^{grid,imp}$	Binary variable to determine r building's grid imports at step k	$[-]$
$u_{r,k}^{P2P,exp}$	Binary variable to determine r building's P2P exports at step k	$[-]$
$u_{r,k}^{P2P,imp}$	Binary variable to determine r building's P2P imports at step k	$[-]$
y_k	Database value for instant k	$[W/m^2]$
$\hat{y}_k$	Predicted value for instant k	$[W/m^2]$
z_k	SOC at step k	$[\%]$
z_{k-1}	SOC at previous step, $k-1$	$[\%]$
$z_{r,k}^{BT}$	Building r local BT state of charg at step k	$[\%]$
$z_{r,k-1}^{BT}$	Building r local BT state of charge at previous step, $k-1$	$[\%]$
z_k^{CESS}	CESS state of charge at step k	$[\%]$

Symbol	**Description**	**Unit**
z_{k-1}^{CESS}	CESS state of charge at previous step, $k-1$	[%]
$\underline{z_r^{BT}}$	r buildings' local BT minimum SOC	[%]
$\overline{z_r^{BT}}$	r buildings' local BT maximum SOC	[%]
$\underline{z^{CESS}}$	CESS minimum SOC	[%]
$\overline{z^{CESS}}$	CESS maximum SOC	[%]

List of Figures

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Scientific contributions

Within this thesis, several scientific contributions to the literature were published.

JOURNAL ARTICLES:

a. I. López, **N. Goitia-Zabaleta**, A. Milo, J. Gómez-Cornejo, I. Aranzabal, H. Gaztañaga and E. Fernandez, 2024. European energy communities: Characteristics, trends, business models and legal framework. *Renewable and Sustainable Energy Reviews*, vol. 197, June 2024, 114403. DOI: 10.1016/j.rser.2024.114403.

b. **N. Goitia-Zabaleta**, A. Milo, H. Gaztañaga and E. Fernandez, 2023. Two-stage centralised management of Local Energy Market for prosumers integration in a community-based P2P. *Applied Energy*, vol. 348, 15 October 2023, 121552. DOI: 10.1016/j.apenergy.2023.121552.

c. P. N. Botsaris, P. Giourka, A. Papatsounis, P. Dimitriadou, **N. Goitia-Zabaleta**, C. Patsonakis. Developing a Business Case for a Renewable Energy Community in a Public Housing Settlement in Greece—The Case of a Student Housing and Its Challenges, Prospects and Barriers. *Sustainability*, 13 (7), 3792. DOI: 10.3390/su13073792

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d. **N. Goitia-Zabaleta**, A. Feijoo-Arostegui, A. Milo, H. Gaztañaga and E. Fernandez, Techno-Economic Evaluation of a Battery-as-a-Service Business Model in an Energy Community, in 20th International Conference in the

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n. A. Rodriguez Aparicio, **N. Goitia-Zabaleta**, A. Milo Urquiola and H. Gaztañaga Arantzamendi, GECEL - SOFTWARE PARA EL ANÁLISIS DE LAS COMUNIDADES ENERGÉTICAS LOCALES EN SU FUNCIONAMIENTO COMO CONJUNTO DE AUTOCONSUMOS INDIVIDUALES O CON ESTRATEGIAS P2P DE COMPARTICIÓN DE ENERGÍA FOTOVOLTAICA, *(GECEL - Software for the analysis of Local Energy Communnities in their operation as a set of photovoltaic individual self-consumers or with P2P energy sharing)*, January 2023.

Hasiera baino ez da hau.

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