POWER IN OUR HANDS

D2.5 – Enabling conditions for consumer-centric energy system

BLUEPRINT

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Energy Activated Citizens and Data-Driven Energy-Secure Communities for a Consumer-Centric Energy System

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Preface

ENPOWER will design, develop, and demonstrate SSH-driven methodologies, interactive and closed-loop tools, and data-driven services for energy-activated citizens and energy-secure cross-sector communities towards a citizen-centric energy system. We combine leading-edge ICTs with social/behavioural dimensions and with sharing economy and value stacking business models to deploy: 1) a Social Science Framework for energy citizens activation and innovative multidimensional incentives for citizens' participation in energy markets; 2) AI-based consumers clustering and segmentation algorithms; 3) interactive tools and facilitation services for energy community planning; 4) Energy Data Space adaptation to support community-level data-driven activation and interoperable automated privacy and sovereignty-preserving Demand Response (DR); 5) P2P DLT/Blockchain digital marketplace for tokenized energy and non-energy assets reciprocal compensation; 6) data-driven services and apps for energy efficiency and activation performance management; 7) ICT services and Digital Twins for community-level energy optimisation and aggregated flexibility management to trade off local self-consumption against grid service provisioning, while boosting a beyond-energy community social welfare; 8) Edge monitoring hubs for automated DR; 9) Business Sandbox for novel sharing economy and social innovation-based business models; 10) methodologies for evaluating different energy community setups, upscaling and replication. ENPOWER framework will be validated along 4 Front Runners energy communities' pilots and further replicated in 2 Early Adopters, covering different levels of maturity of communities, to demonstrate increased Renewable Energy Sources (RES) local self-consumption and consumers participation in the energy markets, while nurturing increased local security of supply. ENPOWER Leadership Programme and blueprints will support EU-wide replication and advise regulatory bodies on communities-friendly enabling frameworks.

Who we are

No	Participant Name	Short Name	Country	Role
1	National Technical University of Athens	NTUA	GR	Coordinator
2	Design Strategy Technology S.r.l	DST	IT	Technology providers
3	INESC TEC - Institute for Systems and Computer Engineering, Technology and Science	INESC TEC	PT	
4	Fundación CARTIF (CARTIF Technology Center)	CARTIF	ES	
5	COMSENSUS D.O.O.	COMS	SL	
6	European Dynamics Luxembourg SA	ED	LU	
7	Audencia Business School	AUDENCIA	FR	Business modelling
8	Regulatory Assistance Project	RAP	BE	Regulatory assistance
9	ICLEI Europasekretariat GmbH	ICLEI	DE	Policy & capacity
10	University of Basel *(associated partner)*	UNIBAS	CH	Social framework
11	Blueprint Energy Solutions GMBH	BLUEPRINT	AT	Pilot 1 - Austria (Front runners)
12	OurPower Energiegenossenschaft SCE	OurPower	AT	
13	Cooperativa de Desenvolvimento Sustentável, CRL	COOPERNICO	PT	Pilot 2 - Portugal (Front runners)
14	WATT-IS SA	WATT-IS	PT	
15	Cooperativa Eléctrica do Vale D'Este CRL	CEVE	PT	
16	Energy Community of Chalki'Chalkion'	ChalkiON	GR	Pilot 3 - Greece (Front runners)
17	Hellenic Association for Energy Economics	HAEE	GR	
18	Green Energy Aggregator Services SA	GEARS	GR	
19	Parity Platform P.C.	PARITY	GR	

20	Electric Power Research Institute Europe DAC	EEU	IE	Pilot 4 - Ireland (Front runners)
21	University College Cork (MaREI Centre for Energy, Climate and Marine, Environmental Research Institute)	UCC	IE	
22	DC Six Technologies Limited	DCSix	IE	
23	MOL TEIC - Dingle Hub	DINGLE HUB	IE	
24	ESB Innovation ROI Limited	ESB	IE	
25	Békéscsaba Energia ESCO Kft.	BCS	HU	Pilot 5 - Hungary (Early adopters)
26	Enasco Cleantech Alliance LLC.	ENASCO	HU	
27	Montajes Eléctricos Cuerva SL	CUERVA	ES	Pilot 6 - Spain (Early adopters)
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Executive Summary

This deliverable integrates the final outputs of the ENPOWER Work Package WP2. It encompasses key elements such as use case capitalization, co-creation process, the Business Sandbox, and functional specifications. The report consolidates the work carried out across tasks T2.1 to T2.6 up to Month 16 (December 2024), building on the foundational deliverables D2.1 [1] through D2.4 [81].

The deliverable aims to establish the enabling conditions for a consumer-centric energy system, which is critical for achieving inclusive, effective, and sustainable energy solutions. By combining innovative co-creation methodologies, targeted consumer segmentation, and incentive mechanisms, this report provides actionable frameworks to enhance consumer engagement at both individual and community levels. The introduction of the Business Sandbox offers a practical environment for testing and validating business models, ensuring they are aligned with functional requirements and regulatory considerations. These advancements pave the way for creating robust, socially driven energy systems that align with the broader objectives of the ENPOWER project.

The previous work in WP2 laid a strong foundation for the ENPOWER project by addressing critical aspects of a consumer-centric energy system. In D2.1 [1], the initial high-level use cases (HLUCs) were introduced, along with a gap analysis of the regulatory framework, identifying barriers and opportunities for implementing innovative energy solutions. D2.2 [2] focused on ENPOWER community building and co-creation, as well as consumer analysis and segmentation. It also introduced social-driven incentive mechanisms designed to enhance engagement at both individual and collective levels. In D2.3 [80] AUDENCIA has designed and developed innovative business models (BMs) for energy communities (EnCs) using a consumer-centric approach to empower citizens. By merging stakeholder engagement through semi-structured interviews and a structured Excel-based data collection framework, the project identified the unique technological, financial, social needs of the six pilot communities, while took into consideration the regulatory challenges, and the restrains for further expansion. These insights shaped adaptable BMs that prioritize sustainability, community engagement, individual-consumer engagement and technological integration. Building on this, D2.4 [81] outlined the end-user and business requirements, coupled with functional specifications, which detailed the technical and operational needs for developing and deploying consumer-centric energy systems. Together, these deliverables provided a cohesive framework for the work consolidated in D2.5.

Building on D2.1 [1], this document completes the remaining tasks of T2.1 by expanding the market design analysis to assess gaps hindering consumer participation. It also presents an updated set of HLUCs, along with derived use cases and Sub-UCs, mapped and tailored to specific pilot sites through collaboration with technical partners and pilot representatives. These refinements form a solid foundation for deploying ENPOWER solutions and connect seamlessly to ongoing project tasks and pilot implementations.

The results of tasks T2.2 and T2.3 were documented in Deliverable D2.2 [2], which involved interviews, online focus groups, and a multi-country survey with a discrete choice experiment. Following this, UNIBAS organised a workshop on cocreation which focused on qualitative SSH (Social Sciences and Humanities) methods in co-creation processes, covering: planning and executing co-creation workshops, engaging stakeholders and analysing outcomes as well as take-

home strategies. The workshop effectively answered participant pre-submitted questions and provided practical tools for planning and conducting co-creation workshops. Emphasis was placed on stakeholder diversity, fostering inclusivity, and managing group dynamics.

The “deliberative workshops” focusing on the aspect of “energy data sharing”, conducted in Dingle, Ireland, and Poysdorf, Austria provided an insightful overview and analysis of the qualitative collected data. These workshops explored diverse perspectives on data sharing, emphasizing regional and cultural nuances. Additionally, the “thought leaders’ workshop” held in Budapest, Hungary, provided a broader, more strategic understanding of the topic from a range of expert viewpoints. However, the Portuguese workshop results will be available in D5.2 [82] with an analysis comparing all three front-runner pilot sites, where the deliberative workshops took place.

The findings from these workshops are synthesized into a comprehensive summary, highlighting key insights and patterns across all sessions. The chapter concludes with thoughtful recommendations for leveraging these outcomes in both social and technical domains, aiming to guide future initiatives and foster innovation in energy data sharing practices.

In D2.5, AUDENCIA has redefined the Business Models (BMs) initially developed in D2.3 [80] to better reflect and adjust the UC on the flows, ensuring alignment with real-world applications and pilot-specific needs. This process incorporated insights from technical partners and energy citizenship questionnaires, linking technological enablers with citizen empowerment across various segments. The refinements bridge conceptual frameworks with practical application, pointing out community benefits and energy transition targets. These updates were integrated into a robust foundation for the formation of ENPOWER solutions.

The "Functional Specifications" chapter outlines DST's contribution to the project by defining the technical and operational frameworks necessary for implementing consumer-centric energy solutions. This section includes the methodology used to gather and refine functional specifications, ensuring alignment with project objectives and stakeholder needs.

Building on prior work in WP2, the chapter consolidates and extends insights from use case analysis, pilot collaboration, and stakeholder feedback to create a comprehensive foundation for the deployment of tools and services. The chapter also revisits previously completed work, connecting it with the specifications outlined to provide a clear and cohesive framework for implementation.

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List of acronyms

AOF	Activation Optimization Function
ADMS	Advanced Distribution Management System
AMI	Advanced Metering Infrastructure
AI	Artificial Intelligence
aFRR	Automatic Frequency Restoration Reserves
BSPs	Balancing Service Providers
BESS	Battery Energy Storage System
BM	Business Model
BMC	Business Model Canvas
CEC	Citizen Energy Community
CMOL	Common Merit Order List
CES	Community Energy Storage
CPP	Critical Peak Pricing
XBID	Cross-Border Intraday
DR	Demand Response
DRP	Demand Response Programms
DSM	Demand Side Management
DLC	Direct Load Control
DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
EnC	Energy Communities
EDS	Energy Data Space
ESG	Environmental Social Governance
EC	European Commission
EEX	European Energy Exchange
ENTSO-E	European Network of Transmission System Operators for Electricity
FBMC	Flow-Based Market Coupling
ICT	Information and Communication Technology
IoT	Internet of Things
IL	Interruptible Load
LCR	Load as a Capacity Resource

LMP	Local Marginal Price
mFRR	Manual Frequency Restoration Reserves
MARI	Manually Activated Reserves Initiative
M	Month
OTC	Over the Counter
EUPHEMIA	Pan-European Hybrid Electricity Market Integration Algorithm
P2P	Peer-to-Peer
PV	Photovoltaic
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PPAs	Power Purchase Agreements
RTP	Real Time Pricing
REC	Renewable Energy Community
RES	Renewable Energy Sources
ROI	Return of Investment
STOR	Short Term Operating Resource
SDAC	Single Day-Ahead Coupling
SSH	Social Science and Humanities
SaaS	Software as a Service
Sub-UC	Sub-Use Case
SDG	Sustainable Development Goals
ToC	Table of Contents
T	Task
TE	Technology Enabler
TES	Thermal Energy Storage
TOU	Time of use
TERRE	Trans-European Replacement Reserves Exchange
TSO	Transmission System Operator
UC	Use Case
V2G	Vehicle to Grid
V2H	Vehicle to Home
VPP	Virtual Power Plant
WP	Work Package
WPL	Work Package Leader

1 Introduction

1.1 ENPOWER project and objectives

The overall vision of ENPOWER is to design, develop and demonstrate SSH-driven methodologies, interactive and closed-loop tools and services for energy activated citizens and data-driven energy-secure communities towards a consumer-centric energy system. ENPOWER combines leading-edge ICTs technologies [Internet of Things (IoT), Artificial Intelligence (AI), big data, DLT/Blockchains] with social / behavioural dimension, and with sharing economy and value stacking governance and business models.

The strategic goal is to activate consumers and foster community-level aggregation to improve both local and system-wide energy efficiency while enhancing supply security. By using a co-creative approach, we connect consumers and prosumers to the energy market, enabling them to be informed, collaborate, and co-create a sustainable future that aligns with energy and climate goals.

ENPOWER will design, scale, and validate a comprehensive social, technological, and business framework through field pilots with Front Runners and Early Adopters. This framework is adaptable for diverse consumer collectives, including Citizen Energy Communities (CECs) and Renewable Energy Communities (RECs).

1. **Social Layer**: Employs SSH-based methodologies, combining qualitative and quantitative research with Design Thinking to engage consumers in the energy transition and support community development.
2. **Technological Layer**: Builds a digital backbone compliant with Energy Data Space (EDS) standards to support data-driven consumer activation, privacy-preserving DR, and tools for consumer engagement, planning, and optimization. These tools enable both individual and collective energy management and interaction with grids and other infrastructures.
3. **Organisational/Business Layer**: Develops and validates new market roles and hybrid business models that incorporate public and private value chains across various energy carriers, supporting a sharing economy approach.

1.2 Objectives of WP2

Work in WP2 provides the foundation for citizen engagement and multilevel knowledge creation within energy-secure communities to facilitate a consumer-centric energy system in Europe.

Its goal is to establish the basis for the development of the ENPOWER social, technological and organisational/business framework, providing groundwork for energy market, community building and co-creation process, consumers analysis and segmentation, co-development of the concept of data-driven energy-secure communities through deliberative citizen engagement, as well as a Business Sandbox for a consumer-centric energy system. Its ultimate achievement is a co-creation and co-implementation process for the design of financial / non-financial incentives mechanisms for individual and collective-level consumer engagement.

Since the goal is for the solutions proposed to be tested and studied in real applications, a systematic analysis is required about both the conditions under which the technological solutions are expected to operate, as well as of the new socio-economic environment formed and the new opportunities created by the widespread application of the proposed solutions.

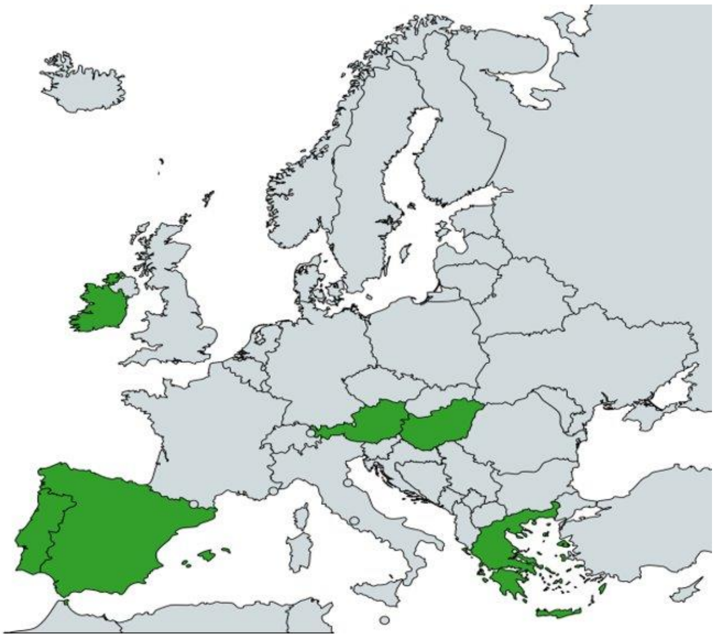

Figure 1: ENPOWER pilots with geographic distribution.

Figure 1 shows the ENPOWER pilots with geographic distribution. The description of the overall UCs for each pilot is as follows:

Pilot 1 Austria (Front Runner): P2P renewable energy community real time marketplace for energy and flexibility demand versus supply near time information sharing and matching

In Austria, a P2P renewable energy community real-time marketplace is being developed, focusing on the sharing and matching of energy and flexibility demand versus supply. This system facilitates the exchange of near-time information, promoting a more dynamic and responsive energy market within local communities.

Pilot 2 Portugal (Front Runner): Integrating cross sector local collective self-consumption with virtual community flexibility

In Portugal, the integration of cross-sector local collective self-consumption with virtual community flexibility is being tested. This innovative approach allows communities to generate, share, and manage energy consumption while simultaneously providing flexibility in response to grid demands, creating a more resilient and efficient energy system.

Pilot 3 Greece (Front Runner): Community-level flexibility optimal provisioning to isolated power distribution grid

In Greece, the focus is on optimal flexibility provisioning at the community level, aimed at supporting isolated power distribution grids. This initiative seeks to enhance the grid's resilience by enabling local communities to provide flexibility, ensuring a more stable and sustainable energy supply for off-grid areas.

Pilot 4 Ireland (Front Runner): Cross-sector social value community-centered services for enhancing grid flexibility and paving the way for increased share of self-sufficiency

In Ireland, cross-sector social value community-centered services are being explored to enhance grid flexibility. The goal is to create services that not only improve energy efficiency but also increase local self-sufficiency. This pilot paves the way for a future where communities are more energy-independent and contribute to a more sustainable energy grid.

Pilot 5 Hungary (Early Adopter): Municipality-driven P2P market for a new local community

Hungary is working on a municipality-driven P2P market for a new local community. This initiative aims to empower local residents to engage in energy sharing, fostering a more decentralized and sustainable energy model, while also building a community-based marketplace that encourages energy collaboration.

Pilot 6 Spain (Early Adopter): Small DSO as EnC Developer

In Spain, a small DSO is taking on the role of an EnC Developer. This pilot focuses on how small DSOs can support the development of local energy communities, facilitating decentralized energy generation and consumption while ensuring the system remains balanced and reliable.

The work in WP2 is structured into six main tasks, each targeting essential elements of consumer-centric energy market design and community engagement. T2.1 focuses on conducting a comprehensive gap analysis and use case capitalisation to support a consumer-oriented energy market and regulatory framework. This task includes the analysis of gaps in market design, an assessment of regulatory barriers, and the refinement of use cases to empower consumer participation in energy markets.

T2.2 emphasizes the development of the ENPOWER community through co-creation and consumer segmentation. This includes fostering collaboration among stakeholders and analysing consumer behaviour to segment audiences effectively. T2.3 explores innovative, socially driven incentive mechanisms designed to promote engagement at both individual and community levels.

T2.4 focuses on co-developing the concept of data-driven energy-secure communities through active citizen engagement and deliberation, while T2.5 develops business models based on sharing economy principles and social innovation to enhance community-driven energy solutions.

Finally, T2.6 establishes end-user and business requirements alongside functional specifications. This includes defining requirements and developing technical specifications that align with the project’s objectives and stakeholder needs. Together, these tasks create a comprehensive approach to fostering citizen engagement, energy security, and regulatory adaptability in the evolving energy landscape.

1.3 Purpose and audience of the document

This report is the last deliverable of WP2 that aims to establish the foundation for Demand Response (DR) in European energy communities (EnC), with a keen focus on socio-economic enablers that form an integral part of the design of the ENPOWER solutions. The report includes the work done by the partners from T2.1 to T2.6 from the time they submitted their last deliverables up until M(Month)16.

The deliverable D2.5 ('Enabling conditions for consumer-centric energy system') aims to integrate and finalise the findings and methodologies developed from Tasks T2.1 to T2.6, covering the co-creation process, segmentation, social-driven incentive mechanisms, Business Sandbox, and requirements. The purpose of D2.5 is to provide a comprehensive overview of the enabling conditions for DR in EnCs, with a particular focus on advanced energy-efficient systems.

The project plans to address related scientific audience (incl. audience both from the Smart Grids and the energy area) and strategic decision makers (such as stakeholders, EU energy ministers and general secretariats of investment, head of research departments, professors etc.) in related research facilities (both in industry and academia).

The primary audience for this document includes project team leaders, researchers, and administrative personnel from each partner organisation within the ENPOWER consortium plus other external stakeholders. The document is intended to offer these stakeholders detailed insights into the methodologies and findings related to DR implementation in EnCs, ensuring that all partners are aligned with the project's goals and strategies. By detailing the co-creation processes and socio-economic considerations, D2.5 aims to guide the practical application and integration of DR solutions within the pilot sites, fostering effective collaboration and informed decision-making across the consortium.

1.4 Relations to other activities

The work in D2.5 provides essential groundwork for WPs 3, 4, 5, 6, and 7.

In WP3, the findings from D2.5 directly inform the development of an interactive decision-support tool designed for energy citizens, as well as the creation of innovative social-driven incentive mechanisms. These mechanisms aim to encourage citizens to actively participate as prosumers within self-consumption structures, whether individually or as part of an EnC. D2.5's insights into user needs and segmentation enable a more targeted approach to consumer engagement in this work package.

Building on this, WP4 uses D2.5's foundational requirements to deploy a digital backbone that is fully compliant with the EDS, as well as the ENPOWER marketplace. These systems integrate D2.5's frameworks to ensure that digital infrastructure and marketplaces can support a consumer-centered, flexible energy system, with robust, data-driven, and consumer-friendly features.

For WP5, D2.5 provides the basis for enhancing existing digital services and developing new consumer data-driven energy services that meet the unique needs of energy-secure communities. By using the requirements and social-driven incentive mechanisms outlined in D2.5, WP5 can design digital models and tools to implement these services effectively in pilot sites.

In WP6, D2.5's frameworks are essential for deploying ENPOWER solutions and demonstrating the impact of the project's social, technological, and business models in real-world settings. This work package leverages D2.5's groundwork to deliver solutions tailored for four specific use cases in Austria, Portugal, Greece, and Ireland, allowing for practical validation and impact assessment.

Finally, WP7 uses the frameworks from D2.5 to support the replication and scaling of ENPOWER tools, approaches, and Front Runners to additional Early Adopters, other stakeholders, and regions within the EU. The insights into social-driven mechanisms and consumer engagement from D2.5 also inform WP7's policy recommendations on adapting regulations to support effective organizational and business models, ensuring that the consumer-centric solutions developed are sustainable and scalable across different regulatory landscapes.

1.5 Structure of the document

Chapter 1 introduces the ENPOWER project, detailing its objectives, the goals of WP2, the document's purpose and target audience, its connections to related activities, and its overall structure.

Chapter 2 of this document builds upon and refines the work initiated in D2.1 [1], expanding the analysis of market design to provide a more detailed assessment of gaps hindering consumer participation.

Chapter 3 presents an updated set of HLUCs, the initial version of which was introduced in D2.1 [1], along with a list of 21 use cases and 5 sub-use cases (Sub-UCs) derived from them. These use cases have been mapped and tailored to specific pilot sites through collaborative efforts with technical partners and pilot site representatives. The refinements provide a strong foundation for the deployment of ENPOWER solutions and serve as a critical link to the project's ongoing tasks and pilot implementations.

Chapter 4 provides the results of a co-creation workshop, planned and presented by UNIBAS, which was designed to strengthen and empower members of the ENPOWER consortium when it comes to running their own co-creation workshops and focus groups. Results from T2.2 and T2.3 are provided in the earlier deliverable D2.2 [2].

Chapter 5 provides a concise analysis of key insights from three workshops focusing on energy data sharing. The "deliberative workshops" in Dingle, Ireland, and Poysdorf, Austria, capture diverse perspectives, reflecting regional and cultural differences. Meanwhile, the "thought leaders' workshop" in Budapest, Hungary, offers a strategic, expert-level understanding of the topic. The chapter concludes with a synthesis of findings from all three workshops, identifying common themes and actionable insights. Practical recommendations are provided to inform future work, emphasizing opportunities for progress in both social and technical aspects of energy data sharing.

Chapter 6 provides insights into the initial work conducted in D2.3 [80], outlining the rationale, the mentality and methodology behind the development of consumer-centric innovative Business Models (BMs). These BMs were refined to integrate the newly updated use cases (UCs), as developed in Chapter 3, securing that the archetypes valuably reflect the practical application of Technological Enablers (TE) in real-world scenarios. By leveraging inputs from technical partners through energy citizenship questionnaires, the refined BMs bridge conceptual concepts with field implementation, advancing community and citizens' benefits and enhancing energy citizenship. This iterative process establishes a solid ground for ENPOWER solutions and their deployment.

Chapter 7 provides a comprehensive list of functional requirements identified for the project, detailing their relevance and application across different pilots. In addition to presenting the specifications themselves, the chapter describes the methodology used to develop and refine them, ensuring alignment with stakeholder needs and the project's objectives. This section builds upon the initial work in D2.4 [81], incorporating updates and insights gained during the project’s progression.

2 Gap analysis on market design (Blueprint)

2.1 Task 2.1

The initial task description for Task 2.1 focuses on identifying gaps in market design and regulatory frameworks to enhance consumer participation in energy markets. The task is divided into three key areas.

First, the **gap analysis of market design** examines the current state of energy systems, flexibility mechanisms, EU-level market platforms, and control schemes. It aims to uncover obstacles that hinder fair consumer participation through energy communities or aggregators across different market segments, including wholesale, retail, and peer-to-peer (P2P) markets, while considering country-specific differences within the EU.

Second, the **regulatory framework analysis** assesses barriers in policies like the Clean Energy Package and Fit for 55, focusing on issues such as stakeholder coordination, participation of small consumers, congestion management, and the roles and responsibilities of energy stakeholders.

Finally, the **use case capitalization**, based on an EU standard methodology, develops HLUCs through a co-creation effort. From these HLUCs, UCs are designed for digital tools that empower consumers as prosumers, community participants, and active players in energy markets. This approach aligns with the EU's energy and digital transition objectives, serving as a foundation for future tasks and pilot implementations.

2.2 Previous work in WP2

The work conducted under Task 2.1 has been documented in both Deliverable, D2.1 [1] and D2.5. D2.1 [1] includes a **regulatory framework analysis**, addressing legislative and market barriers at both the EU level and within specific pilot sites.

What can be found in D2.5 is a continuation and refinement of the work initiated in D2.1 [1]. The **gap analysis of market design** is expanded to include a more detailed assessment of gaps hindering consumer participation.

The **use case capitalization** will be addressed in Chapter 3.

2.3 Centralized Market Models

This chapter describes and analyses different models of centralized energy markets applied in the European Union focusing on the ENPOWER pilot countries. The first possible gaps with regard to consumer participation and the transformation to sustainable energy sources are pointed out, which will be taken up again and analysed in more detail in the subchapters.

Centralized energy markets operate with a central entity or mechanism that oversees electricity procurement, pricing, and allocation. In these models, electricity transactions occur through organized markets or centralized platforms, complemented by auctions or agreements for capacity and balancing. The European Union’s electricity markets are structured to balance centralized mechanisms with competitive dynamics. However, centralized features — such as power exchanges, coordinated capacity mechanisms, and market coupling — play a key role in integrating renewables and harmonizing energy trade across borders.

Centralized electricity markets are organized around power exchanges, where day-ahead and intraday transactions are conducted. A central system clears these markets by determining prices based on aggregated supply and demand, ensuring transparency and efficiency. Capacity mechanisms are also a key feature, with centralized auctions securing commitments from generators to provide energy during peak demand periods. Additionally, balancing services, coordinated centrally, address real-time discrepancies between electricity supply and demand, which are especially critical for integrating intermittent renewable energy sources. The different timeframes of centralized markets are additionally illustrated in figure 2.

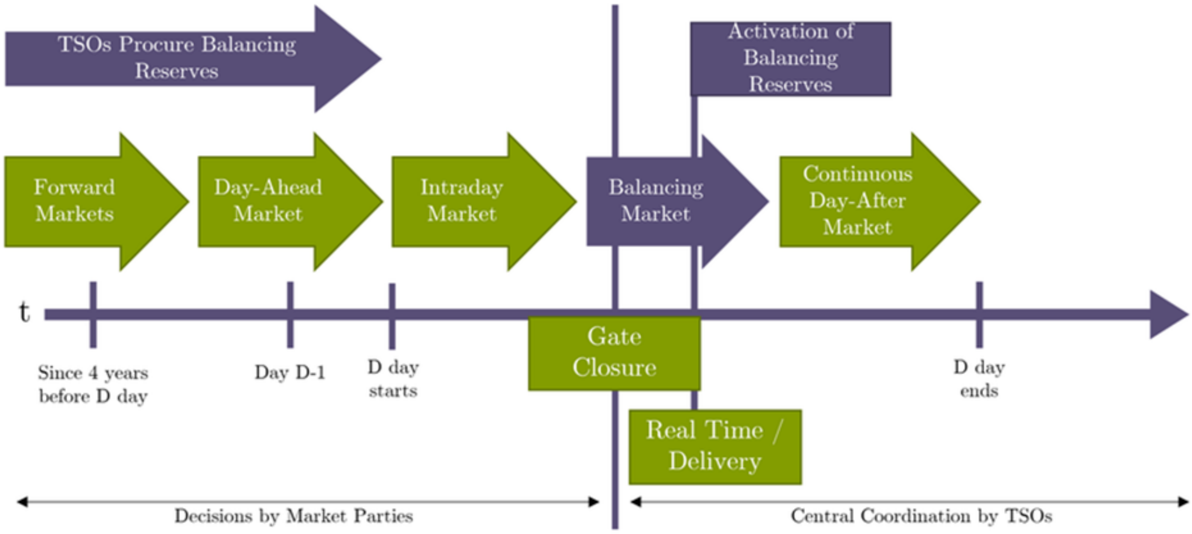

Figure 2: Time sequence of electricity markets [83].

Core Mechanisms of Centralized Markets

Centralized markets are structured around optimization algorithms that govern electricity trading and system operations across multiple temporal scales. The main market is the **day-ahead market**, where bids for electricity delivery are matched with anticipated demand for the following day. These bids, submitted by generators, retailers, and large consumers, are processed by market-clearing algorithms such as EUPHEMIA [84], which operate on principles of cost minimization and social welfare maximization. EUPHEMIA integrates supply curves, demand profiles, and grid constraints to determine local marginal prices (LMPs) that reflect the cost of delivering energy at specific nodes, factoring in transmission congestion and losses [3].

Following the day-ahead market, the **intraday market** enables participants to refine their schedules as closer-to-real-time information becomes available. This market is particularly critical for balancing intermittent renewable energy sources, such as wind and solar, whose production forecasts can significantly change within hours. Unlike the discrete auction model of the day-ahead market, intraday trading often occurs continuously, requiring sophisticated IT systems that process trades in real time and update market positions dynamically [4].

The **balancing market** operates as the final safety net, addressing real-time discrepancies between supply and demand. Managed by TSOs, the balancing market procures reserves through pre-arranged contracts or auctions, ensuring the availability of upward and downward flexibility. Activation mechanisms for these reserves include automatic frequency restoration reserves (aFRR) and manual frequency restoration reserves (mFRR), each with distinct response times and operational scopes. This layered approach ensures that imbalances, which could destabilize the grid, are corrected promptly and efficiently [5].

Consumer Participation in Centralized Markets

Historically, centralized markets have been dominated by large-scale generators, industrial consumers, and institutional players [6]. However, the increasing penetration of distributed energy resources (DERs) and advancements in digital technology have paved the way for smaller actors, including residential consumers, prosumers, and energy communities, to participate. Mechanisms such as DR programs, aggregators, and energy communities are becoming crucial in integrating consumer participation into centralized systems.

Aggregators act as intermediaries that pool the flexibility of small-scale consumers and prosumers, enabling them to participate collectively in energy markets. By aggregating the capacity of thousands of distributed assets, such as residential batteries, electric vehicles, and smart appliances, these entities can offer balancing services, DR, or ancillary support to TSOs. For example, virtual power plants (VPPs) operate as aggregated portfolios of DERs, using advanced algorithms to optimize their contribution to centralized markets [7].

Energy communities further decentralize energy ownership and operation while remaining integrated into centralized markets. These communities — commonly composed of local stakeholders — often generate, consume, and share energy within their networks, but their excess capacity or flexibility can be sold on centralized markets. This dual participation enhances local energy resilience while contributing to system-wide efficiency [8].

Barriers to Consumer Integration

Despite the technical feasibility and regulatory frameworks supporting consumer participation, significant barriers remain. One of the primary challenges is regulatory asymmetry. While centralized market rules are designed for large players, they often impose prohibitive requirements — such as minimum bid sizes, prequalification criteria, and compliance costs — on smaller entities. For example, energy communities may face difficulties in accessing intraday or balancing markets due to the complexity of registration processes and transaction costs. Another critical issue is the lack of interoperable infrastructure. For aggregators and energy communities to operate effectively within centralized systems, advanced metering infrastructure (AMI), real-time communication networks, and smart grid technologies must be universally deployed. The absence of such infrastructure in certain regions limits the scalability of consumer-driven initiatives [9], [10], [11].

Market design inertia also hampers the full integration of consumer participation. Centralized markets were historically optimized for large, predictable generation assets. The integration of distributed, variable resources introduces operational challenges, such as increased forecasting errors and the need for more granular market intervals. These changes require significant overhauls to existing market architectures, which are often slow to materialize due to institutional resistance or competing priorities [9], [11].

Advanced Mechanisms Supporting Consumer Participation

Some centralized markets are pioneering solutions to enhance consumer integration. For instance, dynamic pricing schemes in retail markets, coupled with smart home technologies, enable consumers to respond to real-time price signals, indirectly influencing centralized market dynamics [12]. Similarly, the use of blockchain technology in P2P trading platforms allows consumers within energy communities to trade excess energy while interfacing with centralized systems for additional flexibility needs. The role of digital platforms is also expanding, with software-as-a-service (SaaS) solutions enabling aggregators to optimize their portfolios in real-time markets. These platforms use machine learning algorithms to predict market trends, manage bidding strategies, and optimize asset dispatch, lowering entry barriers for smaller players and increasing their competitiveness in centralized markets [13].

2.3.1 Wholesale Energy Markets and consumer participation

This chapter takes a closer look at each of the centralized market systems mentioned above, how they work and possible gaps for consumer participation.

2.3.1.1 Forward Markets

Forward markets are a key component of the European Union's energy market framework, allowing participants to secure electricity for future delivery while managing price volatility and mitigating risk. These markets operate alongside day-ahead and intraday markets, providing a longer-term perspective that complements the short-term flexibility of other market segments. This analysis examines the structure, mechanisms, and strategic role of forward markets in the EU's energy system and the possibilities and gaps to participate as a consumer.

Market Structure

Forward markets enable energy producers, consumers, and intermediaries to trade electricity for delivery at a specified time in the future, typically weeks, months, or years ahead. These markets are characterized by bilateral contracts or standardized products traded on exchanges such as the **European Energy Exchange (EEX)**. Contracts specify volumes, prices, and delivery periods, offering participants financial hedging against price fluctuations [14]

Forward market products include **base load** and **peak load** contracts, catering to different consumption profiles. Base load contracts provide consistent energy delivery, while peak load contracts address higher demand periods, typically during daytime or weekdays. The long-term nature of forward markets supports investment planning for renewable projects and large-scale infrastructure.

Bidding zones and transmission capacities play a less prominent role in forward markets compared to day-ahead and intraday markets, as physical delivery is not immediately linked to grid operations. However, forward trading indirectly impacts these shorter-term markets by providing a financial benchmark for price formation [15].

Pricing and Financial Hedging

Forward markets rely on futures pricing, which reflects expectations of supply, demand, and external factors such as fuel prices, carbon costs, and weather conditions. Prices in forward markets are often linked to the **reference price** established in day-ahead markets, creating a strong interdependence between these segments [16].

A key function of forward markets is **price hedging**. By locking in prices for future delivery, market participants protect themselves against short-term volatility. For instance:

- **Producers** hedge against declining prices, securing stable revenues for their output.
- **Consumers**, such as large industrial users, hedge against rising prices, ensuring predictability in operational costs.
- **Retailers and Aggregators** use forward contracts to stabilize costs and manage their portfolios efficiently.

Financial players, including banks and energy trading firms, also play a vital role by providing liquidity and facilitating risk transfer. These actors use derivative instruments, such as swaps and options, to create customized risk management strategies [17].

Operational Framework

Forward markets in the EU operate predominantly through two mechanisms: **Over-the-Counter (OTC)** trading and **exchange-based trading**.

1. **OTC Trading** is conducted directly between parties, offering flexibility in contract terms. While this approach provides customized solutions, it lacks the transparency and standardization of exchange-based trading. It is particularly prevalent in long-term contracts for large-scale infrastructure or renewable projects [15].
2. **Exchange-Based Trading**: Standardized products on exchanges like the EEX provide greater transparency and accessibility. These markets operate with centralized clearing houses, reducing counterparty risk by acting as intermediaries. Standardization facilitates liquidity, allowing participants to enter and exit positions efficiently [15].

Forward contracts in the EU are typically financially settled, with physical delivery occurring only in a subset of agreements. Financial settlement ensures participants can hedge against price risks without directly managing physical electricity flows [16].

Consumer Engagement and Strategic Role

Forward markets primarily cater to large-scale participants, such as energy producers, industrial consumers, and financial intermediaries. However, smaller players, including energy communities and aggregators, are increasingly accessing these markets through intermediaries.

Renewable Energy Integration: Forward markets play a strategic role in renewable energy financing by enabling power purchase agreements (PPAs). These long-term contracts between renewable developers and consumers provide financial certainty, encouraging investment in projects with high upfront costs [15].

Investment Planning: By providing price signals over extended periods, forward markets guide investment decisions for generation capacity, grid expansion, and demand-side resources. This role is critical in transitioning to a low-carbon energy system, where planning horizons are extended.

Challenges and Opportunities

Forward markets face several challenges that can limit their effectiveness:

- **Market Liquidity**: Liquidity is uneven across EU member states, with smaller markets often experiencing limited trading activity. This reduces the ability of participants to find counterparties and achieve competitive prices [17].
- **Regulatory Barriers**: Variations in national regulations and taxation create friction in cross-border trading, impeding the integration of forward markets across the EU.
- **Renewable Variability**: Increasing shares of variable renewables challenge the predictive accuracy of forward contracts, requiring advanced forecasting tools and adaptive strategies [15].

Opportunities for forward markets include:

- **Digital Innovation**: Blockchain and AI can enhance market transparency, efficiency, and accessibility.
- **Regional Harmonization**: Aligning market rules across member states can boost liquidity and facilitate cross-border participation.
- **Increased Renewable Participation**: Expanding access to PPAs and financial hedging instruments can further integrate renewables into forward markets.

2.3.1.2 Day-Ahead Markets

Day-ahead electricity markets are a crucial additional system of the European Union's energy trading, ensuring the alignment of supply and demand through a structured and transparent mechanism on a shorter timeframe. These markets operate one day before physical delivery, enabling the efficient allocation of energy resources across the EU. By fostering cross-border cooperation and integrating renewable energy sources, day-ahead markets can contribute to the EU’s goals of decarbonization, market efficiency, and regional integration.

The EU Day-ahead electricity market is based on the **Single Day-Ahead Coupling (SDAC)** mechanism, which harmonizes trading across the region [85]. This integration is achieved using the **EUPHEMIA algorithm** (Price Coupling of Regions), a tool that matches supply and demand across all bidding zones while accounting for network constraints and available transmission capacity [14]. Bidding zones typically align with national boundaries, although exceptions exist, such as Italy's multiple zones and the shared zone between Germany and Austria, reflecting internal grid conditions [16].

Day-ahead markets utilize a blind auction format. Participants submit their bids by noon, detailing their supply or demand for every hour of the following day. Clearing prices are determined for each hour based on market supply and demand curves, with prices reflecting locational marginal costs [17]. This market design ensures transparency and efficiency, allowing for a fair allocation of resources.

Price-Setting Mechanisms

Day-ahead markets employ a **marginal pricing model** where the price of electricity is determined by the last accepted bid necessary to meet demand. This system, known as the **pay-as-clear mechanism**, ensures that all participants receive or pay the market clearing price, incentivizing cost-efficient generation and consumption [15].

The **merit order principle** underpins this model, prioritizing the dispatch of generation units with the lowest marginal costs. Renewable energy sources such as wind and solar are typically dispatched first due to their near-zero marginal costs. Fossil fuel plants, with higher variable costs, are only utilized when demand surpasses renewable availability. This structure not only ensures economic efficiency but also supports the EU’s decarbonization goals [15].

Operational Framework

The operational framework of day-ahead markets is characterized by robust coordination between market operators and TSOs. After gate closure, the EUPHEMIA algorithm calculates optimal electricity flows, considering network constraints, interconnection capacities, and supply-demand dynamics [16].

The **flow-based market coupling (FBMC)** mechanism further enhances operational efficiency by dynamically allocating transmission capacities based on real-time grid conditions. Unlike traditional methods, FBMC optimizes cross-border flows by factoring in physical grid limitations, reducing congestion and improving renewable energy integration [15].

Consumer Participation and Engagement

The evolution of day-ahead markets has increasingly enabled diverse participants, including energy communities, aggregators, and individual consumers, to engage meaningfully. **Aggregators** pool DERs, such as residential solar panels and batteries, enabling smaller actors to participate in wholesale markets. By aggregating these assets, they provide balancing services and flexibility to the grid [15].

Energy communities are also gaining prominence, particularly as frameworks like the Clean Energy for All Europeans package encourage local renewable generation and consumption. Through P2P energy trading, facilitated by digital platforms, communities can share surplus energy while interfacing with centralized day-ahead markets for additional flexibility [17].

Demand response (DR) mechanisms offer consumers financial incentives to adjust their energy usage during peak periods, enhancing system efficiency. VPPs further integrate small-scale producers into the market, using advanced algorithms to optimize their dispatch based on market signals and real-time grid conditions [15].

Challenges and Opportunities

While the EU's day-ahead markets fundamentally work well, several challenges remain:

- A key aspect of consumer participation is energy neutrality. Consumers generally shift their load from high price periods to low price periods instead of reducing overall consumption. This load shifting without reducing total consumption may smooth high-price periods but could fail to decrease overall grid strain or energy demand, limiting system-wide flexibility benefits. To avoid this, it requires complex optimisation strategies to maximise system wide economic benefits [18].
- **Market Access for Small Actors**: High entry barriers and complex compliance requirements can discourage smaller participants, such as energy communities, from engaging fully.
- **Infrastructure Limitations**: Insufficient interconnection capacities and aging grid infrastructure hinder optimal cross-border electricity flows [16].
- Smaller consumers and energy communities may not be able to generate enough **savings or revenue** to justify the investment and operating costs of participating in the market [18].
- **Integration of Variable Renewables**: As renewable energy sources become dominant, market designs must evolve to manage increased intermittency and forecast uncertainty [15].

Opportunities to address these challenges include expanding digital infrastructure to enhance market accessibility, advancing energy storage technologies to support renewable integration, and harmonizing regulations across member states to streamline participation and compliance.

2.3.1.3 Intraday Markets

Intraday markets operate in the shortest time horizon, addressing the critical need for flexibility in the face of increasing shares of renewable energy sources (RES). Operating between the closure of day-ahead markets and the real-time delivery of electricity, intraday markets enable adjustments that are essential for maintaining system balance and minimizing the risks associated with RES variability. The transition towards renewable energy and the EU's Green Deal objectives have highlighted the limitations of day-ahead markets in accommodating real-time fluctuations in supply and demand. Intraday markets fill this gap by providing a mechanism for participants to refine their trading positions closer to delivery, based on updated information about RES output, consumption patterns, and grid constraints [19]. Unlike day-ahead markets, intraday trading enables adjustments that align generation with consumption as close as five minutes before delivery. This adaptability is essential for mitigating forecasting errors, particularly for wind and solar power, which are highly sensitive to environmental conditions [20]. By enhancing the system's responsiveness, intraday markets play a pivotal role in integrating RES into the grid while ensuring operational stability. Operational Mechanisms of Intraday Markets Intraday markets in the EU operate through two main mechanisms: continuous trading and intraday auctions. Continuous trading allows market participants to execute transactions at any time by matching buy and sell orders immediately. This mechanism provides the agility needed to respond to unforeseen changes, such as rapid shifts in wind speeds or unexpected cloud cover that impacts solar generation. The ability to trade continuously ensures real-time adaptability and minimizes imbalances [21].

Intraday auctions, on the other hand, are conducted at specific intervals and consolidate liquidity by aggregating trades into discrete sessions. This method facilitates price discovery and reduces volatility by concentrating trading activity at predetermined times. Auctions also offer enhanced transparency, providing participants with clear price signals that inform their trading strategies [22].

By combining continuous trading with scheduled auctions, intraday markets balance the need for immediacy with the benefits of aggregated liquidity and price stability.

Cross-Border Integration and XBID

The Cross-Border Intraday (XBID) platform represents a significant milestone in the integration of EU intraday markets [86]. By connecting national markets, XBID creates a unified trading environment where participants can engage in cross-border electricity transactions seamlessly. This integration optimizes resource allocation, enhances liquidity, and reduces inefficiencies caused by market fragmentation [16].

XBID relies on advanced algorithms to manage the complexity of cross-border trading, ensuring that energy flows align with grid constraints while maximizing social welfare. The platform enables participants to access price signals and trading opportunities across multiple countries, promoting regional collaboration and market harmonization [15].

Addressing Renewable Variability

One of the primary drivers of intraday markets is their ability to accommodate the variability of RES. As wind and solar power depend on fluctuating weather conditions, their output can change rapidly within short timeframes. Intraday markets provide a flexible solution by allowing participants to adjust their trading positions in response to updated forecasts. This capability reduces the financial and operational risks associated with forecasting errors, particularly for renewable energy producers and aggregators [23].

For example, wind farms experiencing unexpected drops in generation can purchase additional electricity in intraday markets to meet their contractual obligations. Conversely, solar producers anticipating excess generation during periods of high insolation can sell surplus electricity to avoid curtailment and maximize revenue [15].

Consumer Participation and Aggregators

The rise of DERs has expanded the role of consumers and prosumers in intraday markets. Aggregators act as intermediaries, pooling resources from multiple participants and enabling collective market engagement. By consolidating DERs such as batteries, electric vehicles, and flexible loads, aggregators enhance the scalability of intraday markets and improve grid flexibility [24].

Energy communities also contribute to intraday markets by generating and managing renewable energy within localized grids. These communities leverage microgrids and AMI to optimize energy use and participate in real-time trading [25].

Technical Challenges and Barriers

Despite their advantages, intraday markets face several challenges that must be addressed to unlock their full potential:

- **Infrastructure Gaps:** The uneven deployment of advanced infrastructure across EU member states creates disparities in the accessibility and efficiency of intraday markets. For instance, smart meters and IoT devices are essential for providing real-time data on energy consumption and production. However, some regions still rely on legacy systems that lack real-time capabilities, limiting participants' ability to respond to intraday market signals. Furthermore, grid infrastructure in certain areas is not optimized for handling the dynamic flows associated with high shares of renewable energy, which exacerbates bottlenecks during intraday trading. Addressing these gaps requires coordinated investments in digital infrastructure, grid modernization, and harmonized standards for device interoperability across the EU.
- **Interoperability Issues:** Interoperability challenges extend beyond cross-border integration to encompass compatibility issues with DERs and end-user devices. While the XBID platform represents a significant step towards market unification, its effectiveness is undermined by differing protocols, data formats, and operational standards across national markets. Additionally, the lack of standardized communication interfaces between DERs, such as solar panels, BESS, and EV chargers, complicates their integration into intraday markets. These inconsistencies hinder seamless data exchange and limit the scalability of aggregation models, which are crucial for maximizing flexibility. Solving these issues requires the development and adoption of universal communication protocols and frameworks that facilitate interoperability at all levels.[16].
- **Limited Market Participation:** Many small-scale producers, prosumers, and consumers lack awareness or the technical means to participate in intraday markets. The complexity of trading mechanisms, lack of user-friendly interfaces, and the need for real-time responsiveness act as significant barriers. This limited engagement reduces liquidity and undermines the market's ability to balance supply and demand effectively.
- **Insufficient Forecasting Accuracy:** While advancements in AI and machine learning have improved forecasting, the accuracy of predictions for weather-dependent RES like solar and wind remains a challenge. Even minor errors in forecasting can lead to imbalances, inefficiencies, and financial risks for participants.
- **Regulatory and Market Design Inconsistencies:** Varying regulatory frameworks and market designs across EU member states create significant hurdles for harmonized

intraday trading. Differences in bidding rules, gate closure times, and pricing methodologies complicate cross-border integration and reduce market efficiency. This lack of uniformity also increases transaction costs for participants operating in multiple countries.

Opportunities for Innovation

The future of intraday markets lies in leveraging digitalization and AI to enhance operational efficiency. AI-driven forecasting tools offer unprecedented accuracy in predicting RES output and consumption patterns, enabling proactive trading and minimizing imbalances. Blockchain technology could provide secure and transparent transaction frameworks, reducing administrative costs and increasing trust among participants [25], [26].

Emerging concepts such as decentralized finance and P2P trading also hold promise for expanding the reach of intraday markets. These innovations empower consumers to engage directly in energy trading, creating more dynamic and localized market structures [25].

2.3.2 Balancing Markets, Mechanisms and consumer participation

The increasing penetration of variable renewable energy (VRE), such as wind and solar, poses significant challenges to grid stability and market efficiency. To address these challenges, the European Union has developed a series of balancing platforms aimed at harmonizing market operations, enhancing flexibility, and fostering cross-border collaboration.

This chapter delves into three key initiatives—TERRE (Trans-European Replacement Reserves Exchange), MARI (Manually Activated Reserves Initiative), and PICASSO (Platform for International Coordination of Automated Frequency Restoration and Stable System Operation). Each of these platforms are essential for Europe's balancing market, supporting the transition to a cleaner energy future by integrating demand-side flexibility, consumer participation, and optimizing resource allocation.

The chapter begins by exploring the objectives and operational structures of these platforms, highlighting their innovative approaches to managing grid imbalances. It then examines the role of consumers and aggregators in these mechanisms, shedding light on how DERs are increasingly participating in balancing services. Finally, the chapter outlines future developments and the regulatory impacts shaping these platforms, emphasizing their importance in achieving Europe's energy transition goals.

2.3.2.1 TERRE

TERRE initiative [27], led by European TSOs, aims to create an integrated market for Replacement Reserve (RR) balancing energy. This initiative facilitates cross-border resource sharing to enhance energy security and operational efficiency across Europe. Implemented on the LIBRA [87] platform, TERRE provides a common framework for coordinating RR activation, enabling TSOs in participating countries such as Switzerland, France, and Spain to harmonize balancing operations and contribute to regional grid stability.

TERRE's operational structure is organized into six functional areas, or "lots," covering aspects such as hosting services and financial settlement. Significant developments have been made to improve its efficiency, including algorithmic enhancements and operational adaptations. For example, TERRE initially planned to increase to 96 clearings per day, but this adjustment was postponed due to regulatory changes and the anticipated end of the project by 2025. The LIBRA platform utilizes a centralized merit order list, ranking bids by price to ensure cost-efficient selection. This "pay-as-clear" approach activates the cheapest offers first, balancing energy needs while minimizing costs. The clearing process begins 55 minutes before the required balancing energy (H-55), with gate closure for TSO bids set at H-40 and activation at H-30. This timeline optimizes coordination among TSOs and local resources for real-time balancing.

Consumer participation in TERRE is primarily enabled through Balancing Service Providers (BSPs), typically aggregators, who represent consumer resources like DERs in the market. BSPs submit aggregated bids from consumers, such as those generated by solar PVs or energy storage, integrating them into the RR platform. This setup allows consumers to indirectly participate, contributing to grid stability by adjusting energy use in response to signals from aggregators. By facilitating demand-side flexibility, TERRE supports grid balance as renewable energy sources expand.

The LIBRA platform further enhances cross-zonal balancing by enabling BSPs to meet supply needs across different zones. In this framework, integrating consumer-generated energy improves grid reliability, while regulatory frameworks ensure effective consumer engagement. BSPs must adhere to a strict prequalification process, including compliance with standardized RR product requirements under the Electricity Balancing Regulation.

Due to regulatory changes introduced by the Electricity Market Design Regulation, TERRE is set to cease operations at the end of 2025. The current timelines do not align with the EMDR's new intraday cross-zonal gate closure requirement of H-30, highlighting the need for faster response times in balancing mechanisms. These regulatory shifts are likely to impact future consumer participation and cross-border coordination within the European energy market.

2.3.2.2 MARI

MARI [27] is a collaborative effort among European TSOs to manage shorter-term grid imbalances through the exchange of manually activated Frequency Restoration Reserves (mFRR). The primary objective of MARI is to improve grid stability by enabling TSOs to activate manual reserves in response to supply and demand fluctuations, enhancing responsiveness within Europe’s electricity market.

MARI operates using a centralized platform that aggregates mFRR bids from different TSOs into a Common Merit Order List (CMOL). This setup ensures economic efficiency by prioritizing cost-effective solutions for manual reserve activation. The platform is built around the mFRR Implementation Framework, which standardizes balancing energy products, manual activation methods, and settlement structures between TSOs. The LIBRA platform coordinates operations using an Activation Optimization Function that matches demand with available mFRR products, integrating variables like cross-zonal capacities and activation times to efficiently manage energy needs across borders.

Consumer participation in MARI is facilitated through BSPs, often aggregators, who compile consumer-generated energy bids to contribute to the mFRR market. By pooling small-scale DERs such as home batteries and solar panels, BSPs enable consumer resources to indirectly support grid stability. This demand-side flexibility is vital for balancing mechanisms as renewable energy sources grow. Regulatory frameworks ensure that BSPs meet compliance standards, including location designation and delivery obligations, to maintain accountability in balancing services.

MARI’s future roadmap aligns with the European Commission’s guidelines for an integrated energy market, focusing on regulatory updates and operational standardization to address new demands and facilitate renewable energy integration. These efforts aim to enhance grid stability and flexibility across Europe.

2.3.2.3 PICASSO

PICASSO [27] is a European initiative to coordinate the automatic activation of balancing energy from aFRR across TSOs. Operating on a TSO-to-TSO model, PICASSO supports a harmonized cross-border balancing market by standardizing processes such as order clearing and employing a CMOL to prioritize economically efficient bids.

Launched in June 2022, PICASSO integrates cross-zonal capacities and TSO demands through its AOF, dynamically adjusting to frequency fluctuations and optimizing balancing energy volumes while maximizing economic surplus. The platform tracks cross-zonal capacities monthly to ensure balancing needs are met without grid overloads, stabilizing the European energy market through efficient resource allocation.

Consumer participation is indirectly facilitated through BSPs such as aggregators, who compile bids from DERs like home batteries and PV panels. By integrating consumer-generated energy, PICASSO supports grid stability and demand-side flexibility.

PICASSO's future developments emphasize on stakeholder engagement and operational refinement to adapt to regulatory changes and evolving market demands. The initiative aligns with broader EU energy market integration goals, contributing to an economically and operationally optimized grid.

2.3.3 Retail Markets and Consumer Participation

The electricity retail markets in the EU connect wholesale electricity markets with end-users, enabling competition among suppliers and fostering consumer choice. These markets are governed by the EU's regulatory frameworks, which ensure transparency, non-discrimination, and alignment with broader energy policy goals.

Electricity retail markets in the EU are designed to offer a competitive environment where multiple suppliers operate and consumers have the freedom to choose among them. The key structural elements include [28]:

- Suppliers: Retailers purchase electricity on wholesale markets and resell it to consumers under diverse pricing schemes. Suppliers also offer additional services, such as energy management tools and renewable energy guarantees.
- Consumers: Final users, including residential, commercial, and industrial sectors, are the primary participants. Consumers can also act as prosumers, generating electricity (e.g., via rooftop solar) and injecting surplus power back into the grid.
- Regulated and Competitive Segments: While retail electricity prices are fully liberalized in some member states, others maintain regulated tariffs for specific consumer categories, particularly vulnerable households.
- Market Enablers: DSOs manage local grids and ensure electricity delivery to end-users but are strictly unbundled from retail activities to prevent conflicts of interest.

The EU retail electricity market operates through specific mechanisms designed to ensure efficiency and consumer engagement:

Supply Contracts

Retailers provide electricity to consumers through various contract types, such as [29]:

- Fixed-price contracts: Prices remain constant over a set period, offering predictability.
- Dynamic pricing contracts: Prices fluctuate based on wholesale market conditions, encouraging consumers to adapt their usage.

Contracts often include renewable energy options certified by Guarantees of Origin.

Smart Metering and Data Access [30]

- Smart meters are key enablers of retail market innovation, providing real-time consumption data to consumers and suppliers.
- Consumers gain access to detailed billing information and usage patterns, enabling informed decision-making and participation in programs like DR.

Value-Added Services [31]

Retailers increasingly offer additional services to differentiate themselves, including:

- Energy efficiency consultations.
- Smart home integration for automated energy management.
- Apps providing usage insights and optimization recommendations.

Consumer participation in the electricity retail market is primarily facilitated through three interlinked mechanisms: **supplier choice, prosumerism, and demand-side flexibility**. Each mechanism plays a critical role in enabling consumers to influence market dynamics and contribute to broader energy system goals.

Supplier Choice

The liberalization of electricity retail markets across the EU has enabled consumers to freely choose their electricity suppliers. This competitive environment encourages retailers to offer innovative products, including green tariffs and dynamic pricing schemes, tailored to meet diverse consumer preferences. Switching between suppliers is supported by EU directives that require member states to ensure a seamless and penalty-free switching process, often within 21 days (Directive (EU) 2019/944). Additionally, digital tools, such as price comparison websites and mobile applications, enhance transparency, allowing consumers to identify and select suppliers that align with their preferences for cost, service quality, or environmental impact [29].

Prosumers and Energy Sharing

A growing number of consumers in the EU retail market are transitioning into prosumers—individuals or entities that generate, consume, and, in some cases, sell electricity. Technologies such as rooftop solar panels and small-scale wind turbines enable prosumers to produce electricity, reducing reliance on traditional suppliers and lowering energy costs. Prosumers can sell surplus electricity back to the grid or to peers through retail arrangements or emerging P2P energy trading platforms. These activities are supported by frameworks for energy communities, which allow consumers to pool resources for collective energy generation, consumption, and trading, fostering local energy autonomy [32].

Benefits of Consumer Participation

Consumers gain greater control over their energy choices and costs through supplier switching, access to transparent pricing information, and the ability to produce their electricity. The availability of tailored pricing schemes and value-added services further enables consumers to align their energy consumption with their financial or environmental priorities. The engagement can also foster competition among suppliers, driving innovation and efficiency in retail market operations. Active participation by prosumers and DR participants also improves market efficiency by balancing supply and demand, particularly during peak periods or renewable energy surpluses [33].

Challenges of Consumer Participation

Many consumers lack sufficient information about their rights, available tariffs, or the benefits of switching suppliers and participating in demand-side programs. This knowledge gap is particularly pronounced among vulnerable groups, such as low-income households and elderly individuals, who may be less familiar with digital tools and market mechanisms.

The proliferation of pricing schemes and tariff structures can overwhelm consumers, deterring them from exploring new suppliers or engaging with dynamic pricing models. Simplified and standardized offerings, along with user-friendly comparison tools, are essential to mitigate this issue [34].

The deployment of smart meters and other enabling technologies is uneven across member states, limiting access to real-time consumption data and dynamic pricing opportunities for many consumers. Investments in infrastructure and digital literacy programs are needed to bridge this gap [34].

Active participation in retail markets often requires upfront investments in technology, such as rooftop solar panels or home energy management systems. This creates a risk of excluding low-income consumers from the benefits of participation, potentially exacerbating energy inequalities [35].

2.4 Decentralized Market Models

Decentralized market models represent an alternative to the traditional centralized approach by shifting control and decision-making from a few central entities to a distributed network of participants. In these systems, individual actors—such as prosumers, local generators, and energy communities—can directly engage in electricity generation, consumption, and trading. The model emphasizes local autonomy, flexibility, and innovation, making it particularly well-suited to integrating DERs and supporting renewable energy adoption [36].

Principles of Decentralized Market Models

Decentralized market models are based on several principles. The first is local optimization, which prioritizes energy use and trade within smaller geographic or organizational boundaries, such as neighbourhoods or microgrids, before relying on the larger grid. This approach reduces transmission losses, minimizes congestion, and fosters local energy resilience [37].

The second principle is P2P trading, which enables participants to directly exchange electricity without intermediaries. Prosumers, for example, can sell excess solar energy to neighbours, often facilitated by digital platforms that use advanced algorithms to match supply and demand dynamically. This direct engagement bypasses traditional retail structures, offering greater transparency and potential cost savings [37].

The third pillar is flexibility and demand-side participation. In decentralized models, consumers are not passive entities but active market participants who adjust their consumption patterns or supply flexibility services to balance the system. This participation is often incentivized through mechanisms such as dynamic pricing, DR programs, or local energy marketplaces [88].

Realisation of Decentralized Markets

Decentralized markets rely on advanced technological infrastructure to function effectively. At their core can be distributed ledger technologies (DLTs), such as blockchain, which enable secure, transparent, and tamper-proof transactions among participants. Blockchain technology can be particularly valuable for P2P energy trading, where it provides a trusted record of energy flows and financial settlements without requiring centralized oversight [15].

Another critical component is smart metering infrastructure. Smart meters collect real-time data on electricity consumption and generation, enabling accurate billing, detailed energy insights, and responsive market participation. Combined with IoT devices, these meters allow appliances and systems to act autonomously, optimizing energy use based on price signals or grid conditions [34].

Decentralized markets also rely on local energy storage. Batteries and other storage systems enable participants to store excess energy during periods of low demand or high renewable generation and discharge it when needed. Storage not only enhances energy self-sufficiency but also provides critical grid services, such as frequency regulation or peak shaving [37].

Digital energy platforms as a software layer that aggregates data, forecasts energy flows, and matches supply with demand bring the different components together and are essential for feasibility. These platforms use machine learning algorithms to optimize trades, predict renewable generation, and manage distributed assets, ensuring smooth operation despite the variability of decentralized resources [38].

Consumer Participation in Decentralized Markets

Consumer participation is fundamental for decentralized market models, driven by mechanisms that empower individuals and communities. Energy communities play an important role, as they enable consumers to collectively own and operate energy assets, such as solar panels or wind turbines. These communities not only produce and consume energy locally but also trade surplus electricity with other members or the wider grid. This participatory model democratizes energy access and promotes local economic development [39].

Prosumers, individuals who both produce and consume energy, are also key actors. Prosumers participate by selling excess electricity, providing grid services through DR, or contributing flexibility to local markets. Digital tools, such as mobile apps and energy dashboards, make participation more accessible, allowing prosumers to monitor performance, track savings, and optimize their energy behaviour [40].

Aggregators, although also associated with centralized markets, are increasingly relevant in decentralized systems. They pool the resources of prosumers and small-scale generators, enabling them to participate in larger energy markets or provide ancillary services. Aggregators act as intermediaries, bridging the gap between local actors and broader energy systems.

Benefits of Decentralized Markets

Decentralized market models can offer several advantages over centralized systems. They enhance local energy resilience by reducing reliance on distant generation and centralized infrastructure. This is particularly valuable in remote or underserved areas, where decentralized systems can provide reliable electricity access.

Decentralized models can improve the integration of renewable energy. By matching local generation with local consumption, these systems mitigate the variability of renewables and reduce the need for extensive grid upgrades. They also allow for greater experimentation with innovative technologies, such as vehicle-to-grid (V2G) systems, where electric vehicles contribute energy back to the grid [37].

Greater consumer engagement and empowerment can be achieved. By giving individuals and communities control over their energy resources, these models align with societal trends toward sustainability, transparency, and self-reliance. They also create opportunities for economic participation, enabling consumers to benefit financially from energy trading or grid services [41].

Challenges of Decentralized Markets

Despite their potential, decentralized market models face several challenges that must be addressed to achieve widespread adoption. One significant issue is regulatory uncertainty. Many energy systems are still governed by frameworks designed for centralized models, which may not fully accommodate P2P trading, microgrids, or other decentralized arrangements. For example, questions around grid fees, taxes, and consumer protections remain unresolved in many jurisdictions [37].

Another challenge is the technical complexity of managing decentralized systems. Coordinating thousands of distributed assets requires robust digital platforms, real-time communication networks, and advanced analytics. Without these systems, the variability of renewable energy and the unpredictability of consumer behaviour can lead to inefficiencies or instability [42], [43].

Economic barriers also exist. While the costs of solar panels, batteries, and other technologies have declined, the upfront investment required for decentralized systems can still be prohibitive for some participants. Additionally, the economic viability of decentralized markets often depends on subsidies, feed-in tariffs, or other policy mechanisms, which can be subject to political change [42].

Decentralized systems must also navigate social and cultural challenges. This also requires the development of proper consumer engagement strategies to facilitate their participation in this type of market, which is one of the goals of the ENPOWER project. Successful implementation often requires community buy-in, which can be hindered by lack of awareness, trust, or technical expertise. Ensuring equitable participation, particularly among marginalized or low-income groups, is also a critical consideration [42], [43].

Advanced Applications and Innovations

Innovations in decentralized markets are continually pushing the boundaries of what these systems can achieve. For instance, transactive energy frameworks use real-time price signals to enable devices, such as thermostats or EV chargers, to autonomously optimize their energy consumption. This creates a decentralized marketplace where every device becomes an active participant.

Another promising development is the use of AI to enhance decision-making. AI algorithms analyse vast datasets, identifying patterns and predicting energy flows to optimize market operations. These tools are particularly valuable in managing the complexity of decentralized systems, enabling scalability and reducing operational costs.

2.4.1 Peer-to-Peer Energy Markets

P2P energy markets represent a decentralized approach to electricity trading, enabling direct transactions between energy producers and consumers. These markets leverage DERs, advanced digital technologies, and localized market structures to challenge traditional centralized systems.

By creating a platform for autonomous energy exchanges, P2P markets align with the EU's broader goals of decentralization, renewable integration, and consumer empowerment. This section explores the requirements and challenges of P2P energy markets, their operational mechanisms, and practical implementation.

Possible Approach to Implementation of P2P Energy Markets

The foundation of P2P energy markets can be a decentralized digital platform that facilitates energy transactions between participants. This platform integrates multiple technological layers to ensure efficient, secure, and autonomous operation.

A critical component of these platforms is DLT, such as blockchain. Blockchain provides a tamper-proof, transparent ledger where all transactions are recorded. This ensures trust among participants by eliminating the need for centralized oversight. In P2P energy markets, each transaction is logged on the blockchain, creating an immutable record of energy flows and payments. The decentralized nature of blockchain makes it particularly well-suited to managing the high volume of micro-transactions typical in P2P systems [13], [37].

Smart contracts, built on blockchain platforms, automate the execution of energy trades. These self-executing contracts contain pre-defined rules that trigger actions, such as payments, once specified conditions are met. For instance, a smart contract could release funds to a seller's account once a buyer's smart meter confirms the receipt of the purchased energy [13], [44].

The integration of smart meters is essential in P2P energy markets. These devices measure energy production and consumption in real time, providing the data necessary for accurate billing and transaction validation. Smart meters also enable dynamic pricing by continuously updating energy values based on supply and demand conditions [38].

IoT further enhances the functionality of P2P platforms by enabling interconnected devices to communicate and act autonomously. IoT devices such as home energy management systems, batteries, and electric vehicles (EVs) optimize their operation in response to real-time market signals. For example, a home battery might charge during periods of low energy prices and discharge during peak demand to maximize economic benefits[11], [38].

Energy flows in P2P markets are managed through bidirectional grids, which facilitate the movement of electricity between prosumers and consumers. These grids require advanced control systems capable of handling decentralized transactions while maintaining grid stability [45]. To support this, DSOs must deploy intelligent systems for congestion management, voltage control, and load balancing.

Operational Mechanisms

In a typical P2P energy market, prosumers generate electricity using DERs such as PV panels, wind turbines or combined heat and power systems. Excess energy not consumed on-site is fed into the grid and made available for trade. Consumers can purchase this surplus energy through the P2P platform, selecting offers based on criteria such as price, source, and proximity. The trading process is facilitated by the platform's matching algorithms, which pair buyers and sellers based on their preferences and market conditions. These algorithms consider factors like energy availability, demand profiles, and grid constraints to optimize matches and ensure efficient energy flows. Once a match is made, a smart contract governs the transaction, automating the exchange of energy and payment.

Dynamic pricing is a defining feature of P2P markets. Prices fluctuate in real time based on localized supply and demand, encouraging consumers to shift their usage to off-peak periods and take advantage of renewable generation surpluses. This market-driven approach not only incentivizes behavioural changes but can also support grid stability by flattening demand peaks [46].

Integration with Traditional Systems

P2P energy markets often operate within the framework of existing grid infrastructures, requiring careful coordination with traditional market participants. DSOs play a critical role in facilitating the physical flow of electricity between P2P participants while maintaining grid stability. This requires enhanced grid monitoring and control systems capable of handling the bidirectional energy flows characteristic of P2P trading. To ensure seamless integration, P2P platforms must comply with existing market regulations and technical standards. This includes adhering to grid codes, ensuring interoperability with traditional market platforms, and participating in ancillary service markets. For example, surplus energy from P2P transactions could be aggregated and offered as a balancing service, supporting system-wide reliability [47].

European Case Studies

Several European pilot projects have demonstrated the potential of P2P energy markets, providing valuable insights into their technical and operational dynamics:

The Pylon Network in Spain is a notable P2P energy market case study. This blockchain-based platform enables energy producers and consumers to trade renewable energy directly. It incorporates smart metering and tokenized transactions to ensure transparency and efficiency. The project highlights how decentralized energy trading can empower prosumers and enhance the integration of renewable resources into local grids [48].

ENERCHAIN project in Germany is a blockchain-based platform that allows European utilities and other large players to conduct P2P energy trades. It integrates automated market clearing mechanisms and focuses on reducing the costs associated with centralized trading platforms [49].

The Quartierstrom Project (Switzerland): In this pilot, a decentralized platform allows households with solar installations to sell surplus electricity to neighbours. The project combines blockchain for transaction management with advanced forecasting algorithms to optimize local energy exchanges [50].

The NRGcoin Project (Netherlands): This initiative explores the use of cryptocurrency as a means of payment in P2P energy markets. Participants earn tokens for generating renewable energy, which can be used to purchase electricity or traded on external markets [51].

Challenges and Barriers

The difficulties are similar to the general difficulties in decentralised energy markets and are listed here in an abbreviated and adapted form for the sake of completeness:

- Regulatory Complexity: Existing energy regulations often fail to accommodate the decentralized nature of P2P markets. Issues such as grid fees, taxation, and compliance with market standards can complicate operations and reduce economic viability.
- Grid Integration: Managing bidirectional energy flows and ensuring system stability in decentralized environments requires significant upgrades to grid infrastructure and control systems.

- Economic Viability: While the cost of technologies like blockchain and IoT is declining, the initial investment required for P2P platforms and DERs can still be prohibitive for some participants.
- Consumer Engagement: Successful P2P markets depend on active participation and trust among users. Raising awareness and providing education on the benefits and operation of P2P systems is critical.

Future Directions

Emerging technologies and innovative market designs are expected to address many of the current challenges. For instance, integrating AI into P2P platforms could enhance decision-making by predicting market trends, optimizing matching algorithms, and improving load forecasting. Similarly, advancements in V2G systems will enable EVs to act as active participants in P2P markets, providing both energy and flexibility.

The development of standardized protocols for interoperability and the establishment of supportive regulatory frameworks will also play a crucial role in scaling P2P energy markets. As these systems evolve, they are likely to complement traditional markets, contributing to a more decentralized, consumer-centric energy ecosystem.

2.4.2 Key Differences in National Market Designs Across Pilot Countries

Decentralized energy markets across the ENPOWER Pilot countries Austria, Greece, Hungary, Ireland, Portugal, and Spain reflect diverse approaches influenced by technological readiness, economic strategies, and consumer engagement. Below are country-specific findings of decentralized market development.

Austria

Austria shows solid developments in decentralized energy markets through its Renewable Energy Expansion Act, which facilitates the creation of CECs and RECs. These frameworks allow participants to collectively produce, consume, and trade renewable energy while benefiting from localized management and reduced dependency on centralized systems [52].

- Energy Communities: RECs and CECs are evolving, relatively far developed fundamentals of Austria's decentralized market. They encourage collaboration among households, local businesses, and municipalities, prioritizing local production and consumption.
- Support Schemes: Austria has introduced subsidies for rooftop solar PV systems and feed-in tariffs for hydropower and wind energy, making renewable energy projects more financially viable.
- Smart Metering Rollout: Over 95% of households have access to smart meters, enabling real-time data tracking and optimizing renewable energy use at the consumer level.
- Grid Integration: Efforts are being made to modernize the grid infrastructure to manage the influx of DERs, although rural grid capacities remain a challenge.
- Austria’s approach combines community empowerment with government incentives, though grid bottlenecks in certain regions pose a hurdle to scaling these initiatives.

Greece

Greece has prioritized decentralized renewable energy as a pathway to enhance energy security and sustainability, focusing on its abundant solar and wind resources. Through targeted legislative reforms and investments in smart grid technology, Greece aims to position itself as a leader in renewable integration.

- Energy Communities Law: Enacted in 2018, this law incentivizes collective renewable projects by providing tax relief, grants, and administrative support, ensuring equitable energy access for small and large stakeholders.
- Smart Grid Investments: With significant upgrades underway, including pilot projects on islands such as Tilos, Greece is improving the reliability of renewable integration and addressing intermittency issues.
- While Greece has made notable progress, grid congestion and delays in project permitting remain significant barriers to a fully decentralized energy ecosystem.

Hungary

Hungary is gaining momentum in REC deployment within Central Europe, driven by government policies aimed at diversifying energy sources and reducing fossil fuel dependency. Although the decentralized energy market is still in its early stages, Hungary has adopted pilot programs and incentives to encourage distributed generation.

- Residential Solar Boom: Hungary offers substantial subsidies for rooftop PV systems under its Green Economy Financing Scheme, leading to exponential growth in residential solar installations.
- Energy Communities Pilots: Limited-scale pilot projects focus on testing models for shared renewable energy resources among communities, a relatively new concept in Hungary.
- Regulatory Development: The Hungarian Energy and Utilities Regulatory Authority is working to streamline processes for integrating DERs into the grid while ensuring compliance with EU directives.
- Despite these advancements, Hungary faces challenges in raising consumer awareness and addressing grid modernization needs.

Ireland

Ireland's decentralized energy market is driven by the goals set out in its Climate Action Plan, which focuses on empowering communities and small-scale producers to contribute to the energy transition.

- Micro-Generation Support Scheme: Launched in 2022, this scheme allows small producers, such as households and farms, to export surplus renewable electricity to the grid and receive payments, a significant step towards incentivizing micro-generation.
- Community-Led Renewable Energy Projects: Ireland supports initiatives through grants and capacity-building programs facilitated by the Sustainable Energy Authority of Ireland.
- Flexibility Measures: DR programs encourage consumers to shift usage patterns to match renewable supply availability, easing grid pressure during peak times.
- While Ireland has successfully mobilized communities, grid connection is evolving and capacity constraints present challenges as renewable deployment scales.

Portugal

Portugal is a pioneer in achieving high renewable energy penetration, with a robust framework for decentralized energy systems. Its policies are designed to support collective self-consumption and community energy projects.

- Self-Consumption and Energy Sharing: Recent legislation simplifies the process for communities to share locally produced renewable energy, improving energy self-sufficiency and reducing costs.
- Focus on Green Hydrogen: Portugal is investing heavily in green hydrogen projects to complement its renewable strategy, enabling decentralized storage and energy security.
- Smart City Integration: Urban centres like Lisbon and Porto are piloting smart grid technologies to integrate renewables seamlessly into the urban energy landscape.
- Portugal faces administrative hurdles in project licensing and grid reinforcement requirements to accommodate rising decentralized production.

Spain

Spain has become a leading example of a decentralized energy market after reforms, including the removal of the "sun tax," which had previously discouraged self-consumption.

- Self-Consumption Revolution: Spain now permits consumers to share renewable energy within buildings and communities, with simplified registration processes making solar PV adoption more accessible.
- Energy Cooperatives: Public-private collaborations have led to a rise in energy cooperatives focused on renewables, often utilizing innovative financing models to scale projects.
- Digital Platforms for Trading: Blockchain-based platforms and P2P energy trading pilots are enabling greater consumer participation in decentralized markets.
- Spain's primary challenges lie in ensuring grid stability as decentralized generation grows and addressing regional disparities in access to renewable resources.

2.5 Energy Community Models and Archetypes

Energy communities represent a transformative paradigm in energy systems, enabling collective participation in energy production, distribution, consumption, and management. The two primary models recognized under the EU's legislative framework are RECs and CECs. This chapter explores their design, operation, and technical nuances, highlighting the mechanisms that drive their integration into modern energy markets and therefore enhance participation of consumers and prosumers on the energy market.

2.5.1 Renewable Energy Communities (RECs)

RECs [52], [53] are grounded in the principles of localism, sustainability, and inclusivity. Defined under the EU Renewable Energy Directive (RED II), they prioritize environmental and social benefits over profits. RECs comprise local stakeholders, including individuals, municipalities, and small enterprises, and their activities centre on renewable energy generation, self-consumption, storage, and sharing. The primary goal is to enhance local energy resilience while fostering community involvement in the clean energy transition [53].

Operationally, RECs are built around decentralized energy generation, utilizing technologies like PV systems, small-scale wind turbines, biomass plants and hydropower. These installations are designed to meet local energy demands, reducing reliance on centralized grids and minimizing transmission losses. Surplus energy generated by community members is often shared within the network or exported to the grid. (P2P) energy trading mechanisms, facilitate this exchange, ensuring transactions are transparent, secure, and automated [52].

Grid integration, while secondary to local energy use, remains an important aspect of RECs. Communities connected to the national grid can sell excess electricity in wholesale markets or procure additional energy when local production falls short. Technologies like bidirectional smart meters and advanced distribution management systems (ADMS) facilitate this integration, allowing RECs to contribute to grid stability and benefit from market participation.

From a technical perspective, the successful operation of RECs relies heavily on digital infrastructure. Smart meters equipped with IoT capabilities provide real-time data on energy usage and production, enabling precise energy management. Microgrids, often at the heart of RECs, use sophisticated controllers to balance loads, integrate variable renewable resources, and manage dispatch. Blockchain technology has emerged as a cornerstone for P2P trading, offering a secure and cost-effective platform for energy transactions.

Despite these advantages, RECs face notable challenges. The high upfront cost of renewable installations and storage systems often requires external funding or subsidies, which can be difficult to secure. Regulatory complexities, such as grid codes and market access requirements, pose additional hurdles. Furthermore, the technical expertise needed to manage advanced energy systems can be a barrier for smaller or less-resourced communities.

2.5.2 Citizen Energy Communities (CECs)

CECs [54] expand the concept of collective energy action beyond renewable energy, encompassing a broader range of activities, including electricity supply, DR, and aggregation. Defined under the EU Electricity Directive, CECs aim to empower citizens by increasing their participation in energy markets, enhancing local resilience, and fostering innovation.

The operational framework of CECs is diverse, reflecting their wide scope. Many CECs act as electricity suppliers, purchasing energy from wholesale markets and distributing it among members. Unlike traditional utilities, these communities often adopt dynamic pricing models, where electricity prices fluctuate based on real-time market conditions. This approach incentivizes members to adjust their consumption patterns, aligning demand with supply and reducing costs.

Aggregation is a key function within CECs. By pooling the resources of members, such as rooftop solar panels, home batteries, and electric vehicles, CECs can create VPPs. These aggregated resources are managed through advanced software platforms, which use machine learning algorithms to predict demand, optimize dispatch schedules, and participate in balancing and ancillary markets. This capability allows CECs to play an active role in maintaining grid stability and providing flexibility services.

Energy sharing within CECs mirrors the mechanisms seen in RECs, but with a broader energy mix that may include conventional resources alongside renewables. Advanced metering infrastructure (AMI) supports this functionality, enabling accurate billing, remote load control, and detailed analytics. Additionally, digital platforms provide members with real-time insights into their energy usage and generation, fostering greater engagement and transparency.

The technological sophistication of CECs extends beyond resource management. Many communities integrate DR programs, where members adjust their consumption based on signals from the grid operator or market prices. For example, smart appliances and home automation systems can be programmed to operate during periods of low electricity prices, optimizing costs and supporting grid efficiency. Blockchain technology is also increasingly utilized, particularly in energy sharing and trading platforms, ensuring secure and efficient transactions.

Despite their potential, CECs face several challenges. Regulatory requirements for market participation, such as prequalification criteria and compliance costs, can be onerous for small-scale actors. Coordinating diverse stakeholders with varying priorities and technical expertise requires robust governance structures. Moreover, the reliance on advanced digital infrastructure poses scalability challenges in regions with less developed technological capacity.

2.5.3 Comparison of Energy Community Models

While RECs and CECs share common goals of fostering local energy autonomy and community engagement, they differ significantly in scope and operational focus. RECs are primarily oriented towards renewable energy and local sustainability, often centred on microgrids and energy storage. In contrast, CECs have a broader mandate, engaging in energy supply, aggregation, and market participation. These differences are reflected in their technical requirements, with CECs relying on more sophisticated systems for market integration and flexibility services [55].

Both models benefit from advancements in digital technology, but their success depends on addressing key challenges. For RECs, the focus must be on reducing upfront costs, streamlining regulatory processes, and building technical capacity. For CECs, overcoming market entry barriers, fostering stakeholder collaboration, and expanding digital infrastructure will be crucial.

2.5.4 Energy Communities Integration across Pilot Countries

Austria's EnC framework is relatively developed, supported by the Renewable Energy Expansion Act (EAG). This legislation explicitly defines RECs and facilitates their establishment by enabling local generation, consumption, storage, and trading of renewable energy.

- Key Features: Austria's energy communities leverage advanced digital technologies, such as smart meters and blockchain-based platforms, to enable P2P trading. They are strongly integrated into the grid, allowing surplus energy to be sold to the market.
- Technological Integration: Widespread deployment of smart grids and advanced distribution management systems enhances operational efficiency.
- Challenges: Administrative complexity and high initial costs can limit the scalability of these communities, particularly in rural areas.

Greece has positioned energy communities as tools for addressing energy poverty and fostering renewable energy adoption. The Law 4513/2018 established a supportive framework for energy communities, emphasizing social and solidarity economy principles.

- Key Features: Greek energy communities focus on inclusivity, often involving municipalities and cooperatives. They are particularly active in regions with high energy poverty or isolated island systems.
- Technological Integration: Many communities operate hybrid microgrids, combining solar, wind, and storage to ensure local energy autonomy.
- Challenges: Outdated grid infrastructure and limited deployment of smart technologies restrict scalability and integration with the national grid.

Hungary's EnC framework is evolving, with pilot projects and small-scale initiatives leading the way. The country's EnC models primarily focus on integrating solar PV systems into local networks.

- Key Features: Hungary's energy communities are nascent, with limited formalization in national energy policy. Pilot projects emphasize solar integration and local consumption.

- Technological Integration: Adoption of smart meters and grid automation is limited, which hampers operational efficiency and data-driven decision-making.
- Challenges: Regulatory ambiguity and lack of incentives for community formation are significant barriers to growth.

Ireland's EnC models are unique in their strong focus on aggregator-led participation and demand-side flexibility. The Renewable Electricity Support Scheme includes specific provisions for community projects.

- Key Features: Irish energy communities may be involved in wholesale and balancing markets through aggregators. Flexibility services, such as DR, are key components.
- Technological Integration: AMI and VPPs enable efficient resource aggregation and dispatch.
- Challenges: Rural regions face barriers due to limited infrastructure, and administrative processes for market entry can be complex.

Portugal has embraced energy communities as a means of enhancing rural energy resilience and integrating renewable energy. The Decree-Law 162/2019 provides a legal framework for self-consumption and energy sharing within communities.

- Key Features: Portuguese energy communities frequently deploy microgrids, integrating solar, wind, and battery storage to reduce reliance on the national grid.
- Technological Integration: DEMS optimize local energy flows and support the operation of microgrids.
- Challenges: Limited digital infrastructure and high initial costs pose barriers to broader adoption.

Spain is recognized as a leader in enabling prosumers and fostering energy communities, supported by progressive regulations such as Royal Decree 244/2019. This decree facilitates collective self-consumption and energy sharing. This Royal Decree was updated with RDL 23/20 which transposed the concept of REC from EU Directive 2018/2001, introducing them as stakeholders in the electricity sector. Following it, public consultations and funding calls have been proposed by the national government to support the energy communities implementation (MITERD, PRTR-C7.R3, Auctions, CE-IMPLEMENTA calls, etc.). Finally, RDL 5/23 transposes the concept of CECs from EU Directive 2019/944, introducing them as stakeholders in the electricity sector and defining some regulatory principles.

- Key Features: Spanish energy communities are highly active in collective installations and sharing the energy production of a renewable energy installation. However, P2P trading is not allowed and cannot utilize blockchain technology for secure and transparent money transactions, unless a Regulatory Sandbox is promoted. They can use blockchain for deciding the energy coefficients to share energy, but they should be communicated to the DSO 4 months in advanced so they cannot be dynamic and in real time. Transactions could be used to adjust part of the billing inside the community.
- Technological Integration: Smart meters are widely spread across the country, which facilitates smartness. Advanced digital platforms enable dynamic pricing and real-time energy management.
- Challenges: Grid capacity constraints and administrative hurdles, such as lengthy approval processes, limit scalability. Energy flexibility requires high bids and therefore the role of an aggregator (not defined in the current regulatory framework).

2.5.4.1 Development and barriers

This chapter aims to provide a comparative overview of the strategies and trends affecting EnCs across the participating countries, diving deeper in possible challenges. To achieve this, input was collected from pilot site representatives, leveraging their on-the-ground experience and localized knowledge.

Austria

Austria has observed that while RECs provide physical energy independence by encouraging local generation and consumption, their pricing remains tied to general market dynamics. Since the energy crisis, there has been a shift towards short-term contracts, exposing REC participants to fluctuating market prices.

The provincial utility "Energie Burgenland" has recently presented a noteworthy initiative. They want to offer a fixed electricity price through a statewide EnC for a certain period, which aims to provide price stability and energy autonomy. The price guarantee offers participants predictability, which could enhance the attractiveness of RECs, particularly for those concerned about the risks associated with fluctuating prices.

There are several critical factors to consider:

- Legal and Regulatory Frameworks: The long-term price guarantee may face legal hurdles, particularly around public procurement, state aid, and competition law. Burgenland’s approach also brings up issues with governance and taxation, which could affect its rollout and sustainability.
- Market Impact: The initiative could disrupt competition within the energy market, raising concerns about its broader implications for pricing and market dynamics.
- Balance Between Stability and Flexibility: While the fixed price guarantees stability, participants may miss opportunities to benefit from lower market prices. It also raises questions about how flexible this model can be in adapting to future market conditions or policy changes.

Greece

Greece faces similar challenges when it comes to EnCs, particularly in terms of pricing mechanisms and market exposure. Greek EnCs are tied to the general market dynamics, which exposes them to fluctuations in energy prices, especially following the energy crisis. However, Greece’s energy market is still evolving when it comes to regulatory flexibility for fixed-price models or other innovative schemes. Balancing local generation and consumption is a key feature of Greek EnCs, but the issue of price stability remains unsolved.

Regulatory Barriers: Greek EnCs face several legal and regulatory hurdles. The framework for energy sharing, self-consumption, and collective generation is still developing. Regulations surrounding grid access, taxation, and energy trading often make it difficult for EnCs to operate smoothly.

High Initial Costs: The cost of setting up renewable energy systems, particularly for smaller communities, can be prohibitive. There is also a need for financial mechanisms and incentives to make these projects more viable.

Energy Market Dependence: EnCs in Greece are also heavily exposed to the fluctuating prices of the energy market. The lack of long-term contracts or stable pricing mechanisms makes it challenging for participants to predict their energy costs.

Administrative Complexity: Navigating bureaucracy and acquiring the necessary permits can delay projects significantly. Many smaller communities struggle to get expert advice on legal and technical requirements.

Greece does not have a fixed-price mechanism like the proposed model in Austria "Energie Burgenland" initiative for energy communities. Pricing remains largely tied to the wholesale energy market, meaning EnC participants are exposed to price fluctuations. In practice, Greek EnCs typically follow short-term market prices for electricity, which can be volatile due to recent energy market shifts.

However, there are ongoing discussions about introducing reforms to support local communities and cooperatives, including financial support through government or EU programs, but fixed-price guarantees have yet to be implemented.

Apart, from ChalkiOn, which is the Greek pilot site for ENPOWER one other significant case in Greece is the Tilos Island Project, which became one of the country's first examples of a renewable EnC. Tilos achieved near energy self-sufficiency by combining wind, solar, and battery storage. However, even though it demonstrates the technical potential of EnCs, the island remains exposed to energy market prices for grid-related electricity, similar to other communities.

Another example is the Agricultural Cooperative of Karditsa (ARK), which has established a biomass heating project. While it helps reduce dependence on external energy sources, ARK's participants still face challenges related to market-based pricing and legal hurdles around energy trading.

Hungary

Compared to Austria, Hungary's EnC framework is less developed, with fewer successful initiatives to date. This nascent stage of development means Hungarian energy communities may have less capacity to experiment with complex pricing models or advanced governance systems like those proposed in Burgenland. Moreover, unlike Austria, where provincial utilities such as Energie Burgenland are key enablers, Hungary does not have a strong tradition of regional utilities driving EnC initiatives. Most support comes from national programs or EU-funded projects. Grid access and integration challenges are also more pronounced in Hungary, limiting the ability of energy communities to achieve true energy independence. This adds another layer of difficulty in introducing models that depend on stable local generation.

Hungary's energy market is characterized by significant challenges and opportunities, as highlighted in several recent analyses:

Market Exposure to Negative Prices: Hungary's energy market faces issues related to negative electricity prices, driven by its reliance on imported energy and its challenges in managing renewable energy surpluses during low-demand periods. This volatility is exacerbated by a grid capacity that has struggled to adapt to the rapid increase in renewable energy projects. For instance, a recent government policy significantly restricted new grid connections for renewable projects, which limits further expansion opportunities despite Hungary reaching its initial solar capacity targets ahead of schedule.

Residential Energy Subsidies: Hungary continues to provide extensive subsidies to shield households from high energy prices. These subsidies, while offering short-term relief, contribute to a significant fiscal burden. In 2024, the net cost of such subsidies is projected to decrease slightly as energy prices stabilize and adjustments are made to public investments

Limited Role of Energy Communities: Energy communities, which could democratize energy production and reduce energy poverty, remain underdeveloped in Hungary. Barriers such as low public awareness, regulatory challenges, and limited funding impede their growth. This contrasts with more successful European examples, such as renewable cooperatives in Belgium and Portugal, which demonstrate the potential of such initiatives to lower energy costs and promote sustainability

Energy communities in Hungary face several challenges that hinder their growth and effectiveness:

- Regulatory Uncertainty: While Hungary has transposed parts of the EU directives on energy communities (e.g., Renewable Energy Directive II and Electricity Market Directive), there are gaps and ambiguities in the legislative framework. These include unclear definitions of EnCs, limited guidance on their operation, and insufficient incentives for community-based projects.
- Grid Access and Infrastructure: Energy communities struggle with access to the national grid, as grid operators prioritize traditional energy producers. Additionally, aging grid infrastructure limits the integration of decentralized energy generation.
- Administrative Complexity: Setting up and operating an EnC involves navigating complex legal and administrative processes, which can be a significant barrier, especially for smaller or less experienced groups.
- Financial Constraints: Many energy communities face challenges in securing funding for initial investments. Limited access to affordable financing mechanisms, combined with insufficient government subsidies or grants, exacerbates this issue.
- Public Awareness and Engagement: The concept of energy communities is still relatively new in Hungary, and there is limited public awareness of their benefits.

Pricing mechanisms in Hungary:

- Universal Service Pricing: Electricity pricing for residential consumers is heavily regulated, with the government capping prices to shield households from market volatility. This mechanism limits the financial attractiveness of decentralized energy generation and self-consumption models for energy communities.
- Grid Usage Fees: Energy communities must pay grid usage fees, which reduce the financial viability of local energy trading and self-consumption.

Ireland

Ireland is experiencing its own energy crisis, exacerbated by global market fluctuations and the transition towards renewable energy sources. We have seen a significant shift towards short-term contracts, which can lead to price volatility for consumers. This environment creates uncertainty for communities attempting to establish local energy solutions, as they grapple with the unpredictability of market prices.

The current energy crisis, particularly in the EU, is characterised by a shift in security mechanisms from reliance on Russian gas to global LNG supply chains. While this enhances supply security, it also introduces greater price volatility due to factors such as global demand fluctuations and external policies, like potential US export taxes. The storable nature of oil allows for market volatility, but this is less influenced by media than gas prices, which are now closely tied to LNG market dynamics. Consequently, electricity costs are increasingly unpredictable, creating barriers to electrification for consumers. To address these issues, it's crucial to break down the energy crisis into key components—security, volatility, and market pricing—and communicate these clearly to the public.

Main Challenges for Energy Communities in Ireland:

Regulatory Hurdles: Energy Communities in Ireland face significant regulatory challenges that can impede their development. The complexities involved in navigating energy regulations, licensing, and compliance with EU directives can create barriers to entry for local initiatives.

Funding and Investment: Securing funding for renewable energy projects remains a pressing challenge. While there are grants and supports available through initiatives like the Sustainable Energy Authority of Ireland (SEAI), many communities struggle to access sufficient resources to initiate and sustain projects.

Market Access: Energy Communities may find it difficult to access the market effectively. The current market structures are often tailored to larger players, making it challenging for smaller, community-based initiatives to compete.

Pricing Mechanisms in Ireland:

The regulatory framework in Ireland includes several pricing mechanisms aimed at supporting renewable energy and community initiatives:

Feed-in Tariffs (FiTs): These mechanisms provide a guaranteed payment for energy produced from renewable sources, which can help stabilise income for community projects. However, the rates may not always be sufficient to cover costs, especially given recent inflation.

PPAs: These are contracts between energy producers and buyers that can help ensure price stability. However, like in Austria, they can expose communities to market fluctuations if not structured carefully.

Renewable Energy Support Schemes (RESS): This government initiative aims to incentivize the development of renewable energy projects through auctions that determine the price at which energy is sold. While it encourages competition, it can also lead to price volatility for smaller players. The introduction of the Small-Scale Renewable Energy Support Scheme (SRESS) for 50kW to 1MW projects is intended to support smaller players more effectively.

Insights and Case Studies

A relevant case study in Ireland is the Cloughjordan Ecovillage, which has successfully established a community-based energy model that includes renewable energy generation and energy efficiency measures. This initiative illustrates the potential benefits of local energy solutions, but it also highlights the challenges related to regulatory compliance and funding that other communities may face.

The SEAI Sustainable Energy Framework plays a crucial role in guiding Ireland's transition to a low-carbon energy system. It provides a roadmap for enhancing energy efficiency and increasing the adoption of renewable energy technologies. This framework aims to empower communities by providing resources, funding opportunities, and a strategic approach to developing sustainable energy projects. The SEAI's support can help address some of the funding and regulatory challenges faced by RECs, fostering a more conducive environment for their growth.

SEAI resourcing includes support for data-gathering tools such as the Energy Master Plan. This is a valuable tool to establish baseline energy balances and identify a register of opportunities. While access to adequate data and expertise in developing these Energy Master Plans remains a challenge the support provided by SEAI is a notable asset for local SECs, giving them a significant advantage over other countries looking to initiate and communicate EnC partnership benefits. Portugal, for example, has no access to such supports.

While Ireland shares many challenges with Austria regarding the development of RECs, the specific regulatory environment, market access issues, and funding mechanisms present unique hurdles. Addressing these challenges will be crucial for fostering a sustainable and resilient energy future for our communities.

Portugal

In Portugal, the shared tariffs in an EnC are fixed, not indexed to the market. Hence, each EnC is free to agree the respective sharing tariffs with the participants, which should be lower than what the participants are already paying to the energy retailer but still higher than what the producers would get if they sold directly to the grid through a utility.

With this, several financial models can be deployed other than investing in a solar photovoltaic system and selling directly the production excess by the producer to the other participants. For example, a given energy utility can propose to invest in a solar PV system to one of its clients and then the client would benefit from a tariff reduction of the self-consumed electricity (which turns into an income to the utility). Additionally, the utility can further sell the production excess to the other EnC participants. These agreements can have a contract duration agreed between the parties.

The energy tariff that is agreed can be fixed (a single €/kWh) or can vary according to the time of the day (p.e. €/kWh for peak periods and another €/kWh for off-peak periods) and varying according to the contracted power of the client.

There are two ways of applying those tariffs to the shared energy in an EnC:

- Through fixed coefficients
- Through proportional coefficients

The fixed coefficients refer to sharing the excess production with pre-determined percentages of that energy to the participants. These pre-determined percentages can, however, have different values across the year. The proportional coefficients, on another hand, are indexed as well to the consumption level of each participant.

Other coefficients are envisioned but still only allowed in pilot projects, such as the dynamic coefficients. These coefficients can follow more complex rules taking into consideration several variables.

Finally, the biggest hurdle in Portugal is in the bureaucratic process of creating an EnC. The validation process is still taking too long, which can discourage the creation of EnC. However, the energy communities are ramping up and there is an intention by all the regulatory bodies in Portugal to encourage the creation of energy communities in Portugal.

Spain

In Spain, Energy Communities are in a phase of development and expansion, driven by the transition towards a more sustainable and decentralized energy model.

In Spain, users of an EnC can choose tariffs from both the free market and the regulated market:

1. Free Market: In this market, a user can negotiate specific conditions with energy suppliers to achieve more favourable prices. This allows for some flexibility and the possibility of accessing fixed-price contracts, but the offers depend on negotiations with the supplier and do not always guarantee competitive prices against market volatility.
2. Regulated Market (PVPC): The regulated PVPC tariff (Voluntary Price for the Small Consumer) is also available to users of energy communities. This type of tariff varies every hour according to the wholesale market price, which can result in savings during low demand periods, but also involves greater exposure to price fluctuations.

In Spain, there is also a discount called the Social Bonus for those individuals in more vulnerable situations. The Social Bonus is a discount on the electricity bill aimed at vulnerable consumers (such as individuals with low incomes, large families, among others) who apply for the PVPC and meet certain requirements. This bonus is a measure of social protection and offers discounts ranging from 25% to 60%, depending on the consumer's level of vulnerability.

Regulation of Surplus Compensation in Energy Communities:

- Collective Self-Consumption and Surplus Distribution: The regulations allow for defining distribution coefficients for each member of the community, ensuring that each user receives a portion of the generated energy and the surpluses as agreed.
- Compensation Price: Compensation for the surplus is based on the wholesale market price (for those in the regulated market) or on a price negotiated with the supplier (if they are in the free market).

The generated surpluses are sold to the grid and are reflected as a discount on the bill of each member. Economic compensation is calculated separately for each user based on their percentage of participation in the surpluses.

- Monthly Balance Without Negative Balance: As in individual self-consumption, the bill balance for each member cannot be negative. This means that the compensation for surpluses can only reduce the electricity bill to a value of zero. If the value of the surpluses exceeds consumption, the excess is not accumulated or paid in cash; it is simply discarded.
- Flexibility in Distribution Agreements: The distribution coefficients among members can be adjusted to accommodate changes in consumption or community structure. This distribution can be registered with the supplier and the electricity distributor, who will apply the corresponding compensations to each user based on the agreed values.
- Support and Additional Benefits: Energy communities often have access to public subsidies, such as those from European funds and tax deductions in some cases, which help reduce the initial installation cost and improve the profitability of the collective self-consumption system.

Main Challenges for Energy Communities in Spain:

- Administrative and Regulatory Complexity: The establishment and management of energy communities require navigating a complex administrative framework and a regulation that is still under development. The lack of a specific regulatory framework and simplified processes can discourage interested citizens and entities.

- Financing and Initial Costs: Although there are grants and European funds available, the high initial costs for establishing energy generation and storage infrastructures remain a barrier for many energy communities, especially in rural areas or those with limited economic resources.
- Access to the Grid and Storage: To manage and optimize their energy production, energy communities need access to the distribution grid and, ideally, storage systems. However, connection agreements with distributors can be complex, and the regulations regarding grid access are still being developed.
- Public Awareness and Citizen Training: Many communities are still unaware of the advantages and functioning of energy communities. The lack of information and awareness campaigns limits citizen participation and support for these initiatives.

Currently, most Spanish energy communities are in pilot or growth phases, so specific pricing models for communities are still scarce and varied. Some initiatives aim to offer fixed prices or time-of-use rates to provide greater stability, but national regulations do not yet fully account for specific tariffs for energy communities.

Lastly, it should also be mentioned that in Spain the P2P energy market is not allowed and still faces regulatory and technological limitations. However, there is a growing interest in this model.

2.6 Energy System Flexibility

This chapter looks at various common approaches to flexibility in the energy market for participants such as consumers, prosumers, aggregators or energy communities. Currently, one of the most promising participation opportunities for consumers is through flexibility and therefore further analysed in the following.

2.6.1 Demand Response Programs

Demand Response Programs (DRP) involve adjusting electricity consumption in response to supply conditions, for optimizing energy usage, reducing cost and support the overall renewable energy integration and resilience within an EnC. These programs reward customers for reducing consumption during hours of highest demand on the grid and for increasing consumption during periods of high production, aiding in overall efficiency and reliability. The literature distinguishes between two types of DRPs: **price-based DRPs** and **incentive based DRPs** [56], [57]. There are several types and mechanism utilized in those frameworks. The most important and usable on a community or district level are explored and discussed in the following.

Explicit DR: The community has a contract with an aggregator or directly with an actor interested in flexibility (e.g. a DSO or TSO). When this actor needs flexibility and notifies the community, the latter is required to deliver the amount of flexibility for a specific amount of time, which is agreed upon in the contract. Non-compliance may result in a penalty.

Implicit DR: Energy prices are dynamic and reflect the (dis)balance between demand and supply and/or the available capacity of the network. This creates a financial incentive for households and communities to shift energy demand to moments in time when prices are low.

Price-based DRPs

Price-based DRPs (self-dispatched) utilize the adjustment of consumers to the given price and price fluctuations. The most common and effective strategies are Time-of-use (TOU) pricing, Critical Peak Pricing (CPP) and real-time pricing (RTP), which are based on price signals that encourage consumers to shift their electricity use. These pricing schemes align electricity prices with conditions of supply, encouraging consumers to decrease consumption during peak hours and add loads to off-peak times when the cost of purchasing electrical energy is lower. Therefore, it can aid energy communities to maximize self-consumption and possibly minimize the total amount of consumed electricity [56], [58], [59]. The strategies primarily differ in their frequency of price adjustments:

TOU is a rate structure that varies the price of electricity based on the time of day, season, and day type (weekday or weekend/holiday) and is designed to reflect the actual cost of electricity production and delivery at different times. Prices typically remain fixed for specific time periods like months or seasons [56], [58].

CPP is a dynamic electricity pricing strategy designed to manage peak demand and promote grid stability. This mechanism causes significantly higher electricity prices during specific high-demand periods, usually lasting a few hours on select days throughout the year, which are known as "critical peak events". Prices are relatively predictable for customers as the peak events occur in known patterns.

RTP is a strategy that reflects real-time supply and demand conditions in the electricity market and involves electricity rates that vary frequently (hourly or more frequently) based on prices formed on wholesale electricity markets.

Incentive-based DRPs

Incentive-based DR programs, also known as dispatched DR, are programs that encourage customers to reduce their electricity consumption during specific periods in exchange for financial incentives or bill credits. They are particularly effective for managing peak demand, addressing grid emergencies, and providing ancillary services to the power system by offering a more direct and immediate response compared to price-based DR programs [56], [57]. This makes them valuable tools for grid operators in maintaining system balance and reliability both large scale and small scale and can also lead to economic benefits.

Shifting loads through various incentives can for instance be achieved by offering consumers payments for shifting use of their EV charging and energy storage to off-peak time. Energy communities can enhance their level of self-consumption and again decrease energy costs overall by consuming more electricity when renewable generation is high (or however prices are low). Load shifting strategies balance local generation against consumption peaks, thus optimizing the exploitation of resources available and relieving the power grid [60], [61]. Different strategies differ in terms of their time frame of application.

A selection of the most common incentive-base DRP types is explained below.

Long-Term Capacity strategies

Long-term capacity strategies intend to curtail (non-essential) loads during peak demand periods that are forecastable or expectable. As the grid approaches overload, this might involve temporarily reducing or even shutting off discretionary loads like water heaters and HVAC systems as well as major appliances. Energy communities can rapidly adjust their energy supply-demand imbalances, avoid importing expensive electricity from the grid during peak hours and reduce system restraints by preventing non-essential loads. Curtailment is commonly regulated by predefined binding contracts and compensation rates. The most common mechanism used for curtailment strategies are Direct Load Control (DLC), Interruptible Load (IL) and Load as a Capacity Resource (LCR). DLC mechanism enables the ability for grid operators to remotely control and manage certain electrical devices or appliances. Usually, customers opt-in to the program in exchange for incentives like financial compensation. IL utilizes a similar mechanism. Consumers are notified by a signal from the grid operator to reduce their demand when requested. The difference is that the operator does not have direct access to manage consumption. LCR is the commitment to reduce or suspend consumption by a predetermined amount if system failures occur [57].

The mechanisms mentioned differ mainly in their time horizon and the type of compensation.

Short-Term Operating Reserve and Continuous Regulation strategies

Short-Term Operating Reserve (STOR) and Continuous Regulation are both important DR strategies used to maintain grid stability and operate on different, shorter timescales to serve distinct purposes.

STOR is designed to provide rapid, significant power adjustments during unexpected events or emergencies. It typically involves larger loads or generators that can respond within minutes and sustain their response for several hours. STOR participants commit to providing a specific amount of power or load reduction when called upon, often with advance notice of 20 minutes or less. This mechanism is crucial for addressing sudden, substantial imbalances in the grid, such as power plant failures or unexpected demand spikes [57], [61].

In contrast, Continuous Regulation operates on a much faster and more frequent basis. It involves making constant, small adjustments to electricity consumption or generation to maintain grid frequency within acceptable limits. These adjustments occur automatically, often within seconds, in response to real-time grid signals. Continuous Regulation participants must be capable of both increasing and decreasing their power output or consumption rapidly and frequently [57], [61].

2.6.2 Energy Storage Systems

Energy Storage Systems are a promising factor in storing surplus energy which can be utilized at the time of need to provide high grid operational flexibility and improve renewable generation integration. They provide benefits through peak shaving and energy arbitrage, contributing to grid stability, reliability and independence for energy communities or districts. A common approach is to use community energy storage (CES) within an EnC or district which involves independent battery systems but can also include thermal storage or electric vehicles and other technologies. Numerous studies have shown that shared or community energy storage is superior to individual storage, especially in terms of flexibility for the community and economic efficiency [62], [63], [64].

CES is defined as an energy storage system ocated at the consumption level, capable of serving multiple purposes beneficial to both consumers and DSOs. Research indicates that CES offers advantages over Home Energy Storage (HES) systems, such as economies of scale, energy trading, and improved grid balancing. A centralized Energy Management System (EMS) is proposed to manage CES, distributing energy among households with DERs, leading to increased self-consumption and cost savings. Furthermore, a framework enabling energy trading with CES through a dynamic non-cooperative repeated game model has been proposed, optimizing next-day energy trading. Studies also suggest predictive smart charging mechanisms for CES, though the benefits to individual households are not fully explored. Comparisons between Li-ion and Pb-acid batteries in CES show that Pb-acid batteries require larger storage capacities to achieve cost reductions [65].

In the context of this elaboration BESS and TES as flexibility options are explored in more detail. These two types are currently the most commonly used and are also suitable for small-scale applications. Other systems such as capacitor solutions currently under development or mechanical storage are also conceivable for larger applications.

Battery Energy Storage Systems (BESS)

Battery energy storage systems are becoming increasingly important in context of energy communities and shared use of energy systems. This type of CES enables a more efficient usage of local produced renewable energy through storage of surplus energy and its provision during times of high demand. Studies have shown that the integration of BESS in energy communities can offer both technical and economic advantages. They can contribute to an increase in self-consumption, reduced operational costs, and the potential to enhance community revenues. Furthermore, BESS help minimize grid back feed and improve grid stability. The optimal planning and control of these systems requires complex algorithms, that consider factors like demand forecasting, renewable energy production and energy pricing [66].

To provide optimal configurations and operation schemes of energy communities, it is possible for CES to be used in load balancing and peak shaving. CES allows to feed in or discharge power from the grid, helping with supply-demand mismatches and replacing expensive peak generation. This process, called net load ramping, is a functionality batteries perform particularly well because they can rapidly increase and decrease their average output to offset changes in the critical area of the power system. Moreover, by optimizing BESS operations while accounting for battery degradation, energy communities can achieve significant cost savings and lower carbon emissions, particularly when integrating renewable energy sources. The primary objective is to minimize operational costs while ensuring stable and efficient performance at the lowest possible price [67], [68].

Thermal Energy Storage for Heating and Cooling Demands

TES can be utilized to shift heating and cooling needs off peak-hours. TES stores energy when it is thermally available, during low demand periods. This can help to reduce the need for peak power generation and increase capabilities of solar- or wind-energy systems. This can lead to both economic and environmental benefits for the EnC by optimizing self-consumption and reducing reliance on fossil fuel [68].

2.6.3 Distributed Energy Resources

DER comprise a large number of decentralized generation, storage and control systems that are typically installed close to the end consumer and often at the level of energy communities or energy districts. The term includes photovoltaic systems, battery storage, small wind turbines, micro combined heat and power (micro-CHP) systems and DSM systems. In combination, these technologies can offer significant potential for the provision of flexibility, which is increasingly seen as a key element for the integration of renewable energies and the stabilization of the energy system [69]. In energy communities and energy districts, the use of DER enables flexibility to be increased through two main channels: local DR and energy sharing. The ability to increase energy demand in times of high generation or decrease it in times of scarce resources is one of the key requirements for flexibility markets and a prerequisite for the integration of high shares of renewable energy. This flexibility provision can be optimized through local regulation, coordination and aggregation of DER, which also strengthens the resilience and cost efficiency of the EnC [70].

The provision of flexibility via DER in energy communities or districts takes place through various control mechanisms, including automated controls and real-time energy price signals. Aggregators play a central role here, as they can bundle the flexibility of several small DER and offer it in bundles on flexibility markets. The aggregation and provision of this flexibility can be realized through digital platforms and control systems that take into account real-time data on electricity prices, demand and generation. The use of such control mechanisms is necessary to manage the volatility of energy consumption and generation and to ensure efficient operation of the electricity grid [58], [71]. Modern measurement and control technologies (such as smart meters and IoT sensors) collect real-time data on consumption and generation and transmit it to centralized or decentralized control units. With the help of algorithms for forecasting and optimization, these systems can then react automatically to fluctuations and adjust consumption or generation. One common approach is real-time load control through DMS. DSM makes it possible to control energy consumption in specific time windows. By adapting loads in households or commercial facilities to fluctuations in renewable energy generation in real time, energy demand can be reduced during periods of low production and increased during periods of high availability.

In the following two common approaches suitable for energy communities or districts are elaborated.

Microgrids with Islanding Capability

Microgrids, often referred to as active cells in power systems, can operate in two distinct modes: interconnected or islanded. In interconnected mode, microgrids manage power flows between the local grid and the larger utility grid, optimizing the integration DERs. In contrast, in islanded mode, the microgrid temporarily disconnects from the main grid and operates autonomously, which is particularly valuable during grid disruptions or in regions with unreliable power supply.

With well-designed control capabilities, microgrids can flexibly transition between these modes, ensuring operational stability and efficient DER management under varying conditions. Microgrids often incorporate PV, small wind turbines, battery storage, and emergency generators, making them versatile tools for enhancing resilience and reliability.

In the context of energy communities, microgrids serve as a critical enabler for localized energy generation, consumption, and sharing. They offer an alternative model of operation that prioritizes self-sufficiency and reduced dependence on the primary grid. This is especially relevant in energy communities seeking greater resilience and autonomy. For remote or isolated communities, islanded microgrids provide a sustainable solution to address energy access challenges, offering a pathway to reliable and clean electricity supply without requiring extensive grid infrastructure.

By highlighting their dual-mode operation, microgrids stand out as a flexible solution adaptable to both rural and urban settings, as well as for remote or interconnected applications. Whether serving as a backup system for emergencies or as the backbone of an energy community, microgrids empower decentralized energy systems while complementing larger grid networks. [72].

Electric Vehicle (EV) Integration

The growing number of EVs offers considerable potential for flexibility through V2G technology. Here, electric vehicles not only act as electricity consumers, but also as mobile energy storage units that can absorb surplus energy from the grid and feed it back into the grid when required. This bidirectional energy flow option offers flexibility for the grid, especially during peak times. While EVs are charged when demand is low, they can be used as an energy source at peak times. Targeted control of these V2G systems could make a significant contribution to grid balancing and flexibility services [73].

This requires intelligent charging stations that contribute to flexibility. Such charging stations enable precise control of charging times and power and adapt to the availability of renewable energy or the grid load. Bidirectional charging stations can be programmed to charge during periods of low grid load and pause or even feed power back into the grid when grid load increases. This technology allows EVs to be flexibly integrated into the grid and at the same time offers end users economic incentives [74].

2.6.4 Sector Coupling

Sector coupling refers to the integrated use and connection of different energy sectors such as electricity, heat, mobility and industry. The aim is to increase flexibility in the energy system, particularly at the level of energy communities and energy districts. Sector coupling plays a central role in decarbonization and enables the efficient use of renewable energy by transferring surplus energy from one sector to another and storing or using it there. Sector coupling enables flexibility by balancing demand and supply across the various sectors. For example, a local energy surplus can be used to charge battery storage systems, produce hydrogen or heat thermal storage systems. One well-known example is power-to-heat systems, which convert electrical energy into thermal energy and can be used for heating systems or hot water [75].

Power to Heat: Use of surplus electricity for heat production

Power-to-heat applications are particularly valuable for energy communities as they enable surplus electricity to be efficiently converted into heat. Surplus energy from local solar or wind installations is converted into heat by electric boilers or heat pumps, which is then used in heating systems or hot water storage tanks. By using a heat storage tank, the heat produced can be called up when needed so that residents can benefit from sustainable energy at adjusted time. For energy communities, this solution not only reduces the need for fossil fuels, but also the need to feed surplus electricity into the main grid, which helps to avoid grid bottlenecks. In addition, the integration of power-to-heat reduces operating costs, as the energy is used locally and there are no additional costs for grid connection or transportation. Studies show that power-to-heat systems can increase local added value and significantly reduce CO_2 emissions at the same time [75].

Power-to-Gas: Long-term storage through hydrogen production

Power-to-gas offers a way of storing surplus electricity in the long term, which is particularly useful in energy communities with highly fluctuating renewable energy yields. One method is to use the surplus electricity to split water into hydrogen and oxygen using electrolysis. The green hydrogen produced can either be stored on site or fed into existing gas grids.

Hydrogen is a versatile energy carrier: it can be used to generate electricity in fuel cells or burned in heating systems as required. As hydrogen can also be stored in large quantities, power-to-gas is particularly suitable as long-term storage for the winter, when solar energy production is lower. The use of power-to-gas technologies enables energy communities to be almost self-sufficient, as hydrogen can also be used for industrial applications or as a fuel for fuel cell vehicles. Scientific research shows that power-to-gas is a key solution for integrating high shares of renewable energy, as it increases seasonal storage capacity and improves energy security [76].

Power-to-cooling: using surplus energy for cooling

Power-to-cooling is an efficient application of sector coupling, especially in regions with high cooling requirements. By using surplus electricity from renewable energies, the cooling of buildings can be made more energy efficient. The process works in a similar way to power-to-heat, but uses cold instead of heat as a form of storage. If surplus solar power is available, it is used to operate cooling devices or thermal storage units, which then provide cold water or cold air for air conditioning systems.

An integrated power-to-cooling system could reduce the load on the grid during periods of high temperatures and strong solar radiation, while providing greater comfort for residents. Research has shown that power-to-cooling combined with thermal storage is an efficient way to reduce peak loads and maximize the use of solar energy by smoothing energy demand and stabilizing the grid [77].

2.6.5 Barriers to Flexibility in Current Market Models

Flexibility is increasingly recognized as a critical factor for integrating renewable energy, improving grid stability, and enhancing the overall efficiency of energy systems. However, the current market models often pose significant barriers to achieving flexibility at scale. These barriers can be broadly categorized into regulatory, economic, technical, and behavioural gaps. These are explored in the following:

Regulatory Barriers

- Inadequate Market Design for Flexibility

  Many existing electricity markets prioritize centralized generation and fail to effectively accommodate decentralized resources such as DERs or aggregated flexibility. For example, the absence of frameworks for valuing flexibility services in local markets restricts their integration into grid operations. Additionally, regulatory ambiguity concerning the roles of aggregators or energy communities leads to uncertainty and limited participation.

- Fragmented Policies Across Jurisdictions

  Disparities in regulatory approaches across regions hinder the standardization and interoperability required for cross-border flexibility trading. Energy communities often face varying rules regarding grid access, compensation mechanisms, and data-sharing requirements, complicating the implementation of flexibility solutions.

- Barriers to Aggregator Participation

  Aggregators, which are pivotal for bundling small-scale flexibility resources, encounter significant hurdles such as high licensing costs, complex registration procedures, and unclear settlement mechanisms. For instance, market entry costs for aggregators in the European Union remain high despite the Clean Energy Package’s intention to promote their inclusion.

Economic Barriers

- Insufficient Monetization of Flexibility

  Existing market structures often undervalue flexibility services, particularly those provided by residential prosumers or energy communities. While ancillary service markets cater to large-scale actors, smaller participants are often excluded due to high transaction costs or insufficient compensation structures.

- High Investment Costs

  Flexibility-enabling technologies, such as BESS, TES, and smart grid infrastructure, require significant upfront capital. Studies indicate that the long payback periods associated with these investments deter adoption, especially for smaller energy communities.

- Misaligned Incentives

  Flat-rate tariffs, still prevalent in many regions, fail to provide the price signals necessary to incentivize DR or flexibility investments. While grid operators typically operate under cost-based or incentive-driven revenue frameworks, these models may still create indirect barriers to flexibility. Incentive schemes may prioritize operational efficiency or network expansion over investments in technologies that reduce peak demand or improve demand-side flexibility. This disconnect can limit the deployment of solutions that align with broader energy transition goals, such as reducing grid stress during peak periods or enhancing system reliability through demand-side participation.

Technical Barriers

- Limited Grid Infrastructure

  Legacy grid infrastructure, designed for unidirectional power flows, struggles to accommodate bidirectional flows from DERs or V2G systems. Upgrades to enable real-time data exchange and automated control are often costly and time-consuming.

- Interoperability Issues

  The absence of standardized communication protocols and control frameworks impedes the integration of diverse flexibility resources. For example, proprietary systems for DERs often lack compatibility, making seamless operation within energy markets challenging.

- Forecasting and Control Challenges

  Accurate forecasting of renewable energy generation and demand is critical for flexibility management. However, uncertainties in weather conditions and user behaviour introduce errors that complicate grid optimization. Moreover, advanced algorithms for dynamic control, while promising, are not yet widely implemented.

Behavioural Barriers

- Lack of Consumer Awareness and Engagement

  Limited understanding of flexibility programs, dynamic pricing models, and the role of energy communities reduces consumer participation. A study by Schittekatte and Meeus [78] highlights that less than 20% of consumers in the EU are aware of DR opportunities.

- Resistance to Change

Behavioural inertia, particularly the reluctance to modify energy usage patterns or adopt new technologies, remains a significant challenge. Consumers often perceive the benefits of flexibility solutions as insufficient or abstract, further discouraging adoption.

- Perceived Complexity

  Navigating flexibility programs, such as understanding dynamic tariffs or aggregator-led schemes, can overwhelm consumers and small organizations. The lack of user-friendly interfaces exacerbates this issue, as noted in studies on smart grid acceptance.

Implications and Development Directions

Addressing these barriers requires a coordinated approach that combines regulatory reform, technological innovation, and targeted stakeholder engagement. Policymakers should prioritize harmonizing flexibility market frameworks, ensuring fair market access, and valuing services provided by smaller participants. Technological research should focus on developing cost-effective, interoperable solutions and improving forecasting and control mechanisms. Public awareness campaigns and educational initiatives are critical for empowering consumers and promoting active participation in flexibility markets.

3 Use case capitalisation towards a consumer-centric energy market design (Blueprint)

3.1 Previous work in WP2

A methodology for describing HLUCs was developed, following the IEC 62559 standard [79], which provides a structured approach for defining and describing use cases. Eight pre-liminary HLUCs were identified, each thoroughly detailed in terms of scope, objectives, stakeholders, preconditions, and the steps required for implementation. Furthermore, a detailed gap analysis highlights challenges and opportunities in the deployment of these HLUCs. This work forms the basis for subsequent project tasks and the deployment of use cases at pilot sites, ensuring a cohesive strategy for achieving ENPOWER's goals. This work is documented in D2.1 [1].

3.2 Overview

Chapter 3 presents the remainder of the work covered in T2.1, "Use Case Capitalization," building upon D2.1.

An **updated set of HLUCs**, developed through an extensive co-creation process involving all technical partners and numerous collaborative meetings, is presented in Chapter 3.3. This process emphasized a comprehensive approach, including defining HLUCs, establishing a standardized methodology and template, identifying relevant domains, and involving key actors. The detailed methodology underlying this work is thoroughly documented in Deliverable D2.1. However, due to the high-level nature of the HLUCs compared to UCs and their integration of multiple TEs, it was not possible to map the HLUCs directly to the pilot sites.

Furthermore, building on the refined HLUCs, a comprehensive **set of UCs** was developed. These UCs were carefully derived from the HLUCs through a rigorous process that adhered to the IEC standard. The development of these UCs also involved an extensive co-creation effort, bringing together technical partners and pilot site partners in a series of structured and collaborative meetings. This collaborative approach ensured that the UCs were not only technically robust but also tailored to the specific needs and contexts of the pilot sites. The outcome of this process was a well-defined collection of **21 UCs and 5 Sub-UCs**, each designed to address specific functionalities and objectives outlined in the HLUCs. These UCs and Sub-UCs represent a critical bridge between the higher-level conceptual framework of the HLUCs and the technical implementation of solutions of the ENPOWER project. The detailed presentation of the developed UCs and Sub-UCs can be found in Chapter 3.4.

Additionally, their relevance and applicability to the pilot sites have been carefully assessed, and a comprehensive **mapping** of these UCs and Sub-UCs **to the pilot sites** is provided in Chapter 3.5. This mapping demonstrates how the developed use cases will be operationalized within the project's framework to achieve its overall goals.

An overview of technological enablers (TE) supporting HLUCs and UCs identification can be seen in Table 1. The table also includes the partners responsible for developing the Technological enablers. All TEs are described in detail in D2.1.

Table 1: ENPOWER Technological Enablers.

TE #	TE Description	Partner

TE-1	Interactive decision support tool for EnC planning	CARTIF, INESC TEC
TE-2	SITEC-Sizing tool for EnCs	INESC TEC
TE-3	CRP social engagement management platform	DCsix, EEU
TE-4	Energy Data Space compliant tools for sovereign data management, sematic interoperability and exploitation	ED, DST
TE-5	DLT/Blockchain/smart contracts multi-purpose marketplace for increased Trust & Sovereignty and for P2P tokenised assets sharing and compensation	DST
TE-6	Digital Twins for consumer activation	INESC TEC, DST
TE-7	Consumers clustering and segmentation tools	NTUA, UNIBAS
TE-8	FATEC - Flexibility Assessment tool for EnCs	INESC TEC
TE-9	Self-consumption optimisation tool	NTUA, GEARS
TE-10	Closed-loop optimal load control and intelligent monitoring of electric appliances for residential users	NTUA, COMS
TE-11	V2G-based flexibility management platform for providing incentives to communities of EV drivers	PARITY
TE-12	OSTEC-Optimised Scheduling Tool for EnCs	INESC TEC
TE-13	AI-Powered Virtual Energy Manager (WIS4Households)	WATT-IS
TE-14	Nudging Apps for near real time closed loop consumers activation	OurPower, BLUEPRINT
TE-15	Blockchain-based hybrid coalition-based flexibility aggregation tool	DST, COMS
TE-16	P2P digital tools and platforms for consumer activation and social engagement	OurPower, BLUEPRINT
TE-17	P2P energy markets designs and algorithms	INESC TEC
TE-18	Privacy preserving tools for automated interoperable DR	EEU, DCSix, MaREI, COMS

3.3 Description of refined HLUCs

This section provides a comprehensive overview of the refined HLUCs, accompanied by detailed descriptions of the implementations identified for each HLUC. The development of these HLUCs was the result of a thorough and collaborative co-creation process, which involved active participation from all technical partners. These partners played a key role, as they are directly responsible for the development and integration of the technological enablers (TEs) that underpin the project’s objectives.

The co-creation process was intentionally structured to foster close collaboration and alignment among stakeholders, ensuring that the HLUCs are not only conceptually robust but also practical and aligned with the functional requirements and technological capabilities of the solutions being implemented. Through iterative discussions, workshops, and reviews, the HLUCs were refined to encapsulate both the high-level goals of the project and the specific functionalities that the TEs can support. This approach ensured that the HLUCs are well-grounded in the technical realities of the project, enabling a seamless transition from conceptualization to implementation.

The detailed presentation of these refined HLUCs in this section provides insight into their purpose, scope, and the ways in which they guide the development and deployment of the project's technological solutions. A list of refined HLUCs grouped by domain can be found in Table 2.

Table 2: List of refined ENPOWER HLUCs grouped by domain.

Domain	#	Name of UC
Digitalisation of EnCs	HLUC1	EnC clustering and segmentation
Forecasting and modelling of EnC	HLUC2	Flexibility assessment of EnC
Forecasting and modelling of EnC	HLUC3	Digital Twins for consumer-aware optimal flexibility provision
Community-Centered Digital Service	HLUC4	Community centred services
EnC market operation	HLUC5	P2P renewable marketplace for energy and flexibility demand
User-centered Interaction in support of EnCs	HLUC6	Nudging for near real-time EnC consumers activation
User-centered Interaction in support of EnCs	HLUC7	Flexibility management providing incentives to communities of EV drivers
EnC market operation	HLUC8	Decentralized Energy and Resource Exchange: A Blockchain-Enabled Tokenized Marketplace for Secure and Trustworthy Asset Sharing and Compensation
Data Sovereignty and Interoperability for EnCs	HLUC9	Privacy-preserving data collection and automated DR
Data Sovereignty and	HLUC10	Sovereign Data Management, Semantic interoperability and exploitation: EDS compliant tools for sovereign data sharing and federated learning

Interoperability for EnCs		

HLUC1 EnC clustering and segmentation.

Brief Description	Energy communities require several services for its planning and operation such as prospective EnC planning, control services, demand side management or automatic fault detection. For providing the services, detailed energy consumption (predicted or estimated) at different levels and for different end-users is required. Thus, the prediction or estimation of energy is a supporting service that is an input for other services in ENPOWER. Predictions should be as robust as possible to uncertainty and account for missing or incorrect data. However, it is not feasible to train a predictive model for every customer. Thus, clustering the end-users based on their consumption time-series is somewhat mandatory to handle the diversities of demand behaviour. Also, when there is lack of data and in combination with answers from questionnaires specifically tailored to target the behavioural and socio-economic aspects of end-users segmentation can still be possible. HLUC is combining cross-sectoral fields based on the set of socio-economic, geographic, socio-cultural, and socio-political factors and historical energy consumption data or estimated data.
Actor(s)	Aggregator EnC manager Flexibility manager Services related to end customers
Priority	high (must do)
Technology Enabler	Consumers clustering and segmentation tools (TE-7)
Trigger	Request for clustering of end customers (TE-7)
Pre-conditions	AI based library models established. Survey questionnaire answers
Post-conditions	Demand consumption and/or DR potential of EnC end customers based on a set of socio-economic, gender, geographic, socio-cultural, and socio-political factors and energy consumption data.
Basic Flow (TE-7)	Receive historical and real-time data (energy consumption of buildings or assets,.) and responses for surveys and questionnaires. Communicate the output command to other HLUC (control services, performance assessment, smart control, etc.).

HLUC2: Flexibility assessment of EnC.

Brief Description	Estimates the potential flexibility of EnC based on casual models expanding them from individual to collective assessment, considering the flexibility request signals present during the operation of a EnC.
Actor(s)	EnC manager EnC members (DER owner, end consumers) Flexibility procurers
Priority	high (must do)
Technology Enabler	FATEC Flexibility Assessment tool for EnCs (TE-8)
Trigger	Request for estimation of flexibility potential
Pre-conditions	Availability of historical timeseries data (electricity consumption and prices) where flexibility request signal (dynamic tariffs, flexibility activation, etc) are provided to the Enc members.
Post-conditions	Flexibility potential of EnC members according to their response to the flexibility request signals ranking members based on that flexibility potential
Basic Flow	Step 0. EnC operation data is collected where flexibility request signals are provided. Step 1: Collected data are provided to FATEC. Step 2: FATEC assess the elasticity of EnC members and EnC as an aggregating entity in response to the flexibility request signals. Step 3: Provide the flexibility potential to the flexibility procurers requesting the service, that can use it for strategic purposes (pre-qualification, aggregation, optimization of DR strategies, etc)

HLUC3: Digital Twins for consumer-aware optimal flexibility provision.

Brief Description	Schedule flexibility-capable energy and cross-sector assets for DR flexibility provision, such as thermoelectric water boilers, heat pumps, behind-the-meter and community storage and EVs. DT allow energy and cross-sector assets be operated stand-alone or integrated into EnC energy management systems (EMS, as in HLUC 05-operation) for explicit or implicit flexibility activation depending on the assets and scenarios considered. Its integration in EMS allows also to consider their flexibility in EnC planning process (HLUC 05 planning) with simplified representative data from clustering process. In the Portuguese pilot, TE-13 will provide feedback on the impact of the adopted DR actions. Add value to end consumers with cross-sector assets by activating implicit or explicit DR flexibility and monetising their flexibility potential in the energy sector. For implicit flexibility, gains come from the savings obtained according to the supplier selling and buying tariffs (opportunity costs) of the EnC members. For explicit flexibility, gains depend on how third parties' flexibility needs and willingness to pay for it, such as DSO or BRP.

Actor(s)	EnC manager / Aggregator (the EnC could be the aggregator) EnC members (DER owner, end consumers) Suppliers Flexibility procurers
Priority	high (must do)
Technology Enabler	Digital Twins for consumer activation (TE-6) and WIS4Households (TE-13)
Trigger	DR response to implicit or explicit flexibility request, stand alone or integrated into an EMS, that should be executed from a DER or EnC management platform to supply the required inputs and apply the resulting schedules.
Pre-conditions	For operation purposes, opportunity costs and short-term forecasts of consumption and generation are needed, and the DR optimization algorithms will provide the optimal schedules for the flexible assets according to their comfort constraints. For planning purposes, expected opportunity costs and long-term forecasts or representative series of consumption and generation are needed, as well as cross-sector assets constraints. In case of SITEC (TE-2), cross-sector assets are not sized but their flexibility can be considered in the sizing process of energy assets.
Post-conditions	For operation purposes, DR outputs are used to schedule the flexible assets.
Basic Flow	Step 1: DT modelling for cross-sector assets. Step 2: Cross-sector assets scheduling for optimal operation using their DT. Step 3: KPI assessment from the DT optimal operation. Step 4: DT integration in EnC operation models.

HLUC4: Community centred services.

Brief Description	This HLUC considers planning and operation of EnC. Planning tools: Energy (TE-2) and cross-sector (TE-1) assets will be considered in the planning process of an EnC. The energy sizing assets tools SITEC from TE-2 will integrate DT from HLUC-03 to consider their impact in the energy assets sizing. From expected opportunity costs, flexibility needs and value, and representative series of generation and consumption, SITEC will propose the optimal size of the energy assets considering implicit or explicit flexibility. SITEC will be run from TE-1 that may provide different scenarios to assess the impact on the sizing process.

	Tools developed are based on implementation of forecasting techniques for different energy problems (supervised and unsupervised learning methods, as well as artificial neural networks. In this HLUC the aim is to increase accuracy of services by training a large set of ML/DL models utilising a rich dataset of heterogenous static and dynamic data – ie., Greek and Hungarian pilots in order to deliver a self-optimisation consumption tool for consumers and EnCs. Another set of scenarios, such as the integration of heating and cooling assets, among others, will be considered in EnC planning (TE-1). For this purpose, open-source models will assist the energy modelling of EnCs for providing pre-feasibility studies. The tool will rely in country specific data and EnC clustering and segmentation to provide a recommendation to the user. Operation tools: energy management tools TE-9 and OSTEC (TE-12) compute the optimal schedules of the flexible assets considering the opportunity costs of the EnC members, the assets constraints, the short-term forecasts of consumption and generation of the EnC members, and in case of explicit flexibility, the expected flexibility needs and value. DT from HLUC-03 will be integrated. In the Portuguese pilot, TE-13 (WIS4Households) will provide load disaggregation and AI-powered recommendations for end users, trigger DR and will be coupled with an EnC management platform (WIS4Communities).
Actor(s)	EnC manager / Aggregator (the EnC could be the aggregator) manager / Aggregator (the EnC could be the aggregator) EnC members (DER owner, end consumers, citizens) Suppliers Flexibility procurers
Priority	high (must do)
Technology Enabler	TE-1 and SITEC (TE-2) for the planning process. TE-9 and TE-12 for the operation process. TE-6 to integrate new assets DT model. TE-13 (WIS4Households) to provide AI-powered recommendations.
Trigger	1) Planning process: request for EnC planning 2) Operation process: a management platform must supply the required data to the operation optimization tools that return the optimal schedules for the flexible assets. These schedules must be recovered by the platform and applied to schedule the assets.
Pre-conditions	The planning process requires representative data resulting from the HLUC-1 and TE-7, expected opportunity costs, flexibility value, assets investments costs. The operation process requires the opportunity costs of the EnC members, assets constraints, flexibility needs and price, and short-term forecasts.
Post-conditions	For planning purposes, outputs provide approximate optimal sizing of the assets considered. For operation purposes, DR outputs are used to schedule the flexible assets.

Basic Flow (Planning)	1) Receive planning request. 2) Scenarios and planning options selection. 3) Receive estimated or historical data (energy consumption of buildings or assets, weather data, etc.). 4) Estimate based on the country database a set of scenarios tailored to the user. 5) End-user can prioritise some scenarios. 6) Calculate the outputs of each scenario and communicate the output to the user (or other HLUC). 7) Show users the results in a user-friendly interface. 8) Receive feedback from the user.
Basic flow (operation)	1) Integrated into a EnC EMS, receives short-term forecasted consumption and generation data, opportunity costs, and assets constraints. 2) Compute the optimal schedules of the flexible assets. 3) Provide the optimal schedules to the EnC platform to be applied to schedule the flexible assets.

HLUC5: P2P renewable marketplace for energy and flexibility demand.

Brief Description	In this HLUC, a P2P marketplace for renewable energy is considered, which enables energy and flexibility trading for and between end users (energy consumers, producers and "prosumers" as well as communities). On the marketplace, end users offer bids considering the energy demand/production, the energy price and availability. In the first step, the local energy market is a post-delivery pool-based tool which computes the transactions after delivery, as allowed by the self-consumption regulation with dynamic coefficients. P2P transactions are computed in a market-based approach, based on the actual behaviour of the P2P/REC members (sellers = producers net injection into the grid, buyers = consumers net consumption from the grid) and their opportunity costs for each Interval Settlement Period. Sellers are active customers who offer their energy production to end customers and buyers are active customers who choose their own supplier. In the second step, flexibility trading is possible. This includes a delivery of notification of activation requests to the EnC as a Flexibility Service Provider in a reliable and timely manner according to the relevant terms and conditions applicable to pilot site. End users can choose to follow the DR (nudging). Furthermore, aggregated energy production (as well as a forecast of the aggregated energy production) can include financial benefits for energy producers due to better market conditions. Large energy production volumes are better valued by energy traders. Local flexibility and energy

	transactions can be integrated to solve the imbalances that the flexibility provision causes to the retailers, i.e. flexibility deliveries are translated into energy transactions to compensate changes in the suppliers expected portfolio's from aggregator's activations using self-consumption allocation.
Actor(s)	EnC manager Active customer Aggregator Services related to end customers Market operator
Priority	high (must do)
Technology Enabler	P2P digital tools and platforms for consumer activation and social engagement (TE-16), P2P energy markets designs and algorithms (TE-17)
Trigger	Energy trading: bids from energy deliveries and opportunity costs. Settlement: energy tradings and self-consumption/production allocations. Request flexibility activation
Pre-conditions	The P2P marketplace requires participant registration, profile management and analysis, flexibility activation and account settlement. Energy trading requires the opportunity costs of the EnC members and access to metered data. Self-consumption regulation also limits the energy market capabilities. Flexibility and DR data models/ontologies that have been established will be used.
Post-conditions	Activation requests are notified and confirmations obtained, schedules optimized and activated, ongoing operations monitored and adjusted, and finally, accounts are settled
Basic Flow	Flexibility Steps • Registrate active customers and create detailed profiles • Aggregate and list available flexibility on the marketplace • Analyze flexibility demand • Manage bid submissions • Evaluate and select bids • Notify activation requests • Obtain activation confirmations • Optimize schedules and activate • Monitor and adjust • Settle accounts Energy trading steps: • Registrate active customers and create opportunity costs profiles, or pricing bids • Access active customers metered deliveries • Receive active customers and flexibility commitments • Compute flexibility energy trade compensations • Compute energy P2P trades • Compute allocation coefficients

HLUC6: Nudging for near real-time EnC consumers activation.

Brief Description	In this HLUC all the end-users (energy consumers, producers and "prosumers") of the nudging applications will interact with the different user interfaces (UI) conceived using a user-centered approach that will adapt to the level of interaction and automation each user demands from the system. The user interfaces will be used by the different end-users considered: building managers, occupants, grid operators and citizens/communities. Each nudging user interface will adapt to the different profiles for each of the users so the different functionalities considered for each of them are presented in an accessible way that can be adapted within user needs. The occupants will be the most favored by these user-centered and self-learning algorithms requiring fewer manual interventions as the services that will appear will be the ones that are needed and that simplify the occupants' life. ENPOWER user interfaces will consider the different aspects and needed functionalities for each of the end-users' profiles so they will not see content that is not necessary to complete their related functionalities. The objectives of this HLUC are related to the user satisfaction when using applications and: 1. Should be easy to use and accessible 2. Should only have each user profile related functionalities 3. Should adapt to the different users 4. Should accomodate the ability to manage relationships between users and communities 5. Should allow all stakeholders to be able to interact (community, manager, System Operator or Citizen
Actor(s)	EnC manager Services related to end customers Market operator Citizens
Priority	high (must do)
Technology Enabler	CRP social engagement management platform (TE-3), Consumers clustering and segmentation tools (TE-7), FATEC - Flexibility Assessment tool for Energy Communities (TE-8), Nudging Apps for near real time closed loop consumers activation (TE-14)
Trigger	Register of opportunites from Energy Audit, Register of opportunities from Master Plan Community Campaign TSO DSO Request from flexibility operator to activate DR
Pre-conditions	The following steps are necessary to implement the different features within the application: • Identify each actor (building managers, occupants, grid operators and citizens/communities) requirements

	- Receive the data that will be collected, processed, and stored by the application and - identify the different functionalities needed for each of the profiles that will be created on the application (HLUC1) Involve the actors in the development of the application interfaces
Post-conditions	Dashboards to present all the data from HLUC01 and this HLUC and the different data considering energy profile, local weather data, building energy, energy flows, energy consumption/production and energy prices (e.g. hourly prices). A set of metrics demonstrating the Energy efficiencies and or flexibility unlocked
Basic Flow	Pre-Steps: - Collect and analyse the details for each pilot site (existence of nudging App, details about users/communities/buildings, baseline consumption, flexibility ability, etc.) - Use input by the segmentation questionnaires as well as by the facility manager questionnaires - Realize the co-creation workshops for every pilot site - Collect feedback from the co-creation workshops - Design nudging interventions based on the above steps Main flow: - Deploy nudging services

HLUC7: Flexibility management providing incentives to communities of EV drivers.

Brief Description	EV charging management platform (including an app for EV drivers) provides real time data related to charging stations and manages future reservations on publicly accessible charging stations. In ENPOWER, this UC will be enriched with smart charging module which can investigate smart charging load management patterns, such as Load Valley filling (load management that decreases charging during peak loads). It will also facilitate vehicle-to-grid transactions and incentivise users to shift charging schedule or discharge their vehicle to support the grid.
Actor(s)	EnC manager Services related to end customers (EV) DSO Market operator
Priority	high (must do)
Technology Enabler	V2G-based flexibility management platform for providing incentives to communities of EV drivers (TE-11)
Trigger	Request to shift charging schedule or discharge their vehicle to support the grid
Pre-conditions	The following steps are necessary to implement the different features within the application: Identify each EV owner requirements

	• Receive the data that will be collected, processed, and stored by the application and • identify the different functionalities needed for each of the profiles that will be created on the application (HLUC1) • Involve the actors in the development of the application interfaces
Post-conditions	Dashboards to present all the data from HLUC01 and this HLUC and the different data considering EV profile, energy flows and energy consumption.
Basic Flow	Receive historical and real-time EV data (energy consumption, charging locations, load profiles, etc.). Communicate the output command to other HLUC (control services, performance assessment, smart control, etc.).

HLUC8: Decentralized Energy and Resource Exchange: A Blockchain-Enabled Tokenized Marketplace for Secure and Trustworthy Asset Sharing and Compensation.

Brief Description	This task will deliver an open interoperable tokenised marketplace (TE-5) where different types of energy and nonenergy resources, tangible, and intangible assets will be valued, shared, and exchanged. Tokens will be utilised as a rewarding mechanism for services offering, while also allowing to exchange reciprocal surplus of heterogeneous intangible and tangible resources. The marketplace will implement trustable and secure mechanisms for heterogeneous assets tokenisation. These mechanisms will be implemented relying on smart contracts to be executed in the blockchain platform. They will include all the policies of accessing / exploiting and the valorisation strategy of these digital assets, which will be completely transparent for the market participants.
Actor(s)	Active customer DER owner End user Grid operator
Priority	high (must do)
Technology Enabler	DLT/Blockchain/smart contracts multi-purpose marketplace for increased Trust & Sovereignty and for P2P tokenised assets sharing and Compensation (TE-5)
Trigger	The benefits for customers vary depending on the DR or energy type. For Implicit DR, gains are calculated based on suitable tariffs, which can either be market-based or driven by sustainability goals such as green tariffs. For Explicit DR, gains are determined by incentives aimed at addressing external signals like congestion or balancing market prices.
Pre-conditions	• It enables to activate flexibility options and handle financial settlements. • The marketplace uses specific data structures called flexibility and DR data models or ontologies to organize and understand the data effectively.

Post-conditions	• Activation requests are notified and confirmations obtained depending of the validation of each user. • Schedules are optimized and activated. • Ongoing operations are monitored and adjusted. • Accounts are settled.
Basic Flow	1. Register participants and create detailed profiles. 2. Aggregate and list available flexibility on the marketplace. 3. Analyze flexibility demand. 4. Manage bid submissions. 5. Evaluate and select bids. 6. Notify activation requests. 7. Obtain activation confirmations. 8. Optimize schedules and activate. 9. Monitor and adjust ongoing operations. 10. Settle accounts.

HLUC9: Privacy-preserving data collection and automated DR.

Brief Description	This task will deliver a means to collect, process and manage data in a privacy-preserving way while conforming to GDPR. A platform will provide grounds to expose the data to the services in an interoperable, transparent and traceable manner. It will provide integration of DERs and other data sources according to the owner's consent and preferences, provide a GDPR-compliant user privacy preservation mechanisms and provide standardised APIs to services. The platform will provide a blockchain and non-blockchain-based solution for traceable privacy protection engine that allows to manage rules, policies, consents and permissions for data collection, processing and exchange. The platform will provide tools to monitor EnC and individual user 58resumption, plan and execute DR requests.
Actor(s)	DER unit Active customer EnC manager DER owner End user Flexibility manager
Priority	high (must do)
Technology Enabler	TE-10: Closed-loop optimal load control and intelligent monitoring of electric appliances for residential users TE-15: Blockchain-based hybrid coalition-based flexibility aggregation tool TE-18: Privacy-preserving tools for automated interoperable DR
Trigger	1) Customer requests/allows data collection and data processing to provide DR 2) EnC manager creates new user in EnC and starts collecting data and processing data to provide DR
Pre-conditions	USG-based privacy-preserving data collection and automated DR system has to be deployed by EnC manager and data collection equipment installed on user's premises. All users has to provide consents for data

	collection, data processing or data sharing according to GDPR. In case the user enforces his/her right to be forgotten, all collected data has to be deleted.
Post-conditions	System collects data from EnC users that gave consent for data collection and data processing. Based on the available data, the system provides aggregated 59resumption data to the EnC manager which enables him/her to optimise EnC 59resumption and provide DR.
Basic Flow	1. EnC manager deploys privacy-preserving data collection and automated DR system for EnC management 2. Data collection equipment has to be installed at EnC user premises 3. Data collection services have to be deployed 4. Each EnC user has to provide consents for each data source for data collection, data processing and data sharing 5. System collects data for users that provided consents 6. System aggregates 59resumption profiles for whole EnC 7. Collected data can be exposed to other services in an interoperable way 8. DR can be exposed over common interfaces 9. If EnC user exercises his/her right to be forgotten, user's data has to be deleted, data collection stopped and user completely removed from EnC

HLUC10 Sovereign Data Management, Semantic interoperability and exploitation: Energy Data Space compliant tools for sovereign data sharing and federated learning.

Brief Description	The use of **Energy Data Space compliant tools** (TE-4) in order to provide interconnectivity among local business platforms and marketplaces, enabling a set of data-driven services (WP5). We will leverage on H2020 BDNRG IDSA/GAIA-X compliant User Access Control and on H2020 BRIGHT and PHOENIX Privacy Preserving Secure Universal gateway to develop and deploy a DLT/Blockchain/Smart Contract based privacy-embedding IDSA/GAIA-X compliant User Access Control. Usage policies and the automatic enforcement of these policies by the Data Space building blocks will give data providers 'control' over the data after it being shared. We will provide a federated privacy-preserving learning environment adapted from H2020 BD4NRG for collective knowledge extraction from data and provision of privacy preserving data-driven services to consumers and communities.
Actor(s)	Data Producer Data Owner Data Consumer Data User
Priority	Normal
Technology Enabler	EDS compliant tools for sovereign data management, sematic interoperability and exploitation (TE4)
Trigger	• Facilitation of interoperability among different systems and platforms

	• Need for data exchange and information in a secured and trusted manner
Pre-conditions	• Onboarding (Registration) • Certification
Post-conditions	n/a
Basic Flow	**Basic Data Exchange [Data Transfer via the Same Infrastructure and Protocol]** 1. Data Offering 2. Contract Negotiation 3. Data Operation Invocation 4. Data Operation Result **Basic Data Exchange [Data Transfer via another Infrastructure and Protocol]** 1. Invoke Data Operation 2. Process Data Operation 3. Provide Access Information 4. Trigger Data Transfer 5. Request Data Operation Result 6. Provide Data Operation Result 7. Notify Success

3.4 List of UCs

The finalized set consists of 21 use cases and 5 Sub-UCs, each carefully designed and tailored to address the unique characteristics and requirements of specific pilot sites. This tailoring was accomplished through an intensive and iterative refinement process, which brought together technical partners, who contributed their expertise in technological enablers, and pilot site representatives, who provided invaluable insights into the practical, real-world contexts in which these solutions will be deployed. The five Sub-UCs (Sub-UCs) were created to focus on specific data-sharing and exchange processes, providing modular components that enhance security, transparency, and interoperability in energy platforms. These Sub-UCs act as foundational elements to support broader use cases, ensuring adaptability and alignment with technical enablers and standards across various project contexts.

These collaborative efforts were conducted through structured workshops, meetings, and consultations, ensuring that the use cases and Sub-UCs were not only technically feasible but also aligned with the operational needs and constraints of the pilot sites. This process emphasized the importance of co-creation and adaptability, enabling the development of solutions that are both innovative and grounded in practicality.

The outcomes of these refinements serve as a robust foundation for the deployment of ENPOWER solutions. By bridging the gap between conceptual frameworks and field implementation, they establish a critical link to the project's ongoing efforts. These use cases and Sub-UCs will directly inform subsequent tasks, guiding the development, testing, and integration of solutions during the pilot phase. Furthermore, they are instrumental in ensuring the scalability and transferability of the project's outcomes, paving the way for broader application beyond the initial pilot sites. Table 3 represents the mapping of the HLUCs and UCs / Sub-UCs.

Table 3: Mapping HLUC and UC / Sub-UC

HLUC	UC / Sub-UC	TE#
HLUC1 - EnC clustering and segmentation	UC1 - Data-driven Electrical Load Consumption Clustering + Segmenting users based on questionnaire responses	TE-7
HLUC2 - Flexibility assessment of EnC	UC2 - Assessing DR Potential in Energy Communities	TE-8
HLUC 3 - Digital Twins for consumer-aware optimal flexibility provision	UC3 - Personalized Consumer Engagement and Activation	TE-13
	UC4 - Simulation with Digital Twins of Individual Thermal Assets and integration into OSTEC EnC Management System	TE-6, TE-12
HLUC4 - Community Centred Services	UC5 - Individual self-consumption optimisation	TE-9
	UC6 - Collective self-Consumption Optimization	TE12, TE13
	UC7 - AI-Powered Virtual Energy Management	TE13
	UC8 - Planning the Expansion of Existing Energy Communities	TE1, TE-2
HLUC5 - P2P renewable marketplace for energy and flexibility demand	UC9 - Optimization of a P2P energy trading platform	TE-16
	UC10 - Development of and EnC management platform	TE-16
	UC11 - Design of local markets and sharing mechanisms for energy and flexibility provision in energy communities	TE-17
HLUC6 - Nudging for near real-time EnC members activation	UC12 - (Near) Real-Time DR Activation through Nudging Apps	TE-14
	UC13 - Social Engagement Management Platform	TE-3, TE-14
	UC14 - Personalized Energy Efficiency Recommendations	TE-3, TE-14
HLUC7 - Flexibility Management Providing Incentives to Communities of EV Drivers	UC15 - Dynamic Pricing and Incentive Management for EV Flexibility	TE-11
HLUC8: Decentralized Energy and Resource Exchange: A Blockchain-Enabled Tokenized Marketplace for Secure and Trustworthy Asset Sharing and Compensation	UC16 - Decentralized Data Marketplace for Energy Data Sharing	TE-5
	UC17 - Tokenized Compensation for DR Services	TE-5

HLUC9 - Privacy-Preserving Data Collection and Automated DR	UC18 - Automated DR for Energy Management	TE-18
	UC19 - Blockchain-Based Privacy-Preserving Flexibility Aggregation for DR Programs	TE-15
	UC20 - Intelligent Monitoring and Control for Privacy-Preserving Load Management	TE-10
	UC21 - Secure and Privacy-Preserving Data Exchange for DR Programs	TE-18, TE-3
HLUC10 - Sovereign Data Management, Semantic Interoperability, and Exploitation: EDS Compliant Tools for Sovereign Data Sharing and Federated Learning	Sub-UCA - Building the SEMAPTIC specification to make a service semantically interoperable	TE-12
	Sub-UCB - Sovereign Data Sharing for Energy Consumption Prediction	TE-4, TE-5, TE-6, TE-7, TE-15, TE-16, TE-17
	Sub-UCC - Federated Learning for Energy Efficiency Optimization	
	Sub-UCD - Secure Data Transfer via Blockchain and Smart Contracts	TE-4, TE-5, TE-15, TE-16, TE-17
	Sub-UCE - Secure Data Exchange	TE-4, TE-5, TE-15, TE-16, TE-17, TE-18

Table 4 presents the UC template that served as the basis for the technical partners to develop the various Ucs, and Sub-UCs. This is followed by detailed descriptions of UC1 through UC21 and Sub-UCs A through E.

Table 4: Use case template.

USE CASE	
ID	<a sequential reference number>
Name	<short name of the use case>
Goal(s)	<the functionality or behaviour that is expected to be provided by the system once the use case is executed>
Actors	<the individuals and their means that trigger system reactions>
Trigger events	<the main action that starts the use case execution>

Preconditions		<those actions that must occur before the execution of the use case to obtain the described behaviour>
Basic Flow	**Description**	'Basic Flow' or 'Main Scenario / STEPS' is the normal workflow in the system. It is the flow of transactions done by the Actors on accomplishing their goals. When the actors interact with the system, as it's the normal workflow, there won't be any error and the Actors will get the expected output.
	Postconditions	those conditions that could occur once the use case has been executed and the system continues its operations>
Alternative flow and exceptions		Major alternative flows or exceptions that may occur in the flow of event
ID of related use case in D2.1		
Corresponding TE		
Pilot Site		

UC1: Data-driven Electrical Load Consumption Clustering and Segmenting users based on questionnaire responses.

USE CASE		
ID		UC1
Name		Data-driven Electrical Load Consumption Clustering and Segmenting users based on questionnaire responses
Goal(s)		To categorize consumers within an EnC based on their electrical load consumption patterns using data-driven clustering techniques. This allows for more efficient energy management and the design of targeted energy solutions. Segment consumers based on their sociodemographic, economic and behavioural characteristics
Actors		Members of the community that use the tools. Community manager
Trigger events		Request for clustering of end customers
Preconditions		Sharing their electrical load consumption that can be connected with the questionnaire. AI based library models established
Basic Flow	**Description**	1. Receive historical and real-time data (energy consumption of buildings or assets, weather data, etc.) and/or responses from surveys and questionnaires. 2. Consumer clustering based on ML/AI and/or statistical models and analysis. 3. Communicate the output command to other HLUC
	Postconditions	Providing load consumption clustering and segmentation based on complete set of socio-economic, gender, geographic, socio-cultural, and socio-political factors.

Alternative flow and exceptions	
ID of related use case in D2.1	HLUC1
Corresponding TE	TE-7
Pilot Site	Portuguese

UC2: Assessing Demand Response Potential in Energy Communities.

USE CASE		
ID		UC2
Name		Assessing DR Potential in Energy Communities
Goal(s)		To evaluate the DR potential within an EnC using the FATEC tool, helping to identify opportunities for shifting or reducing energy usage during peak demand periods. To assess the flexibility potential of individual community members to set up a ranking among them.
Actors		Residential consumers and EnC participants, EnC managers
Trigger events		Request for flexibility assessment, Optimization of DR program
Preconditions		Users are registered and have access to the service. Data provided must include electricity consumption and pricing
Basic Flow	**Description**	The user requires an assessment of the flexibility potential. The user provides the necessary input data to the service. Input data is fed into a data cleaning tool, which assures that the user provides the necessary data, and in the correct format. A data pre-processing tool is applied to the input data for aggregation based on the inferred measurement frequency. The processed data is fed into the causality model, which estimates the price elasticity of demand of individual or set of consumers, and the potential for flexibility given a set of prices. The consumers are ranked by their price elasticity of demand. Finally, the outputs of the causality model and ranking are retrieved by the user.
	Postconditions	The system provides results for a single or aggregated set of consumers, detailing their price elasticity of demand and flexibility potential given a set of prices. The system provides a ranking based on consumer price elasticity of demand.
Alternative flow and exceptions		If some data is not provided (e.g., weather-related variables), the tool attempts to retrieve them from public APIs. If more specific location is not provided, the tool retrieves data that is averaged for the country.
ID of related use case in D2.1		HLUC2

Corresponding TE	TE-8
Pilot Site	Portugal

UC3: Personalized Consumer Engagement and Activation.

USE CASE		
ID		UC3
Name		Personalized Consumer Engagement and Activation
Goal(s)		To use digital twins for personalized consumer engagement, providing tailored tips and possibly DR to enhance flexibility while considering individual household preferences and behaviours.
Actors		Residential consumers and EnC participants.
Trigger events		When the end users register in the pilot and/or when the EnC is established.
Preconditions		Users registered in the pilots and having smart meters that are integrated in the Portuguese smart grid and communicating. Also, for implementing DR, specific controllers and real-time meter (such as WIS-Connector) need to be installed and reliable WLAN network.
Basic Flow	**Description**	Data flows will trigger a service that can identify the best periods to use certain flexible loads with quantified benefit. To implement DR, it is needed the installation of real-time actuators and remeasuring devices at the users' homes, establish the communication with the DR service and optimal scenarios will be calculated and then act within flexible loads, trying to maximize the benefit for the end user (maximizing self-consumption from own PV system or from the EnC and maximizing benefit from time-sensitive tariffs.
	Postconditions	Tailored tips will be provided and continuously fed by historical data and, in the possibility of implementing DR, those houses will keep on having automated control over flexible loads while balancing with a positive user acceptance and comfort.
Alternative flow and exceptions		-
ID of related use case in D2.1		HLUC 3
Corresponding TE		TE-13
Pilot Site		Portugal

UC4: Simulation with Digital Twins of Individual Thermal Assets and integration into OSTEC Energy Community Management System.

USE CASE

ID		UC4
Name		Simulation with Digital Twins of Individual Thermal Assets and integration into OSTEC Energy Community Management System
Goal(s)		To optimize the dispatch of thermal loads (thermoelectric water heaters, EWH - heating, ventilation, and air conditioning - HVAC), and integrate the DT models into OSTEC EnC management system. This solution aims to enhance the efficiency, cost-effectiveness, and dispatch of flexibility assets by analysing consumption data and improving the management of thermal assets.
Actors		Individuals (residential, commercial) or EnC potential members with thermal assets, EnC manager, DSO, Retailers.
Trigger events		Inefficient (not optimized) use of thermal appliances; DR; Load shifting, Flexibility provision, Simulation of an EnC request.
Preconditions		Data availability: consumption and generation, energy buying and selling prices, thermal loads specifications, EnC structure, appropriate regulatory framework.
Basic Flow	**Description**	The digital twins provide cost/energy savings, flexibility periods, and optimized usage calendarization by processing thermal loads diagrams, thermal load specifications, and user-defined inputs. They ensure the delivery of consumer-defined comfort levels, subject to constraints, while minimizing operational costs or total energy consumption. In addition, the digital twins create accurate virtual representations of thermal assets' flexibility, offering planning functionalities for DR services at both individual and community levels by integrating social dimensions for thermal assets. Through their integration into OSTEC, flexible assets can be optimized for energy management, balancing user comfort, cost savings, and flexibility provision. OSTEC provides the control signals (setpoints) to must be applied (by an external systems) to the flexible corresponding assets.
	Postconditions	The system provides results to residential users, EnC managers, and shared building managers, providing the optimized thermal load diagrams, energy savings, and periods of flexibility availability. This ensures that user-defined comfort levels (e.g., minimum hot water temperature, minimum and maximum room temperature, etc.) are respected, while effectively responding to energy management strategies and lower pricing periods by shifting loads/heating to periods of higher efficiency. In addition, OSTEC dispatches all flexible resources including the thermal assets for individuals or at EnC level, and provides each EnC member's energy bill reflecting its contribution to the collective benefit. OSTEC minimizes the total EnC cost, and indirectly maximizing local renewable energy utilization and reducing dependency on external sources.
Alternative flow and exceptions		If no real data are provided for the thermal loads, the end users can provide synthetic data estimating hot-water usage for a 24-

	hour period (EWH Optimization) and other HVAC connection constraints to fit the DT.
ID of related use case in D2.1	HLUC3
Corresponding TE	TE-6, TE-12
Pilot Site	Ireland

UC5: Individual self-consumption optimisation.

USE CASE		
ID		UC5
Name		Individual self-consumption optimisation
Goal(s)		To optimise individual self-consumption by dispatching the flexible assets
Actors		Residential, commercial consumers, municipality.
Trigger events		Need to find out how to reduce self-consumption.
Preconditions		Shared their energy consumption, their flexible loads (appliances, etc.)
Basic Flow	**Description**	The users register in the tool, providing details about their energy consumption patterns, the type and number of flexible assets (such as appliances and electric vehicles), and their preferences for energy usage. The tool collects data from the smart meters and other connected devices across the grid, allowing it to monitor total energy consumption in near real-time. Additionally, the tool will be collecting information on the electricity production of the renewable sources of the grid as well as forecasts on future consumption patterns. Having collected the required data, the actors will receive recommendations on how to shift their consumption loads in a way that maximizes the utility of the grid and the use of the renewables while simultaneously reducing costs.
	Postconditions	To have a tool that provide recommendations to the users to maximize renewable utility and reduce energy costs.
Alternative flow and exceptions		The tool will be monitoring the total consumption and production of the grid and make analysis on macro level even without user input. However, user data is required for the recommendation function.
ID of related use case in D2.1		HLUC4
Corresponding TE		TE-9

Pilot Site	Greek, Hungary, (Spain - Via the planning tool this UC can be partially validated)

UC6: Collective Self-consumption Optimization.

USE CASE		
ID		UC6
Name		Collective self-Consumption Optimization
Goal(s)		To optimize collective self-consumption of an EnC by dispatching the flexible assets, considering shared assets and flexibility provision.
Actors		Residential, commercial and Service Energy Consumers, Prosumers, EnC members with DR resources, EnC manager, DSO, Retailer
Trigger events		Simulation or operation of an EnC
Preconditions		EnC established; Availability of the EnC structure, members consumption and generation forecasts and flexible assets; Availability of a digital platform to provide inputs to the energy management system and apply the outputs to the flexible assets; Appropriate regulatory framework
Basic Flow	**Description**	The EnC is managed by a community manager (EGAC in the Portuguese case) that can run a pre-delivery optimization tool, such as OSTEC, to compute the optimal schedules of the available flexible assets. Community members, including consumers and prosumers that belong to the EnC make available their opportunity costs (energy buying and selling tariffs) and their flexible assets for the EnC energy management. They can buy their energy to their retailer or locally, depending on their opportunity costs and local price, and can sell their energy internally or to their aggregator (although under the Portuguese regulation EnC surplus must be aggregated and sold by the EnC manager. A settlement procedure must also be designed and implemented to compute the optimal transactions for the compensation of the EnC members for the internal energy transactions. WIS4Households can include flexibility optimization based on past consumptions of the end user and the community, triggering tailored feedback for the user to maximize self-consumption and the possibility of implementing DR in flexible loads. Then, this tool will let the users know how they have benefited from the implementation of the flexibility strategies. The flexible resources considered are batteries, electric vehicles and thermal loads (EWH or HVAC) that contribute to optimizing energy usage and reduce energy costs through flexible services.
	Postconditions	The optimal schedules of the flexible assets must be the input of an external module that applies these setpoints to the flexible assets. In case the optimal transactions are computed, a

		settlement procedure must accept them to perform the internal EnC settlement.
Alternative flow and exceptions		-
ID of related use case in D2.1		HLUC 4
Corresponding TE		TE-12, TE-13
Pilot Site		Portugal, (Spain - Via the planning tool this UC can be partially validated)

UC7: AI-Powered Virtual Energy Management.

USE CASE		
ID		UC7
Name		AI-Powered Virtual Energy Management
Goal(s)		To use the digital twin AI-powered virtual energy manager (WIS4Households) to optimize energy management in households, providing automated tailored recommendations for energy-saving actions, predicting and recommending equipment maintenance needs to ensure operation at peak efficiency, and giving tips to improve self-consumption.
Actors		Residential consumers and EnC participants.
Trigger events		When the end users register in the pilot and/or when the EnC is established.
Preconditions		Users registered in the pilots and having smart meters that are integrated in the Portuguese smart grid and communicating.
Basic Flow	**Description**	After the data transfer process is set, historical consumption data is persisted. At the frontend, the user can include metadata from their home (including appliance-related information). With that data, tailored efficiency measures are triggered, such as appliance substitution, behaviour change, among others. PV and tariff optimisation are two services that can be triggered "on demand" by the end user. After 3 months of historical data with 80% quality, a non-intrusive load monitoring (NILM) service disaggregates the load from the past month. This disaggregation further fuels the energy efficiency service, and the end user can see all the tailored feedback in the platform and can even check to adopt measures that then trigger a savings counter. This tool will then be matched with a platform that manages energy communities and where the end user will not only see these previous features but also the energy flows within the EnC. For a set of clients, DR will be implemented, and the users will be able to check the savings from the DR actions.

	Postconditions	The tailored feedback provided to the end user will keep be continuously fed by the new load consumption data, thus updating the results that have been provided. NILM results will be provided each month, and the energy efficiency measures updated within specific time periods around one to two weeks. The "on demand" tools will update their results whenever the end user clicks on the respective buttons.
Alternative flow and exceptions		If no smart meter data is obtained for a specific end user, tailored feedback can be given if the end user has added metadata of their home. Should neither metadata nor historical consumption is available, the end user will still have general feedback. However, if the user belongs to an EnC, historical consumption is mandatory.
ID of related use case in D2.1		HLUC4
Corresponding TE		TE-13
Pilot Site		Portuguese

UC8: Planning the Expansion of Existing Energy Communities.

USE CASE		
ID		UC8
Name		Planning the Expansion of Existing Energy Communities
Goal(s)		The goal is to plan the future expansion of an existing EnC, ensuring optimal use of resources and increasing RES
Actors		- REC managers and decision-makers - Municipality planners - System administrators of a community - Members of a community
Trigger events		- Decision to expand the existing REC - Need for feasibility assessment for new members or infrastructure expansion
Preconditions		- Existing REC is available - Access to necessary geographical, technical, and regulatory data
Basic Flow	**Description**	1. REC manager or municipal planner accesses the Planning Tool. 2. Input data related to the current EnC and prospective expansion areas. 3. Tool evaluates potential new members, and renewable energy sources. 4. Generates simulations of different expansion scenarios (e.g., adding new buildings, integrating additional energy sources). 5. KPIs are used to analyse each scenario.

	Postconditions	- The user receives detailed reports with simulation results. - Stakeholders can make informed decisions on the expansion.
Alternative flow and exceptions		Alternative Flows: - Change in the scale of expansion may occur, requiring recalibration of the planning. - Instead of expansion, it is just increasing the RES of the existing community Exceptions: - Lack of updated or reliable data may halt planning.
ID of related use case in D2.1		HLUC4
Corresponding TE		TE-1, TE-2
Pilot Site		Spanish and Greek pilots

UC9: Optimization of a peer-to-peer energy trading platform.

USE CASE		
ID		UC9
Name		Optimization of a P2P energy trading platform
Goal(s)		To develop a P2P energy trading platform that enables consumers and producers to buy and sell renewable energy directly with each other, optimizing energy use and supporting local renewable energy generation. The P2P energy trading platform allows members multiple participation in energy communities with a meter point (One or more energy communities according to EU's Clean Energy Package and one P2P energy trading platform for surplus feed-in and residual energy demand)
Actors		P2P platform member (consumer, producer) P2P platform manager
Trigger events		Have surplus energy available and want to share it with others; wanting to control where the surplus energy goes and who gets it and at what price
Preconditions		Participation in P2P Energy Trading Platform
Basic Flow	**Description**	User owns one or more metering points (consumption or generation) and would like to share surplus electricity with people within the region. Producers present their power plant and offer surplus energy on the P2P platform and share it with interested parties; P2P platform compiles offers for consumers and ensures that consumers

		receive a balanced mix of electricity from different types of generation to ensure that 100% security of supply is guaranteed at all times. P2P Platform provides users with the ability to manage their electricity relationships, set multiple prices for different consumer groups and select which people have access to different prices. Producers and consumers benefit from stable and transparent prices and strengthen independency.
	Postconditions	Optimized use of surplus feed-in and residual energy demand Stable and transparent energy prices
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC5
Corresponding TE		TE-16
Pilot Site		Austria

UC10: Development of an energy community management platform.

USE CASE	
ID	UC10
Name	Development of an EnC management platform
Goal(s)	To develop an EnC management platform that enables EnC members and managers to monitor and manage their energy consumption and production, share energy inside the community and administrate their community. The EnC management platform allows members multiple participation in energy communities with a meter point additionally (One or more energy communities according to EU's Clean Energy Package and one P2P energy trading platform for surplus feed-in and residual energy demand). The Austrian legislation enables this multiple participation and the possibility must therefore be given.
Actors	EnC member (consumer, producer) EnC manager DSO (data management)
Trigger events	Setting up a new EnC; being the manager of an existing EnC, with the need to manage and bill it
Preconditions	Existing infrastructure of energy communities Existing energy data management system

		Membership of more than one EnC
Basic Flow	**Description**	EnC member owns one or more meter points (consumption or production) and wants to participate in an EnC EnC managers have special access to the EnC management platform, sets the participation factor of the meter point and initiates the participation in the EnC. DSO prepares the energy data. EnC managers have special access to the EnC management platform to gain an overview of the shared energy within the EnC and the EnC members. EnC manager prepares the settlement with the energy data management system and the energy data prepared by the DSO. EnC member regularly receive transparent invoices to gain insights into the energy consumed and produced. This information will be available in more detail on the EnC management platform as the platform provides a personal cockpit for all EnC members.
	Postconditions	Optimized use of surplus feed-in and residual energy demand Stable and transparent energy prices Financial and ecological benefits because of energy communities according to EU's Clean Energy Package
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC5
Corresponding TE		TE-16
Pilot Site		Austria

UC11: Design of local markets and sharing mechanisms for energy and flexibility provision in energy communities.

USE CASE	
ID	UC11
Name	Design of local markets and sharing mechanisms for energy and flexibility provision in energy communities

Goal(s)		Elaborate a systemic view to integrate flexibility provision with post-delivery local energy markets considering the collective self-consumption (CSC) regulation.
Actors		Final consumers and prosumers engaged in self-consumption, aggregators, suppliers, DSO, community manager, flexibility market operator.
Trigger events		Development of REC and flexibility markets
Preconditions		• A definition of the flexibility market and its products. • Flexibility contracts between aggregators and prosumers. • Post-delivery local energy markets. • Self-consumption allocation rules based on allocation coefficients and balancing responsible parties.
Basic Flow	**Description**	When the flexibility market operator requests flexibility from aggregators, they activate flexibility from prosumers they previously procured. Local energy transactions can be used to compensate these prosumers' suppliers for the deviation in expected delivery, but also to allocate the flexibility to the aggregators for BRP purposes. This allocation can also be done using virtual prosumers to represent the aggregators. The settlement of the community must consider all services provided.
	Postconditions	With this use case, other community, local energy markets, and flexibility provision tolls, developed or in development, can be integrated with adjustments in an environment where flexibility provision translates into energy transactions that are settled using CSC rules.
Alternative flow and exceptions		This integration is designed for allocation based self-consumption regulations. Other regulatory models may require adaptions. It also assumes rules that are currently not considered in some countries but are necessary for local energy market to fully operate, such as dynamic allocation and virtual prosumers.
ID of related use case in D2.1		HLUC5
Corresponding TE		TE-17
Pilot Site		Portugal

UC12: (Near) Real-Time Demand Response Activation through Nudging Apps.

USE CASE	
ID	UC12
Name	(Near) Real-Time DR Activation through Nudging Apps

Goal(s)		To use nudging apps to activate energy consumers and producers in (near) real-time for DR events, optimizing energy use and balancing grid demand.
Actors		EnC member (consumer, producer) EnC manager DSO (data management)
Trigger events		A (near) real-time and/or forecast visualisation of the energy consumption/production including a recommendation for DR and an execution/rejection by the EnC member
Preconditions		Existing infrastructure of energy communities Existing energy data management system (near) real-time Existing communication channel (platform, app) Membership of one or more energy communities
Basic Flow	**Description**	EnC manager receives (near) real-time energy data from the DSO and adds the information to the energy data management system Energy data management system makes recommendations based on the (near) real-time energy data and/or the forecast EnC member receives a visualisation of the energy data and recommendations for DR via the communication channel (platform, app)
	Postconditions	After a successful DR, the EnC member (consumer) increased the energy consumption from the EnC and therefore the financial benefits After a successful DR, the EnC member (producer) regulated the feed-in and therefore did not suffer any financial losses if negative prices were necessary for the feed-in during that time
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC6
Corresponding TE		TE-14
Pilot Site		Austria

UC13: Social Engagement for Energy Saving Campaigns.

USE CASE

<table>
<tr><td colspan="2">ID</td><td>UC13</td></tr>
<tr><td colspan="2">Name</td><td>Social Engagement for Energy Saving Campaigns</td></tr>
<tr><td colspan="2">Goal(s)</td><td>To leverage a social engagement management platform to run campaigns that nudge EnC members towards energy-saving behaviours in near real-time.</td></tr>
<tr><td colspan="2">Actors</td><td>EnC member (consumer, producer)
P2P platform member (consumer, producer)
EnC manager
P2P platform manager
Social engagement manager</td></tr>
<tr><td colspan="2">Trigger events</td><td>Campaigns to raise awareness for renewable energy and energy communities and on the ecological use of renewable energy leading to a behavioural change of EnC members / P2P platform members</td></tr>
<tr><td colspan="2">Preconditions</td><td>Existing communication channel (platform, app)</td></tr>
<tr><td rowspan="2">Basic Flow</td><td>Description</td><td>EnC manager / P2P manager shares energy related data with the social engagement manager

Social engagement manager prepares recommendations (campaigns) for behavioural changes of the EnC members / P2P platform members

Social engagement manager communicated with EnC members / P2P platform members via the communication channel (platform, app)</td></tr>
<tr><td>Postconditions</td><td>EnC members / P2P platform members have a raised awareness and improved their energy-saving behaviours in near real-time</td></tr>
<tr><td colspan="2">Alternative flow and exceptions</td><td></td></tr>
<tr><td colspan="2">ID of related use case in D2.1</td><td>HLUC6</td></tr>
<tr><td colspan="2">Corresponding TE</td><td>TE-3, TE-14</td></tr>
<tr><td colspan="2">Pilot Site</td><td>Austria, Ireland</td></tr>
</table>

UC14 Personalized Energy Efficiency Recommendations.

USE CASE	
ID	UC14
Name	Personalized Energy Efficiency Recommendations

Goal(s)		To use near real-time data and nudging apps to provide personalized energy efficiency recommendations to consumers, based on their current energy usage patterns and behaviours.
Actors		EnC member (consumer, producer) EnC manager DSO (data management)
Trigger events		A (near) real-time and/or forecast visualisation of the energy consumption/production including a personalized recommendation for behavioural changes by the EnC member
Preconditions		Existing infrastructure of energy communities Existing energy data management system (near) real-time Existing communication channel (platform, app) Membership of one or more energy communities Information about personal energy related data
Basic Flow	**Description**	EnC manager receives (near) real-time energy data from the DSO and adds the information to the energy data management system EnC manager receives personal energy related data from EnC member and adds the information to the energy data management system Energy data management system makes recommendations based on the (near) real-time energy data and/or the forecast and the personal energy related data EnC member receives the personalized recommendations via the communication channel (platform, app)
	Postconditions	EnC member receives personalized energy efficiency recommendations and can make targeted adaptations in the energy consumption behaviour
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC6
Corresponding TE		TE-3, TE-14
Pilot Site		Austria, Ireland

UC15: Dynamic Pricing and Incentive Management for EV Flexibility.

USE CASE		
ID		UC15
Name		Dynamic Pricing and Incentive Management for EV Flexibility
Goal(s)		Use dynamic pricing models and incentives to encourage EV drivers to optimize their charging and discharging patterns for grid balancing and energy efficiency.
Actors		Driver
Trigger events		Trigger 1: Lower availability of renewable energy sources, increased demand Trigger 2: Higher availability of renewable energy sources, lower demand
Preconditions		EV Charging stations connected to software backend Wholesale energy market data flow on 15min intervals (for interconnected locations) Data on local renewable energy production (solar , wind) for examined local gird (non-interconnected locations) End-user application (web or mobile) to post information on current price and incentives for EV Charging
Basic Flow	**Description**	Develop applications and incentive models that modify price per kWh according to current to electricity) grid status (high res availability, lower price or other forms of rewards for drivers that charger during that time interval).
	Postconditions	Ensure notifications related to modified pricing or incentives are received by electric vehicle drivers and are meaningfully impacting their charging behaviour
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC7
Corresponding TE		TE-11
Pilot Site		Chalki Island Greece

UC16: Decentralized Data Marketplace for Energy Data Sharing.

USE CASE	
ID	UC16
Name	Decentralized Data Marketplace for Energy Data Sharing

Goal(s)		Enable energy consumers, producers, and other stakeholders to securely share and trade energy data in a decentralized manner. This is achieved by ensuring data sovereignty and privacy through a DLT and blockchain-based system, facilitating seamless interaction between data providers and consumers through an interoperable marketplace.
Actors		Energy consumers Energy producers
Trigger events		Occurs when a participant in the EnC initiates the sharing of energy data or accesses the marketplace for the reciprocal exchange of energy and data assets. Another trigger is the generation of new data from community-level energy optimization tools, edge monitoring hubs, or other relevant sources contributing to local self-consumption and grid service
Preconditions		Users must be registered and authenticated within the decentralized marketplace system. All participants are required to have the appropriate permissions to share or consume energy data. The data to be shared must be available and correctly formatted to meet the marketplace's interoperability and semantic standards, ensuring smooth data exchange between different platforms.
Basic Flow	**Description**	1. The user logs into the marketplace using secure identity authentication. 2. The user selects the type of data they wish to share or consume, specifying access restrictions or usage conditions. 3. The system verifies the user's data-sharing permissions and generates a smart contract to formalize the data transaction. 4. The data is shared or transferred securely using blockchain-based technology, ensuring traceability and accountability.
	Postconditions	• The data transaction is recorded on the blockchain. • The interested stakeholders are notified regarding the exchange completed.
Alternative flow and exceptions		• If the user does not meet the required permissions for accessing certain data, the system denies access and notifies the user. • If a data provider's consent is revoked, the data transaction is halted, and further sharing is prohibited. • In case of a system failure or unavailability of the blockchain service, data transactions are paused and retried once the issue is resolved.
ID of related use case in D2.1		HLUC8
Corresponding TE		TE-5
Pilot Site		Ireland, Portugal

UC17: Tokenized Compensation for Demand Response Services.

<table>
<tr><th colspan="3">USE CASE</th></tr>
<tr><td colspan="2">ID</td><td>UC17</td></tr>
<tr><td colspan="2">Name</td><td>Tokenized Compensation for DR Services</td></tr>
<tr><td colspan="2">Goal(s)</td><td>Incentivize energy consumers and producers to participate in DR programs through tokenized compensation. Facilitate efficient balancing of energy demand and supply, enhance grid stability, and ensure transparent and traceable rewards using a blockchain-based token system.</td></tr>
<tr><td colspan="2">Actors</td><td>Energy consumers
Energy producers</td></tr>
<tr><td colspan="2">Trigger events</td><td>Occurs when a DR event is initiated by the grid or a DR aggregator to balance energy supply and demand. Another trigger occurs when an energy consumer or producer enrolls in a DR program, thereby becoming eligible for tokenized compensation based on their participation.</td></tr>
<tr><td colspan="2">Preconditions</td><td>Participants must be registered with the DR system and have valid authentication. The necessary communication infrastructure must be established between participants, aggregators, and the tokenized compensation platform. All devices and participants must comply with the interoperability and technical standards set by the system to ensure seamless communication.</td></tr>
<tr><td rowspan="2">Basic Flow</td><td>Description</td><td>1. The grid or DR aggregator sends a DR event notification to registered participants.
2. Participants receive the notification and choose to respond by reducing or increasing their energy consumption as requested.
3. The system monitors the participants’ energy response in real-time through smart meters and IoT devices.
4. Based on the participants' response, the system calculates the compensation using predefined criteria.
5. The tokenized compensation is issued to participants through a secure blockchain-based mechanism, ensuring traceability and transparency.</td></tr>
<tr><td>Postconditions</td><td>• The DR event and participants’ responses are recorded on the blockchain.
• Tokenized rewards are distributed to participants based on their contribution to balancing the energy load.
• Participants receive a notification confirming the successful completion of the DR event and the tokenized compensation issued.</td></tr>
<tr><td colspan="2">Alternative flow and exceptions</td><td>• If a participant does not meet the expected response to the demand event, the system adjusts the compensation accordingly or may not issue a reward.</td></tr>
</table>

	• If a participant decides to revoke their consent for participating, they are removed from the event, and no compensation is given.
ID of related use case in D2.1	HLUC8
Corresponding TE	TE-5
Pilot Site	Greece

UC18 - Automated Demand Response for Energy Management.

USE CASE	
ID	UC18
Name	Automated DR for Energy Management
Goal(s)	To enable automated DR in residential (or other sectors) settings.
Actors	DER Unit, Active customer, Grid operator, EnC manager/Aggregator, Flexibility Manager, AMI, EnC Manager, DER Owner, End User, Market Operator
Trigger events	Automated DR may be activated when specific conditions or events are detected: 1. Automated DR devices are configured to respond to price signals indicating higher prices due to grid stress or increased demand. These signals prompt the consumers/prosumers/DER owners/End users of the EnC to initiate DR actions (reduce or increase load/generation). For example, the system may send a signal to encourage users to shift their energy usage to this surplus period or storing energy in the generation peak periods to be released later in the load peak periods 2. Automated DR devices are configured to respond to certain grid conditions. For example, this may occur during peak load times with devices responding to lower overall energy usage or to increase energy use when a surplus or significant amount of renewable energy (e.g., from solar PV) is detected.
Preconditions	Energy communities need to install AMI/smart meters that will provide data to enable clustering and segmentation of energy consumption behaviour. Then, these data sets can be used to forecast consumption, generation and possible grid constraints and, consequently, predict the need to implement DR events. A privacy-preserving mechanism must be in place to ensure that user data is protected. This could include the encryption and access management approaches to prevent unauthorized users and clients access the user data. The CRP will also be important in disseminating the demand-response campaigns.

Basic Flow	**Description**	By using historical consumption data and real-time user data, the system predicts the energy demand of the EnC members for the day ahead or coming days. Simultaneously, historical data and/or real-time data from DER is used to determine the expected generation from renewable sources like solar panels or battery storage, considering factors like weather conditions and battery charge levels. Based on the estimated load and generation conditions and real-time data, the DR control methods, applied via OpenDERMS, then implement the appropriate DR strategy. This might include reducing energy consumption by turning off non-essential appliances, shifting consumption to times when DER generation is higher, or utilizing stored energy in batteries. The system may also accommodate user overrides if they cannot adjust the settings for the appliances during the event. Once the DR event ends, normal operation resumes, and event data is stored to evaluate the contributions of the end users/DER owners to the DR program.
	Postconditions	After the execution of the DR event, energy consumption should be successfully adjusted based on both real-time and historical data, optimizing the use of renewable energy from DERs like solar panels and battery storage. User preferences and overrides should be respected during the event, ensuring personalized control. The event data was securely stored for future evaluation ensuring no personal data was exposed. Once the DR event concluded, normal energy operations automatically resumed, and the contributions of users and DER owners were logged for further analysis.
Alternative flow and exceptions		In cases where the active customer and DER owner decides to withdraw consent for sharing their energy data or participating in DR, the system takes immediate action to remove the device from any DR activities. This decision is recorded by the system, ensuring that no further signals or data sharing occurs. Another potential exception is a technical failure, missing data, or wrong data in the smart meters that can affect the implementation of the DR program. The user or DER owner is immediately notified, and corrective actions are taken before any further events are triggered. Also, active customers and DER owners may decide to override participation in the DR event or decide not to be part of the DR program for a specific period. For example, if a user needs to use an appliance that was set as turned off, they can override it, which then may require to adjust the DR flow accordingly.
ID of related use case in D2.1		HLUC 9
Corresponding TE		TE-18

Pilot Site	Ireland

UC19 - Blockchain-Based Privacy-Preserving Flexibility Aggregation for DR Programs.

USE CASE		
ID		UC19
Name		Blockchain-Based Privacy-Preserving Flexibility Aggregation for DR Programs
Goal(s)		To aggregate flexibility from multiple residential users and energy communities for DR programs using a blockchain-based platform ensuring data privacy and integrity.
Actors		Active customer, DER unit, Grid operator, EnC manager, Flexibility manager, Advanced Metering Infrastructure (AMI), DER Owner, End User, Market Operator
Trigger events		Flexibility aggregation request from flexibility aggregator (e.g., community manager)
Preconditions		Active customers in EnC must be equipped with advanced metering infrastructure to enable prosumption data collection. Each active customer or a group of active customers must be equipped with privacy-preserving gateway to have local interface to the flexible devices, exposing interoperable device interfaces to the EnC management platform or interacting with the flexibility marketplace directly. Flexibility has to be estimated for each active customer and exposed/registered in a privacy-preserving way on the flexibility marketplace.
Basic Flow	**Description**	Flexibility aggregator starts the flexibility registration and bidding cycle. Active users or their local energy management systems with gateways have to estimate the flexibility available after local energy consumption optimization and prepare bid for available flexibility and expose/register it on the flexibility aggregation marketplace. When the bidding cycle is finished, flexibility aggregator collects all the flexibility bids and exposes the collective aggregated flexibility to the flexibility buyer (e.g., DSO, grid operator, etc.).
	Postconditions	When the flexibility is aggregated and offered to flexibility buyer, buyer decides for the amounts of flexibility needed and buys the aggregated amounts. When flexibility is bought, individual contracts for providing flexibility are signed with the selected flexibility providers and flexibility activations are set according to the flexibility activation schedule defined at the flexibility purchase time.
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC9

Corresponding TE	TE-15
Pilot Site	Irish

UC20 – Intelligent Monitoring and Control for Privacy-Preserving Load Management.

USE CASE		
ID		UC20
Name		Intelligent Monitoring and Control for Privacy-Preserving Load Management
Goal(s)		To implement intelligent control and non-intrusive load monitoring systems that optimize energy usage while preserving user privacy.
Actors		Residential and commercial consumers, Community manager
Trigger events		Trigger 1: Lower availability of renewable energy sources, increased demand and lower comfort levels Trigger 2: Higher availability of renewable energy sources, lower demand, lower comfort levels
Preconditions		Smart meters and indoor condition sensors installed, EV charger.
Basic Flow	**Description**	Disaggregation of the cooling loads based on the input from the smart meters. consumption will be adjusted based on comfort metrics and other flexible loads registered in the tool.
	Postconditions	recommendations regarding shifting energy consumption
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC9
Corresponding TE		TE-10
Corresponding TE		
Pilot Site		Greek

UC21: Secure and Privacy-Preserving Data Exchange for DR Programs.

USE CASE	
ID	UC21
Name	Secure and Privacy-Preserving Data Exchange for DR Programs
Goal(s)	To enable secure and privacy-preserving data sharing among multiple stakeholders for DR programs.
Actors	Active customer, Grid operator, EnC Manager, Flexibility Manager, DER Owner, End User, Market Operator.

Trigger events		An actor external to EnC or an actor internal to the EnC requests access to a data resource owned by an EnC member or any other data owner inside the EnC.
Preconditions		The actor requesting data has to demand a consent for data usage from the data owner. Data owner has to sign a consent in order to allow sharing data for requested data sources to the requesting party. Without explicit consent no data sharing is possible for the requesting party.
Basic Flow	**Description**	Requesting party has to create user account inside the EnC portal. User account is created based on the EnC manager invitation to the requesting party. When requesting party successfully created user account inside EnC portal, requesting party can create requests to access user's data. Requesting party has to create consent signing requests for each individual EnC member's energy data separately. Each data owner then decides if he/she is willing to give consent for data sharing and/or data processing (purpose of data access must be explicitly defined). When a consent is signed, a requesting party can make request for protected resources and in case an explicit consent was given to the requesting party to access data, a resource server gives an access to the protected resource. If a consent for a particular data source was not given, a request for a protected resource is rejected.
	Postconditions	If the requesting party was given consent for the data access and/or data processing by a data owner, a request for data is being allowed, otherwise, request for protecting resource is being rejected.
Alternative flow and exceptions		
ID of related use case in D2.1		HLUC9
Corresponding TE		TE-18, TE-3
Pilot Site		Ireland

3.4.1 Sub-UCs

A set of Sub-UCs (Sub-UCs B-E) has been developed with a particular focus on data sharing and exchange processes, aimed at demonstrating their relevance and applicability across various contexts within the project. These Sub-UCs, derived from HLUC10, are not intended to operate as standalone, fully functional business cases but rather as modular components that can be integrated into broader use cases led by pilot leaders and technical partners.

The rationale for this approach stems from the nature of the data-sharing/data-exchange functionalities, which act as enabling sub-processes for many other use cases. For example, Sub-

UC B, "Sovereign Data Sharing for Energy Consumption Prediction," demonstrates a secure and privacy-preserving data-sharing flow, utilizing Smart Contracts and compliance with data sovereignty principles. Similarly, Sub-UC D, "Secure Data Transfer via Blockchain and Smart Contracts," and Sub-UC E, "Secure Data Exchange," provide robust examples of technical implementations that enhance transparency, security, and traceability in data exchanges across energy platforms.

These Sub-UCs were deliberately designed as templates or foundational components to facilitate the integration of secure data-sharing mechanisms into the larger, service-specific use cases being developed for the pilots. They are structured to align with relevant TEs (e.g., TE-4, TE-5, TE-15) and standards (e.g., IDS/GAIA-X), ensuring compliance with interoperability and security protocols. However, their role is inherently supportive and not prescriptive, leaving room for customization and adaptation to meet the specific needs of each pilot and partner.

They are formulated, along with Sub-UC A, focused on semantic interoperability, as such to encourage their incorporation into larger use cases, if and as deemed appropriate. This approach is expected to refine the overall scope of this deliverable, ensuring that the data exchange processes are seamlessly integrated and provide maximum value to the community and stakeholders involved.

Sub-UCa: Building the SEMANTIC specification to make a service semantically interoperable.

SUB-USE CASE		
ID		Sub-UCa
Name		Building the SEMANTIC specification to make a service semantically interoperable
Goal(s)		Create a semantic mapping to enrich a service JSON I/O data and provide it semantic interoperability.
Actors		Service owner, service developer, service user, data producer
Trigger events		Building the SEMAPTIC specification of a service is an offline process. It is therefore triggered by the service development or updates activities, provided that semantic is a service requirement.
Preconditions		Existence of the ontologies is needed to map every I/O variables and parameters that are exchanged.
Basic Flow	**Description**	After syntactic interoperability is ensured, semantic interoperability requires that each variable and parameter exchanged must be mapped to the corresponding classes and properties defined within well-structured ontologies. The SEMAPTIC BUILDER tool can be used to facilitate the creation of a SEMAPTIC specification, developed in the ENPOWER context, to simplify existing approaches and provide fully semantic interoperability.

		The process of building the SEMAPTIC specification is done once when developing the service, and may need adjustments if new I/O parameters or variables are needed during service updates.
	Postconditions	Attachment of the SEMAPTIC specification generated by the SEMAPTIC BUILDER to the variables and parameters exchanged by the services using a suitable exchange protocol, such as REST API, data space connector, or another appropriate method.
Alternative flow and exceptions		Manually create, correct and made changes to the Ontological Semantic Mapping when the service is updated.
ID of related use case in D2.1		HLUC 10
Corresponding TE		TE 12
Pilot Site		Portugal, Spain, Greece, Hungary

Sub-UCb: Sovereign Data Sharing for Energy Consumption Prediction.

SUB-UCE CASE		
ID		Sub-UCb
Name		Sovereign Data Sharing for Energy Consumption Prediction
Goal(s)		Enable secure and privacy-preserving data sharing between energy data producers (e.g., smart meters, building sensors) and data consumers (e.g., analytics platforms) for developing predictive models of energy consumption. The data exchange should be compliant with sovereignty and privacy requirements using blockchain/Smart Contracts.
Actors		Data Producers, Data Consumers, Data Owners, Data Users (i.e., end-results inter-actors)
Trigger events		Request for data access by an authorized analytics platform for energy consumption prediction.
Preconditions		Data producers and consumers are registered and certified. Data sovereignty and privacy policies are defined in Smart Contracts.
Basic Flow	**Description**	**Data Offering:** Data producers offer energy consumption data for prediction services. **Contract Negotiation:** The platform and data provider negotiate usage terms (e.g., data access fees, privacy constraints) through Smart Contracts. **Data Operation Invocation:** The platform invokes the contract and requests data for consumption prediction.

		Data Operation Result: Data is transferred securely, and predictions are made using the shared data.
	Postconditions	Energy consumption predictions are provided to authorized users without violating data sovereignty or privacy.
Alternative flow and exceptions		Data Offering process Exception 1: *Data Offering Fails Due to Incomplete Data:* If the data offering is missing any required metadata or information, the system will reject the offering and prompt the Data Producer to provide the missing fields. Exception 2: *Data Offering is Declined During Contract Negotiation:* The Data Consumer might reject the offered data based on the terms (e.g., price or data usage conditions). In this case, the system reverts to the negotiation stage for revision of terms. Alternative Flow: *Offering Data on a Different Infrastructure:* If the selected infrastructure does not support the necessary protocol(s), an alternative communication protocol will be selected, and the offering will be made using the new infrastructure. Exception 3: *Insufficient Data Metadata* (The Data Offering lacks sufficient metadata to classify or describe the data effectively (e.g., missing timestamps, data source description, etc.): The system will prompt the Data Producer to add the required metadata before allowing the data to be offered. Alternative Flow: *Use of Cached or Pre-Validated Metadata:* If the system has cached metadata from a previous interaction with the Data Producer, it may pre-validate the new offering using this cached information, speeding up the offering process. Contract Negotiation process Exception 1: *Contract Negotiation Fails Due to Non-Agreement:* If both parties cannot agree on the terms, the contract negotiation will be terminated, and no further data operations will be possible. The Data Producer may adjust the contract terms or offer new data. Exception 2: *Negotiation Timeout:* If a certain period passes without a response from the Data Consumer or Producer, the system will issue a notification to both parties and either extend the deadline or cancel the negotiation. Alternative Flow: *Data Operation with Pre-Agreed Contracts:* In cases where a pre-existing agreement covers all necessary aspects, the

	system bypasses the need for negotiation and moves directly to data operation invocation. Data Operation Invocation process: Exception 1: *Data Operation Fails Due to System Error:* If a system error occurs (e.g., network failure or API timeout), the system will notify the Data Producer and Consumer about the failure and retry the operation after a short delay. Exception 2: *Incompatible Data Format or Protocol:* If the data format is incompatible with the requested operation, the system may prompt the Data Producer to reformat the data or choose a different operation. Exception 3: *Data Already in Use (Concurrency Issue - locked by another operation (e.g., another process is currently modifying or accessing the data):* The system will notify the Data Consumer about the concurrency issue and either offer to retry later or provide a read-only snapshot of the data. Alternative Flow: *Invoke Operation on a Secondary Infrastructure:* If the initial infrastructure is unavailable or has issues, the system might automatically switch to an alternative protocol or data infrastructure. Data Operation Result process: Exception 1: *Data Operation Result Not Delivered:* If the data result is not provided within a specified time limit, the system could send a notification to the Data Consumer and Producer, offering the option to retry or cancel the operation. Exception: *Incomplete Data Returned:* If the returned data is incomplete or corrupted, the system will initiate a re-validation process, informing the Data Producer to resend the corrected data. Alternative Flow: *Use Cached Data:* If real-time data is unavailable or incomplete, the system could offer cached data as an alternative, notifying the Data Consumer that the data is not real-time but still actionable for non-critical decisions. Some general exceptions: *Authentication Failure:* If the Data Consumer or Data User fails to authenticate properly, the system will trigger an error, preventing access to the data.

	Policy Violation: If a data request violates the usage policies defined by the Data Owner (e.g., attempting to access restricted data), the system will block the request and notify the requester. *Data Privacy Issues:* If data privacy regulations (e.g., GDPR) are violated, the system will prevent the data operation and notify the relevant parties.
ID of related use case in D2.1	HLUC10
Corresponding TE	TE-4, TE-5, TE-6, TE-7, TE-15, TE-16, and TE-17 are directly related to this. They focus on data sovereignty, privacy-preserving data sharing, smart contracts, and decentralized market tools, all of which align with the use case's need for secure data sharing for energy consumption prediction.
Pilot Site	Given the correlation of the TEs to the pilots as provided in the GA, this case is applicable to ALL pilots.

Sub-UCc: Federated Learning for Energy Efficiency Optimization.

SUB-USE CASE		
ID		Sub-UCc
Name		Federated Learning for Energy Efficiency Optimization
Goal(s)		Leverage federated learning to collaboratively develop energy efficiency optimization algorithms across multiple energy providers while preserving data sovereignty and privacy.
Actors		Data Producers, Data Owners, Energy Providers.
Trigger events		Request for collaborative model training to optimize energy efficiency across various energy communities.
Preconditions		Federated learning environment is established. Participants (e.g., energy providers) are registered and certified.
Basic Flow	**Description**	Data Offering: Energy providers offer anonymized or privacy-preserving energy data for federated learning. Contract Negotiation: Usage and training terms are negotiated through Smart Contracts. Data Operation Invocation: A request is made to initiate the training process across the federated data sets.

		Data Operation Result: Federated learning updates are exchanged, and the global model is optimized without transferring raw data. Notify Success: Participants are notified of the successful completion of the model training.
	Postconditions	A shared model for energy efficiency optimization is developed without compromising data sovereignty.
Alternative flow and exceptions		Similar to UC41
ID of related use case in D2.1		HLUC10
Corresponding TE		TE-4, TE-5, TE-6, TE-7, TE-15, TE-16, and TE-17 are all relevant, particularly for ensuring data privacy, smart contract negotiations, and decentralized cooperation between energy providers.
Pilot Site		Given the correlation of the TEs to the pilots as provided in the GA, this case is applicable to ALL pilots.

Sub-UCd: Secure Data Transfer via Blockchain and Smart Contracts.

SUB-USE CASE		
ID		Sub-UCd
Name		Secure Data Transfer via Blockchain and Smart Contracts
Goal(s)		Facilitate secure and sovereign data transfer between two parties (e.g., energy market participants) using blockchain technology and Smart Contracts to enforce data usage policies.
Actors		Data Owners, Data Consumers.
Trigger events		A request is made to transfer sensitive energy data between platforms or market participants.
Preconditions		Both parties are registered and certified. Data usage policies are embedded in Smart Contracts.
Basic Flow	**Description**	Invoke Data Operation: The data consumer requests data from the data owner through the blockchain platform. Process Data Operation: The Smart Contract verifies the request, checks compliance with data policies, and allows data transfer. Provide Access Information: The blockchain platform shares the access information required for the data transfer. Trigger Data Transfer: The data is securely transferred, and the Smart Contract tracks the operation.

		Request Data Operation Result: The data consumer requests the operation result. Provide Data Operation Result: The result of the operation (e.g., data processed or used) is provided to the consumer. Notify Success: The operation is confirmed as successful.
	Postconditions	Data is transferred securely, and the Smart Contract enforces compliance with agreed policies.
Alternative flow and exceptions		Similar to UC41
ID of related use case in D2.1		HLUC10
Corresponding TE		TE-4, TE-5, TE-15, TE-16, and TE-17 are relevant as they focus on secure, sovereign data exchange, blockchain technology, Smart Contracts, and P2P platforms, which are central to achieving the secure data transfer goal.
Pilot Site		Given the correlation of the TEs to the pilots as provided in the GA, this case is applicable to ALL pilots.

Sub-UCe: Secure Data Exchange.

SUB-USE CASE		
ID		Sub-UCe
Name		Secure Data Exchange
Goal(s)		To enable secure, decentralized data exchange among platforms for energy and flexibility management while ensuring compliance with the federated learning environment.
Actors		Energy platform operators, Data providers, and Flexibility service providers.
Trigger events		Data exchange request from energy platform operators for optimizing flexibility services across energy communities.
Preconditions		Platforms are interconnected and compliant with IDS/GAIA-X standards. Data providers have shared access tokens for data exchange via secure protocols. Data models and ontologies are standardized for semantic interoperability.
Basic Flow	**Description**	The data provider initiates a request for data exchange through the IDS-compliant connector. The system verifies data models and prepares them for exchange in a standardized format (SAREF or NGSI-LD).

	The request for data operation is processed securely by the federated infrastructure. The required data is transferred securely through the platform (eg. using blockchain/DLT protocols.) Data consumers retrieve results and utilize them for federated planning.
Postconditions	In case of DLT utilization: The exchange of data is completed, and all parties receive validated data for energy and flexibility management, ensuring transparency and traceability through DLT.
Alternative flow and exceptions	In case of failure in secure communication channels, data exchange requests may be rerouted via alternative protocols (e.g., IDS Connector backup). If there are discrepancies in data models or failure to comply with the semantic interoperability framework, the exchange request may be denied.
ID of related use case in D2.1	HLUC10
Corresponding TE	**TE-4**, TE-5, TE-15, TE-16, TE-17 and TE-18 are related to the use case as enablers that focus on secure data management, decentralized platforms, blockchain/DLT protocols, and P2P energy markets - all essential for enabling secure and compliant data exchange for energy and flexibility management in a federated environment.
Pilot Site	Given the correlation of the TEs to the pilots as provided in the GA, this case is applicable to ALL pilots.

3.5 UC mapping to pilot sites

This chapter provides a comprehensive mapping of the developed UCs and Sub-UCs to the pilot sites, showcasing the implementation of technological and operational solutions within real-world energy management applications. The mapping serves to connect theoretical UC development with their practical application at each pilot site, ensuring that the technologies and strategies being explored are suited to the specific needs, challenges, and characteristics of these environments.

As a result, implementing UCs and Sub-UCs at different pilot sites will provide insights into how different energy management solutions are adapted to various geographic, regulatory, and technological contexts. It also emphasizes the opportunities and challenges faced at the pilot sites, helping to evaluate the feasibility and scalability of the solutions. Ultimately, the mapping of UCs and Sub-UCs with pilot sites, shown in table 5, plays a key role in assessing the practical impact of the developed UCs and Sub-UCs, ensuring that the pilot sites can generate valuable, actionable results that contribute to the wider objectives of sustainability and energy efficiency.

Table 5: Mapping of UC and Sub-UCs with pilot sites.

UC / SUB-UC	Pilot					
	Austria	Portugal	Greece	Ireland	Hungary	Spain
UC1 - Data-driven Electrical Load Consumption Clustering + Segmenting users based on questionnaire responses						
UC2 - Assessing Demand Response Potential in Energy Communities						
UC3 - Personalized Consumer Engagement and Activation						
UC4 - Simulation with Digital Twins of Individual Thermal Assets and integration into OSTEC EnC Management System						
UC5 - Individual self-consumption optimisation						
UC6 - Collective self-Consumption Optimization						
UC7 - AI-Powered Virtual Energy Management						
UC8 - Planning the Expansion of Existing Energy Communities						
UC9 - Optimization of a P2P energy trading platform						
UC10 - Development of and EnC management platform						
UC11 - Design of local markets and sharing mechanisms for energy and flexibility provision in energy communities						
UC12 - (Near) Real-Time Demand Response Activation through Nudging Apps						
UC13 - Social Engagement Management Platform						
UC14 - Personalized Energy Efficiency Recommendations						
UC15 - Dynamic Pricing and Incentive Management for EV Flexibility						
UC16 - Decentralized Data Marketplace for Energy Data Sharing						
UC17 - Tokenized Compensation for Demand Response Services						
UC18 - Automated Demand Response for Energy Management						
UC19 - Blockchain-Based Privacy-Preserving Flexibility Aggregation for DR Programs						
UC20 - Intelligent Monitoring and Control for Privacy-Preserving Load Management						
UC21 - Secure and Privacy-Preserving Data Exchange for DR Programs						
SUB-UCA - Building the SEMAPTIC specification to make a service semantically interoperable						
SUB-UCB - Sovereign Data Sharing for Energy Consumption Prediction						
SUB-UCC - Federated Learning for Energy Efficiency Optimization						
SUB-UCD - Secure Data Transfer via Blockchain and Smart Contracts						
SUB-UCE - Secure Data Exchange						

4 Co-Creation Workshop (UNIBAS)

4.1 Previous work in WP2

UNIBAS was responsible for tasks T2.2 and T2.3 which are presented in Deliverable D2.2 on Active societal participation, emergence and consolidation factors of energy activated citizens and data-driven energy- secure communities. These tasks were:

T2.2. "ENPOWER community building, co-creation and consumer segmentation" including the comprehensive empirical analysis of citizens' decision preferences and underlying cognitive, affective and social factors in the context of digitally enhanced and grid-friendly communities.

T2.3. "Innovative social-driven incentive mechanisms for individual and collective-level consumer engagement" which analyses social incentives to increase citizen engagement.

This involved interviewing creators of RECs, conducting two online focus groups with the Austrian partner pilot, and conducting a multi-country survey which included a discrete choice experiment. The results were analysed and are presented in the ENPOWER Deliverable D2.2 [2].

4.2 Workshop details

This workshop took place online on the 24th of September 2024, between 1400 and 1600 CET and was led by Drs Annika Sohre, Iljana Schubert and Adam Hearn, from the University of Basel, Switzerland. 19 people registered for the workshop which was attended by 9 participants from across the ENPOWER project, including representatives from: CARTIF, HAEE, Bekescsaba Energia ESCO Ltd., UCC, AUDENCIA and EEU.

4.3 Agenda and Structure

The agenda for the workshop was divided into 4 blocks:

1. Getting started with SSH based qualitative methods
2. Focus groups as SSH based qualitative methods
3. Co-creation/co-visioning workshops
4. Take home messages

In the workshop, participants were instructed on how to plan, recruit/invite for, hold and analyse co-creation workshops. During the workshop participants were asked to take part in two mentimeters as well as participate in 3 break-out room task and discussions.

Prior to the workshop participants were able to list questions that they wanted to have answered. The Agenda and workshop tasks were tailored according to the questions.

4.4 Prior questions from the workshop participants

On preparing co-creation

- What are some best practices for making **stakeholders see the value** and necessity of these co-creation workshops?
- In the context of energy communities, how can **co-creation processes be designed** to ensure that all stakeholders, including marginalized or less vocal community members, have an equal opportunity to contribute their ideas and perspectives?

On doing the co-creation

- How can I **guide conversations without interfering too much**, but still ensure participants have the necessary information and direction to lead on sustainable actions?
- How do I **prevent one individual from taking up too** much space in discussions, ensuring everyone has a chance to contribute?
- What are some effective strategies for dealing with **sceptical stakeholders** who may resist participation or question the process?

On analysis/theoretical models

- Are there **theoretical model-based co-creation approaches**? Is it possible to quantify co-creation outcomes?

4.5 Workshop findings

a) Identifying Stakeholders

As a first step, participants were asked to detail which potential stakeholders would be invited to cocreation workshops, resulting in the mentimeter image below (Figure 3)

Figure 3: Mentimeter, What stakeholders do you commonly work with/have meetings with (list all different types)?

Participants were given access to multiple helpful tools[1].

b) Topic guide

The need for a topic guide was highlighted, including the need for warm-up and opener questions as well as example topic guides. In the first break-out room session, participants were provided

[1] https://unalab.enoll.org/, https://www.wework.com/ideas/professional-development/creativity-culture/effective-brainstorming-techniques, Co-creation Tools - Sockets (sockets-cocreation.eu)

with a topic guide template to work on creating their own guidelines (in two separate groups), based on co-creation workshops that are being planned by attendees for the near future. Group 1 proposed a co-creation workshop in which the topic of data sharing in energy communities is explored. Group 2 focused on a co-creation workshop that aimed to develop an app to engage users in an EnC.

Group 1 came up with two major questions for participants to focus on. The first of these was "What comes to your mind when you hear about data sharing in energy communities?" Additional detailed questions were also added to the guideline, such as "what do you think about security when it comes to data sharing?" The second block focused on the question "Do you have any concerns, and how might security issues be addressed?". We recognised that the first part of this question could result in a yes/no answer so focused more on the second half as it is always better to ask open questions. As a detailed follow-up question the group proposed "What do you need to make it work for you?"

In its breakout room, Group 2 brainstormed potential questions to be asked in a co-creation workshop on apps:

"What problem/What would be the main use of the app?"

"What kind of features do they expect the app should have?"

They further pointed to the following questions:

Can someone share an example of an app that serves your needs?

After:

Provide access to the app and receive feedback

"Which feature engaged you the most?"

"What is that you didn't like?"

"What's one key takeaway you learned today?"

They also noted the potential inclusion of a questionnaire (or survey) that attendees could also fill out, and pointed out that there was also a need for a device on which attendees can check the app, assuming they did not all have smart phones with them.

c) Recruiting strategies

As a second step, following the presentation of information on key pointers on recruiting for co-creation workshops, participants were asked to develop a recruitment strategy for the workshop that they had planned in the previous stage. The task involved the identification of important stakeholder types, deciding how many participants from each stakeholder group would be invited and how these would be approached (through which channels).

Group 1 aimed for 20 participants, all of which were engaged to some extent in an EnC. However, within this they identified numerous sub-groups of hard-to-reach participants, such as women, younger people and members that suffer from energy poverty. Whilst many co-creation workshops might include those groups that are already interested in the subject (e.g. middle-aged men in energy communities), those already engaged were not specifically targeted as the discussion indicated that these are the least difficult to recruit and would likely sign-up to participate even if they were not directly targeted. As members of an EnC are already involved to some extent, there will be existing channels of communication which could be used to invite members to participate in the co-creation workshop, such as a newsletter, email or a WhatsApp group. However, face-to-face invitations were considered to be more optimal, and the need for sensitivity was noted, particularly when dealing with hard-to-reach groups.

The second group determined that in addition to 15 user representatives from the EnC members, a number of further stakeholders would be invited via mail or email invitation. These were IT developers (1), academia and research institutions (up to 3 people), Marketing group (1), EnC Governance (1), TSO/DSO (1), Investors (at least 3). During the discussion it was also clear that the option of a second co-creation workshop on the basis of the first one with just EnC members, was also an option.

d) Dealing with sources of conflict

As a final step, we discussed how to deal with difficult or unforeseen situations during workshops. Firstly, participants shared their experiences of dealing with difficult workshop situations through a mentimeter and then through discussion as a group. The examples below (Figure 4) show that sometimes you have to adjust your workshop plan to accommodate other needs and that you should utilize different tools and methods to engage different participants.

Here are some selected results from Mentimeter:

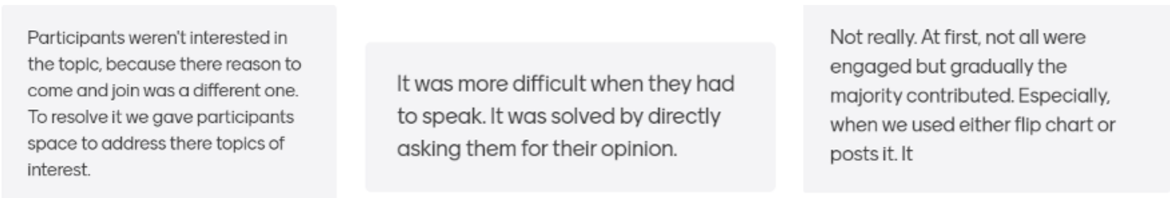

Figure 4: Selected results from Mentimeter.

Finally, in the break-out rooms group 1 & 2 collected strategies on how to deal with a very critical/dominant person, and a very introverted or not interested person

The strategies collected were:

- For a very critical /dominant person, thanking the person that is talking too much: "That is very interesting, thank you, let's look into what someone else has to say about that?
- For critical people: Dominant person that just wants to focus on themselves or their topic, that is complicated. Remind them that the focus is on the group: "The focus is on the group"
- Thanking them for their opinion but emphasise the need to listen to other people's opinions.
- Setting a specific timeframe for the answers to be given.
- Then a private follow-up, to clear up any questions that may arise? Offer them the opportunity to discuss things later.

For quieter people:

- Ask a direct question emphasizing on the fact there is no wrong answer, it's an opinion

e) Conclusion of the workshop

Finally, attendees were asked if there were any further questions and if they felt that the questions they had asked prior to attending (via a google form) had been answered. The slides associated with the workshop are available as a Pdf.

5 Deliberative Workshops (UCC/MaREI)

This section provides a detailed description of all the deliberative workshops, along with a presentation of the results for each demo site.

5.1 Introduction

Energy data sharing is a developing concept that supports sustainable energy systems through decentralization, RECs, smart systems, and distributed energy resources. As such, we have seen that energy data sharing and big data play a key role in achieving sustainability in energy systems, with new methods for open and collaborative data use emerging across the sector. In Europe, governments are fostering data-sharing practices with energy communities and investing in local renewable energy projects to support these collaborations. In this context, co-creative data-sharing approaches can enhance technology development, improve our understanding of consumer data-sharing preferences, and strengthen privacy and security. Effective management and planning are essential for operating shared energy resources on a small scale, which requires transparent data-sharing processes based on meaningful arrangements. We can also map how different groups approach data sharing variably, focusing on legal, regulatory, governance, or collaborative aspects, each with unique views on data ownership and sharing's importance.

The work is focusing on the three front-runner pilots in ENPOWER, Ireland, Austria, and Portugal who are already working with established energy communities. This is to facilitate engagement and recruitment. Deliberative workshop approaches typically require more time, resources and commitment, and bring added barriers to securing and enabling participation in large numbers. At ENPOWER, we use a combination of sampling techniques to select and recruit participants. These include purposive and snowball sampling. Purposive sampling involves more strategic mapping and targeting of participants from the three front-runner pilot energy communities and embracing the local context to ensure diversity.

In the context of “energy data sharing”, two insightful deliberative workshops were held at several key demo sites: Dingle, Ireland; Poysdorf, Austria; and Lisbon, Portugal. These workshops brought together representatives and community members, fostering a rich exchange of ideas and perspectives. One key takeaway from these events was the distinctiveness of each community. The unique characteristics of these regions meant that while the findings are valuable, they are indicative rather than directly comparable across the sites. Through the tight timeline to organise and execute all workshops in all three pilots, the results from the Portuguese pilot workshops will be presented in D5.2 [82].

The two consecutive workshops were designed to build on each other, maintaining consistency in participants to ensure continuity and depth in the discussions. The first workshop held in each demo location was designed as an exploratory and deliberative session. The primary objective of this initial gathering was to engage participants in a brainstorming exercise to explore the concept of “energy data sharing.” Through open dialogue and creative discussion, participants began to unpack the possibilities, challenges, and potential benefits of sharing energy-related data, laying the groundwork for the second workshop.

The second workshop investigated the concept of "energy data sharing" in depth, aiming to better understand how participants interpret it in specific, community-relevant contexts. Through various scenarios, attendees explored how data sharing could benefit their local energy communities. A key focus of the workshop was on how this concept could be integrated into future EnC activities. The discussions were rich and insightful, generating a wealth of ideas and outcomes tailored to the unique needs of different communities.

To ensure inclusivity and understanding, all workshops were conducted in the participants' local languages. The results were then translated for broader analysis, providing a comprehensive view of the diverse perspectives and solutions discussed.

5.2 Demo Site Dingle, Ireland

Dingle has a well-established and vibrant EnC, primarily driven by two key sectors: agriculture and tourism. Farmers and individuals from the tourism and hospitality industry form the backbone of this community, with several highly engaged members playing pivotal roles in its development. These dedicated individuals are instrumental in fostering collaboration, innovation, and progress within the EnC.

A central hub for this activity is the Dingle Hub, a key organization deeply embedded in the community. The Dingle Hub actively supports the growth of the energy initiative by organizing regular meetings, workshops, and campaigns that resonate with the community’s needs. Through these efforts, the Hub strengthens local engagement, helping to promote sustainable energy practices and drive the community forward in its energy transition.

5.2.1 First Workshop, Dingle

The first workshop held in Dingle in February 2024, attracted 11 participants, comprising six women and five men, where the men were mainly from the farming sector, with a few participants representing the tourism and hospitality industry. The workshop was designed as an interactive brainstorming session to gather participants initial thoughts on the concept of “energy data sharing.”

The session started with four key questions, posed one after the other through the online platform Slido. Participants were encouraged to share their thoughts, ideas, and concerns, leading to engaging discussions on specific aspects of the topic. This approach allowed for a diverse exchange of perspectives and helped to capture a broad range of insights into energy data sharing from the community members.

The four questions were:

1. What comes to mind when you think about energy data sharing?
2. What is the value of data sharing?
3. What concerns do you have about data sharing?
4. What future opportunities could there be for data sharing?

During the first workshop in Dingle, several key themes emerged as participants discussed the concept of “energy data sharing.” One of the primary concerns revolved around “financial benefits”: participants questioned whether sharing energy data would lead to cost savings for individuals as well as for the community as a whole. Alongside this, the idea of “non-financial benefits” was raised. Participants saw the potential for the community to gain a stronger collective voice, become less dependent on major energy providers, support the energy transition through optimized energy sharing, and contribute to a greener, more sustainable future.

A dominant topic throughout the discussion was also the “handling of shared data”. Concerns were voiced about who would use the data, for what purposes, and who would own it. Participants worried about whether data might be exploited for marketing purposes, and whether data sharing could lead to penalties if energy use didn't align with specific requirements. These concerns tied closely to issues of "privacy", as participants expressed apprehension about how the data would be shared, by whom, and for what reasons.

A strong and recurring theme in all workshops and events in Dingle was the importance of "education" and "engagement" within the community. Participants emphasized the need to involve more people and provided numerous suggestions on how to better educate the wider community about the energy transition and the importance of sharing energy data to improve the local energy system. The idea of "community champions", individuals who could lead by example by showcasing their own investments in energy-efficient technologies, was highlighted as a way to inspire others. These champions could demonstrate the financial and environmental benefits of such investments.

Other ideas included offering information on how to read energy bills, raising awareness through community outreach, and creating accessible platforms, such as a dedicated website or a local hub, where people could go to ask questions and learn more about energy data sharing. These initiatives would help build a more informed and engaged community, driving collective progress toward a more efficient and sustainable energy system in Dingle.

During the workshop, the "DCsix Citizen Renewable Platform" was introduced, showcasing how it could assist users in transitioning to more energy-efficient homes and businesses. The platform offers a variety of tailored approaches, including conducting energy audits to help individual consumers find the most suitable solutions for their specific needs.

DCsix also provided an expert perspective on "energy data monitoring", using a dairy farm as a real-world example. This presentation offered valuable insights into how energy data is collected, why it is gathered, and how the information is presented to the farm owner. Participants gained a clearer understanding of the practical applications of energy data monitoring in agricultural settings.

A local farmer who had already made investments in energy-efficient technologies gave a testimonial, sharing his experience and demonstrating the positive impact these changes had on his farm. His story served as an inspiring example for other community members, highlighting both the financial and environmental benefits of adopting new energy-efficient assets.

5.2.2 Second Workshop, Dingle

The second workshop in Dingle which took place in April 2024, was more structured and aimed to deepen participants' understanding of "energy data sharing." The workshop had 9 attendees, primarily farmers, along with experts and organizers from the Dingle Hub, which made a total of 13 participants. The group was predominantly middle-aged to older men, and efforts were made to ensure everyone had a clear understanding of the key concepts surrounding energy data sharing.

To achieve this, participants were given a "three-dimensional questionnaire" designed to illustrate the broader context of energy data sharing. The questionnaire outlined potential stakeholders involved, such as network operators, energy service companies, and local energy communities. It also explored various reasons why data might be collected, including billing, quotation offers, and P2P trading, as well as the types of data that could be shared, such as personal data, load profiles, and occupancy patterns.

After the questionnaire, three community-relevant scenarios were presented to give participants a real-world perspective on how energy data sharing might be applied. These scenarios included "grid flexibility", "asset optimization", and "vehicle-to-grid" integration. After each scenario was presented, participants were asked to provide feedback via a dedicated sheet, which led to the identification of key topics that emerged repeatedly across all three scenarios.

Financial/Economical

- Financial incentives not just for the individual but also for the community
- Return of investment, cost versus benefits analysis

Communication/Education

- Education (young people as well), learning, understanding (also about savings/costs); knowledge leads to change; educating all is vital – not just those who have the resources to invest in new assets or retrofit their properties; understand the importance of data sharing in the community
- Workshops etc.
- Communication to drive change (storytelling); transparent well organised EnC groups; use of social media
- Demonstrations through role models who have already installed new assets; showing examples, learning by seeing, showing benefits of using new technology; share learning experiences and identify best approaches.
- Learning from peers
- Having space to talk about potential investments with others
- Behavioural change (adjusting behaviour and re-learning how to operate our homes and businesses); showing flexibility
- Include motivated people to drive the change, ambassadors, role models, champions, heroes
- Taking digital literacy into account – fear of new technology
- Concerns

Sustainability/Environment

- Environmental benefits, general impact, impact of decisions
- Sustainable tourism; delivering on the experience
- Guests value sustainable approaches
- Broaden the spectrum of the EnC by looking at all sources of renewable energy
- Cultural shift for the tourism and hospitality sector

Technical/Operation

- Emphasis on supported AI tools and systems
- Monitoring devices and apps (need to be simple and accessible by older people as well)
- Power/control is in the hand of the users
- Standardisation of tools and data
- taking digital literacy into account – fear of new technology
- Concerns
- Privacy aspects need to be considered in the context of data sharing

Regulations/Rules

- Regulations need to be flexible and adapted to the needs of communities

- Keep the bigger picture in mind as for example global resource management
- Trust towards aggregators and service companies
- Installing and maintaining assets need to be easily accessible and is of important
- Raising awareness of grants

At the end of the workshop an interactive ballot was introduced, where every participant could give their feedback, if the questions were understandable and if the answer categories needed to be adjusted. After finding a comment agreement people could vote which categories were the most relevant for them and bring the answers in an order of important. The ballot results closely align with the recurring themes identified throughout the discussions. The first question, which addressed the technical aspects of data sharing, highlighted the same key factors mentioned in the various scenarios presented. When asked, "Which of the following incentives can be most useful to motivate energy data and knowledge sharing in practice?" “Financial gains” emerged as the most significant motivator Figure 55. This was followed by the importance of “having tools to securely share data in an anonymized manner”. Additionally, the recommendation of establishing a "one-stop shop" was seen as a potential driver to encourage participation, with the aim of enhancing both individual and community-wide impacts through data sharing.

The second question of the ballot Figure 66 focused on the social dimension of energy sharing, asking participants, "Which challenges require the most attention to help support further participation in energy data-sharing initiatives?" The responses overwhelmingly emphasized the “need for education” and “effective communication”, reinforcing the key points raised in the earlier scenarios.

Participants recognized that raising awareness and providing clear, accessible information are crucial to fostering greater engagement in energy data-sharing efforts. The feedback underscored the importance of helping the community understand both the benefits and implications of energy data sharing, ensuring that people feel informed and empowered to participate in these initiatives.

The final question asked the participants: “Should data sharing for the performance of operating renewable energy assets be developed primarily as…”

1. a commercial activity
2. a public good that requires public action and public governance
3. both in collaboration.

The favoured answer was the third option, emphasizing the importance of collaboration between commercial interests and public governance Figure 77.

The aspects raised in this ballot, along with the main themes from the scenario exercises, are deeply relevant to the Dingle community and resonate far beyond the specific topic of data sharing. This broader significance became clear during the presentations at the “Energy Master Plan launch”[2] in October 2024, which attracted a huge crowed from the tourism and hospitality sector, where similar topics were discussed. The consistency of these themes across different events highlights their importance to the community as a whole, reinforcing the need for ongoing dialogue and collective action on these critical issues.

[2] https://dinglehub.com/wp-content/uploads/2024/12/20241209-EMP__ENG.pdf

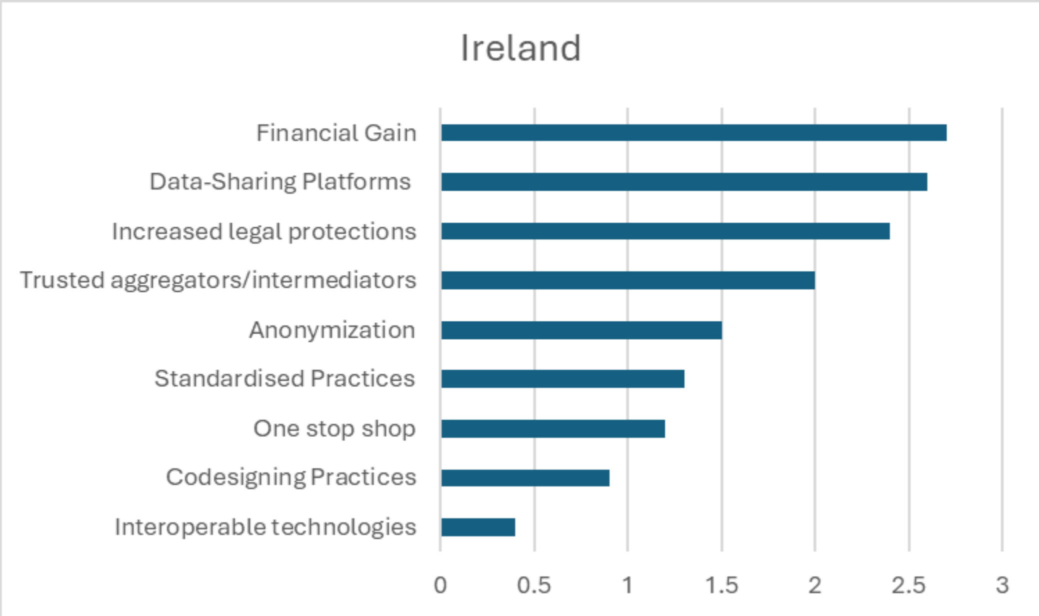

Figure 5: Which of the following incentives can be most useful to motivate energy data and knowledge sharing in practice?

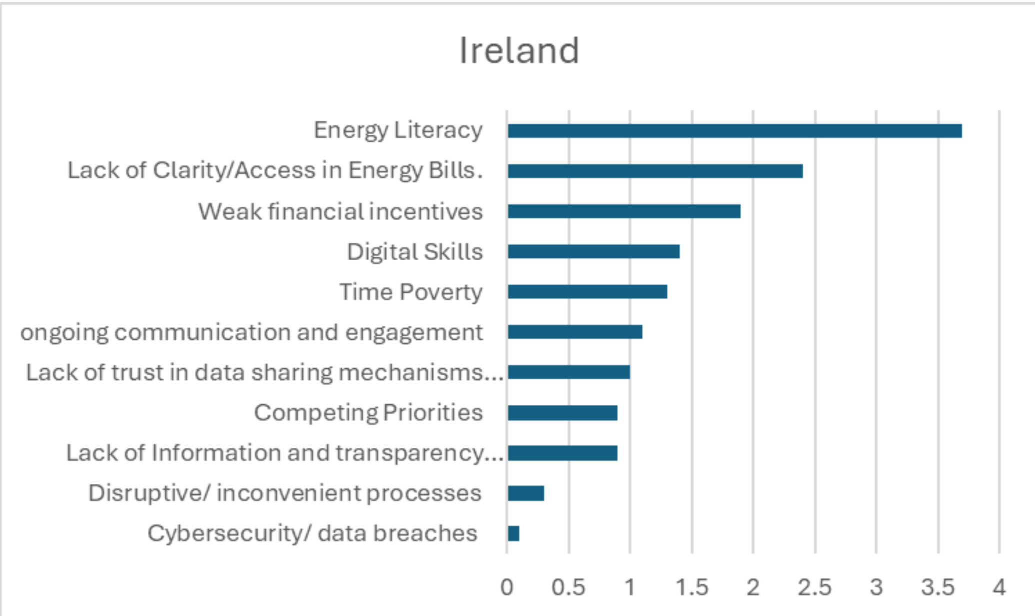

Figure 6: Which challenges require the most attention to help support further participation in energy data-sharing initiatives?

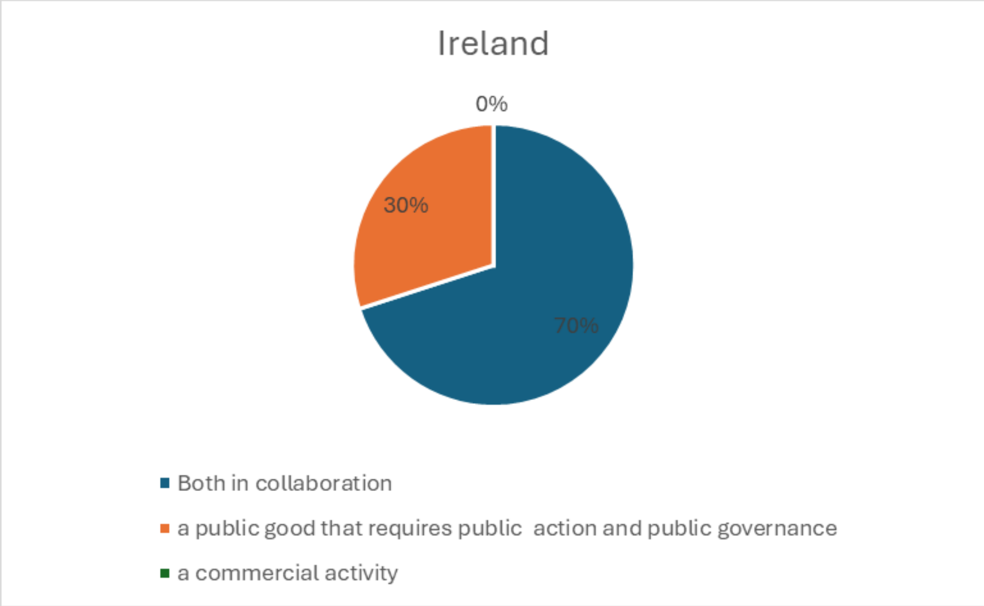

Figure 7: Should data sharing for the performance of operating renewable energy assets be developed mainly as…

5.3 Demo Site Poysdorf, Austria

The EnC in Poysdorf is still in its early stages. It represents a fresh and innovative concept for the local stakeholders, many of whom are also engaged with the OurPower business model. A key difference between this emerging EnC and other similar projects lies in its underlying motivations.

For example, when compared to the Dingle community in Ireland, a clear contrast emerges. In Dingle, the primary driving force behind the energy initiative is the Dingle Hub, which operates with no direct financial interests in the community's energy activities. Its focus is more on sustainability, community development, and the transition to clean energy.

On the other hand, the EnC in Poysdorf, led by OurPower, is motivated by strong financial incentives to develop and grow the community. This introduces a distinct difference in their core goals: while Dingle's approach prioritizes collective, non-commercial interests, the Poysdorf model, driven by OurPower, is more commercially focused. This contrast reflects the varying fundamental interests shaping the two communities and their approach to energy transition.

5.3.1 First Workshop, Poysdorf

The first workshop in Poysdorf was held in July 2024, bringing together 11 male participants, along with two organizers, one representing OurPower and the other from University College Cork. The workshop followed the same structure as the sessions previously conducted in Dingle, aiming to foster collaboration and creativity.

Through an interactive brainstorming session, the participants worked together to co-create and explore the concept of "energy data sharing." This approach encouraged open dialogue and collective problem-solving, allowing the group to generate ideas and discuss the potential benefits and challenges of sharing energy data within the community.

The four key questions asked, were the same as in Dingle:

1. What comes to mind when you think about energy data sharing?
2. What is the value of data sharing?
3. What concerns do you have about data sharing?
4. What future opportunities could there be for data sharing?

The discussion during the workshop in Poysdorf moved from the intended focus. Rather than addressing the key questions individually, the conversation was dominated by participants' personal interests in buying or selling energy. This shifted the dialogue towards a broader question: Is "personal data" necessary, and if so, what does this entail?

As the discussion evolved, participants explored the distinction between personal data, such as demographics, and energy data, and what it truly means to share energy data. It became evident that there were differing interpretations of the term "data." One participant summed up the general sentiment by stating, “When it comes to sharing data, I see it as follows: as little as possible, as much as necessary.”

There was a consensus that data could be shared with the network operator, but only for purposes such as billing. The group strongly agreed that data should not be shared with other participants. Instead, the prevailing view was that personal data wasn't required. Only abstract and generalized energy data should be used to inform members, for example, to help them adjust their energy consumption based on the availability of energy in the grid. This approach ensured privacy while still enabling useful insights to optimize energy use within the community.

The workshop's discussion in Poysdorf largely cantered around financial concerns, particularly from individual energy producers who were focused on selling their energy at favourable prices to consumer members of the OurPower platform. A major concern for these producers was the possibility of negative energy prices and how to navigate such situations.

In addition, privacy and GDPR issues were repeatedly raised, along with legal challenges specific to Austria, such as those surrounding the Vehicle-to-Grid (V2G) concept. Although scenarios were not initially part of the workshop agenda, participants showed significant interest in these topics as part of the broader effort to develop the EnC. The discussion expanded to include the idea of sharing EVs and using them as mobile energy storage, with some participants even exploring the potential of Vehicle-to-Home (V2H) applications.

The conversation also touched on the possibility of using mixed-generation technologies, rather than relying solely on photovoltaics (PV), as an approach to diversify energy production within the community. Another suggestion was to integrate a storage system with a large PV setup to increase efficiency and stability.

The group also addressed the challenge of changing consumer behaviour and how best to encourage energy-saving practices. One simple yet effective idea was an app using a traffic light system to indicate optimal times for energy use, helping members adjust their consumption in real-time. Inclusivity was highlighted as essential, particularly for those who may not be deeply interested in the energy transition. Energy savings should be presented in a clear and informative way, with automation tools supporting behavioural changes. This approach aimed to make the energy transition accessible and practical for all community members, ensuring broad engagement and participation.

5.3.2 Second Workshop, Poysdorf

The second workshop, held in August 2024, followed a major event organized by OurPower, where citizens from Poysdorf were invited to learn about the OurPower platform, its functionality, and to ask questions or sign up. Despite the outreach, only five participants attended the workshop, which followed after the main event. These individuals had not participated in the first workshop and were relatively unfamiliar with the concept of energy communities in general. As a result, the specific topic of "energy data sharing" was challenging to communicate, and in-depth discussions could not be initiated.

Due to this, the feedback provided by participants lacked meaningful validity and presenting it alongside the results from the Dingle community would lead to misleading comparisons.

Despite the challenges faced, valuable lessons were learned from this workshop, providing important insights for organizing future sessions.

Firstly, it became clear that deliberative workshops should not be scheduled alongside large-scale events, as this can reduce focus and participation.

Secondly, participants need a foundational understanding of key concepts, such as energy transition and energy communities, before diving into more specific topics like "data sharing." Without this basic knowledge, meaningful discussion is difficult to achieve.

Thirdly, it is essential to first educate participants on the broader context—helping them understand the relevance of energy transition and energy communities both as individuals and as members of a wider community.

Fourth, workshops should provide space for participants to ask questions, express concerns, and share their needs, ensuring they feel engaged and understood. Meeting people where they are is crucial.

Finally, once the foundational concepts are well understood, future workshops can successfully tackle more specific issues. This approach will allow for deeper and more productive discussions.

5.4 Thought Leaders Workshop

The “Thought Leaders Workshop” was a one-time event held in Budapest, Hungary. The session followed a hybrid format, with 10 experts participating. The online portion of the event was conducted in English, while the in-person discussion that followed was held offline in the local language.

The topic of the workshop was "Energy Communities and Data Sharing” and brought together a diverse group of participants both in-person and virtually. The workshop focused on key aspects of data sharing within energy communities, highlighting both the challenges and opportunities. Participants underscored the vital role that data plays in enhancing community energy projects, addressing barriers to data sharing, and identifying incentives for adopting data-driven services. The event provided a valuable platform for exchanging insights and expertise on data sharing and data-driven solutions for energy communities.

The workshop opened with a thorough introduction to the ENPOWER project, followed by expert presentations from both academic and corporate perspectives. Special attention was given to the

Hungarian pilot project. This introduction established the workshop's direction, emphasizing the project's goals and the importance of collaboration in reaching them.

A variety of presentations were given to highlight the topic from multiple perspectives. The role of energy communities in decarbonization, Smart grids and GDPR, Flexibility and metering in energy communities and Data sharing from a socio-economic perspective and emerged prioritizations from previous ENPOWER workshops in Dingle.

In summary, the "Energy Communities and Data Sharing" workshop addressed various dimensions of data sharing within energy communities, including technical, legal, economic, and social. This created a dynamic exchange of knowledge and ideas. Bringing together a diverse group of participants, the workshop laid the groundwork for future collaborations and advancements in this vital area. It highlighted the essential role that data plays in ensuring the success and long-term sustainability of energy communities.

5.5 Conclusion

The workshops held across different demo sites provided valuable insights on the topic of “energy data sharing.” In Dingle, the workshops provided a comprehensive view, and the highly engaged community got involved in vibrant discussions. The local sense of community was a driving force behind this engagement. Key themes that emerged included:

1. Financial/Economical
2. Social: Communication/Education
3. Sustainability/Environment
4. Technical/Operation
5. Regulations/Rules

Interestingly, these themes were also echoed during the “Thought Leaders Workshop” in Budapest, highlighting their universal relevance regardless of participants’ geographical location or background. This consistency across workshops underscores the importance of addressing these key areas in future engagements with energy communities. It shows that these themes are not only central to discussions but also essential in shaping the future of energy data sharing and community engagement.

The workshops in Poysdorf followed a different trajectory compared to those in Dingle and the “Thought Leaders Workshop” in Budapest. The primary motivation for participation in Poysdorf's first workshop was largely financially driven, making direct comparisons with the other sites challenging. However, the second workshop in Poysdorf revealed interesting parallels, despite involving less experienced participants.

When discussing the presented scenario, similar overarching themes began to surface, mirroring those found in other workshops. Notably, in the social category, the focus shifted toward fairness and transparency, which became key concerns for the participants. This highlights that even with varying levels of experience, core themes such as social ones need to be considered in future discussions.

The current findings from the workshops provide a valuable foundation for shaping future engagement with energy communities and guiding the development of user-friendly technical tools. To ensure that these tools meet the needs of end-users, the key themes identified across the workshops should be thoughtfully incorporated into the design of the front-end interfaces. Key considerations include:

1. Financial clarity: Energy savings and return-on-investment must be presented in a clear, easily understandable way to empower users to make informed financial decisions.

2. Social aspects as communication: Websites and apps should provide opportunities for interaction, such as event notifications or forums where members can share experiences, discuss investments, and offer mutual support.

3. Sustainability focus: Sustainable actions, such as switching to LED bulbs, should be highlighted with relatable examples e.g., "Saving this much energy is equivalent to baking X number of pizzas in an oven."

4. Simplified technical data: Technical concepts like kWh or reading an energy bill need to be explained in straightforward terms, making energy data accessible to all.

5. Clear legal guidance: Legal aspects and regulations surrounding energy investments should be explained clearly, helping participants understand the implications, why certain actions may be restricted, and how to apply for available grants.

By addressing these elements, future tools and platforms can better serve energy communities and foster greater engagement.

6 Business Sandbox (AUDENCIA)

6.1 Creating Innovative Business Models for Energy Communities with a Consumer-Centric approach

To create business models (BMs) for EnCs, using a consumer-centric approach, in the context of ENPOWER project an inclusive methodology was employed by AUDENCIA that focused on capturing the needs and preferences of each community. This approach was based on principles of social innovation, where business models were designed as tools for civic empowerment, that facilitated decentralized energy production and community-driven decision-making. With a combination of structured stakeholder engagement and data-driven analysis, we developed robust, adaptable business models that fall in line with the distinct priorities of energy citizens, thus placing them at the center of the socially informed energy transition.

The methodology consisted of two primary stages: **1. direct stakeholder engagement through semi-structured interviews** and **2. detailed quantitative and qualitative data collection using Excel**. Together, these tools allowed for a comprehensive understanding of each EnC's needs, ensuring that the BMs reflected the diverse social, technological, and financial contexts of the communities

6.2 Previous work: Stakeholder Engagement: Semi-Structured Interviews

The first stage of our methodology was a process of stakeholder engagement through semi-structured online interviews, which allowed stakeholders to share specific insights about their roles, objectives, and expectations within the EnCs in D2.3 [80]. The objectives of these discussions were as follows:

Market Environment: Stakeholders provided details into the local energy market, identifying key resources, channels, activities, and partnerships integral to each EnC's operation. This step mapped the complex connections within each community, highlighting prosumers, regulatory bodies, technology providers, and local authorities.

Expected Impact: Each stakeholder presented the anticipated impacts of their pilot project, both short- and long-term, on their local context. This feedback allowed us to align the BMs with community goals, ensuring they could provide tangible social, economic, and environmental benefits to each EnC.

Financial Structure: Stakeholders analysed their revenue streams and cost structures. This included revenue models, such as energy sales and community memberships, along with operational and maintenance costs. These details were critical for ensuring that the BMs would support both individual and community-wide financial sustainability and longevity.

Innovation and Competitive Advantage: The interviews also uncovered each pilot's unique selling points and competitive advantages, such as digital energy management tools that allow citizens greater control over their energy usage and costs. By capturing these strengths, we could design BMs that leveraged local innovations.

By following a semi-structured format, we were allowed the flexibility needed to explore each community's specific needs and challenges, with open-ended questions encouraging stakeholders to share deeper insights about their roles, expectations, and interactions within the EnC.

6.3 Data Collection via Excel-Based Framework

Moving on to the second stage of our methodology, we implemented a quantitative and structured data collection approach using a comprehensive Excel-based questionnaire. This framework consisted of eight sheets, each designed to cover a critical aspect of the BM components. The structured nature of the Excel file allowed us to analyse the information systematically, ensuring that all responses contributed directly to a cohesive BM design tailored to each pilot's needs.

The eight sheets in the Excel document are as in Table 6:

Table 6 Questionnaire structure via Excel-Based Framework.

Excel Sheet	Key Questions Included
Stakeholder Roles and Responsibilities: **This sheet captured each stakeholder's role within the EnC, focusing on their specific responsibilities and interactions.**	What are your primary responsibilities in the EnC? What specific roles do you fulfil in relation to other stakeholders? How do you see your role impacting the broader BM?
Technological Integration: **This sheet assessed the technological landscape, identifying current and anticipated digital tools.**	What digital tools or platforms are currently in use? Which technologies are essential for your community's operation? Are there specific technologies you foresee adopting in the future?
Financial Viability and Revenue Streams: **To clarify financial sustainability, this sheet gathered data on income sources, expenses, and economic balance.**	What are the primary revenue streams for your EnC? What are the main expenses associated with your activities? How do you ensure financial sustainability?
Community Engagement and Participation Levels: **This sheet focused on the modes of participation among community members.**	What are the typical modes of participation for community members? How are community members encouraged to engage in decision-making? What channels do you use to facilitate engagement?
Social and Environmental Impact Metrics: **Aligning with sustainability goals, this sheet collected data on social and environmental objectives, with questions such as:**	What social impacts do you aim to achieve with your energy activities? What environmental goals are set within your community? Do you track specific metrics related to ESG (Environmental, Social, Governance) or SDG (Sustainable Development Goals)?
Competitive Landscape and Challenges: **To understand external influences, this sheet focused on market conditions and obstacles. Questions included:**	What are the main challenges your community faces in the energy market? Are there regulatory barriers that limit your operations? How do you differentiate your community from other energy providers?

Local Preferences and Cultural Considerations: **Recognizing local values, this sheet explored cultural and demographic factors.**	Are there cultural values that shape community preferences for energy use? How do demographic factors affect participation? Are there any local traditions or norms that influence energy decision-making?
Decision-Making and Autonomy in the EnC: **This sheet addressed governance dynamics, focusing on autonomy and stakeholder influence.**	How are major decisions made within the community? Do individual community members have a say in decision-making? What mechanisms exist to resolve conflicts among stakeholders?

By addressing each of these aspects of our pilots, we managed to gather meaningful data in a holistic manner. For example, understanding responsibility distribution enabled effective task and authority allocation, while insights into technological needs ensured alignment with current and future capabilities. Moreover, analysing financial data allowed us to build sustainable and adaptable models suited to each community's economy. On one hand, recognizing community engagement preferences helped design adaptable structures for varying participation levels, and on the other hand, integrating impact metrics aligned the models with sustainability goals, and understanding the competitive landscape ensured each model could thrive. Additionally, respecting local values and demographics guaranteed cultural sensitivity, and grasping governance structures supported decentralized decision-making and collective ownership. This approach ensured our BMs met each community's unique needs and promoted empowered, sustainable energy citizens.

The structured data from the Excel sheets provided both quantitative and qualitative insights, uncovering patterns and correlations among stakeholders' needs, technological capabilities, and financial structures. On one hand, closed-type questions offered clear, comparable data points across pilot cases, whereas open-ended responses provided depth, helping tailor the BMs to reflect each EnC's specific context.

Key insights included:

- Analysis of the **Stakeholder Roles and Responsibilities** sheet showed a diverse range of functions within each EnC, guiding BMs that support distinct roles and collaborative relationships.
- The **Technological Integration** sheet highlighted differences in digital tool adoption, allowing for BMs that scale according to each community's technological capacity.
- The **Financial Viability and Revenue Streams** sheet revealed various revenue approaches, prompting BMs that could support long-term financial resilience.
- Insights from **Community Engagement and Participation Levels** sheet, showed unique engagement preferences, leading to BMs with adaptable structures for community involvement.
- The **Social and Environmental Impact Metrics** underscored strong ESG and SDG alignment, leading us to embed sustainability metrics within each BM.
- The **Local Preferences and Cultural Considerations** sheet informed BMs that respect community-specific values, enhancing acceptance and involvement.

To sum up, this dual-method approach combining structured interviews with Excel-based data collection enabled the development of consumer-centric BMs uniquely suited to each pilot case. By organizing data into eight core sheets and analysing stakeholder responses, we managed to create adaptable BMs that prioritise financial viability, technological flexibility and community empowerment. This methodology ensured that each BM not only reflects local needs but also empowers energy citizens as active participants in the energy transition, promoting a sustainable, community-driven future.

6.4 Key Elements of ENPOWER's Innovative Business Models

- **Bidirectional Participatory Process**: ENPOWER's approach diverges from traditional business models by treating consumer input and engagement as core elements. Rather than viewing consumers as passive participants, ENPOWER recognizes them as active stakeholders whose behaviours, needs, and insights directly inform and shape the community's energy-related choices. This bidirectional process is made possible through structured participation channels—such as community boards, direct feedback loops, and public consultation platforms—where citizens can voice their opinions, participate in discussions, and contribute to energy strategies. This integration of citizen insights not only enables each EnC to be more responsive to the community's evolving needs but also ensures that the value propositions of the business models reflect the priorities of their members, which could include local energy optimization, cost-saving opportunities, and increased transparency.
- **Enhanced Business Model Canvas (BMC)**: The project adapts the traditional BMC by incorporating citizen-driven energy and financial flows, adding an extra layer of connectivity and illustrating the relationships among stakeholders, from individuals to energy producers and service providers. These adapted BMCs map out complex interactions and exchanges, showcasing energy and data flows, financial transactions, and "community involvement flows" which capture the various ways in which technical enablers empower citizens within the community. The visual models emphasize citizen influence on decisions, reflecting the collaborative nature of these new BMs, and illustrate the depth of their involvement in the EnC's decision-making and operational procedures.

Within these adapted BMC diagrams (**Figure 8, Figure 9, Figure 10, Figure 11**), several new dimensions have been added:

- **Direct Relationships and Interactions**: Representing direct P2P connections, these show how citizens can engage not only within the community but also in external market interactions. For example, citizens can act as both buyers and sellers, depending on their energy needs or surpluses.
- **Empowerment Flows**: New flows represent the "power" afforded to citizens through TEs which support their active roles as decision-makers, contributors, and prosumers. For instance, some TEs provide citizens with real-time data on energy usage, allowing them to adjust consumption patterns, while others enable blockchain-secured transactions for transparent P2P exchanges.
- **Energy and Data Exchange**: These flows illustrate how energy production, storage, and usage data circulate within the EnC, enabling citizens to make informed choices. Data exchange also supports better integration with national energy frameworks and local markets, enhancing the EnC's role in the broader energy landscape.

- **Dual Identity Representation**: ENPOWER recognizes that citizens have both individual and collective identities within EnCs. These adapted BMCs capture this dual role, showing citizens as self-sustaining energy users with personal incentives and as active community members working towards shared goals. This representation of dual identity highlights the varied motivations and impacts that each citizen brings to the EnC, reinforcing the value of consumer-centric designs.
- **TEs as Catalysts for Change**: Eighteen TEs play a critical role in enhancing citizen agency within the EnCs by facilitating transparency, data accessibility, and decision-making empowerment. TEs are integrated into the models and serve as catalysts that enable citizens to make informed choices, engage with other energy actors, and actively participate in EnC governance.

Examples include:

- **TE-1** provides decision-support tools, allowing communities and their members to access economic, social, and environmental insights before making energy-related decisions.
- **TE-5** leverages blockchain technology to establish trust in P2P transactions, ensuring that all community members have secure and transparent records of their energy exchanges.
- **TE-14** provides nudging applications that offer real-time feedback on energy usage, helping citizens adapt their behavior based on current consumption trends, available supply, or energy prices.

These TEs are pivotal in fostering "energy citizenship" by empowering citizens not only to consume but also to participate in the production, storage, and distribution of energy within their communities. In addition, tools like blockchain-secured exchanges and nudging applications for consumption adjustment ensure that citizens' energy interactions are both dynamic and secure. They give consumers control over their own energy data and interactions, supporting a more democratized, transparent, and flexible energy system.

Bellow are provided the pilot cases with established EnCs that established new "flows" after the introduction of the corresponding UCs.

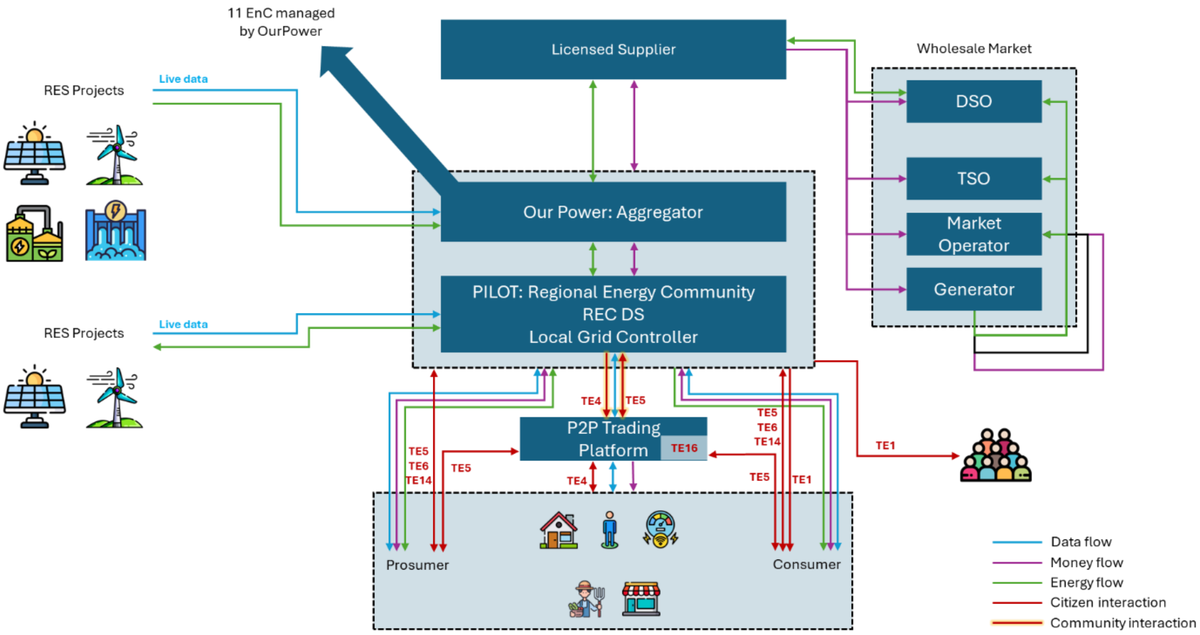

Figure 8: The flows before introducing the UCs, Austrian Pilot.

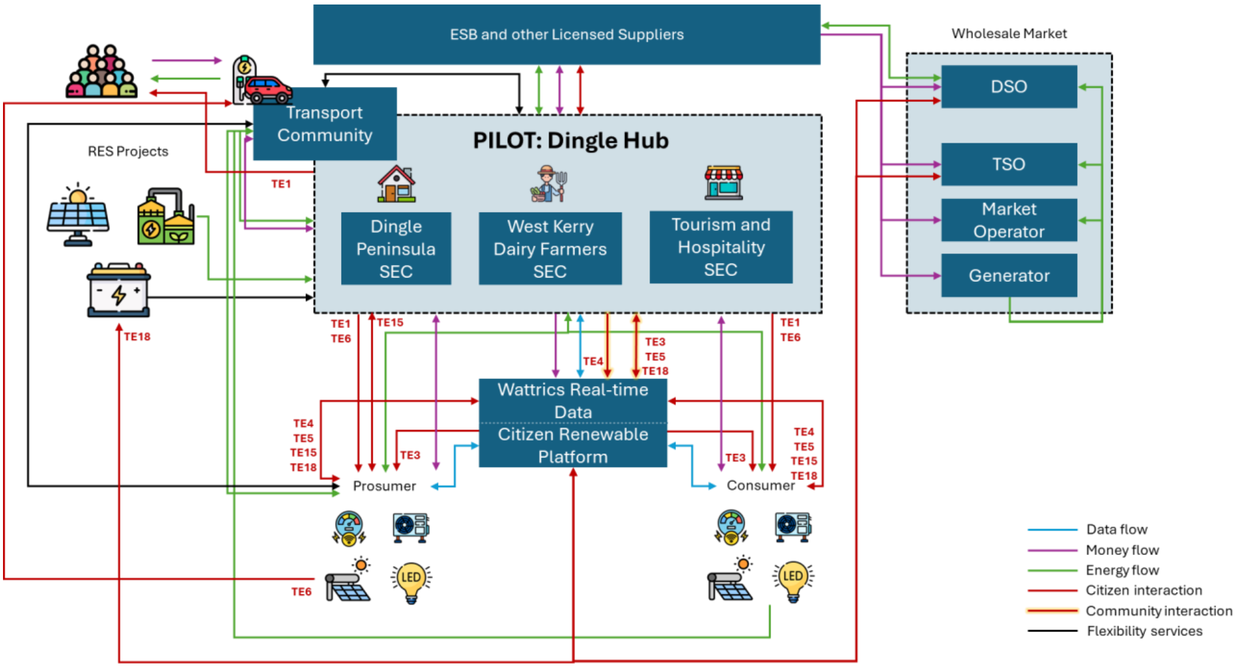

Figure 9: The flows before introducing the UCs, Irish Pilot.

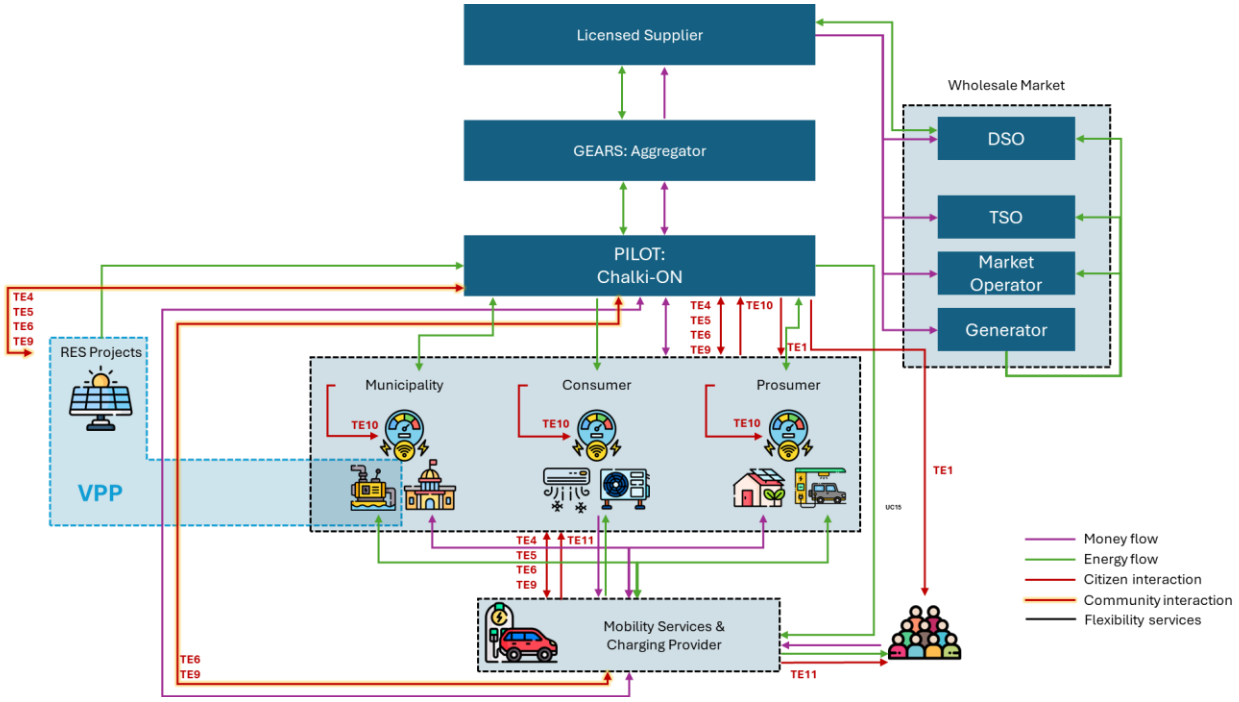

Figure 10: The flows before introducing the UCs, Greek Pilot.

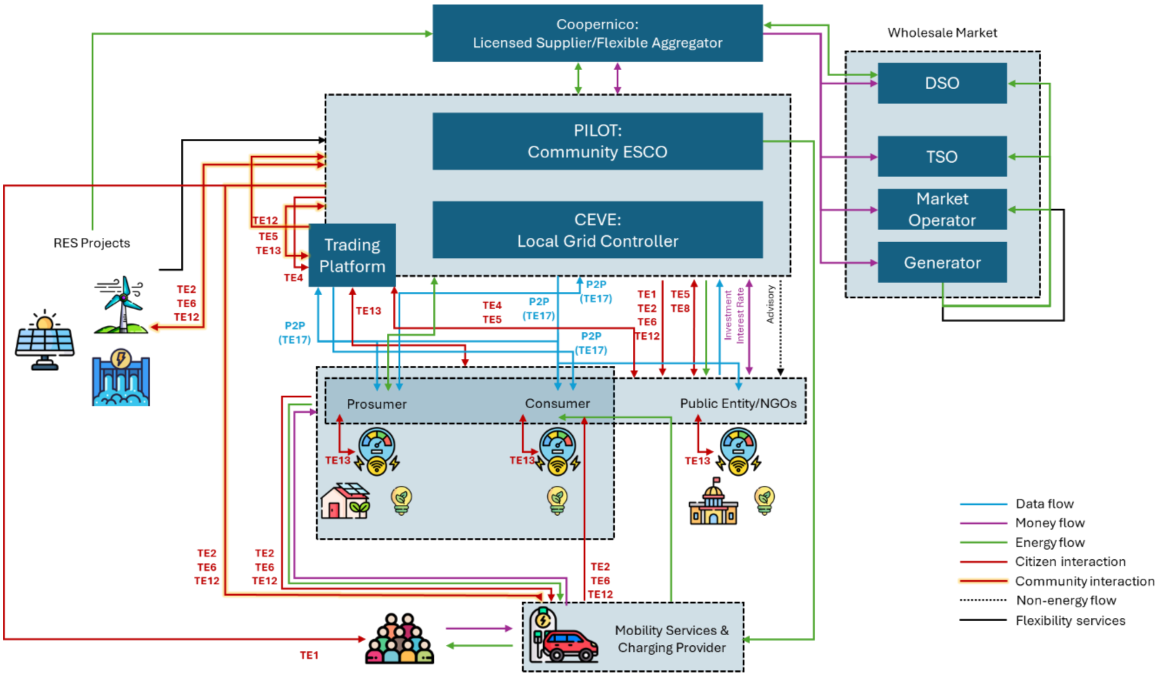

Figure 11: The flows before introducing the UCs, Portuguese Pilot.

6.5 Connecting Technical Enablers with Energy Citizenship

The up to now BMs for EnCs depicted

a. The decarbonized energy systems, since the main activities of the EnCs are based on RES and low-carbon technologies,
b. Decentralized energy systems since energy production facilities are located closer to where energy consumption takes place,
c. Digitalization that comes with the use and implementation of cutting-edge technologies and what was missing was the concept of the value of democratization.

To feed the fourth force, Democratization, AUDENCIA, tried to answer the below-mentioned questions:

- What is the degree of participation of the energy citizen in each pilot case?
- Are we referring to the consumer form of participation, direct forms of participation, or representative forms of participation?
- How does the energy citizen manage their rights within the EnCs?
- How do the technical enablers applied to each pilot case empower the energy citizen's capabilities or enhance its role in decision-making within the EnCs?
- How do these internal upheavals act on the other forces of the energy transition?

The elements of energy citizenship were broken down to the following categories: individual choice, consumer reference group, prosumerism, EnC as a common entity, social movements, participation in public consultation and then a participation barometer was developed. This barometer illustrates a spectrum ranging from individualistic forms of participation to collective and fully representative forms. Subsequently, to better design the BMCs and to illustrate how each TE could be converted into a 'vehicle' that fosters energy citizenship in its various forms, we performed a conceptual-level exercise. This exercise focused on examining and analyzing how the functionality of each enabler impacts energy citizenship within the context of each pilot case. Strengthening consumer leeway via technical enablers resulted in the new conceptualisation of energy citizenship and energy democratisation. The extended powers from the digital tools that are given to energy citizens worked as a safety net, against the commercialisation of the operation of the communities, support trust, efficiency, and transparency of the procedures within the community, and upgrade the role of citizens.

To include this in D2.3 [80], we designed new BMCs for each pilot case, that depicted in diagrams not only the flows of energy and money, but the initial archetypes were enriched by adding data flows and "citizen engagement" and "community involvement flows", constructing a very complex archetype, that illustrates the complexity of relationships between the involved actors, the directness of the information exchanges, the dependency between the actors and the multi prismatic interactions of the energy citizens both within the framework of the Community but also with external market stakeholders.

ENPOWER's business models foster a diverse and inclusive ecosystem involving stakeholders at local, regional, and national levels, with the inclusion of innovative technologies, such as interactive digital tools, engagement and management platforms, nudging apps and decision-making and supporting tools, as a "change agent" towards more energy democratized and dynamic models. These new business models offer potential new sources of benefits and revenues and fully customized solutions (mainly occurring through the increased powers and freedom of choices and actions of the energy citizens) tailored to the unique needs of individual energy consumers across ENPOWER's six pilot cases.

Some TEs allow citizens to directly address other sellers, transform themselves into buyers, shape their consumption behaviours, decide when to store and increase their level of energy literacy.

Other enablers allow citizens to express their opinions and insights and share their experiences in community/advisory board meetings, citizens' council and public consultations, reinforcing a more collective and representative form of participation in the EnC procedures.

To delve deeper and enhance the specificity and applicability of the Business Models (BMs) as developed by AUDENCIA, we utilized the use cases capitalization towards a consumer-centric energy market design, as elaborated in Chapter 3 by Blueprint.

The finalized set includes 21 use cases and 5 Sub-UCs (Table 3), each meticulously designed and customized to meet the unique characteristics and demands of the specific pilot sites. This customization was achieved through a rigorous and iterative refinement process. The process involved technical partners, who provided expertise in technological enablers, and pilot site representatives, who contributed crucial insights from the practical, real-world contexts where these solutions will be implemented.

Following the identification of TEs implemented in each UC, AUDENCIA conducted a comprehensive analysis of the initial mapping of TEs activated at each pilot site. The detailed mapping is presented in Table 7: UCs and Sub-UCs with the implemented TEs.

Table 7: UCs and Sub-UCs with the implemented TEs.

UC\ Pilot	Austria	Portugal	Greece	Ireland	Hungary	Spain	TEs per UC

UC1							TE7						
UC2							TE8						
UC3							TE13						
UC4							TE6	TE 12					
UC5							TE9						
UC6							TE12	TE 13					
UC7							TE13						
UC8							TE1	TE 2					
UC9							TE16						
UC10							TE16						
UC11							TE17						
UC12							TE14						
UC13							TE3	TE 14					
UC14							TE3	TE 14					
UC15							TE11						
UC16							TE5						
UC17							TE5						
UC18							TE18						
UC19							TE15						
UC20							TE10						
UC21							TE3	TE 18					
SUB-UCA							TE12						
SUB-UCB							TE4	TE 5	TE 6	TE 7	TE 15	TE 16	TE 17
SUB-UCC							TE4	TE 5	TE 6	TE 7	TE 15	TE 16	TE 17

SUB-UCD							TE4	TE 5	TE 15	TE 16	TE 17		
SUB-UCE							TE4	TE 5	TE 15	TE 16	TE 17	TE 18	
Involved TEs per Pilot	TE1	TE1	TE1	TE1	TE1	TE1							
	TE4	TE2	TE4	TE3	TE4	TE2							
	TE5	TE4	TE5	TE4	TE5	TE3							
	TE6	TE5	TE6	TE5	TE6	TE4							
	TE7	TE6	TE7	TE6	TE7	TE5							
	TE14	TE7	TE9	TE7	TE9	TE6							
	TE16	TE8	TE10	TE15	TE10	TE7							
		TE12	TE11	TE18	TE11	TE8							
		TE13			TE12	TE12							
		TE15			TE14	TE13							
		TE17			TE16	TE15							
						TE17							
						TE18							

The findings from these mappings provided valuable insights for the various flows represented within the designed BMs that were tailored for each pilot site. The integration of new TEs at each pilot site led to the identification of additional flows that were not present, neither taken into consideration, in the initial investigation, thereby making the new flows more complex than before. While the fundamental BM archetypes that were identified for each pilot remained unchanged, the dynamics of data transfer, citizen engagement and community interaction within the examined ecosystem became more complex and intricate.

Within this framework, the BM archetypes originally developed in D2.3[80] were redesigned and refined with minor modifications to reflect the updated flows (**Figure 12, Figure 13, Figure 14, Figure 15**). These adjustments were made with the dual purpose of establishing a robust foundation for the deployment of ENPOWER solutions, effectively bridging the gap between conceptual frameworks and on-the-ground implementation and ensuring alignment with the conclusions and progress of deliverables from other project partners.

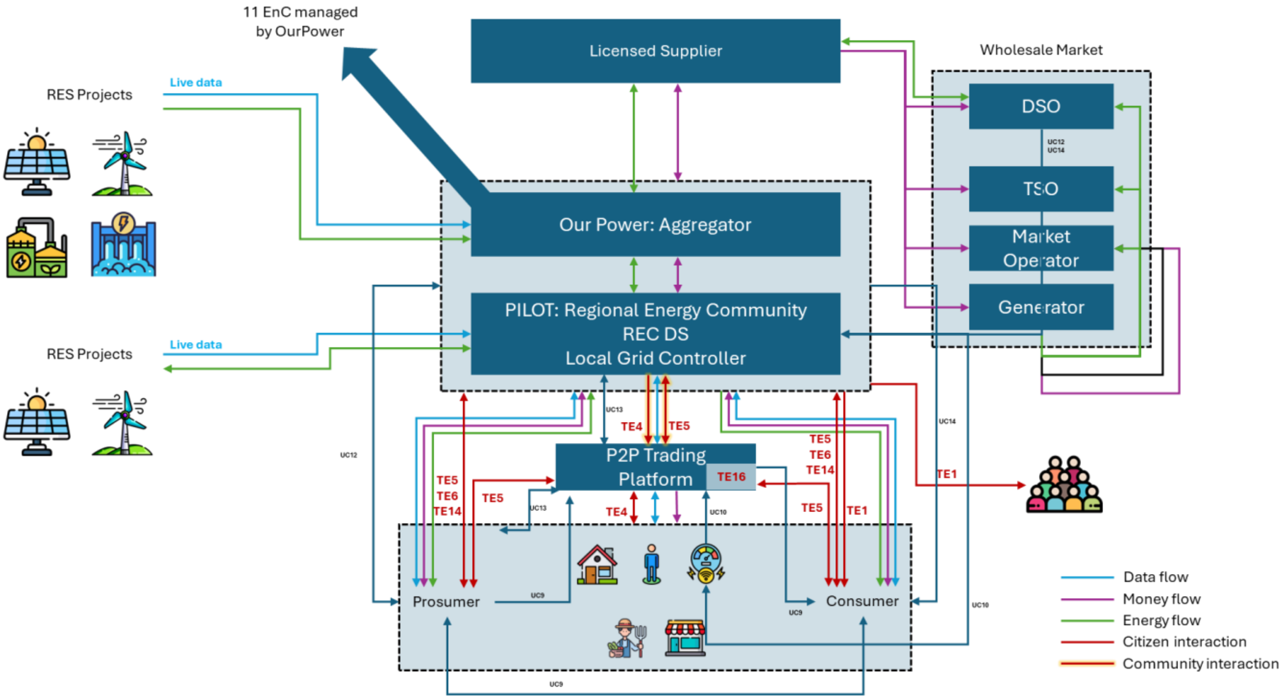

Figure 12: The new flows after introducing the UCs, Austrian Pilot.

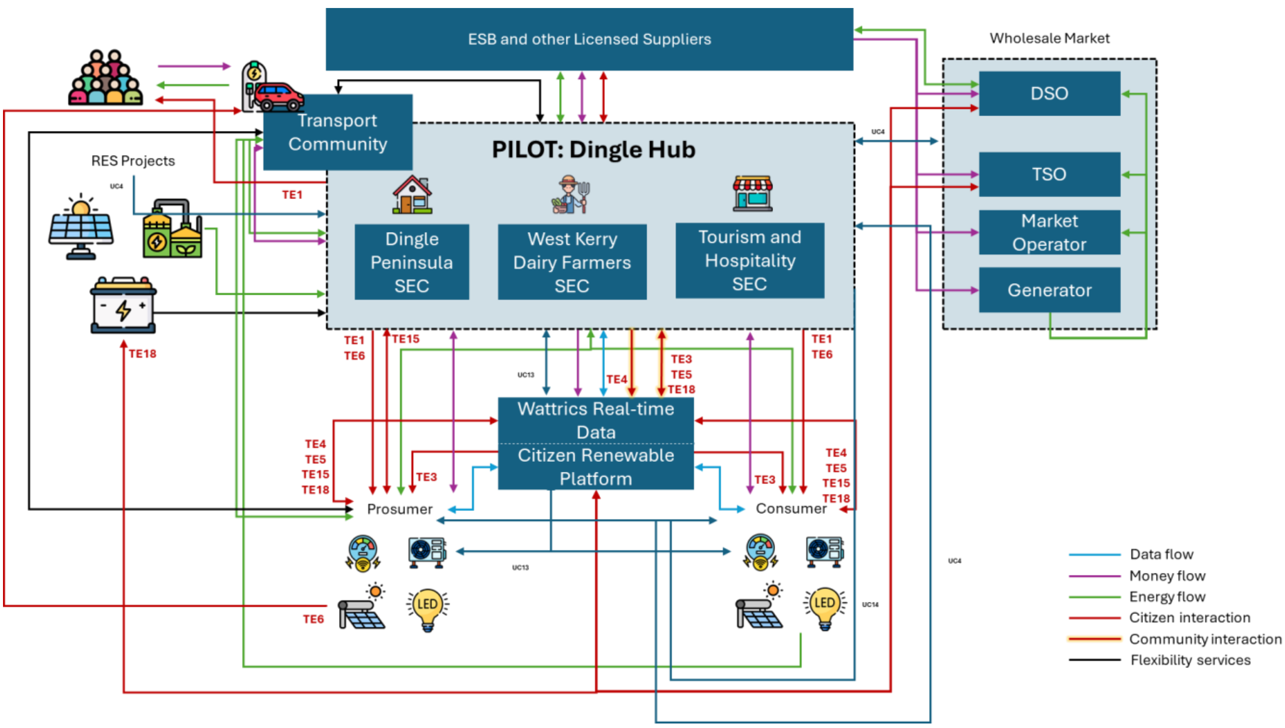

Figure 13: The new flows after introducing the UCs, Irish Pilot.

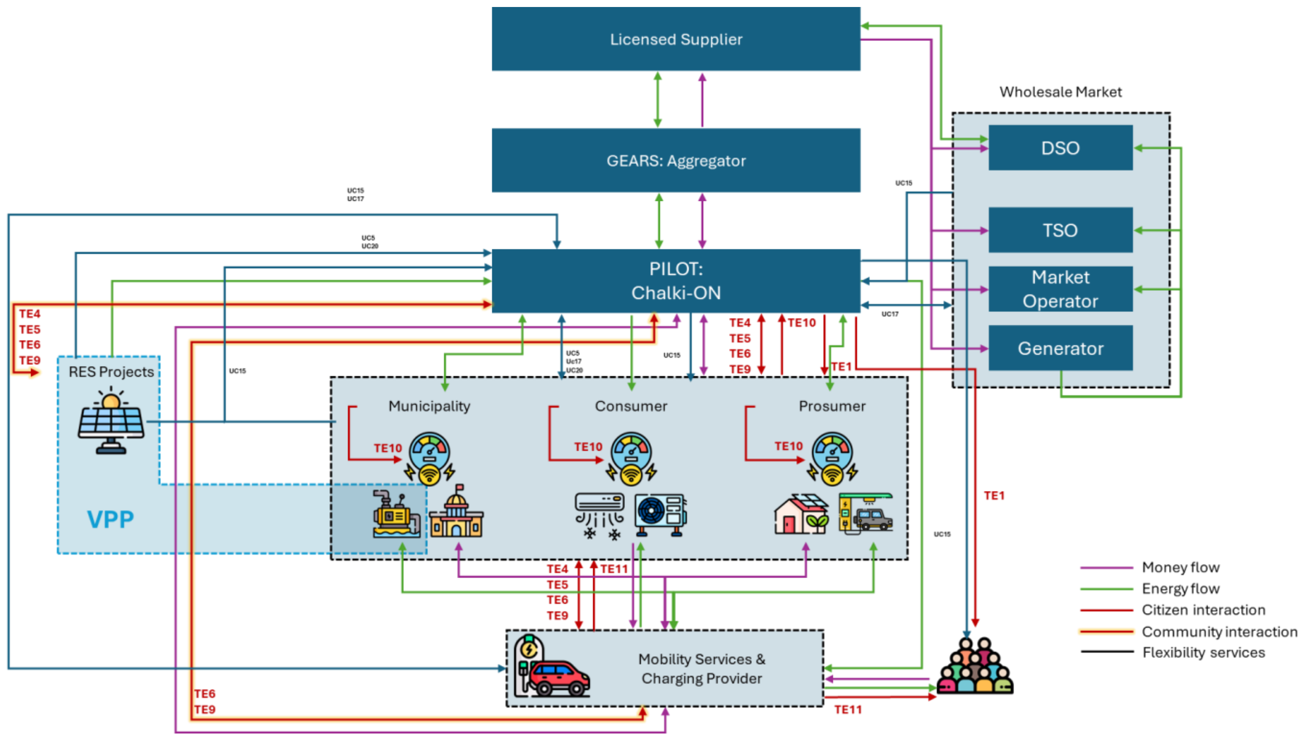

Figure 14: The new flows after introducing the UCs, Greek Pilot.

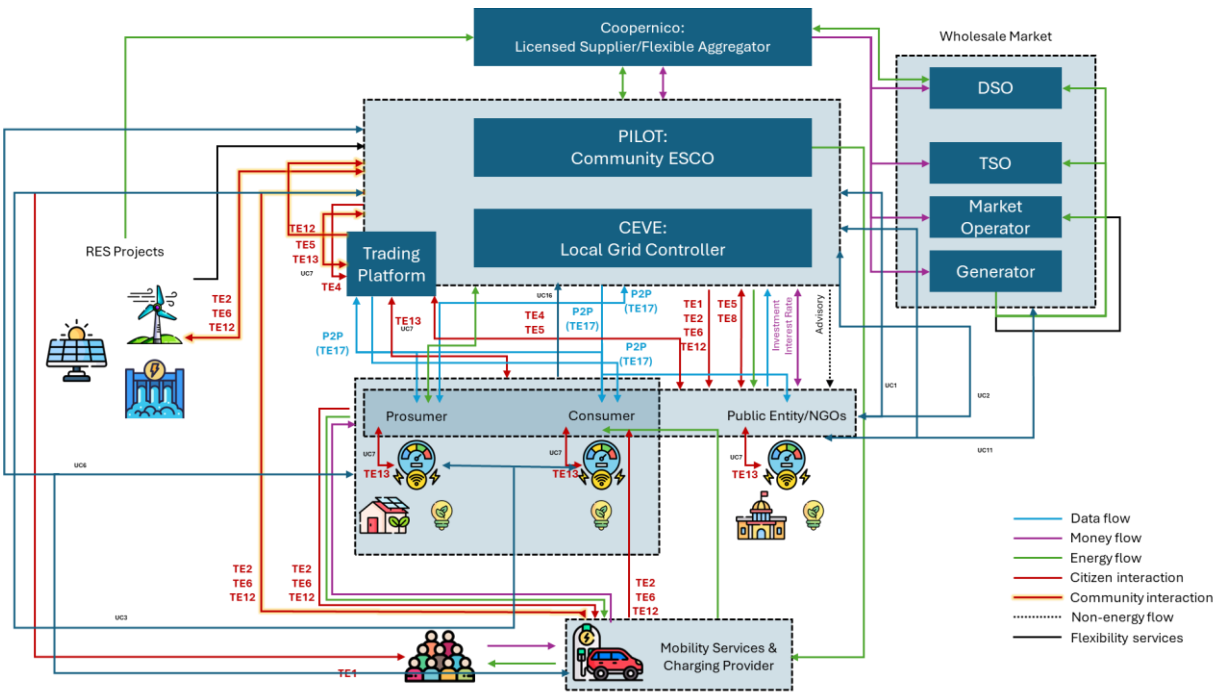

Figure 15: The new flows after introducing the UCs, Portuguese Pilot.

As an example, the BMs formulated for the use cases in the front-runner pilots in Austria, Portugal, Ireland, and Greece are included.

Furthermore, it is worth noting that to create more participatory BMs and to integrate input from those directly involved in the development of technological enablers, energy citizenship questionnaires were sent to the following technical partners: CARTIF, INESC TEC, Dcsix, EEU, ED, DST, NTUA, UNIBAS, GEARS, COMS, WATT-IS, OurPower, BLUEPRINT and UCC.

The purpose of these questionnaires was to gather their insights on how the technologies they are developing contribute to fostering and empowering energy citizenship. Specifically, respondents were asked to indicate:

Which segment of the energy citizenship, as described in the barometer which has been developed in D2.3 [80], their contributions mainly feed and affect. The segments include:

- Consumers who are not members of Energy Communities (EnC)
- Individual choice
- Consumer reference group (Group of common interest)
- Prosumers
- Participants in protests and movements
- Collective interest of EnC
- Policymakers

The benefits their technical solutions provide, by selecting from categories derived from thorough desktop analysis and grey literature review. These categories include:

- Influence in the community and trust
- Local interaction within the community and bringing people together
- Increased local acceptance of renewable energies
- Local income generation
- Access to alternative sources of finance
- Better information and knowledge sharing
- Increased local cohesion and sense of community
- Increased grid reliability
- Protection of energy citizens' rights
- Secured data valorization
- Increased energy literacy
- Formalized participation in energy governance
- Reduced energy costs
- Energy sobriety (changing consumption patterns)
- Facilitating bilateral training
- Coordination between multiple parties
- Other specified benefits

Based on the delivered by the technical partner responses, the flows of the UCs in each pilot were re-examined and adjusted in the newly developed BM archetypes. It is worth mentioning that there was alignment between the theoretical descriptions of each tool and its practical application, demonstrating clear benefits for both energy citizens and energy communities.

Besides the renewed and adjusted-with the new flows BM archetypes-the type and the range of citizen and community participation that each UC unlocks, was analysed with the use of the “citizenship participatory barometer”(Figure 16: Different levels of citizen participation based activated by UCs), the same way as implemented for the first time TEs in D2.3[80], with direct inputs from the technical partners. This is essentially a deeper dive into the analysis of the "participatory powers" conferred by these specific ENPOWER TEs, as was extensively broke down in more specific 21 special UCs, outlined by Blueprint in Chapter 3. This approach aims to provide a detailed understanding of how these tools operate across various application contexts, highlighting both the opportunities they unlock and the challenges that arise from their adoption.

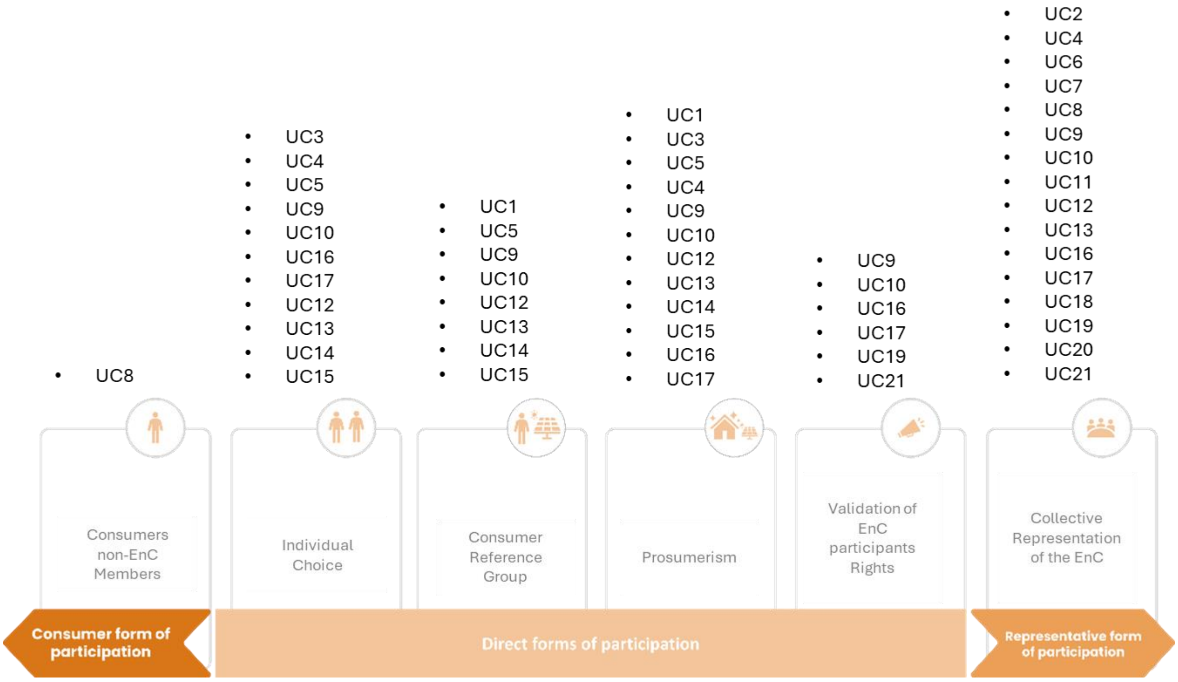

Figure 16: Different levels of citizen participation based activated by UCs.

7 Functional Specifications (Dst)

7.1 Previous work in WP2

DST played a pivotal role in defining the functional specifications in D2.4 [81], focusing on analysing HLUCs to develop a comprehensive high-level functional specification list. The primary goal of defining these specifications was to establish a clear and structured framework that directly addresses the pilot requirements and supports the execution of the use cases. This approach ensures that the functionalities are closely aligned with the practical needs and objectives of the pilots. In addition to this, we actively contributed to the creation of the ENPOWER overview architecture, ensuring that the proposed framework aligned seamlessly with the project's strategic goals.

Our involvement extended to the collaborative development of use cases, working closely with project partners to tailor these scenarios to fit perfectly with the technological enablers and functionalities within our scope of work. D2.4 [81] also showcased our efforts in assessing user needs and identifying key technological enablers, including blockchain for secure energy trading, privacy-preserving demand-response systems, and AI-driven tools for consumer engagement. These contributions laid the foundation for the next steps in refining and implementing detailed functional specifications. By linking these specifications to pilot requirements and use cases, the contributions ensured that the proposed functionalities could effectively support the validation and implementation of the project's innovations.

7.2 Methodology for Functional Specification Definition

The methodology adopted for defining the functional specifications in this project builds on the foundational work established in previous deliverables. In D2.4 [81], a high-level functional specification list was developed, grounded in HLUCs identified in D2.1 [1]. This list served as a structured starting point for detailing the project's technical and operational requirements.

To refine and expand this high-level list into a detailed set of functional specifications, we employed a multi-step methodology:

1. **Analysis of Use Cases**

   The use cases provided in D2.1 [81] and further elaborated in this deliverable were meticulously reviewed to ensure that the specifications align closely with the project's objectives. This process involved identifying the functionalities required to address the specific needs of each use case and mapping them to the broader framework of the ENPOWER system.

2. **Integration of Project Knowledge**

   The detailed functional specifications were also informed by the comprehensive information available in various ENPOWER deliverables. These documents provided valuable insights into technological, social, and business dimensions, offering a holistic perspective that enriched the functional specifications.

3. **Stakeholder Engagement**

Stakeholders participated in a review phase of the functional specifications to ensure alignment with their operational needs, validating their accuracy, feasibility, and consistency with project objectives. Their feedback was instrumental in refining the specifications to address any gaps or adjustments required for successful implementation.

This iterative approach ensured that the functional specifications were both comprehensive and adaptable, reflecting the diverse contexts and objectives of the project while maintaining coherence with its overarching goals.

7.3 Functional Specifications List

FS1: Data-Driven Consumer Clustering and Segmentation for Energy Management.

Brief Description	This specification defines the requirements for a data-driven consumer clustering feature that supports energy management by categorizing consumers based on consumption patterns and demographics. Leveraging historical and real-time data with AI clustering, this functionality aids community managers in making targeted energy decisions for optimized solutions.
Functional specifications	• **Data Input:** ○ The system must support the integration of historical and real-time energy consumption data and weather data. ○ Questionnaire responses capturing sociodemographic and behavioural details of community members must be incorporated. • **Clustering and Segmentation:** ○ The system should use AI or statistical models, such as K-means or hierarchical clustering, to classify users. ○ Segmentation should be based on factors like geographic location, socio-economic status, age, gender, and behavioural characteristics. • **Output:** ○ The system must generate user classifications in distinct categories and present these results in an accessible format, including visual summaries or detailed reports for community managers.
Use case reference	• UC1

FS2: Assessing Demand Response Potential in Energy Communities.

Brief Description	This specification outlines the functionality for evaluating DR potential within an EnC using the FATEC tool. It assesses individual flexibility based on price elasticity, identifying opportunities to shift or reduce peak usage and optimize DR for the benefit of providers and consumers.
Functional specifications	• **Data Input:**

	○ The system must allow users to provide electricity consumption data and relevant pricing information. ○ Data must be clean, in the correct format, and, if needed, supplemented by weather data or location-specific information, which the tool can retrieve from public APIs if not provided. • **Data Processing:** ○ A data cleaning tool should verify that all required data is present and correctly formatted. ○ A pre-processing tool will aggregate data according to the measurement frequency. • **Demand Response Assessment:** ○ The system should apply a causality model to estimate the price elasticity of demand for each user or a specified group of consumers. ○ The tool must assess flexibility potential by analysing responsiveness to a set of prices, allowing the system to identify periods when energy demand can be shifted or reduced. • **Ranking and Output:** ○ The system should rank consumers by their price elasticity of demand, establishing a hierarchy based on flexibility potential. ○ Results should be accessible in a detailed report, showing individual or aggregated DR capabilities, price elasticity values, and the ranked list.
Use case reference	• UC2

FS3: Personalized Consumer Engagement and Activation.

Brief Description	This specification defines the functionality for personalized consumer engagement using digital twins to enhance energy-saving actions, predict maintenance needs, and improve self-consumption through tailored DR recommendations. It supports flexible energy use, operational efficiency, and maximized user engagement.
Functional specifications	• **Data Input:** ○ The system must integrate data from smart meters, which are part of the Portuguese smart grid, and use household-specific data for accurate modelling. ○ For DR capabilities, specific controllers, real-time meters (e.g., WIS-Connector), and a stable WLAN network are necessary for real-time communication and control. • **Personalized Recommendations** ○ Using digital twin technology, the system should generate tailored recommendations for energy-saving actions, including optimal periods for using flexible loads based

	◦ on time-sensitive tariffs or self-consumption potential from PV systems. ◦ The tool should also provide predictive maintenance recommendations to ensure efficient operation of household equipment. • **Output:** ◦ The system should deliver continuous, tailored energy-saving tips and updates to users, informed by historical and real-time data. ◦ For DR-enabled households, the tool should maintain automated flexible load control, while also allowing users to monitor and adjust as needed for optimal comfort.
Use case reference	• UC3

FS4: Simulation of Digital Twins of Individual Thermal Assets.

Brief Description	This specification outlines functionality for simulating digital twins of individual thermal assets, like thermoelectric water heaters (EWH) and HVAC systems, to optimize scheduling for efficiency and cost-effectiveness. Consumption data analysis supports energy savings and optimized usage, while adhering to user-defined comfort levels.
Functional specifications	• **Data Input:** ◦ The system must access consumption data, pricing information, and specifications for thermal appliances, including user-defined comfort preferences (e.g., minimum hot water temperature, desired room temperature range). • **Simulation and Optimization:** ◦ Using digital twin technology, the system should generate an optimized schedule for thermal loads, balancing energy efficiency with operational cost reduction. ◦ The tool should analyse thermal load diagrams and appliance specifications to determine cost and energy savings, flexibility periods, and the most efficient usage calendarization. • **Output:** ◦ Results should include optimized load diagrams, highlighting periods of energy flexibility, potential cost savings, and compliance with comfort settings. ◦ Reports must be available for individual users, EnC managers, or shared building managers, detailing thermal load efficiencies, flexibility availability, and recommendations for load shifting to periods with advantageous pricing.
Use case reference	• UC4

FS5: Simulation with Digital Twins of Individual Thermal Assets and Integration into OSTEC Energy Community Management System.

Brief Description	This specification outlines functionality for simulating and integrating digital twins of thermal assets, like EWH and HVAC systems, into the OSTEC energy management system. This integration optimizes load dispatch for efficiency, cost-effectiveness, and flexible asset management, allowing OSTEC to balance user comfort, energy savings, and DR at both individual and community levels.
Functional specifications	• **Data Input:** ○ The system must access data on consumption, generation, pricing (buying and selling prices), thermal load specifications, and user-defined comfort settings. ○ Additional data on EnC structure and regulatory framework should be incorporated to ensure compliance and effective community-level dispatch. • **Digital Twin Simulation and Optimization:** ○ The digital twins should process thermal load diagrams and specifications to generate optimized usage schedules, providing energy savings, flexibility periods, and calendarization. ○ The tool must simulate thermal asset flexibility and offer DR planning functionalities, respecting user-defined comfort constraints while minimizing operational costs and total energy consumption. • **Integration with OSTEC:** ○ Thermal assets should integrate with OSTEC, allowing it to optimize all flexible assets within the EnC for efficient energy management. ○ OSTEC should provide control signals (setpoints) to be applied to the flexible assets through an external system, coordinating load shifting and dispatch of flexibility resources at both individual and community levels. • **Output:** ○ The system should provide residential users, EnC managers, and shared building managers with optimized thermal load diagrams, energy savings details, and periods of flexibility availability. ○ OSTEC should generate a detailed energy bill for each community member, reflecting their contributions and participation in collective benefits, while maximizing local renewable energy utilization and reducing dependency on external sources.
Use case reference	• UC4

FS6: Individual Self-Consumption Optimisation.

Brief Description	This specification outlines functionality for optimizing individual self-consumption by dispatching flexible assets to maximize renewable energy use, reduce costs, and increase efficiency. By analysing consumption patterns and offering tailored recommendations, the tool helps users manage energy usage to enhance grid utility and self-consumption.
Functional specifications	• **Data Input:** ○ The system must collect data on users' energy consumption patterns, details about flexible assets (such as appliances and electric vehicles), and user-defined energy usage preferences. ○ Data from smart meters and other connected devices, including real-time consumption and renewable energy production data, must be integrated for effective monitoring and forecasting. • **Self-Consumption Optimization:** ○ The tool should analyse collected data to identify opportunities for shifting consumption loads to periods of high renewable energy availability or lower costs. ○ Recommendations should be generated for each user, advising them on how to adjust their flexible asset usage to maximize renewable energy utility and minimize energy expenses.
Use case reference	• UC5

FS7: Collective Self-Consumption Optimization.

Brief Description	This specification defines functionality for optimizing collective self-consumption in an EnC by managing flexible assets and shared resources. Using tools like OSTEC and WIS4Households, the community can boost energy efficiency, maximize self-consumption, and reduce costs while providing feedback to enhance member participation in DR initiatives.
Functional specifications	• **Data Input:** ○ The system must access consumption and generation forecasts for community members, details on flexible assets (e.g., batteries, electric vehicles, and thermal loads), and opportunity costs (e.g., energy buying and selling tariffs). ○ A digital platform should be in place to provide inputs for energy management and enable application of outputs to the flexible assets. • **Optimization of Collective Self-Consumption:** ○ The system should allow the EnC manager to use optimization tools, like OSTEC, to calculate optimal schedules for flexible assets, based on forecasts of consumption and generation.

	◦ WIS4Households should provide flexibility optimization based on historical consumption data, offering tailored feedback to maximize self-consumption and potentially implement DR in flexible loads. • **Output:** ◦ The system must generate optimal schedules for flexible assets, which serve as inputs to an external module that applies the schedules to the assets. ◦ Users should receive feedback on how flexibility strategies have benefited their energy usage and costs, along with an overview of their participation in internal transactions within the EnC.
Use case reference	• UC6

FS8: AI-Powered Virtual Energy Management.

Brief Description	This specification outlines functionality for WIS4Households, an AI-powered virtual energy manager that optimizes household energy management. The tool provides personalized recommendations, maintenance predictions, and tips to improve self-consumption, using historical consumption and appliance data to help users adopt energy-saving actions and maximize efficiency.
Functional specifications	• **Data Input:** ◦ The system must collect historical consumption data from smart meters integrated into the Portuguese smart grid. ◦ Users should be able to add metadata about their homes, including information about specific appliances, to enhance personalization. • **Energy Management Optimization:** ◦ The system should provide tailored recommendations for energy-saving actions, including appliance substitution and behaviour modifications, based on the collected data. ◦ PV and tariff optimization should be available as on-demand services, allowing users to access updates when triggered. • **Output:** ◦ The system should continuously update feedback based on new consumption data, with NILM results provided monthly and efficiency measures refreshed every one to two weeks. ◦ On-demand tools should refresh results each time a user requests an update, ensuring real-time feedback.
Use case reference	• UC7

FS9: Planning Existing Energy Communities.

Brief Description	This specification defines functionality for supporting future expansion and resource optimization of existing energy communities (REC). The Planning Tool enables REC managers, municipal planners, and decision-makers to evaluate expansion feasibility, new memberships, and increased renewable energy sources (RES), helping stakeholders make informed, sustainable resource decisions.

Functional specifications	• **Data Input:**
	  ○ The system must allow users to input data on the current state of the EnC, including geographical, technical, and regulatory information.
	  ○ Additional data on prospective expansion areas, new members, and potential renewable energy sources should be collected to support scenario planning.
	• **Expansion Planning and Simulation:**
	  ○ The tool should evaluate potential new members and renewable energy sources for feasibility and compatibility with the existing community.
	  ○ It must generate simulations for various expansion scenarios, including adding new buildings, infrastructure, or energy sources, and calculate the potential impact on community resources.
	• **Output:**
	  ○ The system must provide detailed simulation reports to users, summarizing the projected outcomes for each expansion scenario.
	  ○ These reports should enable stakeholders to make data-driven decisions on whether to proceed with expansion, scale back, or focus on increasing RES within the existing community structure.

Use case reference	• UC7

FS10: Peer-to-Peer Energy Trading Platform.

Brief Description	This specification outlines functionality for a P2P energy trading platform that enables consumers and producers to directly trade renewable energy. The platform optimizes energy use, supports local generation, and gives members control over distribution and pricing, aligning with the EU's Clean Energy Package to foster energy independence and stable pricing.

Functional specifications	• **Data Input:**
	  ○ The system must support users who own one or more metering points (for consumption or generation) and provide details on their energy surplus and demand.
	  ○ Producers should be able to present their power plants and specify surplus energy available for trading, as well as define pricing and access settings for different consumer groups.

	• **Energy Trading and Management:**
	  ○ The platform should compile energy offers from producers, balancing the supply to ensure a stable mix of electricity from various renewable sources and guarantee 100% security of supply for consumers.
	  ○ Users should be able to manage their energy relationships, set multiple price levels for different consumer groups, and control access to their surplus energy based on predefined criteria.
	• **Transparency and Stability:**
	  ○ The platform should provide stable and transparent pricing for both producers and consumers, supporting a clear and independent trading environment.
	  ○ The system must allow for continuous monitoring and updates to ensure that energy prices remain consistent and beneficial for community members.
	• **Output:**
	  ○ The platform must provide users with a summary of transactions, including energy bought or sold, prices applied, and the sources of electricity received.
	  ○ The system should generate reports that help users track their energy savings, income from surplus energy sales, and overall contributions to local renewable energy usage.

Use case reference	• UC9

FS11: Energy Community Management Platform.

Brief Description	This specification defines functionality for an EnC management platform that allows members and managers to monitor and manage energy consumption and production, share energy within the community, and oversee administration. The platform supports the EU's Clean Energy Package, enabling participation in multiple communities and facilitating transparent energy sharing, billing, and optimization.

Functional specifications	• **Data Input:**
	  ○ The platform must integrate data from existing energy management systems, including meter points for each community member (for both consumption and production).
	  ○ The system should prepare and manage energy data provided by the DSO to enable accurate monitoring and billing.
	• **Community Management and Monitoring:**
	  ○ EnC managers should have dedicated access to the platform to monitor shared energy usage, view participant contributions, and manage data independently.

	◦ Each member should have a personal dashboard (cockpit) where they can view detailed insights into their energy consumption and production, as well as receive transparent invoices. • **Settlement and Billing:** ◦ The platform must allow managers to set participation factors for each meter point, initiate member participation, and prepare settlements using the energy data management system. ◦ Members should receive regular invoices that detail their energy usage, production, and associated costs or credits based on their participation in the community. • **Output:** ◦ The platform should provide community managers with overviews of shared energy usage and participant data, supporting efficient management and transparent reporting. ◦ For community members, the platform should generate invoices and provide access to a personal dashboard with comprehensive energy insights, contributing to stable and transparent pricing.
Use case reference	• UC10

FS12: Design of Local Markets and Sharing Mechanisms for Energy and Flexibility Provision in Energy Communities.

Brief Description	This specification outlines functionality for designing and integrating local markets and sharing mechanisms for energy and flexibility provision within energy communities. The framework combines flexibility provision with post-delivery local energy markets, aligning with collective self-consumption regulations to manage transactions, flexibility allocation, and settlement among stakeholders.
Functional specifications	• **Data Input:** ◦ The platform must incorporate definitions of flexibility markets and products, flexibility contracts between aggregators and prosumers, and rules for post-delivery local energy markets. ◦ Self-consumption allocation rules, including allocation coefficients and balancing responsibilities, should be integrated to ensure compliance with CSC regulations. • **Flexibility Activation and Market Integration:** ◦ When flexibility is requested by the flexibility market operator, aggregators should be able to activate flexibility from prosumers who have pre-established flexibility contracts. ◦ The system should facilitate local energy transactions to compensate prosumers' suppliers for deviations in expected energy delivery, while enabling the allocation of

	flexibility to aggregators for balancing responsible party (BRP) purposes.
	• **Settlement and Allocation Mechanisms:**
	  ○ The platform must support settlements that consider all services provided within the community, including flexibility provision and energy transactions.
	  ○ Allocation can be managed using virtual prosumers to represent aggregators, ensuring that all transactions align with CSC rules and are settled accordingly.

Use case reference	• UC11

FS13: Demand Response Nudging App.

Brief Description	This specification defines functionality for a DR nudging app that engages energy consumers and producers in near real-time DR events. The app optimizes energy use and balances grid demand through timely recommendations and visualizations, enabling community members to make informed decisions that improve financial benefits and grid stability.

Functional specifications	• **Data Input:**
	  ○ The system must receive near real-time energy data and/or historical energy data from the DSO, which is then processed by the energy data management system.
	  ○ The communication channel (platform or app) should be capable of displaying near real-time energy consumption, production data, historical data, and DR recommendations.
	• **Demand Response:**
	  ○ The energy data management system should analyse near real-time and/or historical data and forecasts to generate recommendations for DR actions.
	  ○ Recommendations must be delivered to EnC members in a user-friendly visualization, allowing them to either execute or reject the suggested DR actions.
	• **User Interaction and Feedback:**
	  ○ EnC members should be able to view near real-time energy data, historical data, and DR recommendations, then respond by accepting or rejecting the nudges.
	  ○ If the user participates in a DR event, feedback should reflect the impact on their energy consumption or production and any resulting financial benefits or cost savings.

Use case reference	• UC12

FS14: Personalized Energy Efficiency Recommendations.

Brief Description	This specification defines functionality for a system that provides personalized, near real-time energy efficiency recommendations to community members. Leveraging real-time data and nudging apps, the tool analyses energy usage patterns to deliver targeted recommendations that encourage energy-saving actions and optimize energy use within the community.
Functional specifications	• **Data Input:** ○ The system must receive near real-time energy data from the DSO to support up-to-date recommendations. ○ EnC managers should collect personal energy-related data from members, including information on specific energy consumption devices (e.g., washing machines), to refine recommendations. • **Recommendation Generation:** ○ The energy data management system should analyse real-time and forecasted data alongside personal energy data to generate customized energy efficiency recommendations for each community member. ○ Recommendations should address specific behavioural changes, such as adjusting the timing of appliance usage to reduce costs or increasing energy efficiency based on current consumption patterns. • **Communication and User Interaction:** ○ Personalized recommendations should be communicated to EnC members through an accessible platform or app. ○ Members should be able to view and act on these recommendations, enabling them to make immediate adjustments to their energy usage.
Use case reference	• UC14

FS15: Dynamic Pricing and Incentive Management for EV Flexibility.

Brief Description	This specification defines functionality for managing dynamic pricing and incentives for electric vehicle (EV) drivers to optimize charging and discharging patterns that support grid balancing and energy efficiency. By adjusting prices based on renewable energy availability and demand, the system incentivizes EV drivers to charge during periods of high renewable production or low demand, enhancing grid stability.
Functional specifications	• **Data Input:** ○ The system must connect to EV charging stations and receive real-time data from the wholesale energy market in 15-minute intervals for interconnected locations. ○ Local renewable energy production data, including solar and wind generation, should be integrated for non-

	interconnected grids to adjust incentives and pricing accurately. • **Dynamic Pricing and Incentive Generation:** o The application should modify the price per kWh dynamically based on grid conditions, offering lower prices or rewards during periods of high renewable energy availability and lower demand. o Incentive models should be developed to encourage drivers to charge their EVs during optimal periods, with clear information on price variations or rewards provided through the user interface. • **User Notification and Interaction:** o Notifications about modified pricing or incentives should be sent to EV drivers via a web or mobile application. o Drivers should be able to view current prices and incentives, enabling them to adjust their charging behaviour in response to real-time grid conditions.
Use case reference	• UC15

FS16: Decentralized Data Marketplace for Energy Data Sharing.

Brief Description	This specification outlines functionality for a decentralized data marketplace that enables secure sharing and trading of energy data among consumers, producers, and stakeholders. Using DLT and blockchain, the marketplace ensures data sovereignty, privacy, and interoperability, allowing participants to exchange data assets securely and maintain control over their data.
Functional specifications	• **Data Input and Access:** o Users must be registered and authenticated within the marketplace, with permissions verified for data sharing or access. o The marketplace requires data to be formatted to meet interoperability and semantic standards, ensuring compatibility with various platforms and seamless data exchange. • **Data Sharing and Transaction Process:** o Users should be able to log into the marketplace using secure identity authentication, then select the type of data they wish to share or consume, including access restrictions or usage conditions. o The system should verify the user's permissions and generate a smart contract to formalize each data transaction, ensuring traceability and accountability. o Data transactions should be executed via blockchain, maintaining security, traceability, and transparency throughout the data-sharing process. • **User Interaction and Notification:**

	- After a data transaction is completed, stakeholders should be notified of the exchange, ensuring transparency and promoting trust within the marketplace. **Output:** - The system must record all data transactions on the blockchain, creating an immutable record of data exchanges. - Users should have access to transaction histories and be notified upon the completion of each transaction or if any issues arise.
Use case reference	UC16

FS17: Decentralized Data Marketplace for Demand Response Tokenized Compensation.

Brief Description	This specification defines functionality to incentivize energy consumers and producers to participate in DR programs through tokenized compensation. Using a blockchain-based token system, the platform ensures transparent, traceable rewards that encourage active DR participation, helping to balance energy demand and supply and enhance grid stability.
Functional specifications	**Data Input and Authentication:** - Participants must be registered and authenticated within the DR system, and the communication infrastructure should be established between participants, aggregators, and the tokenized compensation platform. - Devices and participants should comply with interoperability and technical standards to ensure accurate real-time monitoring and secure communication during DR events. **Demand Response Event and Participation:** - When a DR event is initiated by the grid or aggregator, a notification should be sent to all registered participants, allowing them to respond by adjusting their energy usage as requested. - The system should monitor participants' responses in real-time via smart meters and IoT devices, recording their level of participation. **Tokenized Compensation Calculation and Distribution:** - Based on participants' responses, the system should calculate compensation according to predefined criteria, such as the amount and timing of energy reduction or increase. - Tokenized rewards should be issued through a secure blockchain-based mechanism, providing traceability, transparency, and ensuring the equitable distribution of rewards. **User Notification and Feedback:**

	◦ After the DR event, participants should receive a notification confirming the completion of the event and detailing the tokenized compensation they received. ◦ Participants should have access to a transaction history, showing their contributions to each DR event and corresponding rewards. • **Output:** ◦ The system must record each DR event and participants' responses on the blockchain, creating an immutable and traceable record. ◦ Notifications and summaries of tokenized rewards should be sent to participants, promoting transparency and reinforcing participation incentives.
Use case reference	• UC17

FS18: Intelligent Monitoring and Control for Privacy-Preserving Load Management.

Brief Description	This specification outlines functionality for implementing intelligent control and non-intrusive load monitoring systems to optimize energy usage in residential and commercial settings while preserving user privacy. Using advanced monitoring techniques, the system analyses and adjusts consumption based on comfort metrics, supporting efficient load management and grid-responsive flexibility.
Functional specifications	• **Data Input and Privacy Requirements:** ◦ The system must receive input from smart meters and indoor condition sensors, along with data from flexible loads, such as EV chargers and cooling systems. ◦ Privacy-preserving mechanisms should be in place to ensure that data related to individual consumption patterns remains secure and anonymous. • **Non-Intrusive Load Monitoring and Disaggregation:** ◦ The system should use non-intrusive load monitoring techniques to disaggregate cooling and other flexible loads based on data from smart meters. ◦ Energy consumption adjustments should be made based on comfort metrics and the status of registered flexible loads. • **Energy Consumption Recommendations:** ◦ The system should generate recommendations for shifting energy consumption, encouraging users to adjust their usage patterns to optimize energy efficiency and align with grid needs. ◦ Recommendations should consider user comfort and the operational requirements of flexible loads. • **Output:** ◦ The system should provide the community manager and users with recommendations for energy consumption

	○ adjustments, highlighting opportunities for load shifting and flexibility. ○ Users should have access to a summary of their energy usage and recommendations, ensuring transparency in energy management and privacy protection.
Use case reference	• UC20

FS19: Secure and Privacy-Preserving Data Exchange for DR Programs.

Brief Description	This specification defines functionality for secure, privacy-preserving data sharing among stakeholders in DR programs. The system ensures data access is granted only with explicit consent from data owners, safeguarding personal and community information while enabling authorized access for DR initiatives.
Functional specifications	• **Data Consent and Access Control:** ○ Actors requesting access to energy data must create an account on the EnC platform through an invitation from the EnC manager. ○ The requesting party must obtain explicit consent from each data owner, specifying the purpose of data access. No data sharing is permitted without this consent. • **Consent Management:** ○ Each data owner should have the option to review and sign consent requests individually for each data source, ensuring full control over what data is shared and for what purpose. ○ If a data owner consents, the system grants the requesting party access to the specified data resource via a secure resource server. If consent is denied, the request is rejected. • **Data Exchange and Privacy Preservation:** ○ Upon receiving consent, the resource server should securely provide access to the protected data resource, ensuring that only authorized data is shared with the requesting party. ○ Privacy-preserving protocols should be implemented to protect user data throughout the sharing process, ensuring compliance with security standards and user expectations.
Use case reference	• UC21

FS20: Building the SEMAPTIC Specification for Semantic Interoperability.

Brief Description	This specification outlines functionality for creating a semantic mapping to enable semantic interoperability of a service's JSON I/O data. Using the

	SEMAPTIC specification, each variable and parameter is mapped to structured ontologies, ensuring consistent interpretation across systems and enhancing interoperability within the ENPOWER framework.

Functional specifications	• **Ontology and Mapping:**
	  ○ The system must access established ontologies to map each I/O variable and parameter exchanged by the service to corresponding classes and properties.
	  ○ Syntactic interoperability should be confirmed before applying semantic mapping, ensuring that each element has an appropriate structural match within the ontologies.
	• **SEMAPTIC Specification Development:**
	  ○ The SEMANTIC BUILDER tool should be used to create the SEMAPTIC specification, linking variables and parameters to semantic definitions in the ontology.
	  ○ This process occurs initially during service development and may require adjustments when service updates introduce new I/O variables or parameters.
	• **Integration and Data Exchange:**
	  ○ The SEMAPTIC specification must be attached to service data exchanges using suitable protocols, such as REST API or data space connectors, to enable seamless semantic interoperability.

Use case reference	• Sub-UCa

FS21: Federated Learning for Energy Efficiency Optimization.

Brief Description	This specification defines functionality for leveraging federated learning to collaboratively develop energy efficiency optimization algorithms across multiple energy providers. The system enables model training without sharing raw data, ensuring data sovereignty and privacy compliance while producing a shared, optimized model for energy efficiency.

Functional specifications	• **Federated Learning Environment Setup:**
	  ○ A federated learning environment should be established, allowing registered and certified participants, such as energy providers, to collaboratively train models.
	  ○ Data producers and data owners must anonymize or apply privacy-preserving techniques to their data before participation, ensuring compliance with data sovereignty requirements.
	• **Data Offering and Contract Negotiation:**
	  ○ Energy providers offer privacy-preserving data for training, with usage terms negotiated and formalized via Smart Contracts.
	  ○ The contract should specify data handling practices, privacy constraints, and terms for federated learning participation.

	• **Collaborative Model Training:**
	  ○ The federated learning process initiates training across decentralized data sets, exchanging model updates rather than raw data.
	  ○ Updates are aggregated to create an optimized global model, preserving data privacy and sovereignty while enhancing energy efficiency optimization.
	• **Output:**
	  ○ The optimized global model for energy efficiency is securely shared with participating energy providers, allowing them to implement insights without accessing others' data.

Use case reference	• Sub-UCc

FS22: Sovereign and Secure Data Sharing for Energy Consumption Prediction and Transfer.

Brief Description	This specification defines requirements for secure, privacy-preserving data sharing between energy data providers and consumers using blockchain and Smart Contracts. The system facilitates energy consumption prediction and data exchange, enforcing data sovereignty and usage policies through secure, Smart Contract-governed transactions that ensure compliance with predefined terms.

Functional specifications	• **Data Registration and Consent Management:**
	  ○ Data producers and consumers must be registered and certified within the blockchain network, with data usage policies embedded in Smart Contracts.
	  ○ Data providers initiate data offerings, allowing consumers to request access through Smart Contracts that enforce privacy, usage restrictions, and consent-based access.
	• **Contract Negotiation and Compliance:**
	  ○ Usage terms, such as access fees and privacy constraints, are negotiated through Smart Contracts. If terms are agreed upon, the contract activates data sharing with compliance checks in place.
	  ○ Pre-existing agreements can bypass additional negotiation, streamlining repeated transactions under established terms.
	• **Data Transfer and Secure Access:**
	  ○ Upon verification, the platform provides secure access details, enabling data transfer between parties. Blockchain/DLT protocols ensure traceability and data integrity.
	  ○ The system supports flexible infrastructure options, rerouting data exchange via alternative protocols if the primary option is unavailable, ensuring uninterrupted data flow.

Use case reference	• Sub-UCb

FS23: Secure Data Exchange.

Brief Description	This specification defines functionality for a secure, decentralized data exchange across platforms for energy and flexibility management. The system ensures compliance with federated learning standards and offers a standardized, traceable approach to data sharing among energy communities, using blockchain and DLT protocols for transparency and security.
Functional specifications	• **Data Exchange Initiation and Verification:** o Data providers initiate a data exchange request through an IDS-compliant connector, ensuring adherence to GAIA-X standards. o The system verifies that data models align with the standardized format for semantic interoperability, preparing them for secure exchange. • **Federated and Secure Data Processing:** o The federated infrastructure processes the data request securely, transferring data across platforms while maintaining privacy and data integrity through blockchain/DLT protocols. o Data transfer should be seamless and compliant with decentralized and federated data exchange frameworks. • **Result Retrieval and Utilization:** o Data consumers retrieve validated data to optimize flexibility services within energy communities, applying the results to federated planning and management. o The blockchain records the transaction, ensuring transparency, traceability, and compliance with federated data exchange requirements. • **Output:** o All exchanged data is validated and accessible for use in energy and flexibility management, supporting federated learning and optimized planning across platforms. o The system maintains an immutable blockchain-based audit trail of data exchange transactions, providing transparency and accountability.
Use case reference	• Sub-UCd

7.4 Mapping Functional Specifications to Pilot Sites

Table 8 Mapping of Functional Specifications with pilot sites.

Functional specification	Pilot					
	Austria	Portugal	Greece	Ireland	Hungary	Spain
FS1: Data-Driven Consumer Clustering and Segmentation for Energy Management						
FS2: Assessing Demand Response Potential in Energy Communities						
FS3: Personalized Consumer Engagement and Activation						
FS4: Simulation of Digital Twins of Individual Thermal Assets						
FS5: Simulation with Digital Twins of Individual Thermal Assets and Integration into OSTEC EnC Management System						
FS6: Individual Self-Consumption Optimisation						
FS7: Collective Self-Consumption Optimization						
FS8: AI-Powered Virtual Energy Management						
FS9: Planning Existing Energy Communities						
FS10: Peer-to-Peer Energy Trading Platform						
FS11: EnC Management Platform						
FS12: Design of Local Markets and Sharing Mechanisms for Energy and Flexibility Provision in Energy Communities						
FS13: Demand Response Nudging App						
FS14: Personalized Energy Efficiency Recommendations						
FS15: Dynamic Pricing and Incentive Management for EV Flexibility						
FS16: Decentralized Data Marketplace for Energy Data Sharing						
FS17: Decentralized Data Marketplace for Demand Response Tokenized Compensation						
FS18: Intelligent Monitoring and Control for Privacy-Preserving Load Management						
FS19: Secure and Privacy-Preserving Data Exchange for DR Programs						
FS20: Building the SEMAPTIC Specification for Semantic Interoperability						
FS21: Federated Learning for Energy Efficiency Optimization						
FS22: Sovereign and Secure Data Sharing for Energy Consumption Prediction and Transfer						
FS23: Secure Data Exchange						

8 Conclusions

This deliverable marks a significant milestone in the ENPOWER project, presenting the culmination of extensive collaborative efforts to design consumer-centric energy solutions. By addressing gaps in market design, refining use cases, and engaging diverse stakeholders through co-creation workshops, the project demonstrates a commitment to fostering energy democratization and consumer empowerment. These achievements lay the groundwork for integrating innovative business models, functional specifications, and technological enablers to meet the project's ambitious goals.

The gap analysis on market design (Chapter 2) explores the barriers and opportunities for consumer-centric energy systems in Europe, focusing on the ENPOWER pilot countries. It examines both centralized and decentralized market models, highlighting the importance of flexibility mechanisms like DR, energy storage, and sector coupling for managing renewable energy variability and ensuring grid stability. While these mechanisms face challenges such as uneven smart grid adoption and lack of incentives, advanced solutions like AI-driven DR show promise. A hybrid market design combining centralized and decentralized models, supported by regulatory harmonization and infrastructure investment, is key to fostering consumer participation and achieving EU-wide energy goals.

Findings from the pilot countries underscore the diversity of national market designs and their varying levels of readiness to integrate innovative consumer participation models. While some pilot countries demonstrate progress in fostering EnC initiatives and renewable integration, others face challenges related to regulatory alignment, infrastructure deficits, and limited access to advanced flexibility mechanisms. Differences in DR programs, energy storage adoption, and the deployment of DERs reveal the need for tailored approaches that address country-specific contexts while aligning with EU-wide objectives.

In conclusion, Chapter 3 builds upon the foundation established in D2.1[1], completing the work of T2.1 by refining and expanding the HLUCs and translating them into a comprehensive set of 21 UCs and 5 Sub-UCs. Developed through an extensive co-creation process involving technical and pilot site partners, the HLUCs and UCs were designed to align closely with the project's objectives while addressing specific functionalities and pilot site contexts. Despite the inability to directly map HLUCs to pilot sites due to their high-level nature, the detailed UCs and Sub-UCs provide a critical bridge between conceptual frameworks and technical implementation. A careful mapping of UCs and Sub-UCs to pilot sites ensures their relevance and applicability, enabling the operationalization of project solutions to achieve ENPOWER's goals. Additionally, the chapter highlights the TEs underpinning the identification of HLUCs and UCs, further supported by detailed documentation in D2.1[1]. This comprehensive approach establishes a solid foundation for the project's technical deployment and collaborative success.

The co-creation workshop organized by UNIBAS effectively addressed participants' pre submitted questions and offered practical tools for planning and facilitating co-creation sessions. The workshop highlighted the importance of stakeholder diversity, promoting inclusivity, and effectively managing group dynamics.

Workshops on energy data sharing, held in diverse locations like Dingle, Poysdorf, and Budapest, revealed universal themes crucial to community engagement. Dingle's workshops highlighted the vibrant involvement of a close-knit community, with discussions focusing on financial, social, environmental, technical, and regulatory aspects. These themes also resonated during the

"Thought Leaders Workshop" in Budapest, demonstrating their global relevance and centrality to energy data sharing and engagement. In Poysdorf, financial motivations dominated the initial workshop, but subsequent sessions reflected a broader alignment with universal themes. Here, social concerns like fairness and transparency became prominent, emphasizing the need to address these issues regardless of participants' experience levels. These findings illustrate the consistent importance of these key themes in fostering EnC discussions and guiding future engagements. Insights from the workshops provide a roadmap for developing user-friendly tools tailored to energy communities. Financial clarity should empower users with simple, actionable information about energy savings and ROI. Social engagement can be enhanced through interactive features like forums and event notifications. Sustainability should be framed with relatable examples to inspire action, while technical data must be presented in plain terms to ensure accessibility. Clear legal guidance is also vital, helping users navigate regulations and available incentives. By integrating these elements, platforms can better serve end-users, encouraging informed decisions and active participation in energy initiatives.

The BMs initially developed in D2.3 [80] were redesigned to incorporate the refined UCs, emphasizing the illustration of energy democratization and citizen empowerment on them. By integrating information from energy citizenship questionnaires that have been completed by the TEs, the models now illustrate enhanced flows of energy, data, and community engagement. These enriched BMs reflect the complexity of relationships and decision-making within EnCs, while interactive tools support trust, transparency, and citizen participation. Tailored to the unique needs of six pilot cases and the updated UCs, they serve as dynamic and inclusive frameworks for ENPOWER’s innovative solutions.

The "Functional Specifications" (chapter 7), initially developed for the D2.4 [81] deliverable, have undergone further refinement and expansion over the past months, culminating in this deliverable as a guide to support the project's implementation. This chapter integrates insights from earlier work while adapting to the evolving needs of stakeholders and the contributions of other project partners. The applied methodology has ensured a consistent and structured evolution of the functional specifications, maintaining alignment with the project's progress and objectives. By incorporating feedback and collaborating with other partners, the specifications reflect a cohesive approach that supports the development of innovative, consumer-centric energy solutions.

The comprehensive work documented in this deliverable provides a robust foundation for ENPOWER's technical deployment and collaborative success. By bridging conceptual frameworks with practical implementation, the refined use cases, co-creation insights, and innovative business models emphasize inclusivity, transparency, and community engagement. Moving forward, these contributions will play a pivotal role in operationalizing consumer-centric energy solutions, ensuring they are adaptable, equitable, and aligned with the diverse needs of stakeholders across pilot sites.

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