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A Blockchain-Based Framework for Peer-to-Peer Energy Sharing in Microgeneration Communities

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Master's in Digital Technologies for Business

Supervisor:
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ISCTE-IUL - Universidade de Lisboa

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To thresholds crossed by a simple "what if".

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Abstract

The transition toward decentralised energy systems based on renewable sources is changing how electricity is produced and traded. Peer-to-peer (P2P) energy sharing in microgeneration communities can increase local utilisation of renewable energy and strengthen the role of prosumers. Still, current markets and infrastructures remain largely centralised, providing limited support for transparent, automated, and economically fair local transactions. This dissertation proposes a blockchain-based framework for P2P energy sharing in microgeneration communities, in which surpluses are traded locally using a pricing model anchored to the day-ahead wholesale market.

The research follows the Design Science Research Methodology (DSRM) and has three main objectives, namely analysing the state of the art in blockchain-supported P2P trading, defining the functional and non-functional requirements for a decentralised platform, and designing and implementing a proof of concept (POC).

The proposed architecture combines smart meters, a Home Energy Management System (HEMS), and a permissioned blockchain with smart contracts and oracles, supporting dynamic pricing, automated matching and settlement, and auditable records.

A POC validates core functionalities, including order management, pricing definition, smart contract-based execution, and integration with simulated metering and market price feeds.

Regarding evaluation, the artefact was assessed against the previously defined functional and non-functional requirements and complemented by an end-user survey. Taken together, the technical assessment and the survey results support the feasibility of the proposed framework in a controlled setting and indicate positive user interest, while motivating further validation through real-world pilots.

The dissertation concludes by outlining limitations (simulated data and simplified conditions) and identifying future work, including real-world pilots, more advanced market mechanisms, and closer alignment with distribution system operators (DSOs) and regulatory frameworks.

Keywords: Blockchain; Peer-to-peer Energy Trading; Microgeneration Communities; Smart Contracts; Smart Meters; Home Energy Management System (HEMS); Dynamic Pricing; Decentralised Energy Systems.

Resumo

A transição para sistemas energéticos descentralizados e assentes em fontes renováveis está a alterar a forma como a eletricidade é produzida e transacionada. A partilha de energia peer-to-peer (P2P) em comunidades de microgeração pode aumentar a utilização local de energia renovável e reforçar o papel dos prosumers, mas os mercados e as infraestruturas atuais continuam maioritariamente centralizados, oferecendo suporte limitado a transações locais transparentes, automatizadas e economicamente justas. Esta dissertação propõe um enquadramento baseado em blockchain para a partilha de energia P2P em comunidades de microgeração, no qual os excedentes são transacionados localmente com um modelo de preços ancorado no mercado diário (day-ahead) grossista.

A investigação segue a Design Science Research Methodology (DSRM) e tem três objetivos principais, nomeadamente analisar o estado da arte sobre transações P2P suportadas por blockchain, definir os requisitos funcionais e não funcionais para uma plataforma descentralizada e conceber e implementar uma prova de conceito (PoC).

A arquitetura proposta combina contadores inteligentes, um Home Energy Management System (HEMS) e uma blockchain permissionada com smart contracts e oracles, suportando preços dinâmicos, correspondência e liquidação automatizadas e registos auditáveis.

Uma POC valida funcionalidades nucleares, incluindo gestão de ordens, definição de preços, execução de smart contracts e integração com dados de medição e de preços de mercado.

No que respeita à avaliação, para além da verificação do artefacto face aos requisitos funcionais e não funcionais previamente definidos, foi aplicado um inquérito a utilizadores finais. Em conjunto, a avaliação técnica e os resultados do inquérito sustentam a exequibilidade do enquadramento proposto num ambiente controlado e apontam para um interesse favorável por parte dos utilizadores, justificando validação adicional através de pilotos em contexto real.

A dissertação termina com as limitações (dados simulados e condições simplificadas) e identifica trabalho futuro, incluindo pilotos em contexto real, mecanismos de mercado mais avançados e maior alinhamento com os operadores de rede de distribuição (DSO) e os enquadramentos regulatórios.

Palavras-chave: Cadeia de Blocos; Transação de Energia Ponto-a-Ponto; Comunidades de Microgeração; Contratos Inteligentes; Contadores Inteligentes; Sistema de Gestão de Energia Doméstica (HEMS); Preços Dinâmicos; Sistemas Energéticos Descentralizados.

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Acronyms

AC	Alternating Current
API	Application Programming Interface
DC	Direct Current
DOI	Digital Object Identifier
DSO	Distribution System Operator
DSRM	Design Science Research Methodology
FR	Functional Requirement
GDPR	General Data Protection Regulation
HEMS	Home Energy Management System
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
JSON	JavaScript Object Notation
NFR	Non-functional Requirement
OMIE	Operador do Mercado Ibérico de Energia (Iberian Energy Market Operator)
P2P	Peer-to-peer
POC	Proof-of-Concept
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
USA	United States of America
USDT	Tether

CHAPTER 1

Introduction

In recent years, the electric power sector has undergone a paradigm shift from centralised, top-down networks to decentralised, distributed energy systems [1]. The widespread adoption of small-scale distributed energy resources, such as solar panels, and advances in digital technology are fundamentally changing how energy is produced, traded, and consumed [1].

Peer-to-peer (P2P) energy sharing has emerged at the heart of this transformation, enabling communities of consumers and producers, also known as prosumers, to collaboratively manage and trade their local energy resources [1]. Such P2P sharing models have the potential to improve prosumers' economic prospects and enhance overall energy resilience and sustainability by leveraging local generation and fostering collective responsibility in energy management [1]. However, despite these advantages, the real-world implementation of community P2P energy sharing remains limited, as current electricity markets have seen only exploratory trials of these models and widespread adoption has yet to occur [1].

One of the key enablers for secure and efficient P2P energy trading is blockchain technology. Blockchain provides a decentralised digital ledger that enables peer participants to transact energy or energy credits directly, without relying on a centralised intermediary [2].

By definition, blockchain ensures that all transactions are transparent, tamperproof, and agreed upon by network consensus, which creates trust among participants who might not otherwise have a reason to trust each other [2]. Also, smart contracts, which are self-executing programs on the blockchain, can further automate and enforce the terms of energy trade agreements, enabling real-time settlement of energy transactions and reducing the need for manual intervention [3]. These attributes are desirable for community energy sharing, where transparency and trust are essential.

Several pilot projects and research initiatives around the world have begun exploring blockchain-based P2P energy trading, and roughly one-third of the over 140 blockchain projects in the energy sector are focused on decentralised energy trading [2].

This dissertation proposes a blockchain-based framework specifically set for P2P energy sharing in microgeneration communities, namely local communities that generate their own power using, for instance, solar panels, and intend to share or trade it among members of that community. In the following sections, the motivation for such a framework is identified, the problems it aims to address are identified, the key objectives of the research are outlined, essential concepts are clarified, and similar cases in force are analysed.

1.1. Motivation

The motivation for a blockchain-enabled P2P energy-sharing framework stems from technical, economic, and social factors associated with the ongoing energy transition. As countries push for cleaner energy and grid decarbonization, more consumers are installing renewable microgeneration equipment such as solar panels or small wind turbines.

P2P energy sharing offers a way for communities to make use of this surplus by trading energy locally, which improves renewable energy utilisation and reduces curtailment, critical to grid stability. Notably, well-designed P2P schemes can increase overall system efficiency, reduce the need for large storage capacity, improve renewable penetration, and even relieve stress on the main grid [3].

Empowering prosumers to trade energy directly also creates "win-win" economic benefits by proposing a transparent, rule-based pricing methodology for community-scale P2P energy trades, in which transaction prices are anchored to the day-ahead wholesale market and adjusted by user-defined margins. This design ensures that prosumers systematically receive more than the wholesale price while consumers pay less than the standard retail tariff, and it is fully implementable in smart contracts.

From a resilience perspective, P2P sharing can strengthen energy resilience by enabling communities to rely on their own generation during grid disruptions or peak-demand periods. For example, research has shown that a microgrid using P2P energy transactions and distributed storage can improve reliability during outages and provide more rapid recovery [3].

By decentralising energy management, communities become less vulnerable to failures of the centralised grid. Additionally, P2P models encourage more equitable and democratic participation in energy markets. Rather than being passive consumers, community members actively decide how to produce, share, and use energy. This participatory approach fosters a sense of ownership and can accelerate the transition to clean energy by increasing local buy-in [1]. Indeed, various pilot projects worldwide, from urban neighbourhoods to rural villages, have demonstrated the feasibility and benefits of community energy trading, reflecting a growing interest in more efficiently using local resources [1].

A primary motivation for introducing blockchain is to overcome the trust and coordination barriers in P2P energy markets. Traditional energy exchanges typically require a trusted central entity to track transactions and balance supply and demand. In a decentralised community setting, that role can be replaced by a blockchain platform which provides a shared source of truth for all participants [2].

1.2. Problem identification

The global energy landscape is undergoing a profound transformation, marked by the urgent need to decarbonise the power sector, democratize energy access, and enhance grid resilience. Rising consumer prices, inadequate prosumer compensation, grid congestion, and environmental costs increasingly challenge centralised electricity systems. These systemic limitations emphasise the need for a decentralised, transparent, and equitable model of energy sharing, particularly in the context of microgeneration communities.

One of the most pressing issues is the economic inefficiency experienced by energy consumers and prosumers. Traditional energy markets are structured around centralised entities that control both pricing mechanisms and energy distribution. This structure results in high-end user electricity prices, partly due to operational inefficiencies, market monopolisation, and lack of transparency in energy transactions. Simultaneously, prosumers, typically through photovoltaic (PV) systems, are frequently undercompensated for the surplus electricity they inject into the grid. Current feed-in tariff schemes are either economically unattractive or administratively bureaucratic, which deters participation and limits the growth of distributed generation capacity [4].

Moreover, the increasing penetration of distributed renewable sources is placing additional stress on legacy grid infrastructures that were not designed for bidirectional energy flows. Centralised grid operators face increasing challenges in managing real-time demand response coordination, voltage fluctuations, and localised congestion, especially in urban and peri-urban areas with high levels of renewable integration [5]. Without a more dynamic and decentralised coordination mechanism, these inefficiencies could compromise grid stability and elevate the cost of balancing services.

Environmental concerns further reinforce the urgency of adopting new models. However, although the adoption of renewable energy has accelerated, the lack of scalability and transparent systems to facilitate direct energy sharing limits its potential, making it harder to reduce the current reliance on fossil-fuel-based power generation, which continues to produce significant greenhouse gas emissions [6].

Blockchain technology is increasingly recognised as a potential enabler of decentralised energy systems, thanks to its distributed ledger capabilities, smart contract automation, and inherent transparency. Recent studies have demonstrated its applicability in enabling secure P2P energy transactions, reducing settlement costs, and fostering trust among participants [7].

Nevertheless, existing blockchain-based energy platforms still face limitations in scalability, consensus efficiency, privacy preservation, and integration with physical grid infrastructure [8].

Observing the high electricity costs, inadequate prosumer incentives, centralised infrastructure stress and environmental challenges reveals deep inefficiencies in current energy systems. The transition to a decentralised, blockchain-enabled framework for P2P energy sharing represents a promising solution. Yet, further research is required to define a technically viable, economically attractive, and socially inclusive architecture that supports energy democratisation at the micro-community level [3] and [9].

1.3. Objectives

To respond to the challenges identified in the current energy paradigm, marked by high consumer prices, undercompensated prosumers, centralised grid limitations and the need for sustainable energy practices. This dissertation defines three interrelated research objectives that collectively aim to explore and design a blockchain-based solution tailored for microgeneration communities.

The first objective is to analyse the current state of research and practice in blockchain-enabled P2P energy sharing, with particular attention to technological trends, implementation challenges, and real-world use cases. The application of blockchain to decentralised energy markets is a rapidly evolving field yet fragmented in terms of technical approaches and governance models [4] and [8]. A systematic understanding of the current landscape is essential to identify successful strategies, persistent obstacles such as scalability and interoperability, and the factors influencing adoption across diverse regulatory and infrastructural contexts.

The second objective is to identify the functional and non-functional requirements for the development of decentralised energy-sharing systems in small-scale or community-based environments. Research indicates that such systems must address technical aspects such as access control, transaction validation, and privacy, while also ensuring social and economic viability through affordability, ease of integration with local infrastructure, and user-friendly design features. These requirements are critical for ensuring that the systems are not only technologically sound but also inclusive and responsive to the real conditions of microgeneration communities [5] and [9].

The third objective is to design a blockchain-based framework for secure, transparent, and decentralised P2P energy sharing tailored to microgeneration communities. The goal is to overcome the limitations of current centralised models by proposing a system architecture that

leverages smart contracts, distributed consensus, and tamperproof audit mechanisms to enable direct energy exchange with trust and transparency. This design draws from recent developments in blockchain integration with smart grids and decentralised energy markets, offering a technically feasible and scalable solution that aligns with the operational needs of local energy networks [8] and [10].

This dissertation addresses these objectives as follows:

O1. Chapter 2 uses a PRISMA-based systematic review and real-world case studies to analyse the current state of blockchain-enabled P2P energy sharing (Objective 1).

O2. Chapter 3 derives functional and non-functional requirements and proposes a layered architecture for a community-scale P2P trading platform (Objective 2).

O3. Chapter 4 design and evaluates a proof-of-concept (POC) prototype that instantiates this architecture in a microgeneration community context (Objective 3).

In addition to an analytical evaluation against functional and non-functional requirements, the solution is assessed through an end-user survey with 30 participants, providing initial evidence of perceived usefulness, clarity and acceptance.

1.4. Key Concepts

Understanding key concepts such as blockchain technology, P2P energy sharing, and microgeneration communities is fundamental and helps to grasp the context and significance of the proposed framework.

Blockchain is a distributed ledger technology that enables a network of participants, also known as nodes, to maintain a shared, tamperproof record of transactions without relying on a central authority. In a blockchain, transactions are grouped into blocks, cryptographically linked to the previous blocks, and validated through a consensus mechanism run by the network peers. Once recorded on the blockchain, data becomes extremely difficult to change, providing a high degree of integrity and trust. In the context of energy sharing, blockchain enables P2P transfers of digital assets between prosumers without intermediaries or a central operator [2].

P2P energy sharing refers to an arrangement in which energy consumers and producers within a community trade electricity directly, rather than buying from or selling to a traditional utility at fixed rates. In a P2P model, any participant who generates surplus energy can sell it to other peers in the community who need it, using a mutually agreed-upon pricing mechanism [1].

A microgeneration community is a group of energy users, such as residents of a neighbourhood, an apartment complex, or a small village, who actively generate their own electricity on a small scale and share it among themselves. These communities typically utilise distributed renewable energy sources, for example, many homes might have solar PV panels, small wind turbines, or combined heat-and-power units. The communities often also have local energy storage, such as home batteries, and may be interconnected into a regional power network that can operate in coordination with or independently of the main grid [1].

Blockchain-based P2P frameworks are a natural fit for such communities because they provide the tools for decentralised coordination. A community can establish its own blockchain-based energy marketplace for members to trade energy transparently and securely. In some designs, the community's prosumers even take on governance roles in the network, for example, local prosumers might serve as validating nodes (miners) in the blockchain, thereby aligning the platform's operation with community interests [8].

1.5. Original Contribution of the Thesis

This work provides three main original contributions:

1. A consolidated architectural blueprint integrating blockchain, smart metering, dynamic pricing, and community governance specifically adapted to microgeneration contexts.
2. A requirement-driven design methodology grounded in DSRM and validated through a POC implementation and a user-end evaluation rather than solely literature.
3. A demonstration of automated P2P trading using smart contracts that execute matching, validation, and settlement without intermediaries, based on a structured testing framework.

These contributions help advance the practical and academic understanding of blockchain's role in decentralised energy systems.

CHAPTER 2

Literature Review

This chapter examines the state of the art on blockchain-enabled frameworks for P2P energy sharing in microgeneration communities. The goal is to critically analyse academic and technical contributions, identify the dominant technological and market design approaches, and uncover gaps that justify the framework proposed in this dissertation. To ensure methodological rigour, the review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which structure the search, screening, and selection of relevant studies [11].

The chapter is organised into three parts:

1. A description of the PRISMA-based review process.
2. A thematic discussion of the selected literature.
3. An analysis of real-world cases that contextualise the proposed framework.

2.1. Prisma methodology

In this dissertation, PRISMA was used to guide the identification, screening, and selection of publications addressing blockchain technologies for P2P energy trading in microgeneration communities. The objective was to obtain a transparent and reproducible corpus of recent, high-quality works that inform the design of a blockchain-based P2P trading framework.

The search strategy was structured around three dimensions: technology, purpose, and scope. From a technological perspective, the terms blockchain and distributed ledger were used to target decentralised infrastructures suitable for managing energy transactions. The purpose dimension was captured through keywords such as peer-to-peer (P2P), sharing, and exchange, focusing on models that support direct trading between prosumers. Finally, the scope dimension included terms such as renewable, energy, framework, architecture, microgeneration, community, and small-scale, ensuring relevance to distributed renewable energy systems.

Based on these considerations, the following search string was applied across Scopus and IEEE Xplore:

("blockchain" OR "distributed ledger ") AND ("peer-to-peer" OR "P2P") AND ("renewable" OR "energy") AND ("sharing" OR "exchange") AND ("framework" OR "architecture") AND ("microgeneration" OR "community" OR "small scale")

To refine the results, several filters were applied. First, documents without a unique identifier, such as a Digital Object Identifier (DOI), were excluded to guarantee academic traceability. Second, duplicate entries arising from database overlap were removed. Third, a temporal filter restricted the selection to the period 2023–2025, reflecting the rapid evolution of blockchain-based energy systems. Finally, titles and abstracts were screened to retain only studies explicitly addressing blockchain-enabled frameworks, P2P energy exchange, and small-scale or community-based renewable energy systems. The overall process is summarised in Figure 1.

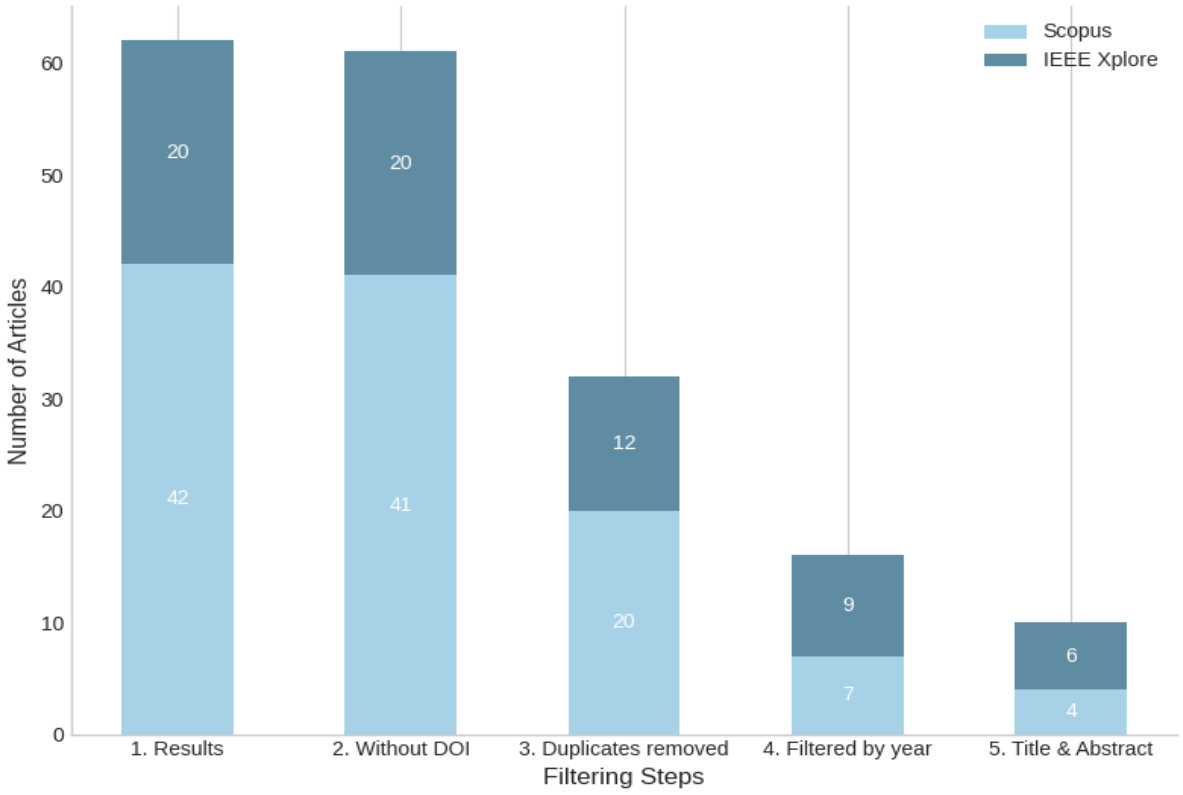


Figure 1 - PRISMA methodology application

Table 1 presents the final set of ten documents selected after completing the PRISMA process. These studies collectively cover blockchain architectures, market mechanisms, resilience strategies, and real-world implementations of P2P energy trading [1–10], [12]. Together, they provide a robust foundation for characterising technological, economic, and governance dimensions relevant to this dissertation and for identifying gaps that motivate the proposed framework.

Table 1 - Selected Literature

Authors	Title	Year
S. Sachdeva; L. Fatehaj; S. Tan; J. James; O. Ajayi; T. Saadawi	A Blockchain based Framework for Secure and Decentralized Energy Trading in a Community [4]	2023
V. Valsan; K. P; M. V. Ramesh; L. Varsha; M. Deeksha; S. Ankith	Blockchain based Smart Energy Trading in a Sustainable Community: A Comparative Technological Analysis [12]	2023
A. Boumaiza	Microgrid Analysis in a Peer-to-Peer Power Marketplace-based Blockchain [5]	2024
A. Boumaiza	Towards a Blockchain-enabled Transactive Renewable Energy Trading Market [10]	2024
N. B. S. Shibu; A. R. Devidas; S. Balamurugan; S. Ponnekanti; M. V. Ramesh	Optimizing Microgrid Resilience: Integrating IoT, Blockchain, and Smart Contracts for Power Outage Management [7]	2024
A. Umar; D. Kumar; T. Ghose; T. A. H. Alghamdi; A. Y. Abdelaziz	Decentralized Community Energy Management: Enhancing Demand Response Through Smart Contracts in a Blockchain Network [8]	2024
Zhou Y.; Lund P.D.	Peer-to-peer energy sharing and trading of renewable energy in smart communities ─ trading pricing models, decision-making and agent-based collaboration [3]	2023
Chinnici M.; Telesca L.; Islam M.; Georges J.-P.	Scalable and Transparent Blockchain Multi-layer Approach for Smart Energy Communities [9]	2023
Liu J.; Tian M.; Mao X.	Overview and Prospect of Distributed Energy P2P Trading [1]	2024
Taouil K.; Aloulou R.; Bradai S.; Gassara A.; Kharrat M.W.; Louati B.; Giordani M.	P2P Energy Exchange Architecture for Swarm Electrification-Driven PV Communities [2]	2024

2.2. Discussion

The reviewed literature confirms that blockchain has emerged as a central enabling technology for P2P energy trading. Its decentralised and tamper-resistant ledger provides transparency, security, and auditability for energy transactions [3], [9]. In community settings, blockchain can trace both the origin and flow of energy, support transparent tariffs, and mitigate data

manipulation, which explains its adoption in many prototype microgrids and smart energy communities [9], [12].

Beyond serving as a secure log, blockchain acts as an active coordination mechanism through smart contracts. On platforms such as Ethereum, smart contracts encode and automatically enforce trading rules, including price calculation, order matching, and settlement [4], [13]. Chinnici et al. [9], for example, propose a multi-layer blockchain ecosystem that integrates smart legal contracts and community tokens to incentivise participation. In such models, tokenised rewards are used to remunerate prosumers for energy contributions and to link energy transactions with broader community services.

However, the literature also highlights several design tensions. While blockchain removes the need for a fully central intermediary and enhances trust, it introduces scalability and integration challenges, particularly in resource-constrained or latency-sensitive environments [9], [12]. The choice of consensus mechanism, for example, proof-of-authority, practical Byzantine fault tolerance, and network configuration between public or permissioned is therefore critical to balance performance, security, and privacy.

Despite these challenges, recent advancements like the consortium blockchains and off-chain scaling are making blockchain-based energy sharing more viable, as evidenced by numerous prototype implementations in microgrid communities [4] and [9].

A consistent solution is the use of smart contracts to automate trading rules and settlement. Umar et al. (2024) [8] integrate an incentive-driven demand response program into a blockchain smart contract framework for community energy trading. In their system, prosumers are rewarded in real time for adjusting loads to contribute to grid balance, with all transactions and reward distributions recorded transparently on the blockchain [8].

A key innovation is the use of a dynamic pricing model that allows energy prices to adapt to real-time supply–demand conditions using a digital token, for instance, a cryptocurrency like Tether (USDT), ensuring fair and efficient market outcomes [8]. This adaptive pricing via smart contracts fosters a more equitable trading environment than static tariffs by quickly reflecting resource availability and encouraging load flexibility. Similarly, Boumaiza et al. (2024) [5] simulate a transactive microgrid marketplace where a local cryptocurrency is mined and used for P2P energy transactions. In their blockchain-enabled microgrid, prosumers and consumers respond to price fluctuations, which incentivises them to modify their consumption profiles in real time [10].

Such designs encourage users to shift or reduce loads during peak times or to use more local solar generation, thereby enhancing the community's grid flexibility and economic efficiency. The results from these P2P market prototypes are promising, as users experience cost savings and automated P2P transactions, coupled with distributed storage, leading to greater energy independence for the community [5] and [10].

P2P frameworks also contribute to resilience and reliability. Sai Shibu et al. [7] propose an outage management strategy in which IoT-connected prosumers share energy during grid failures via blockchain-coordinated P2P trades. Smart contracts orchestrate energy exchanges in affected regions and reward prosumers who supply spare energy, thereby supporting community-level recovery. More broadly, Zhou and Lund [3] argue that well-designed P2P schemes can generate "win–win" outcomes for prosumers, consumers, and even traditional utilities by improving system efficiency, reducing the need for significant storage investments, increasing renewable penetration, and providing ancillary services such as voltage support and congestion relief.

Blockchain-based automation further enhances these mechanisms by enabling secure, real-time transaction settlement with minimal human intervention [3].

Overall, the literature on P2P mechanisms illustrates a range of strategies, from dynamic pricing and tokenised incentives to outage management, all aimed at empowering end-users to participate in energy markets actively. By using blockchain and smart contracts, P2P trading frameworks ensure that this participation is secure, transparent, and efficient, thereby unlocking economic and reliability benefits that traditional centralised models cannot easily provide.

Most of the analysed works focus on renewable-based microgeneration communities, typically neighbourhoods or small groups of prosumers equipped with rooftop PV, small wind turbines, and batteries. These communities embody the transition from centralised to distributed energy systems [1]. Liu et al. [1] emphasise that P2P trading is a key mechanism in this transition, as it enables communities to collectively manage local resources, increase self-consumption of renewables, and reduce reliance on imported grid electricity. This local coordination not only generates economic benefits for prosumers and consumers but also strengthens energy resilience and fosters a sense of collective responsibility in managing energy resources [1], [3].

This not only yields economic benefits for prosumer households by enabling them to sell excess energy, but also enhances energy resilience, as communities become less vulnerable to external grid disturbances [1]. Furthermore, P2P frameworks foster a sense of collective responsibility in energy management, with neighbours actively cooperating to balance supply

and demand, which can strengthen social bonds and acceptance of renewable projects in the community [1].

Concrete case studies reinforce these conceptual benefits. Taouil et al. [2] investigate rural off-grid communities using a "swarm electrification" approach, in which individual solar home systems are interconnected into a Direct Current (DC) microgrid. They design a blockchain-based P2P architecture suitable for environments with limited internet connectivity, ensuring that all trades are recorded and settled on-chain. Experiments show that the community trading scheme reduces peak demand, supplies approximately 11% of a household's energy needs from peers, and limits each battery to one charge/discharge cycle per day, thereby extending battery life [2]. Prosumers experience a 16% reduction in wasted surplus energy by selling to neighbours rather than curtailing production [2]. These findings are consistent with Zhou and Lund's [3] conclusions that P2P trading can enhance renewable utilisation and improve local grid stability.

Another dissertation reports that automated P2P transactions and shared energy storage enabled end-users to achieve greater autonomy and energy savings, demonstrating a viable, sustainable microgrid model for the future [5] and [10].

Despite these promising results, the literature converges on the view that distributed P2P trading is still in an early stage of real-world deployment. Regulatory constraints, market design limitations, and technical challenges, such as interoperability with incumbent grid infrastructure and intermittent connectivity in remote areas, have so far hindered large-scale adoption [1], [2]. Liu et al. [1] note that most electricity markets have yet to integrate community P2P models, and more empirical evidence is needed to understand their long-term economic and operational impacts.

Overall, the reviewed studies demonstrate that blockchain-based P2P frameworks offer a credible pathway towards decentralised, community-driven energy systems. They collectively inform the design choices in this dissertation while also revealing several gaps: a limited focus on microgeneration-oriented architectures anchored to existing wholesale market prices, insufficient evaluation of functional and non-functional requirements within a unified framework, and a lack of implementable prototypes tailored to small communities. These gaps motivate the requirements definition and architectural design developed in Chapter 3.

2.3. Real Cases

To complement the academic literature, this section analyses real-world initiatives that have implemented community energy models with and without blockchain support. These cases provide empirical insights into governance arrangements, incentive structures, and user engagement strategies, and they help position the proposed framework relative to existing practice. In particular, projects such as EDP's "Bairro Solar" in Portugal, the Brooklyn Microgrid in the United States, and Quartierstrom in Switzerland illustrate different approaches to local energy sharing and highlight trade-offs between utility-led and community-governed models.

EDP "Bairro Solar" in Portugal is a utility-led local solar energy community where the electric utility EDP installs photovoltaic panels for a producer, a business, for example, and shares the energy with nearby consumers. Participants do not pay any upfront costs, and the producer's panels are installed at no cost. Neighbours simply join the community to use the solar energy. Both producers and neighbours receive guaranteed invoice savings on the shared solar power, with producers receiving up to a 60% discount on self-consumed solar energy. In comparison, each neighbour enjoys about 35% off the price of the solar energy they consume from the community [14].

Brooklyn Microgrid in the United States of America (USA) is a pioneering blockchain-based community microgrid project in New York. In this pilot, residents with solar panels can directly sell excess power to their neighbours via a local energy market on a blockchain platform. Launched in 2015 by startup LO3 Energy [15], the Brooklyn Microgrid lets community members bid and trade energy P2P using a smartphone app. For example, neighbours can set how much they are willing to pay for local solar energy and find nearby prosumers offering it [16].

Another notable example is Quartierstrom in Switzerland, a 2019 pilot where 37 households formed a local energy market on a permissioned blockchain. In Quartierstrom, community members collectively govern the marketplace, with the local utility only collecting grid fees and serving as a backstop for energy imbalances. Participants there could actively set their selling and buying prices, aligning incentives for local solar consumption [17].

The Governance Model in projects like the EDP's "Bairro Solar" is managed entirely by the utility with fixed rules for hybrid models [14]. Brooklyn Microgrid's market is decentralised via blockchain, but a private company operates the platform [18].

This dissertation proposes a solution for blockchain-based P2P trading in micro-communities that intends to push governance further towards the community itself or a trustless system. In other words, rules and transactions would be enforced by smart contracts and consensus among participants, rather than by a single utility or company. This could resemble the Quartierstrom approach, where prosumers collectively govern the network's rules on a distributed ledger, ensuring transparency and shared decision-making [17]. Such a governance model would differentiate the dissertation solution by minimising the role of any single centralised intermediary and empowering participants to manage their energy exchange.

The user incentives for the existing cases provide financial benefits, but in different ways. In Bairro Solar, user incentives are pre-defined discounts on energy [14]. This is a simple incentive, but it doesn't allow real-time pricing or profit, the utility sets the terms, and participants passively receive savings. In blockchain-based trading communities like Brooklyn or Quartierstrom, incentives are more market-driven as prosumers earn revenue by selling power at competitive rates, and consumers can seek lower prices or greener energy by bidding in the local market [16].

This market-based incentive structure can reward active engagement, prosumers benefit from higher prices when demand is high, and consumers save when they bid for cheaper surplus energy. This dissertation solution would differ by aligning incentives with active participation and efficiency, for example, it might use dynamic pricing or token rewards to encourage users to produce, trade, or even shift consumption to support the community. Unlike a flat discount scheme, the blockchain-enabled model in the dissertation could offer more granular and flexible rewards, motivating users through direct P2P transactions and possibly additional tokens or credits for contributing to grid balance or other community services. This creates a more participatory incentive environment, in contrast to the relatively static benefits in current utility-led models.

The insights derived from the literature review provide a foundation for specifying the requirements and architectural principles developed in the following chapter. Chapter 3 builds upon these findings to define the functional and non-functional requirements, outline the conceptual architecture, and justify the design choices that underpin the proposed blockchain-based P2P energy trading framework.

CHAPTER 3

Requirements Definition and Architectural Design of the P2P Energy Trading System

Energy systems have historically relied on centralised utilities to mediate the sale of electricity. Such arrangements tend to under-reward small producers and limit consumers' access to locally produced renewable energy. This dissertation proposes a P2P trading solution in which prosumers sell surplus power directly to their neighbours. The traded price is indexed to the day-ahead market price set by the Electricity Market Operator, for instance, OMIE in the Iberian market. At the same time, participants define their own margins relative to this benchmark. The platform automates buy and sell orders by allowing users to set time windows and price limits, so that trades are executed whenever predefined conditions are met.

This chapter explains how this dissertation adopts the Design Science Research Methodology (DSRM) and develops a conceptual design for the P2P trading platform. It begins by summarising the DSRM stages relevant to the project, then details the architecture of the proposed solution, including its components, functional layers, actors, and information flows. By focusing on the design itself, the chapter lays the groundwork for implementation and evaluation in later chapters.

3.1. Methodology – DSRM Applied

Design Science Research Methodology provides a structured process for creating and evaluating artefacts in information systems research. Liu et al. [1] define six stages:

1. Problem identification and motivation.
2. Definition of the objectives of a solution.
3. Design and development of the artefact.
4. Demonstration of the artefact.
5. Evaluation.
6. Communication of the results.

In this dissertation, the first two stages are addressed in the preceding chapters, which highlight the need for a decentralised market that rewards renewable generation and empowers consumers. The present chapter focuses on stage (3), detailing the design and development of the artefact and explaining how it is demonstrated in a controlled environment. The stages (4) and (5) are addressed in Chapter 4, which presents the POC and evaluates it both analytically

and through an end-user survey. The final stage of communication is fulfilled through the thesis as a whole.

3.2. Conceptual Infrastructure of the Solution

3.2.1. Vision of the Architecture

The core idea of the solution is to enable prosumers and consumers to transact energy locally, assuming rooftop PV and small household batteries, rather than large industrial plants, based on an objective market reference price. Rather than introducing an entirely new token economy or a complex auction mechanism, the platform anchors community trades to the existing day-ahead wholesale market price obtained from the market operator. Prosumers and consumers specify margins around this reference value, prosumers define a minimum acceptable uplift over the wholesale price. In contrast, consumers define a maximum acceptable discount relative to their retail tariff.

When a bid meets an offer within the same time interval, the platform automatically executes the trade through a smart contract. Trades occur without changing the physical flow of electricity as energy still travels through the local distribution network, but the financial settlement reflects the P2P transaction. Figure 2 provides a high-level view of the system.

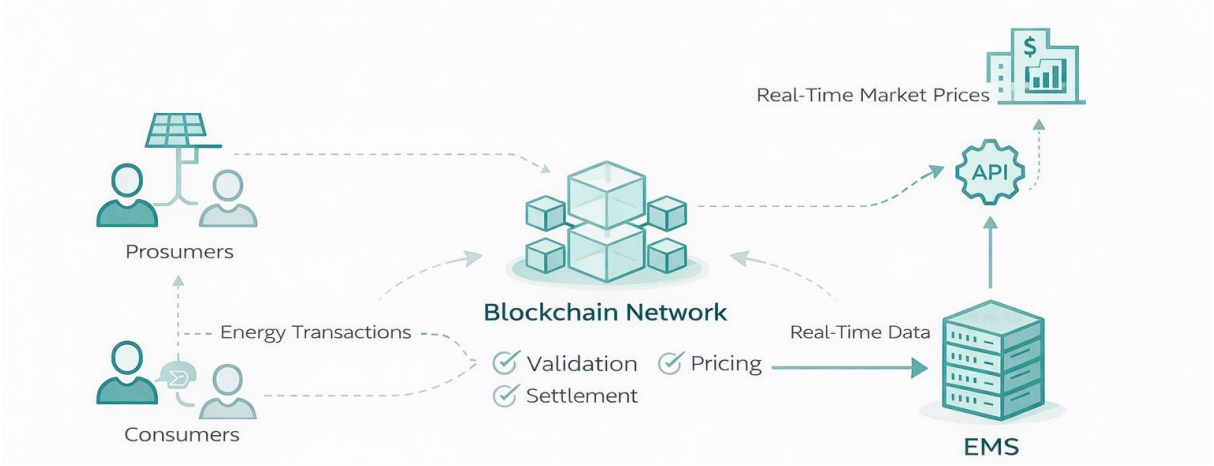


Figure 2 - High level architecture

Figure 2 illustrates the interaction between prosumers and consumers who submit energy transactions to a permissioned blockchain network. The blockchain communicates with an Energy Management System (EMS) via an Application Programming Interface (API), which provides real-time market prices from an energy market operator. These inputs enable transparent validation, pricing, and settlement of local energy trades.

In this conceptual representation, prosumer and consumer homes connect to the local grid via smart meters. A home energy management system (HEMS) collects data from the meters, retrieves the wholesale price via an API, and manages the users' configured trading preferences. The HEMS communicates with a private or consortium blockchain that hosts smart contracts for order matching and transaction recording. External data sources, namely the market operator for price and utilities for meter readings, feed information into the blockchain via oracles, ensuring that off-chain data can be trusted on-chain.

This architecture clearly separates physical energy flows from the digital trading environment. Electricity continues to flow through the existing distribution network, while financial settlement and governance are handled on the blockchain layer. This separation allows the platform to implement fair, automated transactions without interfering with grid operations.

3.2.2. Functional Requirements

The functional requirements specify what the platform must do. They ensure that the system supports all necessary operations, from user onboarding to transaction settlement:

1. Participant registration and account management - The platform must allow households to register as prosumers or consumers, create blockchain accounts and authenticate themselves. Registration also collects facility data, such as generation capacity and network constraints, which the platform uses to validate offers.
2. Processing facility and constraint data - After registration, the system must receive and store information about each participant’s assets and operational limits. This includes solar panel ratings, battery storage capacities and grid constraints. The platform relies on these data to ensure that bids and offers reflect real capabilities and to prevent participants from selling more energy than they can deliver.
3. Real-time order management - The trading engine must enable prosumers and consumers to submit offers and bids dynamically. It collects orders for specific time intervals, matches them based on price and quantity, and confirms trades via smart contracts. To prevent double sale of energy, the platform maintains an ownership state for every kilowatt-hour traded. Dynamic pricing rules allow participants to specify margins relative to the energy market operator's price.
4. Dispatch and settlement - Once bids and offers are matched, the platform must issue dispatch instructions and integrate with home energy management systems to adjust loads or battery operation if needed. After the delivery interval, it verifies the actual energy exchanged via smart meter data and settles payment through the smart contract. A summary of each trade is sent to energy retailers for invoicing adjustments.

5. Reporting and user interface - The system must provide participants with clear reports of their trades, including quantities, prices, revenues and savings. It should also generate performance and compliance reports for operators and regulators. A user-friendly web and/or mobile interface should allow users to configure trading preferences, monitor their generation and consumption in real time and review past transactions. To support real-time control, the HEMS must integrate with compatible applications and provide stable communication between the local gateway and the cloud.

3.2.3. Non-Functional Requirements

Non-functional requirements describe the qualities and constraints that the platform must satisfy to operate securely, reliably and efficiently. They complement the functional requirements by specifying cross-cutting system properties such as security, performance, scalability and support, which are essential for a technically robust and socially acceptable P2P trading solution:

1. Security and compliance - All data, including participant identities, orders and meter readings, must be protected from unauthorised access. The platform should follow legal and compliance rules and store data in secure data centres, using authentication and encryption to ensure that only authorised nodes can read or write to the ledger.
2. Performance - The system must respond promptly to user actions and process bids, offers and dispatch instructions within a defined timeframe. For example, a pilot platform is required to process orders and instructions in under four seconds, ensuring that market conditions are reflected quickly and participants receive timely feedback.
3. Scalability - The platform must handle additional participants and higher message volumes without degrading performance. Pilot guidelines suggest scaling to at least ten concurrent users and higher data flows while maintaining service quality.
4. Availability - High availability is critical so that participants can trade energy whenever needed. In a pilot context, the system should achieve 99% uptime with a maximum tolerable downtime of 1 day.
5. Maintainability and upgradability - As blockchain technologies and energy regulations evolve, the platform must allow for scheduled maintenance and updates. It should support hotfixes and upgrades without significant downtime and permit remote updates to the HEMS software.
6. Interoperability - The platform should exchange data smoothly with external systems such as market operators and utilities, and with different versions of the API schema. It must

support multiple message versions and allow participants to transition from file-based to API-based methods.

7. Auditability - Every transaction must be traceable from initiation to settlement. The system should maintain detailed logs of user actions. Auditability is essential for regulatory compliance and resolving disputes.
8. Support and user experience - The platform must provide technical and business support during regular operating hours. It should log all errors and provide meaningful feedback to users and support staff. Additionally, the home energy management system must maintain reliable connectivity and low latency to support automated control and real-time monitoring.

Taken together, these non-functional requirements ensure that the P2P trading platform not only performs its intended functions but also delivers a secure, reliable and user-friendly experience for all participants.

3.2.4. Components and Functional Layers

The proposed platform is composed of several interdependent components, organised into functional layers that reflect their roles in measuring, processing and recording energy transactions:

1. Smart meters - Each participating household is equipped with a bidirectional smart meter that measures electricity consumption and generation in real time. In the P2P system, they provide the definitive measurement of how much energy each prosumer injects into the grid and how much each consumer draws during a trading interval. The accuracy and real-time nature of smart meters are essential for verifying trades and preventing fraud.
2. HEMS - Beyond basic metering, a home energy management system coordinates distributed energy resources and user preferences. An HEMS integrates hardware and software to collect, analyse and visualise energy data and to control energy flows between connected devices. In the proposed platform, the HEMS, which can be cloud-hosted or installed locally, allows prosumers to configure how much energy they are willing to sell and at what margin, and lets consumers specify their demand and maximum price. It fetches the energy market operator's price via an API and feeds it into the trading logic. The HEMS thus serves as the interface between participants and the marketplace.
3. Blockchain network - To ensure trust without a central intermediary, the system uses a private or consortium blockchain. A blockchain is a distributed ledger that records transactions in an immutable sequence of blocks. It provides transparency and tamper-resistance. The P2P platform deploys smart contracts on the blockchain to

implement the trading rules. Because the network is permissioned, only authorised nodes, for example, community members or regulators, validate transactions, ensuring both efficiency and privacy. The choice of a private or consortium blockchain is deliberate. Community-scale energy trading involves a limited and identifiable set of stakeholders (households, municipalities, retailers and regulators), making permissionless, open participation unnecessary and potentially inefficient. A permissioned network allows the use of energy-efficient consensus mechanisms, such as proof-of-authority or Byzantine-fault-tolerant protocols, which offer fast confirmation times and low computational overhead. This design reduces the platform's environmental footprint and facilitates compliance with sectoral regulations, while still preserving immutability and transparency for authorised participants.

4. Smart contracts - Smart contracts are self-executing programs that reside on the blockchain and automatically enforce the terms of an agreement. In this context, a smart contract encodes the logic for matching bids and offers, recording agreements, and settling payments. When a consumer’s bid meets a prosumer’s offer, the contract logs the trade details and locks the appropriate funds or tokens. After the delivery interval, it verifies the actual metered energy via an oracle and then releases payment proportionally to the energy delivered. This automation eliminates the need for a trusted third party and ensures that both sides of the trade are treated fairly.
5. Oracles and APIs - Smart contracts cannot access off-chain data directly, so oracles bridge the gap between the blockchain and the external world. The platform integrates with external APIs to retrieve day-ahead market prices from energy market operators and meter readings from energy retailers. Oracles feed these values into the blockchain so that smart contracts can use them as inputs for pricing and settlement. This integration enables the trading system to operate autonomously while relying on verifiable, up-to-date external data, thereby aligning on-chain settlement with real-world conditions.

Across these components, the platform comprises three conceptual layers. The physical layer contains the distributed energy resources and smart meters that measure energy flows. The data/control layer includes the HEMS and IoT devices that collect and process information and apply user preferences. The blockchain layer serves as the transactional core, hosting smart contracts and recording trades. Together, as shown in Figure 3, these layers enable a secure, real-time market for local energy trading.

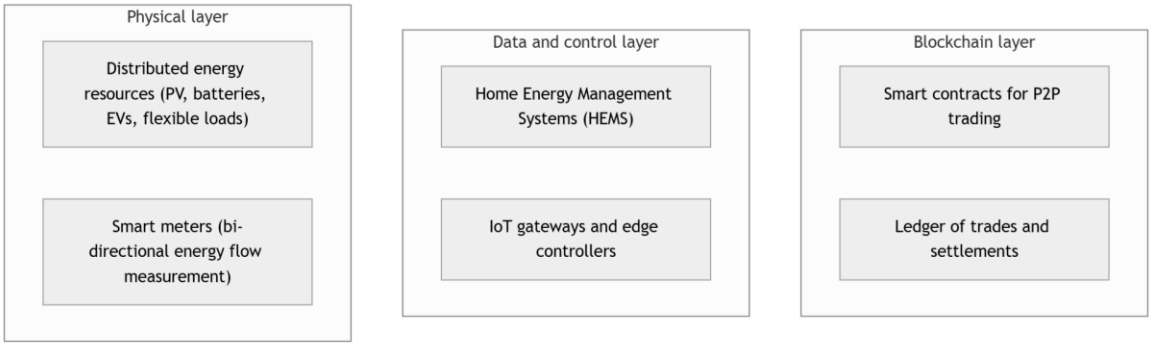


Figure 3 - Conceptual layers

3.2.5. Actors and Roles

The P2P energy trading system involves several stakeholders, each with specific responsibilities:

1. Prosumer - A prosumer is a household or entity that generates electricity, for example, via rooftop solar panels, and consumes it. When their generation exceeds their consumption, prosumers can sell the surplus on the platform. They set the quantity available, the time windows for trading, and the minimum acceptable price, equal to the market price plus a margin. By selling locally, prosumers earn more than they would under traditional feed-in tariffs while supporting their neighbours.
2. Consumer - Consumers are participants who wish to purchase energy from local peers rather than solely from their utility. They specify when they need energy and their maximum price relative to the market. Consumers benefit by potentially paying less than the retail tariff and by knowing their energy comes from local renewable sources.
3. Energy management platform operator - Although the blockchain provides decentralisation, a platform operator manages the non-trading aspects of the system. This role could be fulfilled by the community itself, a municipal energy cooperative or a specialised service provider. The operator maintains the HEMS, integrates APIs, manages the Oracle infrastructure, and ensures that the platform complies with regulations. It does not intermediate trades but can enforce platform rules, such as limiting margins or volumes.
4. Energy retailers - Provide any residual energy that participants cannot obtain locally, handle invoicing and regulatory reporting, and may receive aggregated data from the platform to reconcile P2P trades with conventional billing processes.

3.2.6. Information Flows and Interaction Logic

The platform orchestrates multiple information flows and transactions to enable local energy trading:

1. Price retrieval and order configuration - At the beginning of each trading interval (hourly, for instance), the HEMS obtains the day-ahead market-clearing price from the energy market operator via an API.
2. Matching and smart contract execution - The platform matches buy and sell orders based on quantity, price and time. When a match is found, a smart contract records the pending trade. The agreement specifies the identities of the buyer and seller, the agreed quantity, the price and the delivery window. It may also reserve tokens or funds to ensure payment. This creates a binding digital agreement that is transparent and immutable.
3. Physical energy delivery and monitoring - During the trading interval, electricity flows through the local grid in accordance with physical laws. Smart meters measure how much energy each participant exports or consumes. The HEMS may adjust household appliances or storage devices to meet the scheduled trades. Because energy cannot be directed to a specific neighbour in an Alternating Current (AC) network, the system relies on measurements and compensation rather than physical routing.
4. Oracle-based verification - After the interval ends, the HEMS collects the metered data from the smart meters. An oracle then transfers this data to the blockchain so that the smart contract can verify the actual energy exchanged. If the prosumer delivered less than promised, the contract adjusts the settlement accordingly, and if more energy was delivered, the extra may be credited at a lower rate or carried forward.
5. Settlement and invoicing - Once verification is complete, the smart contract finalises the payment. It transfers tokens or credits from the consumer to the prosumer or notifies the energy retailers of the net trade. The retailer then invoices the consumer only for the net electricity imported and credits the prosumer for the exported energy. This automated settlement ensures that participants are fairly compensated without manual intervention.
6. User feedback and transparency - The HEMS interface presents participants with a summary of their trades, including quantities, prices and monetary outcomes. Because all transactions are recorded on the blockchain, participants can audit trade history and confirm that the system operates as designed. This transparency fosters trust and encourages continued participation in the local market.

3.3. Conclusion of the Chapter

This chapter has applied the Design Science Research Methodology to conceptualise a P2P energy trading platform that aligns with the overarching objective of empowering prosumers and enabling consumers to access local renewable energy. It presented a holistic architecture in which smart meters provide real-time measurements, a home energy management system manages user preferences and retrieves market data, and a permissioned blockchain network with smart contracts automates trade matching and settlement. External price and meter information are incorporated through oracles, ensuring that transactions reflect real-world conditions while remaining tamper-resistant on-chain.

The proposed design addresses the research objectives by:

1. Formalising the functional and non-functional requirements of a blockchain-enabled P2P trading system.
2. Specifying a layered architecture that separates physical, control and transactional responsibilities.
3. Defining actors, roles and information flows that can be instantiated in real communities. In this way, the architecture directly addresses the identified gaps in the existing literature and practice, namely the lack of implementable, validated models for microgeneration communities.

By detailing components, functional layers, actors and interaction logic, this chapter provides the blueprint for the implementation and evaluation activities described in Chapter 4. The POC prototype operationalises the layered model, tests compliance with the stated requirements and demonstrates how smart contracts enforce the trading logic specified here.

CHAPTER 4

Proof-of-Concept Implementation and System Evaluation

This chapter presents the development of a POC implementation of the proposed P2P energy sharing platform and explains how the architectural design is translated into a functional prototype. The POC is used to assess the feasibility and effectiveness of the framework's governance model and core functionalities in a controlled environment.

Specifically, the chapter details the methodology adopted to build and test the POC, evaluates whether the governance mechanisms (such as smart contracts and the consensus protocol) operate as intended, and verifies the extent to which the functional and non-functional requirements identified in previous chapters are satisfied. The POC aims to demonstrate that the platform can support prosumer-to-consumer energy transactions, automated contract enforcement, and key system qualities, including security, interoperability, and scalability.

By the end of the chapter, it should be clear how the critical components of the proposed solution interact in practice, how their performance was validated, and to what extent the POC contributes to the overall research objectives.

4.1. Review of the Proposed Architecture

Before describing the implementation details, it is useful to revisit the main elements of the proposed system architecture and highlight the specific components that are instantiated in the POC. The complete architecture comprises several interacting subsystems, but not all of them need to be fully implemented to demonstrate feasibility. The POC, therefore, focuses on three critical functionalities that are fundamental to the platform's operation and to validating the research objectives.

Firstly, a P2P energy transaction capability, enabling prosumers and consumers to transact energy directly with each other via a dynamic pricing mechanism. In the proposed architecture, this involves handling energy flow from a prosumer to a consumer and computing transaction prices on the fly based on a market reference price and participants. Figure 4 provides a simplified diagram of this process. The prosumer generates surplus energy and sells it, while a consumer with a demand places a purchase bid. The platform's logic matches these in a P2P trade without a central broker. The energy flow is separate from the value flow, but the platform coordinates both. The dynamic pricing model uses an external reference, the energy market operator, and predefined rules such as a markup and a maximum price to settle on a fair price

for each transaction. This component is critical to test because it directly validates the market mechanism.

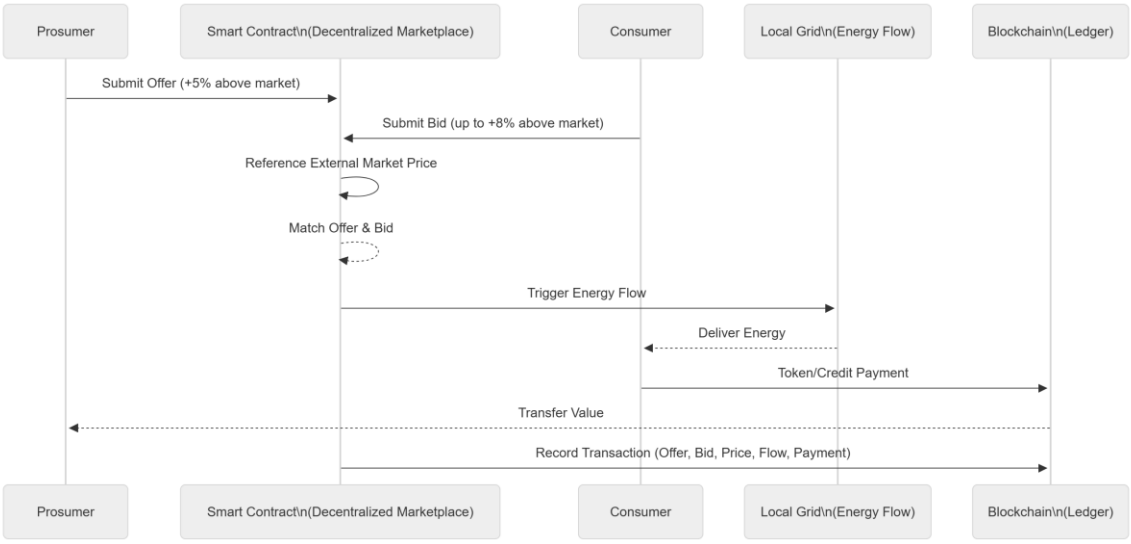


Figure 4 - P2P energy transaction capability

Secondly, the smart contract-based trading automation shows that the platform relies on smart contracts to negotiate and enforce energy trading agreements. Instead of manual or third-party intervention, the smart contracts automatically match supply and demand and execute trades when conditions are met. Figure 5 illustrates the role of smart contracts in the system, with key functions including collecting offers and bids, running a matching algorithm, and handling settlement once a match is found.

The POC implements a simplified smart contract that encodes these rules. Testing this component is crucial to demonstrating that the governance model embedded in the contract code is viable, ensuring trades are executed fairly, securely, and without manual oversight. In the POC architecture, the smart contract resides on a private blockchain network accessible to all participants. The integration of this smart contract with user-facing applications, as a prosumer's HEMS, is designed so that users do not need to interact with the blockchain directly, just see their trades occur seamlessly in the background. Validating this function in the POC confirms that the system can indeed operate in a decentralised manner, with the marketplace rules executed by the smart contract rather than a centralised operator.

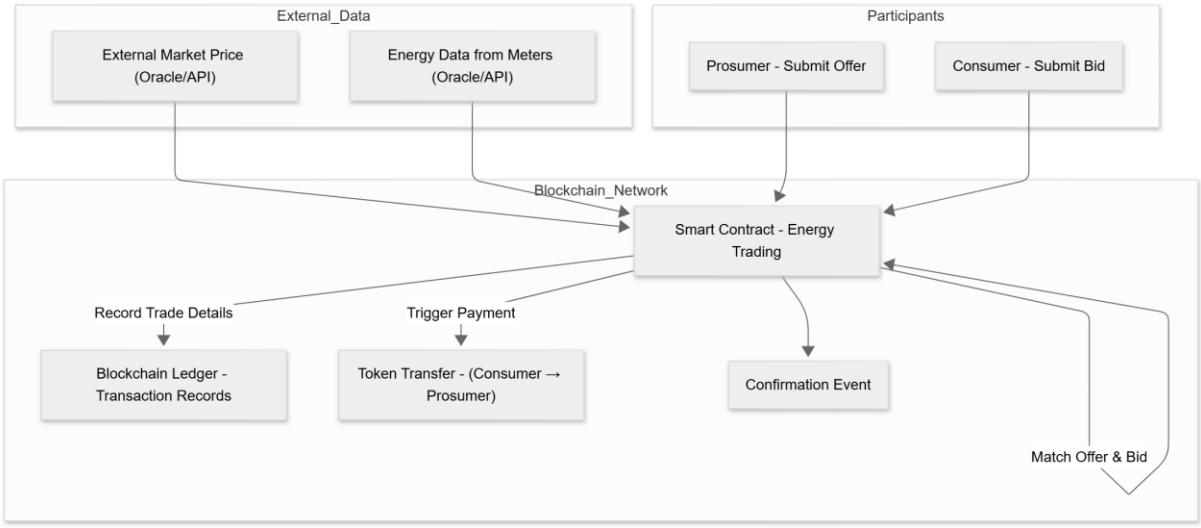


Figure 5 - Smart contract automation of trade

Thirdly, the integration with smart meters and IoT data feeds, whose interoperability is essential to provide real-time data. In a real deployment, each prosumer and consumer would have a smart meter measuring generation or consumption. These data are necessary for the platform's operation, for instance, to verify that a prosumer produced the energy they sold, or to update a consumer's consumption after a trade. The proposed architecture includes an HEMS layer that collects meter readings and communicates with the blockchain platform. Figure 6 provides a simple visual illustration of this integration.

The POC simulates smart meter inputs to test how the platform ingests and uses this information. The smart meter data flow involves sending the data to the HEMS, which then forwards relevant info to the blockchain, either directly into the smart contract or to an off-chain database that the contract can query. This setup is validated by checking that the data interoperability works, for instance, when a prosumer's meter reports available surplus energy, the same amount becomes available for trading on the platform and a consumer's meter reading after a trade should reflect the purchased energy. Testing this ensures the solution can interface with physical devices and external systems, which is key for real-world viability. Moreover, it addresses interoperability requirements by showing that standard data obtained from utility meters can be integrated into a blockchain-based market. In the POC architecture, this might be implemented with a simple API or script that updates the contract with dummy meter values at regular intervals.

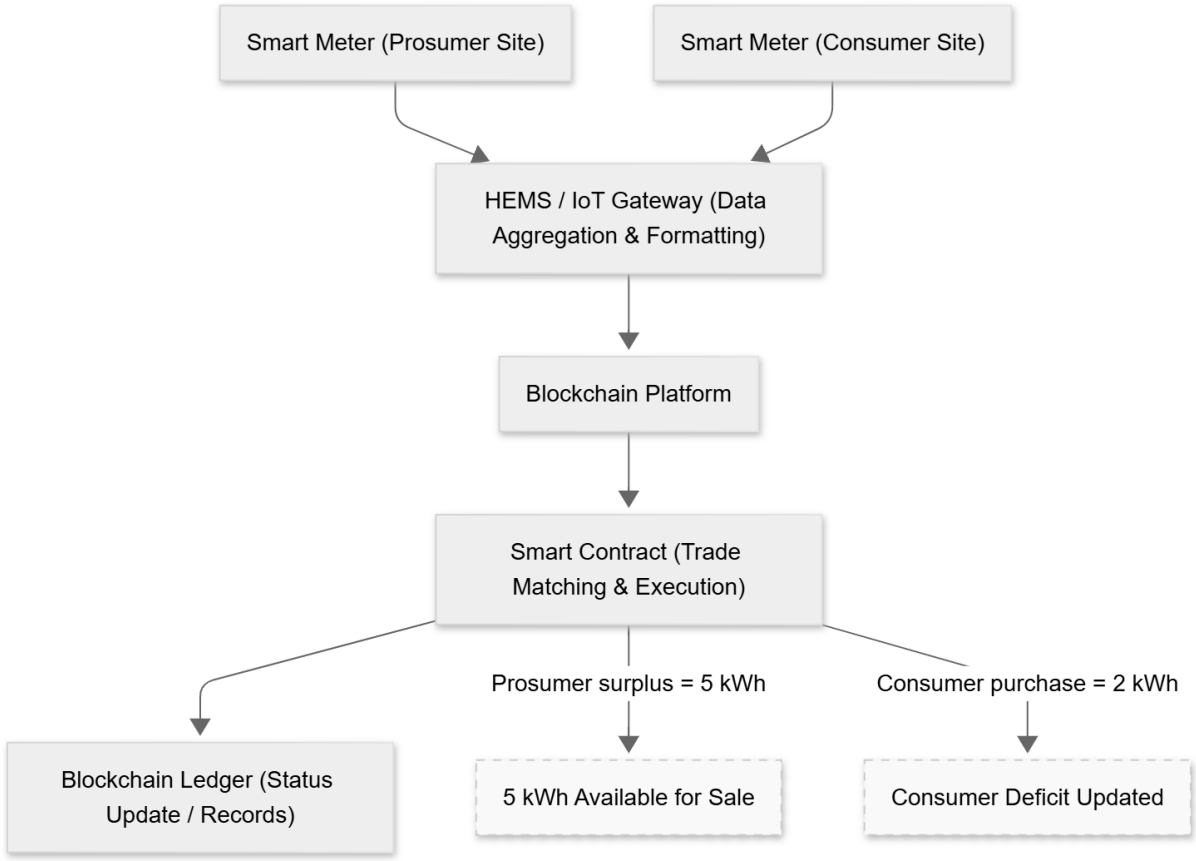


Figure 6 - Integration with smart meters and IoT data feeds

By focusing on these three functionalities in the POC, the most important aspects of the architecture are ensured to be evaluated. Rather than implementing every feature, the POC targets the components that collectively demonstrate the end-to-end flow, from data input (meters) to automated trading (smart contracts) to physical action (energy transfer and payment). This selective implementation provides confidence that the architecture's design is sound and that the chosen technologies can fulfil their intended roles when integrated.

4.2. Testing and Validation

With the critical components identified, the next step is to rigorously test the POC and validate that it meets its intended functionality. The testing strategy covers individual function tests and overall system behaviour under expected scenarios.

The validation is divided into three parts:

1. Functionality testing for transactions.
2. Validation of functional requirements.
3. Evaluation of non-functional requirements.

4.2.1. Test of Transaction Functionality

For the POC to be considered successful, it must accurately perform P2P energy transactions between a prosumer and a consumer. Therefore, a series of tests was designed to verify the transaction workflow, from initiating a trade to finalising it on the ledger. This involves creating realistic scenarios, set in which prosumers and consumers interact through the platform.

Table 2 - Key test scenarios

Test code	Title	Description & Expected Result	Process	Outcome
T1	Basic P2P Trade Execution	A prosumer with 2 kWh surplus submits an offer at a given price, and a consumer places a matching bid. Expected result: The smart contract matches offer and bid, executes the trade, and records a transaction with correct details (IDs, energy amount, price, timestamp).	Trigger the smart contract with a prosumer offer (quantity + price) and a consumer bid.	Prosumer's available energy decreases by 2 kWh; consumer's demand is fulfilled; a blockchain ledger entry is created with correct trade metadata.
T2	Dynamic Pricing and Negotiation	Market price = €0.10/kWh. Prosumer A offers 5 kWh at +5% (€0.105); Consumer B accepts up to +8% (€0.108). Expected result: Trade executed at €0.105 because B's bid exceeds A's ask.	Submit A's offer and B's bid, and feed the market reference price via oracle/input.	Contract matches both for 5 kWh at €0.105; prosumer energy decreases; consumer funds decrease; ledger reflects correct dynamic price calculation and updated balances.
T3	Order Execution & Data Integrity	Multiple orders: A (3 kWh - €0.10), B(2 kWh - €0.09), C(4 kWh ≤ €0.11), D(2 kWh ≤ €0.095). Expected: C matched with A (3 kWh) and B (1 kWh); D matched with B (1 kWh). Total trades ≤ available 5 kWh. Ledger should capture separate, correct transactions.	Input all offers and bids into the system. Contract processes match based on price priority and availability.	Matches do not exceed offered quantities; consumers receive no more than requested; multiple transactions appear correctly in the ledger; internal order book updates reflect new balances and removed/remaining orders.
T4	Error Handling & Edge Cases	Test unmatched bids, invalid prosumer offers exceeding available energy, and concurrency. Expected: Invalid orders rejected; unmatched bids kept pending; contract enforces meter-based validations (e.g., cannot sell more than meter-reported surplus).	Try posting an offer of 5 kWh when the meter shows only 3 kWh; simulate simultaneous submissions; submit bids with no matching offers.	Invalid offer rejected with no state change; unmatched bid remains pending; smart contract prevents overselling; system handles concurrent actions without data corruption or duplicate state changes.

Across all these tests, data logs and blockchain events are recorded. Each step is verified by inspecting the blockchain ledger state or the simulation's log output to ensure that every intended action occurred and no unintended actions occurred. The integrity of data is crucial, for instance, ensuring that if a trade happens, both parties' balances update accordingly, and the

same energy can't be sold twice. After running the above scenarios, the results indicated that the POC successfully handled P2P transactions when offers were matched with appropriate bids, the dynamic pricing logic applied correctly, and completed trades were immutably recorded.

This provides confidence that the system's transaction engine works as designed in a controlled environment, namely the combination of the user interface, the smart contract, and the data feeds.

4.2.2. Validation of Functional Requirements

Beyond individual transaction tests, it would be evaluated whether the POC meets all the functional requirements (FRs) defined in Section 3.2.2 and whether these FRs are validated in the POC. Table 3 summarises how each key functional requirement is addressed in the POC, using a hypothetical example scenario to contextualise the validation.

The scenario considers a microgrid community with three prosumers (P1, P2, P3) and two consumers (C1, C2). Prosumers have solar panels and occasionally export surplus energy, while consumers seek to buy cheaper local green energy. The platform is deployed on a private blockchain accessible to all participants. One afternoon, P1 and P2 have excess energy while C1 and C2 need energy. This scenario illustrates the fulfilment of requirements in the POC.

Table 3 - Functional Requirements Validation

FR - Title	Description	POC Validation
FR1. Participant registration and account management	Households register as prosumers or consumers, create blockchain accounts, authenticate, and submit initial facility data used for later validation.	**Test FR1-T1** Registration and role assignment: create P1, P2, P3 as prosumers and C1, C2 as consumers; expected: each is assigned the correct role and stored with a unique participant ID and wallet address. Evidence: UI screenshots + on-chain registry record. **Test FR1-T2** Authentication/authorisation: attempt platform access with an unregistered account; expected: access denied and no orders accepted. Evidence: rejected transaction/log entry. **Test FR1-T3** Facility data capture at onboarding: submit PV capacity, battery capacity, and max export/import limits during registration; expected: values persist and are retrievable by the validation module. Evidence: registry query output and storage record.
FR2. Processing facility and constraint data	Store participant asset and constraint data (PV, battery, limits, grid constraints) and use it to prevent infeasible bids/offers and overselling.	**Test FR2-T1** Constraint persistence and retrieval: query P1 constraints after registration; expected: exact match with input values. Evidence: query results. **Test FR2-T2** Oversell prevention using constraints: P1 declares a max export of 2 kWh for the interval and submits an offer for 3 kWh; expected: offer rejected with a clear reason code. Evidence: smart contract revert/error + UI message. **Test FR2-T3** Battery/SoC constraint: P2 has a battery SoC insufficient to cover a promised discharge; submits an offer exceeding the feasible supply; expected: rejected. Evidence: validation log.

FR3. Real-time order management	Participants submit bids/offers per interval; the engine matches by price/quantity; smart contracts confirm trades; prevent double sale; apply dynamic pricing margins anchored to a reference wholesale price.	**Test FR3-T1** Basic matching (the scenario): for one afternoon interval, P1 and P2 submit offers, C1 and C2 submit bids; expected: matching clears according to price priority and quantities, with trades created on-chain. Evidence: trade event logs and UI trade summary. **Test FR3-T2** Dynamic pricing anchored to reference: set day-ahead price X; P1 margin +m, C1 margin -n; expected: computed local trade price follows the rule and is consistent across UI and contract events. Evidence: Oracle input and computed price output. **Test FR3-T3** Double-sale prevention (ownership state): P1 submits an offer for the same kWh "slot" twice (or tries to sell already-settled energy); expected: second offer rejected due to already-committed energy state. Evidence: state snapshot before/after + rejection log. **Test FR3-T4** Concurrency/stress: submit N offers/bids within a short window (e.g., 50–100) to simulate parallel activity; expected: no duplicate matches, no inconsistent states, and completion within an acceptable time bound defined in the thesis. Evidence: timing measurements and invariant checks.
FR4. Dispatch and settlement	After matching, dispatch instructions are issued (or integrated with HEMS), delivery is verified via smart meter data, payment is settled on-chain, and a trade summary is produced for retailer/billing adjustment.	**Test FR4-T1** Dispatch instruction generation: after match, generate a dispatch instruction message per participant (e.g., export/import target); expected: instruction created and delivered to the HEMS adapter. Evidence: message payload and adapter log. **Test FR4-T2** Delivery verification: inject smart meter readings for the interval (export/import actuals) and compare to scheduled trades; expected: settlement allowed only if readings meet tolerance; otherwise, partial settlement or dispute path triggered (define policy). Evidence: verification report + contract decision. **Test FR4-T3** On-chain settlement: on successful verification, transfer tokens/credits and record settlement event; expected: balances updated correctly for P1/P2 and C1/C2. Evidence: balance diffs and settlement events. **Test FR4-T4** Retailer/billing summary: generate a structured summary (CSV/JSON) per trade and push to a retailer endpoint; expected**:** successful receipt with audit trail. Evidence: API call log and stored payload.
FR5. Reporting and user interface	Provide participant reports (quantities, prices, revenue/savings), plus performance/compliance reporting for operators/regulators; provide a usable web/mobile UI to configure preferences, monitor, and review history; ensure stable HEMS communications.	**Test FR5-T1** Participant trade history: after the scenario, each user views their history. expected: correct list of trades, quantities, unit prices, total revenue/savings. Evidence: UI screenshots and exported report. **Test FR5-T2** Preference configuration: C1 sets max price; expected: bids reflect preference constraints and matching respects them. Evidence: config record and bid parameters. **Test FR5-T3** Operator/regulator report generation: produce an aggregated report for the interval (total local energy traded, average price, number of trades, failure/reject reasons, audit hash); expected: report generated deterministically and traceable to on-chain events. Evidence: report file and event references. **Test FR5-T4** HEMS communication stability: simulate intermittent connectivity between the local gateway and the platform; expected: retries/backoff work, no silent data loss. Evidence: adapter logs.

The POC meets the functional requirements by implementing each as described above. Each requirement is linked to a concrete mechanism in the prototype and was verified using the

example scenario. All critical functionalities, from posting trades to executing and logging them, have been demonstrated, giving confidence that the system design is functionally sound.

4.2.3. Evaluation of Non-Functional Requirements

In addition to functionality, a robust platform must satisfy diverse non-functional requirements (NFRs) identified in Section 3.2.3. While a POC, by nature, is limited in scope, the tests or analyses were designed to check these aspects as much as possible in a small-scale environment. Table 4 summarises the key non-functional criteria and how the POC addresses or demonstrates them, with a hypothetical context for illustration.

Hypothetical context considers scaling the earlier scenario by imagining the community grows to 50 prosumers/consumers and examining how the system would behave. It also considers aspects such as security by design and simulating performance conditions, such as multiple transactions in a short period.

Table 4 - Non-Functional Requirements Assessment

Title	Description	POC Validation
NFR1. Security and compliance	Protect identities, orders, and meter readings from unauthorised access; ensure only authorised nodes can read/write; apply authentication and encryption; store data in a secure infrastructure.	**Test NFR1-T1** Permissioned access control: attempt to join the network or submit transactions from a non-whitelisted node/account; expected: rejected with an explicit reason. Evidence: node logs and rejected receipts. **Test NFR1-T2** Role-based authorisation: consumer attempts prosumer-only actions (example: submit offer); expected: denied. Evidence: contract revert reason. **Test NFR1-T3** Data minimisation baseline: verify that only required fields are stored on-chain (no unnecessary personal data); expected: stored payload matches schema. Evidence: on-chain event samples and schema.
NFR2. Scalability	Handle growth in participants and message volume without unacceptable performance degradation; pilot guideline: at least 10 concurrent users.	**Test NFR2-T1** Concurrency to 10 users: simulate at least 10 concurrent clients submitting bids/offers; expected: system remains responsive and completes matching without state inconsistencies. Evidence: throughput, p95 latency, and invariant checks. **Test NFR2-T2** Message volume stress: increase metering and order events (example: 5x baseline); expected: acceptable performance trend and no failures beyond defined thresholds. Evidence: performance charts and error rates.
NFR3. Availability	High availability; pilot target example: 99% uptime with maximum tolerable downtime of 1 day.	**Test NFR3-T1** Node failure tolerance: intentionally stop one non-validator node expected: service continues with degraded capacity but no data loss. Evidence: uptime monitor and successful trades during a fault. **Test NFR3-T2** Recovery time: restart the failed component. expected: automatic catch-up and regular operation restored. Evidence: logs and resync confirmation.
NFR4. Maintainability and upgradability	Support scheduled maintenance, hotfixes, and upgrades with minimal downtime; allow	**Test NFR4-T1** Smart contract upgrade procedure: perform a versioned contract upgrade or parameter update; expected: no corruption of state and limited/no downtime. Evidence: before/after state snapshot and upgrade log. **Test NFR4-T2** HEMS remote update: deploy an updated HEMS adapter/container;

	remote updates to HEMS software.	expected: reconnects automatically and continues dispatch/meter reporting. Evidence: deployment log and successful post-update trade cycle.
NFR5. Interoperability	Exchange data with external systems (market operator price feed, utilities, different API schema versions); support transitions from file-based to API-based transfers.	**Test NFR5-T1** Oracle feed integration: swap price feed source while keeping contract interface stable; expected: pricing remains correct, and the system continues to trade. Evidence: Oracle inputs and computed prices. **Test NFR5-T2** API versioning: send v1 and v2 message payloads to the same endpoint; expected: both accepted or v1 gracefully mapped to v2 with clear validation. Evidence: API logs and response codes.
NFR6. Auditability	Full traceability from initiation to settlement; detailed logs of actions; supports compliance and dispute resolution.	**Test NFR6-T1** Trace a trade end-to-end: for one trade, extract a chain of evidence (order submission → match → dispatch → meter verification → settlement); expected: every step is linked by IDs/hashes. Evidence: audit report with event references. **Test NFR6-T2** Dispute reconstruction: introduce a mismatch between expected and reported meter data; expected: system flags dispute/partial settlement per policy and records an auditable trail. Evidence: dispute log and on-chain decision events.
NFR7. Support and user experience	Provide support during business hours; log errors; meaningful feedback to users/support; reliable HEMS connectivity and low latency for control and monitoring.	**Test NFR7-T1** Error observability: force controlled failures (oracle unavailable, invalid payload, network timeout); expected: errors logged with correlation IDs and surfaced to the user/support with actionable messages. Evidence: central log extract and notifications. **Test NFR7-T2** HEMS connectivity and latency: inject intermittent connectivity and measure gateway-to-platform round-trip time; expected: retries/backoff and latency within a defined bound for monitoring. Evidence: adapter metrics and status changes report.

The POC, while limited, was used to gather evidence that the platform's design meets security, performance, and other quality attributes. Some tests, like measuring latency, were direct, while others were analytical or simulated, focusing on security and scaling. The findings indicate that the proposed architecture is sound across these dimensions, though further testing at scale is recommended to ensure full compliance in a production scenario.

4.3. Use Case

To make the platform's operation more concrete, this section presents a practical example of how a P2P energy trade would occur in real time on the POC platform. It means a typical interaction scenario between a prosumer and a consumer, highlighting each step from initiation to completion. Following the narrative, this includes a simplified flow diagram that visualises the process.

The scenario considers prosumer Alice, who has solar panels on her home and, on a sunny afternoon, has excess energy available. On the other side, Consumer Bob, Alice's neighbour, needs additional power to charge his electric vehicle and prefers to buy locally generated green energy if possible. Both are members of a community using our P2P trading platform. The current wholesale market price for that hour is, say, €0.10 per kWh. Alice is willing to sell her excess at a slight premium because it's green and local, and Bob is willing to pay a bit above market price because it's still cheaper than his utility's peak rate.

4.3.1. Step-by-Step Interaction

Step 1. Prosumer (Alice) Offers Energy - Using the platform's app, Alice checks her home energy management dashboard, which shows she has 4 kWh of surplus. She creates a sell offer for 4 kWh at €0.105/kWh, which is 5% above the market price of €0.10. She submits this offer to the blockchain marketplace. At this point, the smart contract records Alice's offer and associates it with her ID and asking price, as shown in Figure 7.

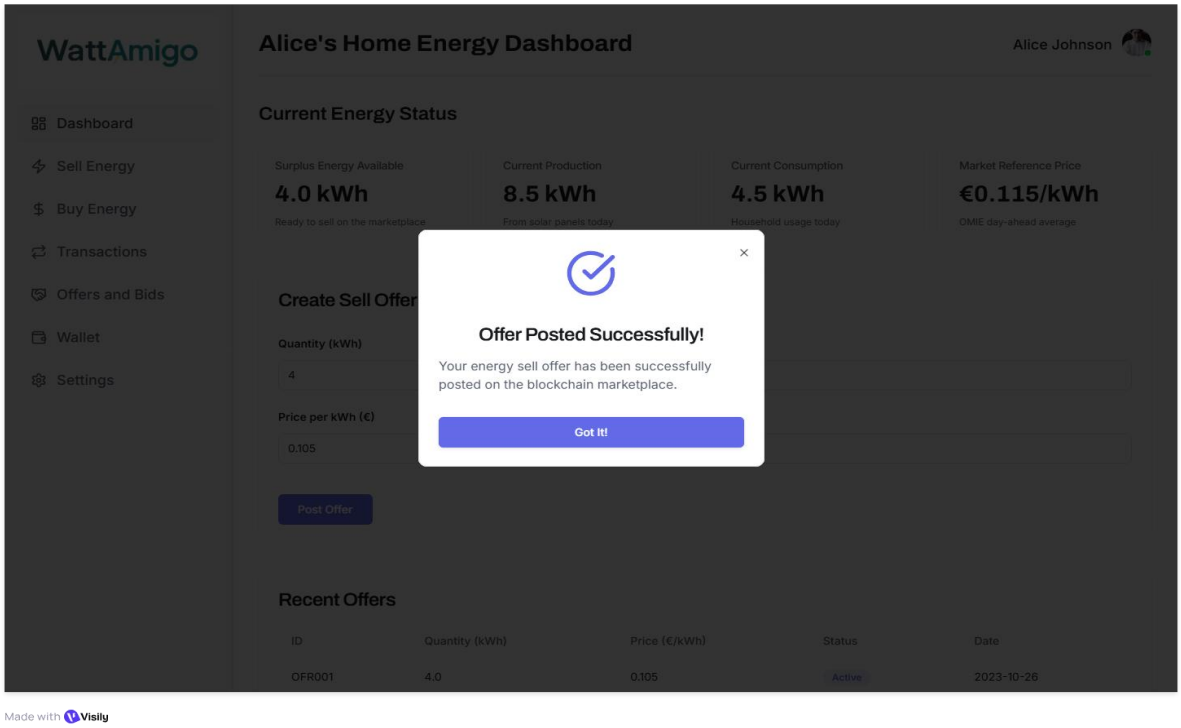


Figure 7 - User interface showing successful posting of a sell offer on the blockchain marketplace.

The interface confirms that a prosumer's energy sell offer has been submitted and recorded on the blockchain. The dashboard displays real-time household energy indicators, including surplus energy, production, consumption, and the market reference price, enabling users to make informed trading decisions.

Step2. Consumer (Bob) Places Bid - Bob, needing energy, opens his app and sees the current market reference price. The Figure 8 shows Bob's decision about paying up to 10% above market, so up to €0.110 for up to 3 kWh and input a buy bid accordingly. This bid is also recorded on-chain by the contract.

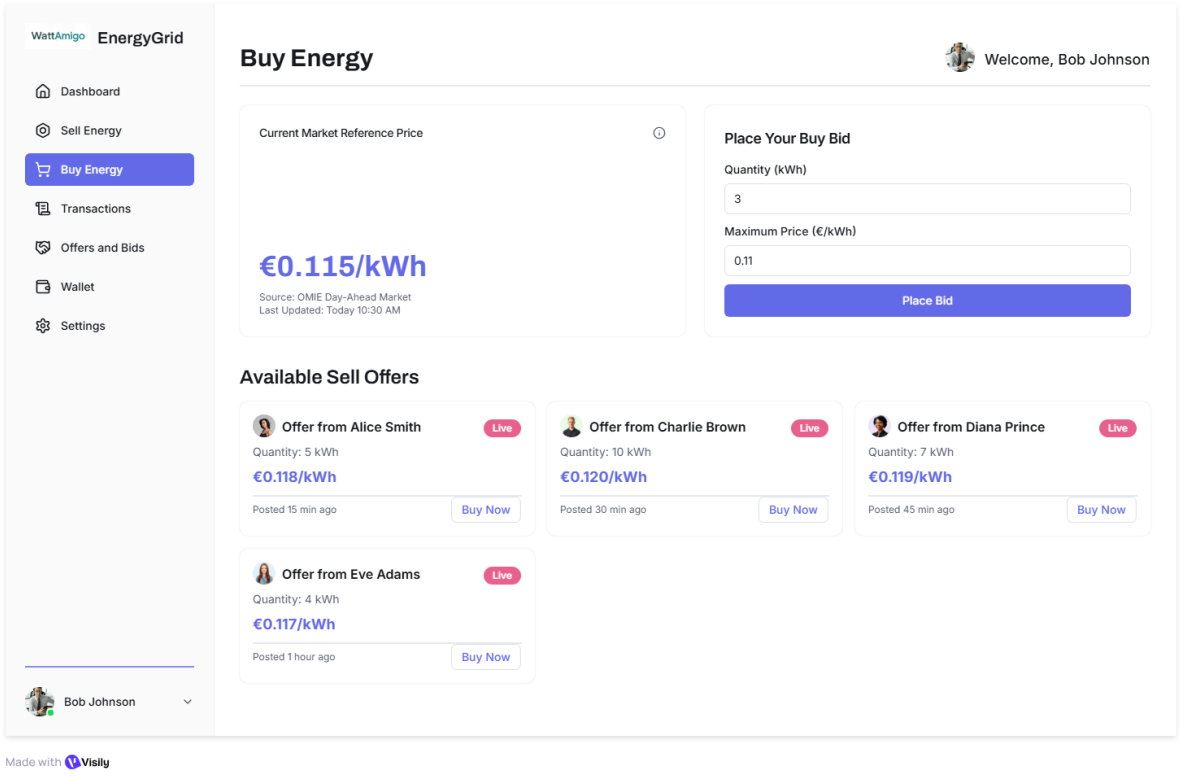


Figure 8 - User interface of the prototype displaying the Buy Energy page.

The interface shows the current day-ahead market reference price, user-defined buy bid parameters, and a list of active sell offers posted by prosumers. Each offer includes quantity, price, timestamp, and a direct purchase option, enabling transparent P2P trading.

Step 3. Automated Matching - Almost instantly, the smart contract's matching function runs. It compares Bob's bid with the list of offers. Alice's offer of €0.105 is within Bob's max of €0.110, and Alice has at least 3 kWh available. Thus, the contract matches, and Bob can buy 3 kWh from Alice at €0.105 each. The contract determines the trade and locks in the participants and price. If there were multiple offers, the contract would find the best-priced one meeting Bob's criteria, which here is Alice's.

Step 4. Smart Contract Validation - Before executing, the smart contract automatically verifies conditions. It checks that Alice still has 3 kWh uncommitted and Bob has sufficient balance or credit to pay for 3 kWh. All conditions are satisfied. If any check failed, the trade would abort here, but in this case, it proceeds.

Step 5. Trade Execution - The smart contract now executes the trade. It creates a transaction record on the blockchain that 3 kWh are transferred from Alice to Bob at the agreed price. It also triggers the payment settlement, a credit of €0.315 is transferred from Bob's account to Alice's account within the blockchain system.

Step 6. Physical Energy Transfer - In a real system, the physical grid would route approximately 3 kWh of energy from Alice's home to Bob's home over the next interval, considering they are on the same local network. On this POC, the physical step is simulated or assumed, but it is marked for completeness. Alice's meter later registers that 3 kWh was exported, and Bob's meter registers 3 kWh imported, which the platform can use for post-trade verification.

Step 7. Confirmation to Users - Both Alice and Bob receive a notification on the app that the trade is complete, as illustrated in Figure 9. Alice's offer now shows 1 kWh remaining since 3 of her 4 kWh were sold, and Bob's bid is fully satisfied with 3 kWh bought. The app displays a confirmation with details like "You sold 3 kWh to Bob at €0.105/kWh" for Alice, and "You bought 3 kWh from Alice, totalling €0.315" for Bob.

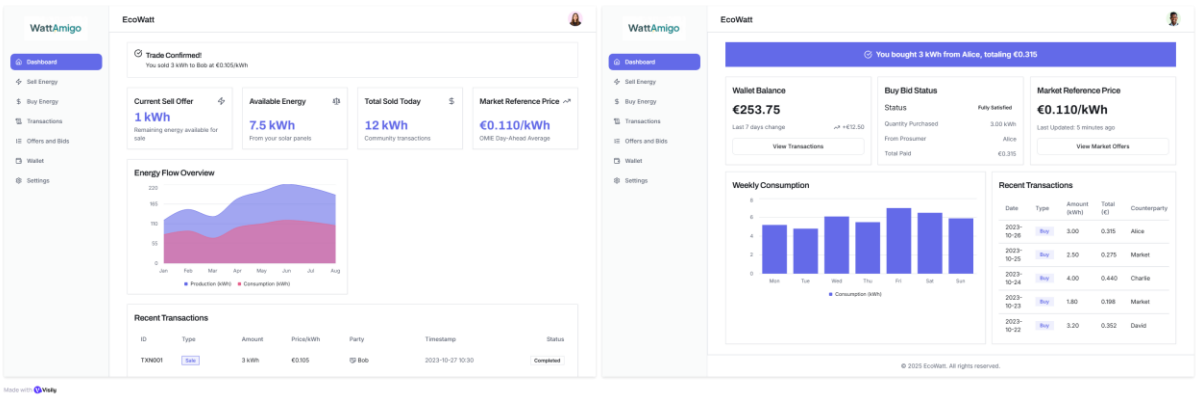


Figure 9 - Dashboard views of the prototype platform showing prosumer and consumer perspectives within the P2P energy trading system.

The left dashboard is for a prosumer, highlighting energy production, available surplus, the market reference price, and recent transactions. The right dashboard illustrates the consumer view, including wallet balance, bid status, weekly consumption trends, and completed purchases. Both interfaces provide real-time feedback on blockchain-registered transactions and energy flows.

Step 8. Post-Trade Updates - The platform updates its records. Alice's revenue account is credited with €0.315, and Bob's account is debited by the same amount. The smart meter data for the next reading cycle reflects the energy exchange. Alice's meter shows 3 kWh sent, and

Bob's shows 3 kWh received (Figure 10), and these can be cross-checked against the blockchain record for consistency.

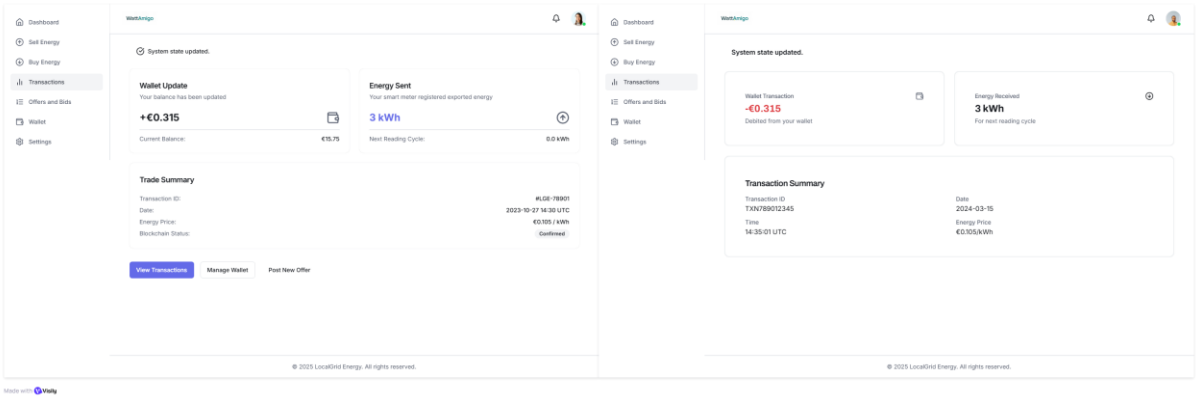


Figure 10 - Transaction update interfaces showing prosumer and consumer settlement outcomes in the P2P energy trading system.

This real-time example demonstrates how the components work in concert. Alice and Bob interacted only with the user interface, while the smart contract handled matchmaking and settlement behind the scenes. The entire process, from Bob placing the bid to getting confirmation, might take only a few seconds, showcasing the efficiency and automation of the system. There was no need for a middleman to approve or facilitate the transaction, and both parties have cryptographic proof of the trade (the blockchain record).

4.3.2. Interaction Flowchart

To visualise the above scenario, Figure 11 presents a flowchart of the interaction, which underscores the sequential logic of the platform's operation and how the smart contract automates what would traditionally be manual processes:

1. The flowchart starts with prosumer posts offer (stage 1) and Consumer posts bid (stage 2) as parallel initiations. Once both an offer and a compatible bid exist, it moves to Match offers and bids via Smart Contract. This decision node checks whether the criteria match.
2. If a match is found, the next step is validate trade conditions (stage 4), where the smart contract verifies meter data and balances.
3. Then execute the trade on the blockchain (stage 5), which includes recording the transaction and transferring the payment. In parallel, Energy is delivered physically.
4. Finally, notify participants & update records (stage 6) concludes the process.

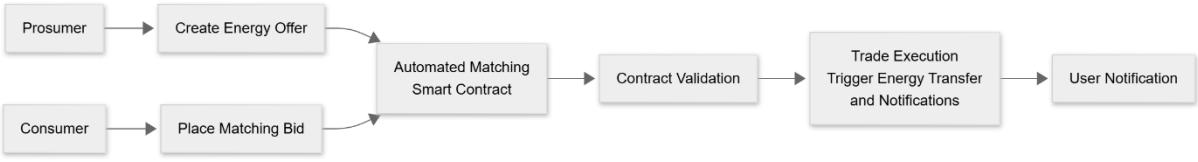


Figure 11 - Workflow of the automated P2P energy trading process implemented through the smart contract architecture.

The diagram illustrates the full lifecycle of a transaction, beginning with a prosumer creating an energy offer and a consumer placing a matching bid. An automated matching smart contract validates compatibility between offers and bids, executes the trade, triggers the energy transfer, and generates notifications for both parties.

Overall, this example and flowchart confirm how user interactions and system automation come together to realise a P2P energy trade. It provides a concrete picture of the user experience, intended to be simple and fast, and of the behind-the-scenes operations, reinforcing the viability of the proposed solution in a practical context.

4.4. Expected Results

In light of the design and tests described in the previous sections, this subsection outlines the expected outcomes of running the POC. These expected results act as success criteria, directly aligned with the project goals and the requirements defined in Chapter 3.

If the POC performs as intended, an improvement in process efficiency should be observable. One key expectation is that the platform demonstrates a highly efficient transaction process, with automation eliminating the need for manual intervention. The POC should show that once offers and bids are submitted, all other steps (matching, verification, settlement) occur automatically and near-instantaneously. This would confirm the promise that smart contracts can streamline energy trading, for instance, trades that might take hours or days to clear in traditional setups can be settled in seconds on-chain. It is expected to measure efficiency in terms of time per trade and the amount of human input required, ideally just the initial order entry.

A successful POC achieves end-to-end trade execution within a short time window and handles multiple trades in parallel without error. This efficiency ties directly to the project's hypothesis that blockchain and smart contracts can significantly speed up and simplify P2P energy transactions.

In terms of compliance with requirements and robustness, another expected result is that the POC meets all specified requirements, meaning each functional and non-functional requirement is either fully satisfied or at least demonstrably addressed in the prototype. For functional requirements, the POC should correctly handle core actions such as order management, price calculation, contract execution, and related functionality. For non-functional ones, the platform should operate securely and without breaches during testing, show

acceptable performance metrics, and integrate external data as needed. Essentially, this outcome is about validating the design assumptions, proving that the chosen architecture can deliver the capabilities it promised. For example, if a requirement were that the system must be interoperable with smart meters, the POC's success criteria would include incorporating meter data into a trade. It is also expected that the system remain stable and error-free under test conditions, without crashes, inconsistent ledger entries, or any invalid inputs, and with graceful handling of any invalid inputs. Meeting these expectations indicates that the POC is not just a theoretical exercise, but a working model that faithfully implements the intended features with reliability.

Lastly, the POC should provide preliminary evidence of the economic viability of the P2P trading concept for both prosumers and consumers. This means showing that transactions on the platform are transparent, which means that everyone can verify the outcomes, and potentially cost-effective. For prosumers, the POC should confirm they can earn a fair price for their energy through the platform, and for consumers, it should show they can purchase energy at competitive rates.

In summary, if the POC runs as designed, it confirms the feasibility of the proposed P2P energy trading framework by showing efficient automation, full compliance with design requirements and positive economic dynamics with transparency. These outcomes collectively validate that the concept can work in practice and is worth advancing to a larger pilot.

4.5. Limitations of the POC

While the POC provides valuable insights into the potential of the blockchain-based energy sharing framework, it is essential to acknowledge its limitations and recognise that, as a constrained prototype, it cannot capture the full complexity of a real-world deployment. These limitations span technical, economic, and scalability dimensions and indicate where further development and experimentation are required.

From a technical perspective, the POC operates in a simplified environment, relying on a small number of nodes to emulate the blockchain network and using smart contracts that encode only the core trading logic. Essential aspects such as advanced consensus configurations, Byzantine fault tolerance, node churn, and network latency variability were not systematically explored. Smart meter readings and market prices were simulated or injected through test APIs, rather than obtained from physical devices or live market operator interfaces. As a result, the

POC does not fully address issues such as unreliable connectivity, clock synchronisation, noisy metering data, or cybersecurity threats that would arise in a production-grade system.

The interoperability layer is likewise simplified. Although the prototype demonstrates that HEMS-like components can ingest meter and price data and relay it to the blockchain, it does so using predefined data formats and a limited set of integration points. Real deployments would need to support heterogeneous meter technologies, multiple communication protocols, evolving API schemas, and robust error handling. Integration with existing billing systems, distribution system operator (DSO) platforms, and regulatory reporting mechanisms remains out of scope for the POC.

From an economic and behavioural standpoint, the POC focuses on validating the feasibility of P2P transactions and the dynamic pricing logic, rather than quantifying long-term financial benefits or modelling participant behaviour. The test scenarios consider a small number of prosumers and consumers and assume rational, cooperative actors. The prototype does not include detailed tariffs, grid fees, or congestion costs, nor does it simulate strategic bidding, demand response saturation, or rebound effects. Consequently, the POC cannot be used to draw definitive conclusions about the economic efficiency or long-term adoption dynamics of the proposed market design.

Regulatory and legal aspects also constitute a significant limitation. The framework is conceptually aligned with emerging community energy and P2P trading models, but the POC does not implement jurisdiction-specific rules for Portugal or the European Union, such as licensing requirements, consumer protection obligations, taxation, or data protection under the General Data Protection Regulation (GDPR). The permissioned blockchain design and the platform operator's role are defined at a conceptual level. Still, the governance processes for onboarding participants, resolving disputes, and enforcing compliance are not fully operationalised in the prototype.

Finally, the evaluation of non-functional requirements is constrained by the scale and context of the tests. Performance and scalability assessments were conducted in a laboratory setting with a limited number of concurrent users and transactions, so the results cannot be directly extrapolated to communities with hundreds or thousands of participants. Security and privacy were primarily addressed through design choices, such as a permissioned network and basic access controls, but were not subjected to formal threat modelling or penetration testing. User experience and acceptance were inferred from the dashboards' and workflows' designs, rather than validated through structured user studies.

These limitations do not undermine the value of the POC as a proof of feasibility, but they highlight that further work is required before the framework can be deployed in real communities. They also inform the future research directions discussed in Chapter 5, where technical, economic, and regulatory extensions to the current prototype are proposed.

4.6. Perception-based evaluation with end-users

The goal of the survey is to obtain initial feedback from potential end-users on perceived usefulness, clarity and acceptance of the proposed P2P energy sharing platform and its pricing concept

4.6.1. Instrument and procedure

The perception-based evaluation was conducted through an online questionnaire implemented in Microsoft Forms. After a short description of the platform concept, respondents were asked to answer a set of closed and open questions.

The questionnaire comprised demographic and contextual items (Q1–Q4), followed by a series of Likert-scale statements and open questions. The Likert items (five-point scale from "strongly disagree" to "strongly agree") were designed to capture four main constructs:

1. Perceived usefulness (Q5 and Q6).
2. Clarity of the concept and pricing mechanism (Q7 and Q8).
3. Trust in the platform and underlying records (Q9 and Q10).
4. Willingness to use the solution either as a consumer or as a prosumer (Q11 and Q12).
5. Perceived barriers and concerns (Q13 and Q15).
6. Perceived strengths of the concept (Q14).

In this way, the questionnaire provides initial evidence on the usefulness, clarity, trust, and acceptance of the proposed framework from an end-user perspective.

The complete questionnaire, including the exact wording of questions Q1–Q15, is provided in Annexe 1.

4.6.2. Sample description

Thirty participants answered the online questionnaire. Most respondents were between 18 and 44 years old, with 40% in the 18–24 group, 37% in the 25–34 group, 13% in the 35–44 group, and the remaining 10% above 44 years.

Regarding their housing and energy profile, 57% reported living in apartments without rooftop solar, 27% in houses without rooftop solar, and 16% in houses with rooftop solar (half of these identifying as self-consumption prosumers). This means that only a minority currently

experience the prosumer role directly, but several respondents indicated interest in installing solar in the future in the open questions.

Familiarity with electricity tariffs and billing was moderate: on a five-point scale (1 = not at all familiar, 5 = extremely familiar), the average rating was 3.1. This suggests that participants have some awareness of how tariffs work but are far from expert users of energy pricing schemes, consistent with the idea that P2P and community-energy platforms are still not widely known to the public.

The sample was a convenience sample, recruited through personal contacts, social media and university mailing lists, and is therefore not statistically representative, so the results should be interpreted as exploratory.

4.6.3. Main results

For the Likert-scale items, respondents showed generally positive perceptions of the proposed solution. Table 5 summarises the main constructs.

Table 5 - Likert-scale questions result

Question (construct)	*Mean (1–5)*	*% agreeing (4–5)*
Q5 – Platform helps the better use of local solar (usefulness)	4.3	83%
Q6 – Financially beneficial for both sides (usefulness)	4.1	77%
Q7 – Understand the basic idea of the platform (clarity)	4.0	73%
Q8 – Pricing rule easy to understand (clarity)	3.8	67%
Q9 – Pricing feels fair for both sides (trust)	3.9	70%
Q10 – Ledger records increase trust (trust)	3.9	70%
Q11 – Would use as consumer (willingness to use)	4.2	80%
Q12 – Would use as prosumer to sell surplus (willingness)	4.4	87%

This indicates that participants find the concept useful and are generally willing to adopt it, with clarity and trust slightly lower but still clearly positive.

For the multiple-choice question on barriers (Q13), the results are presented in Table 6:

Table 6 - Multiple-choice questions results

Options	**Percentage of respondents**
Lack of clear information about savings and benefits	70%
Difficulty in understanding how prices are set	53%
Lack of trust in the technology or in the operator	40%
Low interest in managing energy actively	23%
Regulatory or legal complexity	20%

Several respondents also used the “other” option to indicate that they had never heard of P2P energy sharing or were unsure how such a platform would integrate with their current contracts.

The analysis of the open-ended questions (Q14–Q15) reinforces the patterns observed in the closed items. On the strengths side, respondents frequently highlighted the potential to better use rooftop solar and other renewable investments at the household level, rather than "giving surplus away cheaply" to the grid. Several participants stated that "if I invest in solar panels, I would rather sell the extra energy to my neighbours than almost for free to the supplier", emphasising the potential to retain more of the value created by their own equipment. There was also an evident appreciation for local, community-based solutions and for the prospect of reducing dependence on large electricity retailers, as one respondent put it, "it is positive that the money stays in the community instead of going entirely to big companies". In addition, many participants perceived the proposed pricing rule as intuitively fair, precisely because it guarantees that prosumers receive more than the wholesale price while consumers pay less than the standard retail tariff. This was reflected in comments such as "it seems fair that both sides win: the producer gets a better price, the consumer pays less, and the community benefits."

On the concern side, the main themes are complexity, trust, and regulation. Some respondents expressed doubts about their ability to interpret all the figures presented by the platform without clear explanations of the expected savings, noting, for example, that "I am not sure I would understand all the numbers without a simple summary of what I am saving." Others raised questions about who would operate the platform, how reliable it would be in practice and what mechanisms would exist to deal with errors or disputes, with comments such as "I like the concept, but I would want guarantees that this is legal and that my contract and billing don't become a mess." A further set of concerns centred explicitly on regulatory aspects, namely, whether this type of trading is permitted under current rules and how it would appear on the electricity bill. Taken together, these qualitative insights suggest a combination of high perceived usefulness and willingness to adopt the concept, coupled with a cautious attitude that underscores the need for simple explanations and transparent information about savings, risks and responsibilities.

4.6.4. Discussion and limitations

Overall, the survey suggests that the proposed framework is perceived as both valuable and acceptable by potential end-users, even though most respondents had limited prior familiarity with P2P energy sharing. Average ratings above 4.0 for usefulness and willingness to use indicate that participants recognise value in using a community platform to monetise surplus solar production and access cheaper local energy, which supports the plausibility of the proposed architecture and pricing methodology from a user perspective. Clarity and trust achieved slightly lower, but still positive, scores, consistent with the novelty of the concept and

the fact that respondents interacted only with a short explanation and screenshots, rather than a live system.

The barriers and open comments point to an apparent tension. On the one hand, participants are interested in getting more out of investments in rooftop solar and in local renewable generation. On the other hand, they are unsure about how exactly prices and savings would be calculated, who would operate the platform, and how it would fit within existing contracts and regulations. These concerns align with the technical and regulatory limitations discussed in previous sections, the need for stronger integration with DSO and retailer processes, clear communication about risks and benefits, and supportive regulatory frameworks for community energy and P2P trading.

The survey has important limitations. The sample is small, convenience-sampled, and consists mainly of young adults with an interest in technology and sustainability. It is not representative of the broader population of electricity consumers or prosumers. Participants reacted to a conceptual description, not to a fully deployed platform, so the survey captures perceptions and intentions rather than observed behaviour. Despite these constraints, the results provide an initial indication that the proposed framework and pricing strategy are understandable, attractive and potentially viable for end-users, while highlighting concrete areas where user education, interface design and regulatory clarity is critical in any real-world pilot.

4.7. Conclusion of the Chapter

In conclusion, the POC implementation has successfully demonstrated the fundamental capabilities of the proposed blockchain-based P2P energy-sharing platform while also highlighting areas for improvement. The POC confirmed several strengths of the architectural design, as the use of blockchain and smart contracts enabled secure, transparent, and automated energy trades among community members, the integration of smart meter data proved feasible, and the overall governance model showed that trading rules and roles can be encoded and enforced consistently. In parallel, a perception-based evaluation indicated that the concept is generally seen as useful and attractive, providing an initial user-centred complement to the technical assessment.

Notably, key functionalities, including P2P transaction execution, dynamic pricing, and automatic settlement, were tested and validated. For example, the platform matched offers and bids in real time and executed trades without manual intervention, underscoring the strength of

the decentralised market design. These tested features align with the project's objectives and suggest that the framework can deliver benefits like increased efficiency and prosumer empowerment in energy markets. Survey respondents also recognised these potential benefits, frequently highlighting the possibility of obtaining better value from rooftop solar investments and keeping more of the economic gains within the local community.

The POC also highlighted the robustness of the governance approach. By embedding trading rules and participant rights into the smart contract logic, the system ensured fairness and compliance, as no trades happened outside the agreed rules and participants' actions were limited to what the protocol allowed. This shows that a trustless, community-driven governance model is viable, and that the platform can function and self-regulate through transparent algorithms and consensus, rather than needing a single authority to oversee transactions. The survey results are consistent with this picture: participants generally perceived the pricing rule as fair, as it guarantees that prosumers receive more than the wholesale price while consumers pay less than the standard tariff, even if some respondents expressed a desire for very clear explanations of savings and responsibilities.

Additionally, the results demonstrated compliance with critical requirements such as security, since transactions were secure and tamper-proof, and interoperability, as external data sources like price feeds were successfully used, reinforcing that the architecture's holistic design was well established. At the same time, both the POC and the survey revealed areas for future improvement, including the need for greater scalability, more rigorous privacy safeguards, adaptation to various grid conditions, and more transparent communication about expected benefits, platform governance, and regulatory treatment. For instance, to move from POC to a live pilot, the platform would need to handle more users, interface with existing utility infrastructure for tasks like invoicing or grid safety checks, and provide simple, transparent information so that non-technical users can understand prices and savings.

In this dissertation, the POC serves as a foundation and learning tool, and the survey provides a first indication that the proposed solution is not only feasible but also perceived as promising by potential users, albeit with understandable caution. The insights from both the technical implementation and the perception-based evaluation informs a more advanced prototype or pilot deployment, as the positive results so far justify a pilot while also signalling where additional design and communication efforts are required.

In summary, Chapter 4 has shown that the proposed framework is not only theoretically sound but also practically achievable on a small scale and positively received in an exploratory user evaluation. The lessons learned here guides the journey from this POC to a full-fledged

implementation, driving forward the vision of decentralised, community-driven energy markets and possibly linking them with other sustainable initiatives, such as carbon trading, thereby contributing to the broader goals of the green economy and energy transition.

CHAPTER 5

Conclusion

This dissertation set out to explore how blockchain technology can support secure, transparent, and economically fair P2P energy sharing in microgeneration communities. In a context marked by increasing renewable penetration, under-compensated prosumers, and centralised market structures, the central premise was that a blockchain-enabled architecture could empower local actors to trade surplus energy directly while maintaining compatibility with existing grid and retail arrangements.

Three main objectives guided the research:

Objective 1: Analyse the current state of research and practice in blockchain-enabled P2P energy sharing, with particular attention to technological trends, implementation challenges, and real-world use cases.

Objective 2: Identify the functional and non-functional requirements necessary for the development of decentralised energy sharing systems in small-scale or community-based environments, and derive an appropriate system architecture.

Objective 3: Design and implement a blockchain-based framework for secure, transparent, and decentralised P2P energy sharing tailored to microgeneration communities, and validate it through a POC implementation and a user-end survey.

5.1. Achievement of Research Objectives

5.1.1. Objective 1 – State of the art and practice

This objective was achieved through a PRISMA-based systematic literature review, complemented by analyses of real-world initiatives such as Brooklyn Microgrid, Quartierstrom, and Portuguese community energy projects, including EDP's "Bairro Solar". The review identified key technological building blocks, including permissioned and public blockchains, smart contracts, energy tokens, and IoT integration, as well as recurring challenges related to scalability, governance, privacy, and regulatory alignment. Real-world cases illustrated different governance models, for instance, utility-led, platform-led, and community-governed and incentive schemes (fixed discounts vs market-based pricing). These findings provided a comprehensive and up-to-date understanding of the landscape and highlighted the gap for frameworks that combine community-oriented governance, dynamic pricing anchored in wholesale markets, and explicit treatment of microgeneration communities.

5.1.2. Objective 2 – Requirements and architecture

Building on the literature review and case analysis, the dissertation derived a detailed set of functional requirements (participant registration, offer and bid management, dynamic pricing, automated settlement and reporting) and non-functional requirements (security, scalability, interoperability, auditability, usability). These were systematically documented and then mapped to a layered architecture comprising a physical layer (smart meters and distributed energy resources), a data/control layer (Home Energy Management System and IoT components), and a blockchain layer (permissioned ledger, smart contracts, and oracles). The architecture embeds a market design where P2P transaction prices are anchored to the day-ahead wholesale price, with user-defined margins enabling "win-win" outcomes for prosumers and consumers. The requirements and architecture together fulfil Objective 2 by providing a coherent, justified blueprint for a decentralised P2P energy trading system tailored explicitly to microgeneration communities.

5.1.3. Objective 3 – Framework design and POC validation

The third objective was addressed through the design and implementation of a POC that instantiates the proposed architecture on a permissioned blockchain. The POC includes smart contracts that implement order matching and settlement, a simplified HEMS-like interface for prosumers and consumers, and simulated integrations with smart meter and market price data sources. A structured test plan validated core transaction flows and edge cases, including basic P2P trade execution, dynamic pricing based on margins over the day-ahead price, prevention of overselling, and the creation of immutable audit trails for each transaction. The POC was further evaluated against the previously defined functional and non-functional requirements, showing that the framework can support secure, low-latency automated trades for a small community under controlled conditions.

Beyond the analytical and scenario-based evaluation, the end-user survey with 30 participants provided initial evidence that the concept is perceived as useful and broadly understandable. Participants tended to agree that the platform could help households make better use of local solar generation and that the pricing rule, anchored to the day-ahead wholesale price with user-defined margins, is fair for both prosumers and consumers. At the same time, the survey highlighted concerns about the clarity of the information on savings, the perceived effort required to configure and manage offers and bids, trust in whoever operates the platform, and the legal and contractual implications of such trades. This perception-based evaluation, therefore, complements the technical assessment by confirming the plausibility and

attractiveness of the framework from a user perspective, while signalling concrete areas where additional explanation, usability work, and transparency in governance is needed.

Although the POC does not represent a full-scale deployment, it provides concrete evidence that the proposed framework is technically and conceptually viable and that the DSRM-driven design successfully translates high-level goals into an operational system. Accordingly, Objective 3 can be considered achieved within the scoped limitations of the prototype.

5.2. Main Contributions

The dissertation makes several contributions at conceptual, technical, and practical levels:

1. Conceptual contribution: It articulates a blockchain-based P2P energy-sharing framework explicitly designed for microgeneration communities, combining dynamic pricing anchored in wholesale markets, local trading, and community-oriented governance.
2. Methodological contribution: It applies a PRISMA-based review and the Design Science Research Methodology in an integrated manner, connecting systematic evidence from the literature with the iterative design, implementation, and evaluation of an artefact.
3. Technical contribution: It proposes and instantiates a layered architecture that integrates smart meters, a HEMS-like control layer, permissioned blockchain infrastructure, smart contracts, and oracles to support end-to-end P2P trading.
4. Practical contribution: Through the POC and the Alice–Bob use case, it demonstrates how prosumers and consumers can interact with the system via intuitive dashboards while complex blockchain logic executes in the background, providing a tangible blueprint for future pilots in real communities.
5. Empirical contribution: It conducts an exploratory end-user survey that provides initial evidence on perceived usefulness, clarity, trust and willingness to adopt such a platform, offering a first indication of market receptiveness to this type of solution and highlighting perceived barriers that need to be addressed in real-world deployments.

Collectively, these contributions address the identified gap in the literature and practice by moving beyond conceptual proposals and presenting an operational framework that can be further extended and deployed.

5.3. Limitations Revisited

As discussed in Section 4.5, the work is subject to important limitations. The POC relies on simulated smart meter and price data, runs on a small-scale permissioned blockchain, and focuses on validating core trading logic rather than long-term economic performance or user behaviour. It does not fully address regulatory compliance, tariff design, or integration with distribution system operators and retail billing systems. Security and privacy are considered by design but not exhaustively tested through formal threat modelling or penetration testing, and user acceptance is inferred rather than empirically evaluated.

Recognising these limitations is essential to interpreting the results, the POC confirms the feasibility and coherence of the proposed framework, but it does not claim to resolve all technical, economic, or regulatory challenges associated with real-world P2P energy markets.

5.4. Future Work

The limitations identified in this dissertation naturally point to several promising avenues for future research and development:

1. The small-scale survey conducted in this dissertation should be extended in future work with larger, more diverse samples, ideally involving members of existing or planned energy communities and professionals from utilities, aggregators, and regulators. Such studies would allow a more robust assessment of user acceptance, trust and understanding, and would help refine both the market design and the implementation of the proposed framework in real-world settings.
2. Real-world pilots and field trials - Future work should implement the framework in one or more real microgeneration communities, integrating live smart meter data, actual day-ahead prices, and real prosumer and consumer behaviour. Such pilots would enable a more robust evaluation of system performance, user acceptance, and operational reliability under realistic conditions.
3. Advanced market design and economic evaluation - The current dynamic pricing model can be extended with more sophisticated mechanisms, such as time-of-use tariffs, congestion pricing, locational signals, and incentive schemes for flexibility and storage. Agent-based simulations and techno-economic analyses could quantify the long-term impact of P2P trading on prosumer revenues, consumer costs, grid utilisation, and investment decisions.

4. Regulatory alignment and governance models - Further research is needed to align the framework with evolving regulatory regimes for energy communities and P2P trading in Portugal and the European Union. This includes defining the roles and responsibilities of the platform operator, community cooperatives, and DSOs; designing compliant settlement and billing interfaces; and exploring community-governed models in which participants can collectively decide on rules encoded in smart contracts.
5. Security, privacy, and data protection - A more exhaustive treatment of security and confidentiality is required, including formal threat modelling, penetration testing, and evaluation of privacy-preserving techniques (e.g., pseudonymisation, zero-knowledge proofs, permission scopes). Ensuring compliance with GDPR and sector-specific regulations is essential, particularly when handling granular consumption data and financial transactions.
6. Scalability and performance optimisation - Future experiments should stress-test the system with larger communities and higher transaction volumes, assessing different consensus mechanisms, network topologies, and off-chain or layer-2 approaches to improve throughput and latency. This would help determine how the framework behaves as it scales from small pilots to city-scale or regional deployments.
7. User experience and socio-technical acceptance - Structured user studies involving households, energy cooperatives, and utilities could refine the design of dashboards, notifications, and configuration options, and measure trust, perceived fairness, and willingness to participate. Understanding socio-technical factors is crucial for the long-term success of P2P energy trading initiatives.

5.5. Final Remarks

In summary, this dissertation demonstrates that a blockchain-based P2P energy sharing framework for microgeneration communities is both conceptually compelling and technically feasible. By combining systematic evidence from the literature with a DSRM-guided design, a working POC and a user-end evaluation, it shows how prosumers and consumers can be placed at the centre of local energy markets while maintaining transparency, trust, and compatibility with existing infrastructures. The work is a step towards more democratic, resilient, and sustainable energy systems and provides a concrete foundation for future research, pilots, and policy discussions on community-driven energy transitions.

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Blockchain-based framework for peer-to-peer energy sharing in microgeneration communities

Thank you for participating in this short survey.

You will be presented with a brief description and screenshots of a community platform that allows neighbours in a microgeneration community to trade electricity directly with each other. In this platform, prices for peer-to-peer trades are linked to the day-ahead wholesale market price. Prosumers (households with solar) can set a minimum uplift over that wholesale price, and consumers can set a maximum discount compared with their usual retail tariff. When there is a match, the trade price is set between those two preferences, so that prosumers receive more than wholesale and consumers pay less than the normal tariff.
This survey aims to collect your opinion about how useful, clear and acceptable this concept seems to you.
It takes about 5–7 minutes.

1. Age group

- ◯ 18–24
- ◯ 25–34
- ◯ 35–44
- ◯ 45–54
- ◯ 55–64
- ◯ 65 or older
- ◯ Prefer not to say

2. Country of residence

3. Living situation / energy profile

- ◯ I live in an apartment without rooftop solar
- ◯ I live in a house without rooftop so
- ◯ I live in a house/apartment with rooftop solar, but I am not a self-consumption prosumer
- ◯ I live in a house/apartment with rooftop solar and I am a self-consumption prosumer
- ◯ Other / do not know

4. How familiar are you with how your electricity tariff and monthly bill are calculated?

1	2	3	4	5

Not at all familiar — Extremely familiar

5. This kind of platform could help households make better use of local solar energy in their community.

1	2	3	4	5

Strongly disagree — Strongly agree

6. Being able to buy and sell energy directly with neighbours at prices between wholesale and retail seems financially beneficial for both sides.

1	2	3	4	5

Strongly disagree — Strongly agree

7. From the description, I understand the basic idea of how the platform works.

1	2	3	4	5

Strongly disagree — Strongly agree

8. The way prices are determined (using the wholesale price plus or minus user-defined margins) is easy to understand.

1	2	3	4	5

Strongly disagree — Strongly agree

9. I would trust this pricing mechanism to produce fair outcomes for both prosumers and consumers in the community.

1	2	3	4	5

Strongly disagree — Strongly agree

10. Knowing that trades are recorded on a tamper-resistant digital ledger makes me more likely to trust the platform.

1	2	3	4	5

Strongly disagree — Strongly agree

11. If this platform were available in my area, I would be interested in using it to buy electricity from local prosumers.

1	2	3	4	5

Strongly disagree Strongly agree

12. If I had rooftop solar (or if I already have it), I would be interested in using this platform to sell surplus energy to neighbours.

1	2	3	4	5

Strongly disagree Strongly agree

13. What do you see as the main barriers for people to adopt this kind of platform? (Select all that apply.)

- ◯ Lack of clear information about savings and benefits
- ◯ Lack of trust in the technology or in the operator
- ◯ Regulatory or legal complexity
- ◯ Difficulty in understanding how prices are set
- ◯ Fear of extra risks or responsibilities for prosumers
- ◯ Low interest in managing energy actively
- ◯ Outro

14. In your opinion, what is the most interesting or positive aspect of this concept of peer-to-peer energy sharing in a local community?

15. What concerns, doubts or suggestions do you have about this kind of platform or pricing model?

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