

Scalability of peer-to-peer energy trading markets: A case-based approach

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Declaration

I, Anna Gorbacheva, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

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Abstract

The uptake of decentralised energy resources (DER), such as small-scale solar photovoltaic systems, is transforming traditionally passive energy consumers into local electricity producers, with currently no incentive to actively engage in energy markets. In response, peer-to-peer (P2P) energy trading has been proposed as a mechanism to incentivise trading of energy and other ancillary services locally. Although first pilot projects are already underway, existing policies and regulations impose limitations on testing scalability and adoption of these market models, reducing their informative value.

This research aims to understand how P2P energy trading systems can scale beyond the pilot stage while delivering social, technical and economic value. The exploration of scaling constraints is rooted in the contextuality of specific cases using deterministic modelling to explore how scaling interacts with the case's context and objectives. A combination of empirical case-study data and model sensitivity analysis is applied to explore different market configurations and derive insights for scalable P2P energy trading system design.

Detailed assessments were made of case studies in Colombia and the UK, both of which aimed to deliver social benefits to disadvantaged communities and increase access to DER. While the results of each simulation were heavily influenced by the local context of each pilot project, both cases revealed common socio-technical challenges in implementing scalable markets without regulatory exemptions. This research identifies a critical trade-off between individual and community benefits in P2P energy markets, finding that market designs often prioritise collective welfare over individual optimisation. In addition, the findings highlight that tariff structures play a key role in determining both the distribution of benefits and the economic viability of P2P systems. The equitable distribution of benefits among participants was also found to depend significantly on factors such as load and household characteristics.

Finally, this research highlights the importance of modelling and simulation to address future challenges and limitations of P2P energy trading systems beyond pilot projects. Accurate analysis

of the markets under scaling effects is necessary to enable future uptake of P2P energy trading markets.

Impact Statement

This thesis explores the scalability of peer-to-peer energy trading systems, with a focus on how these emerging business models can move beyond pilot projects to generate social, technical and economic impacts. Initial regulatory efforts to define peer-to-peer energy trading systems have begun in the EU, although more work is needed to fully integrate these models into the existing energy market landscape. There are also early adopters outside the EU, including in regions such as the Global South. The research combines case studies from Colombia and the UK, using a deterministic modelling approach to assess barriers to scaling up in different contexts. The findings of this research are relevant to a wide range of stakeholders, both within and outside academia.

Within the academic environment, this research contributes to the growing body of knowledge on peer-to-peer energy trading. By applying the scalability analysis framework to the field of peer-to-peer energy trading, a template has been developed that can be used in future research to focus more closely on how pilot projects can be scaled up. The findings from the case studies provide valuable context, moving beyond the highly theoretical focus on market mechanisms to provide practical insights into how these mechanisms affect the distribution of benefits within a community, making the research both relevant and applicable to real-world scenarios. In addition, where possible, the data and code have been made publicly available to facilitate replication and validation, and to provide a basis for future analysis.

The findings of this research provide insights for non-academic stakeholders who are active in this field or considering entering it. The research, particularly through the two case studies, highlights how context-specific these types of local energy markets are, as they need to be tailored to the specific needs of individual participants. It also provides valuable insights into how different tariff structures and market design choices affect the performance of peer-to-peer markets in different contexts. The former insights are particularly valuable for policymakers and regulators in designing supportive regulatory frameworks for decentralised markets, while the latter are crucial for stakeholders such

as start-ups and community groups involved in planning and implementing these projects.

The results of this work were shared through conference participation, where posters and presentations were given. Insights into market design and local energy market modelling were presented to industry experts during a two-day masterclass. Specific results from the two case studies were also presented and discussed with representatives from the pilot projects. Future efforts could include working with industry partners and policymakers to discuss scalable system designs, as well as broader outreach through social media and blog posts. These activities would help to disseminate the research findings more widely and contribute to the public discourse on the future of energy systems.

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List of Abbreviations

BSC	Balancing and settlement code
CEC	Citizen energy community
CEP	Clean energy for all Europeans package
CSC	Collective self-consumption
CREG	Colombian Energy and Gas Regulatory Commission
DER	Distributed energy resource
DLT	Distributed ledger technology
DSO	Distribution system operator
EI	Equality index
EU	European Union
EVs	Electric vehicle
FiT	Feed-in-tariff
GO-P2P	Global observatory on P2P energy trading
ICT	Information and communication technology
IEA	International Energy Agency
KPI	Key performance indicator
kWh	Kilowatt hour
kWp	Kilowatt peak
LEC	Local energy community
LEM	Local energy market
MCP	Market clearing price
MLP	Multi-level perspective
NPV	Net present value
P2P	Peer-to-peer
PoA	Plane-of-array
PPA	Power purchase agreement

PV	Photovoltaic
REC	Renewable energy community
RES	Renewable energy systems
TE	Transactive energy
TSO	Transmission system operator
REDII	Renewable Energy Directive II
SEG	Smart export guarantee
SC	Self-consumption
SS	Self-sufficiency
SNM	Strategic niche management
SRA	Scalability replicability analysis
UK	United Kingdom
VPP	Virtual power plant
WHO	World Health Organization

Chapter 1

Introduction

1.1 Changing energy system landscape

Countries globally are facing the challenge of reducing their CO₂ emissions to mitigate the effects of climate change. A decisive breakthrough in this respect was the signing of the Paris Climate Agreement in 2015, whereby participating countries agreed to limit the global average temperature rise to well below 2°C above pre-industrial levels (UNFCCC, 2015). In response, many national governments and state authorities have set ambitious carbon reduction targets. For instance, the European Union (EU) has set the goal of reducing its emissions by at least 55% below 1990 levels by 2030 and achieving carbon neutrality by 2050 (European Commission, 2019). In the United Kingdom (UK), the government has committed to reduce the country's carbon emissions by 78% by 2035 and become carbon-neutral by the second half of this century (BEIS, 2023).

Despite these commitments, the global economy's dependence on fossil fuels persists, contributing to ongoing carbon emissions. Currently, over 63% of the world's electricity generation is still derived from fossil fuels (EMBER, 2024), while the percentage can vary across different countries. In 2022 electricity and heat generation saw the greatest sectoral increase in emissions reaching 14.6Gt reaching an all-time high (IEA, 2022b). These figures underline the need for new and innovative approaches to achieve set Net Zero targets of the energy sector.

Achieving these targets will require a fundamental change to the energy system. The traditional top-down approach of generating electricity from large, centralised fossil fuel power plants and distributing it to consumers via the transmission and distribution grid is becoming increasingly unsustainable as more renewable energy sources (RES), such as solar and wind, are being integrated

into the energy mix. RES produce fluctuating and intermittent energy, requiring a new approach to maintaining grid balance. In addition, RES are typically smaller, distributed and connected directly to the distribution grid, thereby driving a shift towards a more decentralised energy system. These developments introduce new complexities that require a shift in the way energy systems are designed and operated.

1.1.1 Uptake of distributed energy resources

In addition to RES, distributed energy systems (DER) are becoming increasingly important for the decarbonisation of energy consumption and energy generation at a local level. DERs are small-scale energy generation and storage technologies connected at the electricity grid's lower voltage levels. The residential sector, in particular, has seen a notable increase in the adoption of DER in the past years (IEA, 2023a). Improved affordability of photovoltaic (PV) panels allows residential energy users to invest in rooftop PV systems at a low cost (IEA, 2023d). Schemes and subsidies such as Feed-in-Tariffs (FiT) created additional incentives for residential energy users to invest in such technologies. In 2022, the residential segment accounted for 23% of global solar PV capacity additions, while utility-scale PV plants were responsible for 52% and commercial and industrial segments for 25% of PV capacity installed (IEA, 2023c). According to the Global Market Outlook Report by SolarPower Europe (2023), the adoption of solar PV in residential and commercial sectors will continue to grow with a rising interest in self-consumption of the generated electricity and combining installations with storage assets and digital solutions. Rooftop PV systems contributed to 49.5% of total installations globally. Additionally, the integration of PV systems with battery storage has emerged as an effective strategy to mitigate the temporal misalignment between electricity demand and generation cycles. In 2021 the residential battery market in Europe grew by 107% compared to 2020 with a total installed capacity of 5.4 GWh (SolarPower Europe, 2022). Although installations in the residential battery market are declining compared to the energy crisis period, the market continues to grow by 31% in 2024 (SolarPower Europe, 2024). These figures show that DERs are being rapidly adopted in the residential energy sector and will play an increasingly dominant role in the generation and storage of electricity.

1.1.2 Decarbonisation of the residential sector

The increasing installation of DER supports the decarbonisation and hence electrification of the residential energy sector. In 2021, energy consumption in buildings accounted for 30% of the total global energy demand, contributing to 27% of total energy sector emissions. Residential

buildings alone were responsible for 10.9% of indirect emissions and 5.7% of direct emissions¹ (IEA, 2022a).

The urgent need to decarbonise the heating and transport sector has been recognised by policymakers and regulators worldwide. In response, governments have introduced policies to accelerate the transition to EVs and other low-carbon transport solutions. The UK government announced it will end the sale of new petrol and diesel cars in the UK by 2035 (UK Government, 2023). Similarly, the EU has established a ban on the sale of new petrol and diesel cars by 2035, with some member states implementing the ban even earlier (European Commission, 2023). The heating sector too is becoming more electrified. In 2022 global heat pump sales grew by 11% while Europe has seen an increase of almost 40% compared with the previous year (IEA, 2023b) setting further ambitious targets to accelerate the energy transition.

The integration of these DER into the current energy system plays a crucial role in advancing global decarbonisation efforts. However, this integration also brings new challenges to the management of the electricity grid (IEA, 2021). A key characteristic of both DER and RES is their intermittency and variable output. This inherent characteristic complicates balancing electricity supply and demand, which could lead to increasing cost of balancing (Pudjianto et al., 2010). As the energy mix shifts towards a lower proportion of dispatchable generation sources and peak electricity demand increases, more system flexibility will be needed. National Grid's Future Energy Scenarios 2023 report predicts that end-user demand-side response capacity will need to increase by a factor of 3 to 6 to meet the net-zero target by 2050 (ESO, 2023). This need for more flexibility in the electricity grid can be sourced from energy end-users by acknowledging their new role as active energy market actors.

1.2 Local energy markets and peer-to-peer energy trading

A market-based approach could be an effective way of encouraging the installation and efficient operation of DER assets. However, the inclusion of individual residential energy end-users in existing energy market structures may not be feasible due to their comparatively low energy load and generation capacity. Instead, the development of decentralised or local markets that pool these capacities and present opportunities for new entrants and incumbent market players to collaborate, could generate new value streams but would require a review of existing market structures (Morstyn

¹Direct emissions come from the consumption of coal, oil, and natural gas within buildings, while indirect emissions result from the production of electricity and heat supplied to buildings.

et al., 2020a). Aggregating or unifying DER in decentralised markets could provide smaller market players with an opportunity to exchange energy amongst each other and, at the same time, grow to a size significant enough to act or compete with established players in wholesale energy markets (Zepter et al., 2019).

As a response to the lack of incentives local energy markets (LEMs) have gained increased popularity. LEMs are market-based platforms that enable the exchange of energy between local energy users, including energy consumers, prosumers, and aggregators, and can be used to encourage the uptake and manage the increasing penetration of DER (Mengelkamp et al., 2017). In particular, peer-to-peer (P2P) energy trading has emerged as a sub-concept of LEM, allowing DER to be managed through the creation of user-centric energy market designs. In P2P energy trading², energy consumers and small-scale prosumers³ can exchange electricity with each other by taking on an active role in the energy market (Parag et al., 2016). The exchange of electricity refers to the exchange of the value (usually monetary) of metered electricity between each other, as the physical properties of the flow of electricity mean that it is not possible to trace the electricity generated.

However, LEMs and P2P energy trading systems are not only responding to technical constraints on the grid. They can contribute to the empowerment of energy users by increasing awareness of clean energy in a local community, incentivising the installation of renewable energy assets, generating additional income, and strengthening a community's sense of belonging, thus contributing to better energy justice (Jogunola et al., 2017).

In addition to numerous theoretical academic research projects looking into different aspects of P2P energy trading, including social, technical, economic and regulatory aspects, there are also several pilot projects that are conducting initial feasibility studies for P2P energy trading systems. Although most pilots are still in a 'proof-of-concept' stage, a few projects are operating at a commercial level. So far, in industrialised countries, development has progressed further than in developing countries. Nonetheless, countries in the global south have also started approaching this topic, with potential for success given the preferred environmental condition, such as high solar radiation and more stable temperatures.

²Although there are some P2P energy trading systems where heat is exchanged, in the context of this research the term 'energy' mainly refers to electricity, unless explicitly stated otherwise.

³Small-scale energy prosumers are energy end-users who are able to consume and produce electricity and whose primary interest in trading energy is non-commercial.

A key reason why these projects remain in the pilot phase and do not develop into commercial projects is that the energy market regulation in most countries has not yet been adapted to enable LEMs and P2P energy trading. Pilot projects are often carried out in so-called ‘regulatory sandboxes’ set up by the regulatory authorities to conduct live studies in a controlled environment (Ofgem, 2018). However, where these enabling conditions are not in place, projects are often implemented in a modified form to meet the prevailing implementation constraints. These and other reasons, discussed in the following chapters, suggest that P2P energy trading needs further testing and research to understand its scalability and commercial viability in the long term.

1.3 Research aims and contribution

Despite the growing number of pilot projects, most P2P energy trading systems operate under pilot conditions with few examples of commercial scale implementation. The aim of this thesis is to help solve scalability challenges of P2P energy trading systems, with a focus on scaling up P2P energy trading pilot projects by removing the current limitations imposed by their operating environment. In order to achieve this aim, the following objectives have been set:

1. Understand the design and operation of P2P energy trading systems and analyse different market designs and objectives;
2. Understand how current policy and regulatory frameworks and other external circumstances facilitate or hinder the scale-up of existing pilots;
3. Identify the scalability challenges faced by past and present P2P energy trading pilots in different regional contexts;
4. Understand how scaling up P2P energy trading systems can affect the P2P energy trading market’s performance and impact on market participants;
5. Understand the implications of scaling up P2P energy trading systems on different social, technical, economic and regulatory aspects;
6. Identify requirements and provide recommendations for successful scaling up of P2P energy trading systems in different regional contexts.

By achieving these objectives this thesis broadens the current focus of academic research on scaling up P2P energy trading systems, which often focuses on isolated aspects of the scalability of the

market structures without considering a more holistic view of the benefits these systems can provide.

The contributions of the thesis are twofold: First, the thesis provides an understanding of the challenges and implications of scaling up P2P energy trading systems across critical social, technical, economic and regulatory aspects in different regional contexts, supported by evidence from simulated and real case study data. Secondly, the thesis assesses the scalability potential of two P2P energy trading pilot projects by applying a methodological framework that combines empirical data and deterministic modelling to explore different market configurations and derive insights for scalable P2P energy trading system designs.

1.4 Structure of the thesis

The introduction aims to set the scene for the thesis by discussing the evolving energy landscape, highlighting the increasing adoption of DER and the shift towards decarbonisation of the residential sector. It introduces the concepts of LEM and P2P energy trading and outlines the main aims and contributions of the research.

Chapter 2 is structured into two parts. Part One introduces LEMs and P2P energy trading. It outlines key concepts, system designs, and market mechanisms, and reviews the current implementation landscape. This includes an analysis of existing P2P pilot projects, their regulatory environments, and practical challenges. Part Two addresses the issue of scalability in P2P energy trading systems. It presents theoretical and methodological approaches to understanding and assessing scalability, reviews sector-specific barriers, and highlights the unique challenges faced by P2P markets. The chapter concludes with a synthesis of insights and formulates the research gap and questions that guide the remainder of the thesis.

Focusing on the scalability of P2P energy trading systems, Chapter 3 proposes a specific framework for evaluating the scalability of P2P energy trading systems, and addresses the assumptions and limitations of the proposed methodology. The chapter concludes with a summary and an overview of the next steps.

Chapter 4 presents a detailed case study of a P2P energy trading pilot project in Medellín, Colombia. It provides an overview of the project, defines scalability scenarios, identifies performance indicators and discusses data collection methods. Applying the scalability analysis framework presented in the previous chapter, a simulation environment is used to assess the scalability potential of the

Medellín P2P energy trading case study, evaluating social and economic impacts, market design, policy implications, digital infrastructure and integration into the existing energy system.

Following a similar structure to Chapter 4, Chapter 5 analyses the second case study based on the CommUNITY pilot in the UK. It provides a detailed overview of the pilot design, derives scalability scenarios and identifies performance indicators. The scalability analysis is then applied to these scenarios. The chapter concludes with an evaluation of the results, discussing their applicability to existing electricity systems, the role of information and communication technologies and data, market design and transactions, social and economic implications, and policy and regulatory implications.

Chapter 6 summarises the findings of the previous chapters, starting with the limitations of the research conducted in this thesis. It discusses the findings from the case studies and their wider implications for the scalability of P2P energy trading systems. It identifies the main barriers to scaling up these systems and discusses the conceptual and methodological contribution of this thesis. The chapter also discusses potential policy and regulatory reforms needed to support the expansion of P2P energy trading and outlines future research directions.

Chapter 7 concludes the thesis by outlining the main findings of the thesis. It discusses the implications of the findings for the future of P2P energy trading systems and suggests areas for further research to improve their scalability and performance.

Chapter 2

P2P energy trading systems: from theoretical concepts to practical implementation

The integration of DERs, such as rooftop solar and residential storage, is driving fundamental changes in how energy is produced, traded, and consumed. As part of this shift, LEMs, and particularly P2P energy trading systems, are gaining attention as innovative models that allow prosumers to trade electricity locally, increase self-consumption, and contribute to grid flexibility. These models promise new consumer roles and decentralised market structures but face substantial implementation and scaling challenges. To explore these developments, this chapter is structured into two main parts, each addressing a distinct analytical focus. This structure supports the chapter's dual purpose: first, to build a conceptual and practical understanding of P2P energy trading, and second, to analyse the challenge of scaling these systems beyond pilot settings, ultimately leading to the definition of the research gap and research questions guiding this thesis.

Section 2.1 introduces LEMs, outlining their purpose, key characteristics and the importance of geographical proximity and operational infrastructure. It discusses the consumer-centric nature of LEMs, focusing on how they enhance community control over energy resources, encourage technological innovation and promote energy efficiency. A multi-layered approach to understanding LEMs is presented, examining different system designs and their components. It explores different LEM models, including P2P energy trading, transactive energy and community self-consumption, and analyses their unique characteristics and objectives. Section 2.2 takes a closer look at P2P energy trading, its market models and pricing mechanisms. It categorises P2P energy trading markets according to their degree of decentralisation and analyses different market and pricing

mechanisms used in LEMs. Section 2.3 reviews the policy and regulatory landscape for P2P energy trading, discussing key policies, regulatory developments and barriers that shape its development and integration. It provides an overview of global P2P energy trading pilot projects, discussing their objectives, strategies, challenges and implications for scaling up P2P energy trading systems. Section 2.4 begins by exploring how the concept of scaling has been understood in pilot projects across different sectors, introducing key definitions and frameworks that inform energy-sector scaling efforts. Section 2.5 compares two dominant analytical approaches to assessing scale-up potential and considers their relevance for P2P energy trading. Section 2.6 then shifts focus to the specific challenges of scaling P2P energy trading systems, reviewing existing research and identifying practical, regulatory, and socio-economic barriers to scale-up. Section 2.7 synthesises the insights from both parts of the chapter and outlines the research gap and guiding research questions that this thesis will address.

Part I: An overview of local energy markets and peer-to-peer energy trading

2.1 Local energy markets

LEMs have emerged as a solution to the lack of incentives for the deployment of DERs and their integration into the wider energy system (Hvelplund, 2006). These markets can operate on a competitive or cooperative basis, fostering an environment that encourages small-scale energy consumers, producers and prosumers to actively participate in energy exchanges. This enables the local balancing of electricity supply and demand, improving the efficiency and sustainability of energy use within communities (Mengelkamp et al., 2017).

A defining characteristic of LEMs is the emphasis on the geographical proximity of their participants, which are typically located in residential areas (Khorasany et al., 2018). This proximity allows for either collective or individual energy trading activities. Participants can choose to pool their energy resources for collective benefit or engage in direct bilateral exchanges (Muhsen et al., 2022). The operational infrastructure of these markets is often based on online platforms that facilitate communication and coordination between participants and streamline the transaction process with minimal manual input from users (IRENA, 2020).

2.1.1 A consumer-centred market design

A key objective of LEMs, alongside the physical deployment of DERs, is the empowerment of local communities. By establishing structures that give communities greater control over their resources and enable active participation, LEMs foster deeper engagement with energy consumption and generation patterns within the community. This involvement drives technological innovation and the adoption of energy efficient practices, demand response mechanisms and energy storage solutions.

This shift towards a consumer-centric focus in energy markets is becoming increasingly evident, particularly in the EU (ehpa, 2023). Policymakers and industry stakeholders are actively exploring strategies to improve customer engagement, giving consumers more choice and control over their energy use and participation in the market (Catapult, 2021). This trend underlines a significant shift in the energy sector, where the needs and preferences of individual consumers, given their changing role, are being prioritised alongside the traditional economic and operational objectives of the market.

The creation of a consumer-centric energy market requires the continued commitment of its participants. To achieve this, it's necessary to provide incentives that encourage active participation. While financial incentives are common, other forms of motivation can also be effective, such as a sense of community involvement (Scuri et al., 2019) or contributing to environmental sustainability (Smale et al., 2020; Mengelkamp et al., 2018b). Consumer-centricity also means keeping the consumer in mind when designing LEMs. Research has shown that overly complex market designs can lead to user dissatisfaction and reduced engagement (Junlakarn et al., 2022). It's therefore important to strike a balance between providing valuable information about usage and transactions without overwhelming consumers with overly technical data (Heo et al., 2021). There is evidence that consumers value the analysis of their own energy use, which can motivate them to become more active in the market (Ableitner et al., 2020; Wilkins et al., 2020). These findings underline the need to design market systems that are user-friendly and meet consumers' information needs in order to encourage their continued participation.

An important factor for customer engagement in LEMs is the concept of energy independence, which can be understood in two forms: autarky and autonomy. Autarky refers to a state of independence from the main electricity grid, while autonomy implies independence from a specific energy supplier (Adams et al., 2021). While autarky at the individual level can lead to reduced

economic efficiency within the market, autarky at the community level tends to be more beneficial (Hahnel et al., 2020). On the other hand, autonomy has been identified as a key motivator for participation in LEMs, particularly when it comes to setting personal trading preferences and specifying energy prices (Ableitner et al., 2019). Furthermore, research suggests that consumers are often open to some reduction in their autonomy if it results in access to more environmentally friendly and affordable energy options (Kubli et al., 2018). This willingness reflects a growing consumer trend towards sustainable energy choices that balance personal control with wider environmental and economic benefits.

As consumer participation in energy markets increases, the benefits of market access must be matched by the responsibilities that come with it. While consumers enjoy the privileges of market participation, they also bear responsibility for their market actions. This dual role requires a balanced approach to market participation. However, not all consumers have the same level of expertise or resources as professional market participants, which can influence their decisions and actions in the market. Therefore, a strong regulatory framework is essential to protect these non-professional participants (van Soest, 2018). In situations where network rules are inadvertently breached, or contractual obligations are not met due to an individual's limited understanding or resources, there could be a range of consequences starting with fines to disconnection from the market. This scenario highlights the importance of regulations that maintain compliance and grid stability, while providing guidance and support to help non-professional users navigate the complexities of the energy market.

In order for LEMs to function effectively and ensure equitable participation, it's critical that robust governance structures and regulatory frameworks are in place. Addressing disparities in market power and potential imbalances in bargaining power is essential to protect vulnerable consumers and prevent monopolistic behaviour (Bray et al., 2018). Due to the high share of RES in LEMs, advanced forecasting, communication and control technologies are often required to maintain operational stability of the grid (Tsousoglou et al., 2022). Moreover, the successful integration of LEMs into the existing energy landscape is challenged by regulatory and legal complexities. These characteristics show that LEM form complex systems that require the interaction of various components, which can be of a social, technical, economic and regulatory nature.

2.1.2 System and market layers

LEMs can generally be described using a multi-layered systems approach. These layers are connected by an interplay of different rules and responsibilities that ensure the successful operation of LEMs. Understanding the functions and interactions of these layers is crucial, as together they form the foundation of LEMs, enabling innovative energy trading models and ensuring effective market operation. This section looks at the specific characteristics of each layer and highlights their importance in the broader context of the energy market.

In literature, different approaches for the design of LEM system layers can be found. Zhang et al. (2018) propose a four-layer system based on the concept of Smart Grid Architecture Model for the operation of P2P energy trading in a microgrid. This model integrates the ‘power grid layer’, ‘information and communication technology (ICT) layer’, ‘control layer’, and ‘business layer’ to encapsulate the key functionalities of P2P energy trading. The power grid layer comprises the energy system’s physical elements, encompassing the grid itself, transformers, metering devices, DERs, and the electrical loads. The ICT layer is dedicated to communication and data management and includes both the hardware and software required for the infrastructure, such as routers and servers, and the protocols and applications that support the exchange of information within the energy trading ecosystem. The control layer establishes and enforces the rules and procedures for the operation and management of the power system and plays a critical role in maintaining a reliable and secure supply of electricity, including the management of voltage and frequency, among other grid operations. Finally, the business layer drives market operations, providing the tools and platforms for electricity transactions between peers and third parties. Further Zhang et al. (2018) distinguish between the scale at which a P2P market could operate which can range from an individual building, a microgrid or a region as well as the different operational aspects of the market such as the bidding, transaction exchange and market settlement processes. As this system architecture is inspired by the Smart Grid Architecture Model, which is designed for future electricity grids with a focus on prioritising grid optimisation, it lacks the customer-facing aspects of LEMs.

Another approach of structuring the P2P energy trading is proposed by Zhou et al. (2020). In contrast to Zhang et al. (2018), the authors do not specify interrelated layers but focus on individual aspects of P2P energy trading to which they assign separate components. The authors distinguish between ‘market design’, ‘trading platform’, ‘physical and ICT infrastructure’, ‘social science

perspectives’ and ‘policy’. Among other things, they highlight the differentiation of electricity products, including the time period over which the product is traded, but also the type of energy traded, such as grid energy, green energy, etc. They also discuss the integration of P2P energy trading markets with existing market structures such as retail and wholesale markets. In addition, the authors focus on the social aspect of P2P energy trading markets, showing in particular that the socio-cultural factor is equally, if not more, important than the economic aspect.

A middle ground that proposes layers that build on each other but also emphasises the social and customer-oriented aspects of LEMs and P2P was developed as part of the Global Observatory on P2P Energy Trading (GO-P2P)¹. This five-level framework decomposes the LEMs into their underlying components. These include the ‘energy system integration layer’, which manages the physical movement and distribution of energy within the system; the ‘software and hardware layer’, which acts as a bridge between the energy system and market operations and includes the technological tools and systems needed to monitor and manage the functionality of the energy system; the ‘transactions and markets layer’, which includes the mechanisms and platforms through which energy trading and market transactions take place; the ‘social and economic value layer’, which focuses on the market’s ability to deliver desired social and economic benefits; and the ‘policy and regulation layer’, which includes the regulatory frameworks and policies that shape the operation of the market and ensure that it complies with legal and ethical standards. An illustrative overview of all five layers is provided in Figure 2.1, which shows the roles and relationships of these layers in the context of P2P energy trading markets.

For a decentralised energy market to work efficiently, it is critical that its various layers are closely interconnected. At its foundation is the power system integration layer, which is crucial for managing the flow of energy. The software and hardware layer plays a key role in connecting the energy system to market and transaction mechanisms. Meanwhile, the policy and regulation layer sets essential rules that guide market behaviour and ensure that the market meets its social and economic objectives. However, these layers are often misaligned. For example, energy transactions within the markets and transactions layer may not correspond to the actual flow of electricity within the grid in the power systems layer. Similarly, individual economic interests within these layers may not always be aligned with the collective good. These misalignments, shown as white layers in the

¹GO-P2P (<https://www.go-p2p.org/>) is a forum for international collaboration to understand the policy, regulatory, social and technological conditions necessary to support the wider deployment of peer-to-peer, community self-consumption and transactive energy models.

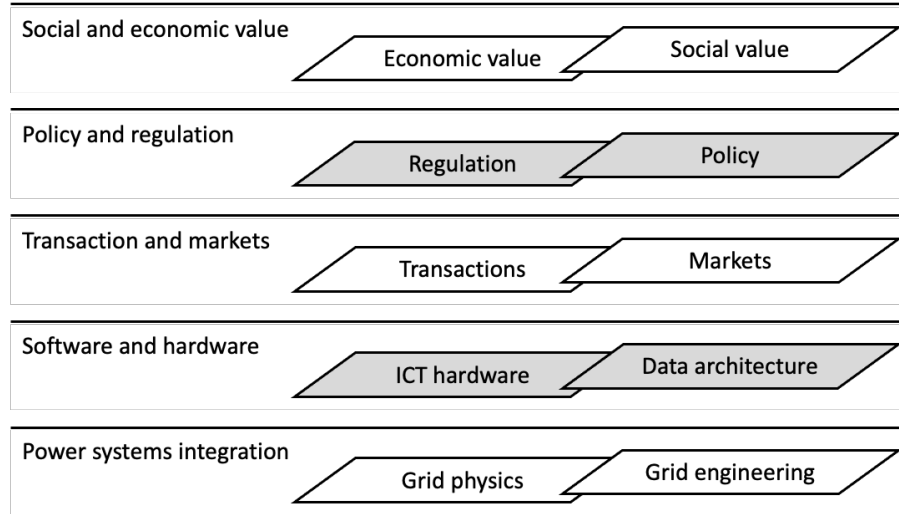


Figure 2.1: Five layers of P2P energy trading markets (adapted from GO-P2P (2019)).

figure, can be addressed by introducing grey layers which establish rules and requirements for LEMs. The ICT and data layer, which include measurement standards, frequency coordination, ontologies and interoperability, facilitates the efficient transfer and integration of data between different systems. The policy and regulation layer involves the creation of policies and rules that address a range of factors, such as the distributional impact of energy transactions, grid disconnection, regional pricing strategies, and more. The establishment of effective policies and regulations creates an environment that promotes the alignment of individual and collective interests, thereby enhancing the efficiency and fairness of the energy market.

Besides the LEM system layers already mentioned, alternative frameworks focus more on the technical execution of LEMs or specific communication technologies. For instance, one proposed framework introduces a seven-layer model centred around distributed ledger technology (DLT) (Zia et al., 2020), while another emphasises distributed communication in P2P energy trading markets (Dudjak et al., 2021). This thesis adopts the five-layer framework outlined by GO-P2P (2019) as a standard for organising LEMs and P2P energy trading systems. This framework is integrated into the thesis's methodological approach, and is discussed in Chapter 3.

2.1.3 Concepts and market models

The term *local energy market* often does not refer to a single concept. Instead, LEMs can be understood as a generic term for a group of models that all focus on the integration of DERs. LEMs are designed to facilitate energy transactions at a local level, but the specific model that can be achieved may differ depending on the key objectives of the market. Commonly referred

to sub-concepts of LEMs are P2P energy trading, transactive energy (TE), and community or collective self-consumption (CSC) (Capper et al., 2022b). This variety of sub-concepts illustrates the diversity of energy market needs and the different objectives of the stakeholders involved.

The differences between the concepts can be traced back to their respective origin and the core needs they seek to satisfy. According to Zhang et al. (2018) P2P energy trading markets enable direct energy trading among users without the need for intermediaries. Their core intention is to incentivise participants to actively engage and participate in energy markets. TE markets have a stronger focus on using decentralised coordination of assets to balance electricity supply and demand by introducing price signals to achieve a change in behaviour of participating actors and allow for autonomous management of DERs. The particular focus lies on providing system stability and reliability (Chen et al., 2017; GWAC, 2015). The term CSC was shaped in the European Renewable Energy Directive II (REDII) (European Parliament, 2018). In contrast to the other terms described above, CSC has a strong focus on empowering energy users by allowing them to trade surplus energy primarily within their community (Frieden et al., 2019; Frieden et al., 2020).

Previous research has addressed the research question of how these three models can be contextually distinguished from each other (Gorbacheva et al., 2024)². Using a mixture of semi-structured expert group interviews and a systematic literature review to capture diverse perspectives on P2P, TE, and CSC models, the authors provided guiding definitions of these models identifying shared characteristics and characteristics that set these models apart. The study's key findings indicate that P2P energy trading and TE are prominent concepts in literature often used interchangeably, while CSC is less clearly defined. The definitions of P2P, TE and CSC are as follows (Gorbacheva et al., 2024):

“[...] P2P is defined according to the following characteristics: it is a sub-market that can operate alongside traditional energy markets. Individuals can trade energy within a community, which can be bound locally or encompass virtual trading across a large geographical region. Participants can be heterogeneous in type but are typically small-scale and equal in size. Although P2P markets are set up to encourage competitive behaviour, with economic incentives and prosumers having individual

²The author of this thesis was a joint first author of this research. The research focused on providing characteristics of peer-to-peer energy trading, transactive energy, and community self-consumption models. The author contributed to the conceptualisation, methodology, validation, formal analysis, investigation, data curation, original draft writing, review and editing and visualisation. A short summary of the research is included in this section. Further information can be found in the full publication.

trading preferences and goals, the overall market aim generally pertains to social, environmental, and energy democratisation benefits.”

“TE is [...] characterised as a non-traditional business model that allows energy end-users to have greater control over their energy trading preferences. It typically provides economic incentives for participants to trade energy in a manner that supports electricity grid balancing. The system can operate across various levels of the electricity grid. Similar to P2P, participants are typically small-scale and equal in size. Different types of energy can be traded. The primary value of TE tends to pertain to systems such as grid stability and reliability while supporting the increasing installation of DER and RES.”

“[...] CSC is defined as a community-oriented framework which operates as a legal entity and focuses on creating shared benefits for local communities. The system is typically bound by the local LV network or a small geographical region. Participants are typically small-scale consumers and prosumers, and ownership of generation assets can be shared within the community.”

All three models have in common that they are “[...] sub-markets that operate within or alongside traditional energy markets. They involve a form of energy trading or sharing; rely on some form of automation of transactions; are characterised by their promotion and support of the local generation and consumption of energy; encompass both geographically-bounded trading and non-geographically bounded trading; and involve trading with or without intermediaries, with price negotiation mechanisms that reflect the aims of the market”.

Due to the diversity of disciplines involved in LEMs, reflected in the five layers introduced in Section 2.1.2, it is important to establish a common understanding of LEMs and their sub-concepts for all parties involved in the design, operation and maintenance of these models. These definitions help to highlight the similarities and to differentiate these models by the different characteristics assigned to them. Which model is chosen for the implementation of an LEM depends on the local context and conditions as well as the key objectives of the project designers and coordinators.

2.2 Peer-to-peer energy trading

The previous section highlighted the characteristics of P2P energy trading and compared and contrasted them with other LEM models. Moving forward, as the focus of this research is on the

scalability of P2P energy trading systems, this section aims to outline the core market models and pricing mechanisms essential to P2P energy trading markets. It will examine various concepts central to P2P energy trading, their applications and evaluations in both theoretical and practical contexts. This examination aims to contribute to a better understanding of the operational mechanics and guiding principles of P2P energy trading markets, providing insights that will influence design decisions for the scalability analysis in subsequent chapters of this thesis.

The emergence of P2P energy trading is closely linked to the emergence of blockchain technology, best known for its application to cryptocurrencies such as Bitcoin. One of the earliest implementations of P2P energy trading in the energy sector was the NRGcoin, launched in 2014 (Mihaylov et al., 2014). This currency gave renewable energy a tangible market value. It allowed prosumers to trade energy directly with the grid operator at market-driven prices, using price signals to efficiently balance energy consumption and production. The novelty of the NRGcoin system was its ability to offer prosumers NRGcoins in exchange for their energy, providing a hedge against rising energy prices and operating independently of the traditional financial sector. Following this development, the Brooklyn Microgrid project emerged as one of the first official P2P energy trading pilot. Launched in 2016, the project focused on a community-powered microgrid in Brooklyn, New York (Brooklyn Microgrid, 2023). Its primary goal was to increase renewable energy generation, thereby improving the community's energy resilience and efficiency. The Brooklyn microgrid symbolised an important step in P2P energy trading and marked the beginning of a further research and adoption of this type of market model in the energy sector. Since then, the field of P2P energy trading has evolved beyond distributed ledger technologies. Today, P2P energy trading is widely used to characterise LEMs that focus on empowering individual participants to take an active role in the energy market. At the centre of the P2P energy trading approach is the idea of enabling consumers and small-scale producers to participate directly in energy exchanges, thereby democratising the energy market.

2.2.1 Market designs

The term 'peer-to-peer', originally used in finance and computing, refers to systems and applications that use distributed resources for decentralised operations described as "a class of systems and applications that employ distributed resources to perform a function in a decentralised manner" (Milojicic et al., 2002). Although this definition is consistent with the general concept of P2P energy trading, the specific application in the energy sector is more complex due to the underlying energy market design and physical electricity grid infrastructure. In the energy context, the literal use of

the term ‘peer-to-peer’ can be misleading, as the energy fed into the grid becomes indistinguishable and part of a larger pool. Therefore, the following is an overview of the prevailing market concepts and designs in P2P energy trading systems.

Market designs for P2P energy trading typically differ in their degree of decentralisation. In the literature, P2P energy trading markets are usually categorised into centralised, distributed and decentralised market models (Parag et al., 2016; Zhou et al., 2020; Muhsen et al., 2022; Sousa et al., 2019; Tushar et al., 2021). Figure 2.2 illustrates these different market designs for P2P energy trading. This categorisation is also known by terms such as ‘community-based markets’ with a central market coordinator, ‘hybrid markets’ with a community manager, and ‘full P2P markets’ without a central coordinator. The following sections explore the operational aspects and applicability of these market designs in different contexts.

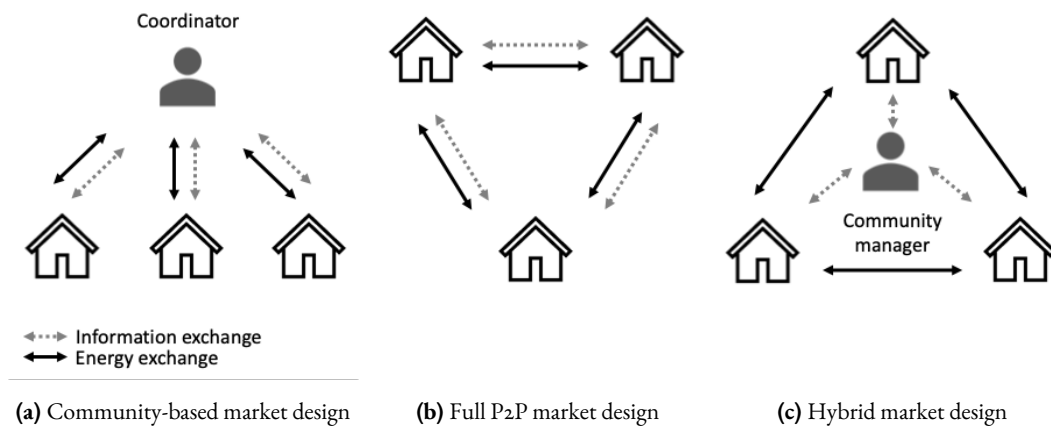


Figure 2.2: Schematic illustration of P2P energy trading markets with different degrees of decentralisation where each house represents a participant in the market.

‘Community-based markets’ as shown in Figure 2.2a are generally suited for energy prosumers that are located in close proximity to each other, specifically referring to a geographical location, i.e. located on the same microgrid or within the same grid connection point (Sousa et al., 2019). The market is usually managed by a centralised third party that coordinates energy transactions inside the community as well as with parties located outside the community (Sousa et al., 2019). This centralised party also referred to as coordinator, is responsible for the matching of buying and selling offers and balancing of demand and supply, acting as a local aggregator of the community (Mohsen Khorasany et al., 2020). The coordinator redistributes financial revenues according to the participation of each market member (Long et al., 2018; Zhou et al., 2020). The identity of

participating community members can remain undisclosed, as only the coordinator is responsible for the matching of transactions (Parag et al., 2016). An advantage of community-based P2P markets is that the community objective function can be defined, maximising the social welfare of the entire community (Zhou et al., 2020; Nguyen et al., 2018). Further, pooling all energy shared with parties outside the community can provide greater benefit due to economies of scale allowing for larger volumes to be traded (Parag et al., 2016). Finally, while having an omniscient central market manager can have many advantages, including full transparency of transactions being conducted, it can pose privacy and security risks to the individual participant. At the same time, the centralised management of the market could lead to high computational costs, especially when trading volumes are high (Zhou et al., 2020). Among others, variations of community-based P2P energy trading markets have been implemented by Kokchang et al. (2020), Lüth et al. (2018), Nguyen et al. (2018), and Zepter et al. (2019).

The ‘full P2P market’ design as shown in Figure 2.2b is derived from the concept of the sharing economy. Similar to Airbnb and Uber, the P2P network is an autonomous and flexible market that emerges from a bottom-up approach (Parag et al., 2016). Transactions in the market are conducted in a bilateral manner between two participants in the market without the need for a third centralised party (Khorasany et al., 2020a). Participants directly negotiate prices and quantity traded with each other, which can result in different outcomes for every trading period (Sousa et al., 2019). Other examples of full P2P market designs are presented by Luo et al. (2019) and Kalbantner et al. (2021). Described by Parag et al. (2016) as an organically evolving market model, full P2P market models are less exposed to changes in the market environment allowing for participants to freely join and leave. Unlike in community-based markets, full P2P markets do not require sharing of all participant and trading information to settle transactions making this market structure more privacy-preserving. At the same time, this absence of information exchange results in higher uncertainties when conducting transactions (Muhsen et al., 2022) which could have negative effects, especially on vulnerable energy customers that are impacted more by strong price fluctuations (Zhou et al., 2020). This could also obstruct the collaboration with Distribution System Operators (DSO) and Transmission System Operators (TSO) when responding to network constraints or aiming to improve the operational efficiency of the grid (Zhou et al., 2020). In contrast to community-based markets, each participant has greater control over its own DER devices (Zhou et al., 2020) and can set personalised trading preferences leading to greater product differentiation (Sousa et al., 2019) also shown by Morstyn et al. (2019b) and Sorin et al. (2019). However, greater benefits for

the individual participant in the market might not necessarily also lead to better outcomes for the community as a whole. As there is no centralised coordinator to set desired market outcomes, this market structure can impair the social welfare maximisation of entire community (Zhou et al., 2020; Guerrero et al., 2017; Morstyn et al., 2019b). Parag et al. (2016) explicitly highlight that, compared to applied concepts of sharing economy in other industries, the energy sector is highly regulated and needs to guarantee energy security and address liability issues. Therefore, the deployment of such markets has to be in accordance with local and national rules and guidelines, which increases the operational complexity of such markets. Examples of fully decentralised P2P energy market models in the literature include Sorin et al. (2019) and Khorasany et al. (2020a).

Finally, ‘hybrid markets’ as shown in Figure 2.2c are a mixture of community-based and full P2P markets operating on two levels. On the first level, individual prosumers can exchange energy directly with the community-based markets, while on the second level, the community manager overviews transactions within the community to identify the net energy generation and consumption and matches any energy imbalances in the first level (Sousa et al., 2019). Compared to the community-based markets, device control is still the responsibility of individual participants while still providing a more structured market design compared to full P2P markets (Zhou et al., 2020). Khorasany et al. (2020b) highlights a potential hybrid market design allowing market participants to set individual trading preferences while being able to respond to network constraints. Moret et al. (2019) and Baez-Gonzalez et al. (2018) have developed hybrid approaches for the trading of energy in P2P energy trading markets.

When implemented, these markets may aim to address different challenges and deliver different benefits to their environments and stakeholders. Morstyn et al. (2020a) have conceptualised a framework to classify a business proposition of a P2P energy trading market in a two-by-two matrix with a value and a scale axis. The value can be focused on either the prosumer or the system operator, and the scale of the market can range from the distribution to the transmission grid level. An illustration of the matrix can be seen in Figure 2.3. For each combination in the matrix, the authors provide four categories of business models for P2P energy trading markets, namely ‘behind-the-meter trading’, ‘local flexibility’, ‘multi-class energy trading’ and ‘federated power plant formation’. Depending on where along these axes a P2P energy trading market is located, the focus is more on the community aspect or on the electricity grid aspect balancing demand and supply. One does not have to exclude the other, it is rather a question of which goal is tackled

first or which objective is optimised first. This also determines which energy asset is traded – in a market focused on delivering value to end users, it is more common for energy to be traded. Energy can be classified according to its origin, i.e. green, subsidised or grid energy. In markets that seek to contribute to the robust operation of the electricity grid, flexibility is more likely to be offered by providing capacity to the market (Morstyn et al., 2020a).

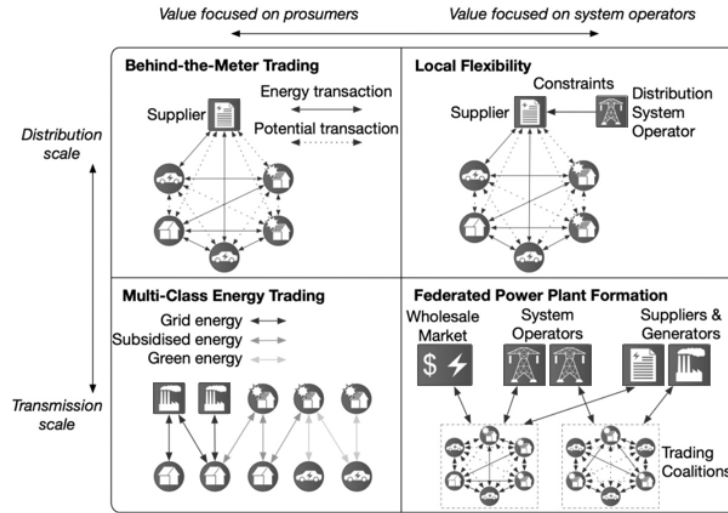


Figure 2.3: Business models supported by P2P energy trading (Morstyn et al., 2020a)

While these frameworks provide insightful characterisations of the structures and scales of P2P energy trading markets, they fall short in describing the spatial evolution of markets as they change. As the dynamics of market parameters change, P2P energy trading markets that may initially be based on behind-the-meter trading could evolve into more complex structures such as local flexibility markets, especially as the system includes an increasing number of assets. This potential for adaptation underlines the dynamic nature of P2P energy trading markets and highlights the need for flexibility and adaptability in planning and development.

2.2.2 Market and price formation mechanisms

The following section assesses the key market mechanisms currently present in local energy markets. The results of this section are part of a systematic literature review conducted by Capper et al. (2022b)³ that reviewed a total of 139 peer-reviewed journal articles that focused on understanding the key market designs and mechanisms that were implemented in the literature. Capper et al.

³The author of this thesis was a joint first author of this research. The research focused on providing an overview of the key market designs and mechanisms that were implemented in the literature. The author contributed to the conceptualisation, formal analysis, investigation, methodology, project administration, data curation, original draft writing, review and editing and visualisation. A short summary of the research is included in this section. Further information can be found in the full publication.

(2022b) have identified six primary market designs, namely ‘futures market’, ‘real-time market’, ‘mixed decentralised/centralised market’, ‘mixed futures/real-time market’, ‘multi-layer market’, and ‘settlement after-the-fact’. In the following, a comprehensive description of each market design identified, along with an analysis of their typical applications, will be provided. The flowcharts presented in Figure 2.4 illustrate the processes involved in each of these archetypal market designs.

The futures market, as seen in Figure 2.4a, involves all trading occurring prior to the settlement period. During the settlement period, market participants try to adhere as closely as possible to their traded positions, and any energy imbalances resulting from deviations from these positions are resolved during the settlement phase. Futures markets are associated with price formation mechanisms such as single auction, double auction, and bilateral negotiation. This market design can often be found in traditional energy markets, as is the case in Great Britain (ELEXON, 2020).

In real-time markets, no trading takes place prior to the settlement period. Figure 2.4b shows a flowchart of a common market design of real-time markets. All trading activities occur during the settlement period, allowing market participants to adjust their positions based on actual supply and demand for energy. Theoretically, this ensures that all participants end the settlement period with a balanced position. However, certain factors, such as unmet supply and demand, may result in imbalances. Most reviewed papers assume that these markets are connected to larger traditional electricity systems, which function as infinite buses capable of accommodating any excess supply and demand. A common assumption made among the analysed literature is the presence of sufficient flexible energy generation or load, where price signals are relied upon to balance supply and demand. Price formation mechanisms observed in real-time markets include single auctions, double auctions, and bilateral negotiations.

Mixed decentralised/centralised markets, shown in Figure 2.4c, entail a bilateral negotiation phase, during which market participants aim to clear the market without intervention from a market operator. Subsequently, a centralised auction, conducted by a market operator, is employed to clear the remaining portion of the market. The centralised auction may be part of the market itself, or alternatively, the market operator may engage in trading with larger traditional market actors to further clear the market. Both single and double auctions are used as price formation mechanisms in the centralised component of these markets.

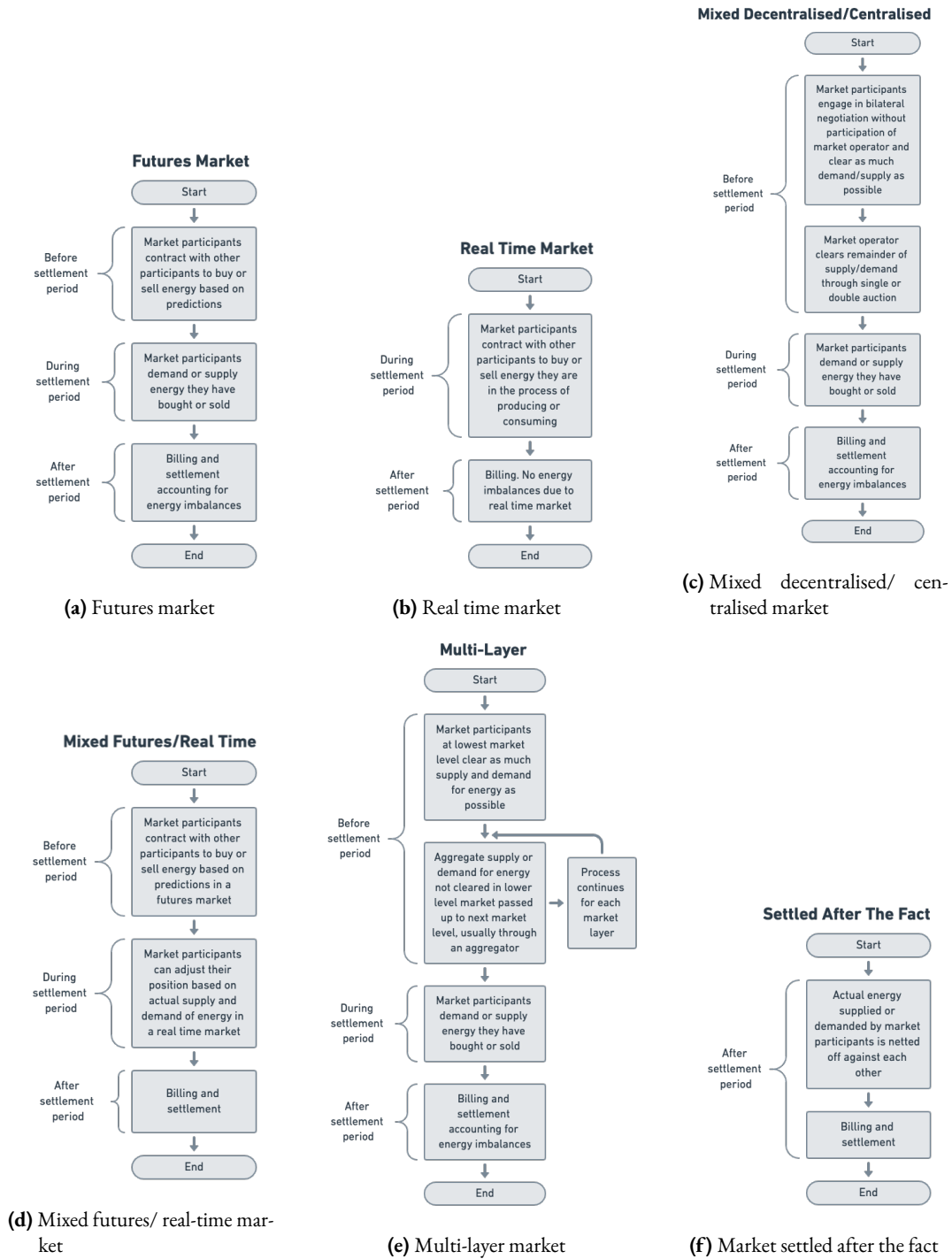


Figure 2.4: Market design flowcharts (Capper et al., 2022b)

Figure 2.4d shows mixed futures/real-time markets where trading occurs both prior to and during the settlement period. The pre-settlement trading relies on predicted supply and demand for energy, while the trading during the settlement period allows participants to adjust their positions in response to any forecasting errors. Both single and double auction price formation mechanisms

are frequently used to clear the market.

The concept of multi-layer markets, as seen in Figure 2.4e, involves settlements occurring at different levels. In this arrangement, first, the core market is cleared. Then aggregators operating within these markets participate in higher-level markets to reconcile imbalances observed in the lower-level markets. In the reviewed literature the implementation of both single auctions and double auctions as price formation mechanisms in multi-layer markets.

Finally, in the settled-after-the-fact market, trading only occurs once the settlement period is concluded. Figure 2.4f shows a flowchart of an exemplary market structure. Participants are compensated or charged based on the energy they supplied or demanded during the post-settlement phase. These markets operate with system-determined price formation mechanism, where energy is bought or sold at fixed prices. Market participants have the freedom to engage in transactions according to their energy requirements at these predetermined prices. Consequently, no trading is conducted prior to the settlement period to establish equilibrium prices and volumes.

The market designs analysed here come from a total of 55 of the 139 papers analysed. It is important to note that these mechanisms have mostly been analysed in a simulated environment. Exactly how they will be implemented in real-world applications remains to be seen. How much autonomy and rationality can be expected from energy end-users is still an open question, as these customers have no commercial interest in trading energy and can only be marginally liable if the market does not operate according to expectations. However, collaboration with professional market actors such as aggregators could support their position in the market. At the same time, it must be emphasised that with increasing complexity of the individual mechanisms, acceptance within a community could decline if the logic of the market is no longer comprehensible to the average citizen (Ableitner et al., 2020).

The previous sections have highlighted which pricing mechanisms are commonly used in combination with specific market mechanisms. The most common pricing mechanisms are described in more detail below. Price formation refers to the process through which market prices are determined. It occurs within the framework of market institutions, which establish the rules governing permissible messages (e.g., buyer bids, seller asks), authorised agents, and transactional procedures. Five main categories of price formation mechanisms were identified by Capper et al.

(2022b)⁴ and studied in detail: single auction, double auction, system-determined mechanisms, negotiation-based mechanisms, and equilibrium-based mechanisms.

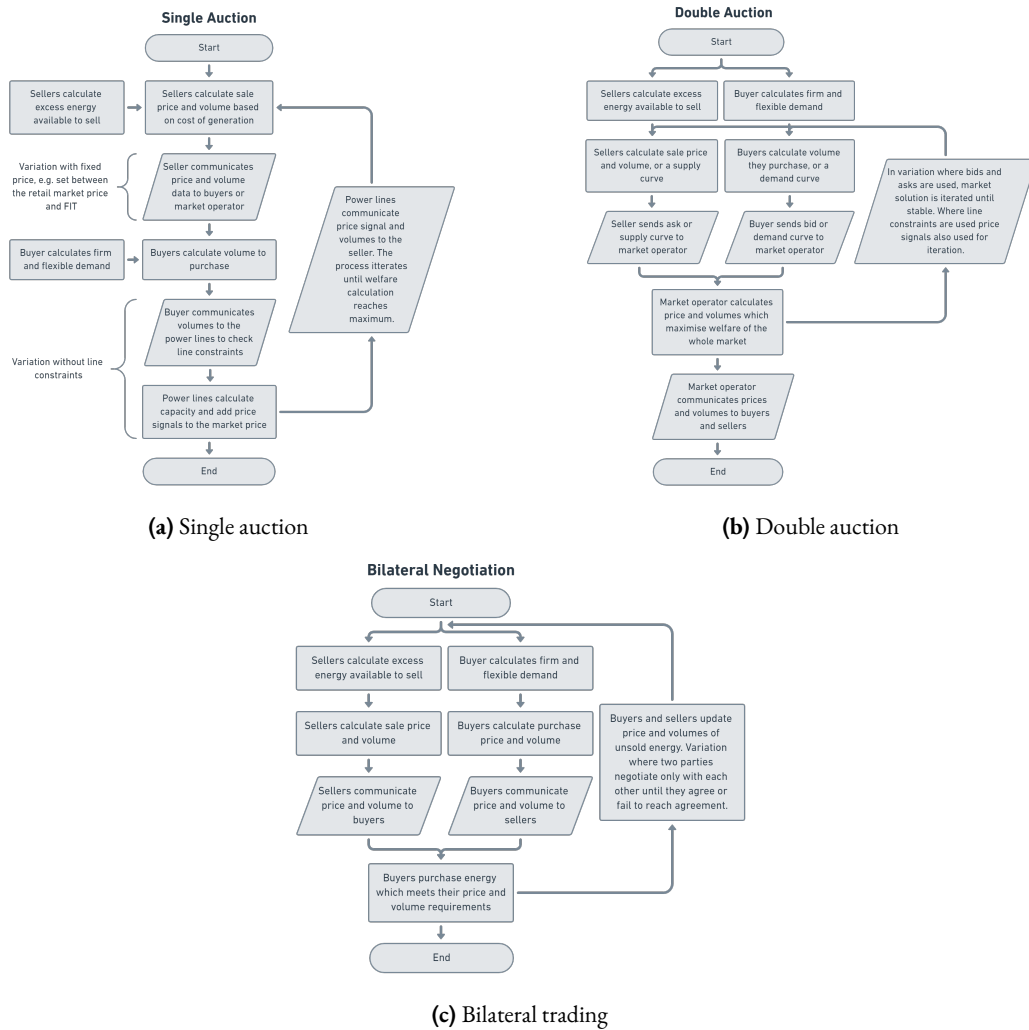


Figure 2.5: Price formation mechanism flowcharts (Capper et al., 2022b).

In a single auction, communication occurs exclusively on one side of the market, which is more commonly seen when there is a single agent representing that side. Figure 2.5a shows an exemplary structure for a single auction price formation mechanism. For instance, in procurement auctions, a single buyer seeks offers from suppliers. The reviewed papers provided examples, such as consumers in a community bidding for excess renewable energy units or demand response units offering

⁴The author of this thesis was a joint first author of this research. The research focused on providing an overview of the key market designs and mechanisms that were implemented in the literature. The author contributed to the conceptualisation, formal analysis, investigation, methodology, project administration, data curation, original draft writing, review and editing and visualisation. A short summary of the research is included in this section. Further information can be found in the full publication.

flexibility services. These auctions involve consumers submitting bids, which are then cleared by various entities, such as aggregators, LEM operators, or DSOs.

The double auction, as seen in Figure 2.5b, allows both buyers and sellers to exchange messages, leading to more efficient outcomes. It is widely used in wholesale energy markets and financial markets. The defining feature of the double auction is that buyers communicate their willingness to pay, reflecting their underlying utility and preferences, while sellers communicate their willingness to accept, reflecting their underlying costs. The literature explores various forms of the double auction, including double clock auctions and continuous double auctions. A double clock auction is cleared at specific time points or regular intervals, while a continuous double auction is continuously cleared, similar to stock markets that employ order books.

Market and price formation mechanisms vary depending on the industry and context. In certain projects where real-time physical coordination and balance of demand and supply are critical, price formation relies on system-determined mechanisms. These mechanisms encompass approaches that do not rely on market bids and offers but are instead determined by a platform operator using pre-agreed mechanisms or formulas. The entity setting the prices, referred to as the ‘system operator’, differs in the research papers studied and can be the community energy aggregator, local retailer, or DSO. Common types of system-determined mechanisms mentioned include uniform or fixed prices, pricing based on fixed feed-in tariffs or time-of-use prices, and mechanisms that establish the price for local renewable energy based on fixed ratios or functions of demand. Additionally, some mechanisms employ cooperative game theory techniques to redistribute benefits among participants in local TE schemes.

Unlike the structured price formation methods of single and double auctions, negotiation-based mechanisms offer a more decentralised approach that resembles bilateral transaction. An example can be seen in Figure 2.5c. In these mechanisms, transactions are often automated using specialised AI-enabled software, such as negotiating autonomous agents. Negotiation prices depend on the local one-to-one (or sometimes one-to-many) offers made and accepted. Although negotiation-based mechanisms have the potential to facilitate truly decentralised P2P energy transactions, the prices are not determined through a centralised market platform like auctions.

Equilibrium-based mechanisms involve the formation of prices based on bids and offer from agents, typically prosumers, suppliers, or flexibility providers. These mechanisms establish price as a

derived equilibrium of their interactions, using game-theoretic solution concepts to construct the equilibrium. Several papers explore how an iterative exchange of bids leads to convergence to a price equilibrium. The most frequently employed game-theoretic equilibrium concept is the Nash equilibrium, although other concepts like Cournot, Stackelberg, or other competitive market equilibria are also used.

While not all papers have specified the price mechanisms used, the authors have found that some price formations, particularly in the context of local communities, are based on relationships rather than prices. For example, in some local community energy projects, excess energy exchange occurs on a reciprocal basis or is redistributed by a local aggregator or operator based on fairness criteria. Especially when pricing energy transactions, it makes sense to have a high level of participation of the participants, as it is an important criterion to compare the fairness and distribution of benefits in the community. An unfair sentiment within the community can lead to a disintegration of the energy market.

2.3 Regulatory frameworks and practical applications

The previous sections discussed the concept of LEMs and P2P energy trading in detail and provided an overview of the current academic research and underlying theories. The aim of this chapter is to take a closer look at the current practical implementation of P2P energy trading markets. The chapter starts with an overview of the policy and regulatory environment discussing key policies and regulations that play a key role in shaping the development of P2P energy trading markets. This is followed by an overview of current efforts to develop P2P energy trading around the world, to illustrate the unique strategies and challenges faced in their deployment. Particular emphasis is placed on assessing the challenges and opportunities for achieving scalability in P2P energy trading systems.

2.3.1 Policy and regulatory developments and barriers

Existing energy market regulations have traditionally been structured around centralised energy systems. However, the emergence of LEMs and P2P energy trading requires the development of new regulatory frameworks. These frameworks are essential for the integration of LEMs into established market structures, requiring clear definitions of the roles and responsibilities of emerging market participants and ensuring their compatibility with existing structures and legacy systems. This chapter aims to provide an overview of the current regulatory landscape in different national and international contexts, with a particular focus on how these emerging models can be successfully

integrated into highly regulated traditional energy sectors.

The EU is often seen as a pioneer in the formulation and regulation of community-centred energy markets, with a strong emphasis on a consumer-centred approach to energy (European Commission, 2015). An important milestone was the Clean Energy for All Europeans (CEP) package, in which the European Commission defined the term ‘P2P energy trading’ for the first time. This definition is captured in Article 2 (18) of the revised Renewable Energy Directive (RED II), providing a legislative basis for P2P energy trading within the EU’s energy policy framework (European Parliament, 2018).

“‘peer-to-peer trading’ of renewable energy means the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers or aggregators;”

The definition highlights that both bilateral trading and trading through a centralised third party will be considered P2P energy trading. Geographical or grid topological characteristics are not mentioned in this definition. Further, RED II continues defining the rights of renewable self-consumers in Art. 21 §2(a), which allows renewable self-consumers, individually or through aggregators (European Parliament, 2018):

“to generate renewable energy, including for their own consumption, store and sell their excess production of renewable electricity, including through renewables power purchase agreements, electricity suppliers and peer-to-peer trading arrangements, without being subject:

- (i) in relation to the electricity that they consume from or feed into the grid, to discriminatory or disproportionate procedures and charges, and to network charges that are not cost-reflective;
- (ii) in relation to their self-generated electricity from renewable sources remaining within their premises, to discriminatory or disproportionate procedures, and

to any charges or fees;”

With these definitions in place, the CEP sets the ground and thereby recognises the participation of active energy consumers in the market and allows them to engage in P2P energy trading markets. While the new directive defines P2P energy trading in a legal sense, it does not provide any further details on the execution of P2P energy trading markets. This is left to the interpretation of the individual member states and can therefore lead to different interpretations at national level. The RED II was in its transposition phase and was expected to be implemented into the EU Member States national legislation by 30 June 2021. However, implementation in many countries is still ongoing (Rescoop, 2024).

Due to the strict regulation of the energy market and high dependency on other sectors, the entire underlying regulatory framework needs to be revised. This will require additional changes in consumer law, contract law, competition law and data law to name a few (De Almeida et al., 2021; Lavrijssen et al., 2023). The prevailing structure of the electricity market, characterised by large-scale production and a passive consumption model, is identified as a significant barrier to the implementation of P2P energy trading. The study by Lavrijssen et al. (2023) argues for a reformed regulatory framework to promote a more sustainable, equitable, and inclusive energy market. It also notes that legal challenges may differ from country to country, and uses Germany and the Netherlands as case studies to illustrate specific national legal barriers to P2P energy trading. In practice, the implementation of these consumer-centric markets would require additional regulatory changes, such as multiple supplier models to allow participants to contract with an additional P2P platform provider alongside their traditional energy retailer (Watson et al., 2020; Jogunola et al., 2024) or the regulation of network charges, which are currently not cost-reflective of actual network use (Zhou et al., 2023). Although some countries are gradually implementing RED II, P2P energy trading is not yet widely used as regulation is often not clearly defined and thus inhibits market innovation.

Globally, there is a wide variation in the regulatory maturity of P2P energy trading (Shan et al., 2023). Only a few countries have implemented supportive regulation to enable P2P energy trading. In countries where regulation is not yet in place, so-called regulatory sandboxes are often used instead. These allow innovative business models to be tested within the existing regulatory framework under exceptional conditions, often for a limited period of time. One of the earliest adopters of regulatory sandboxes in Europe was the Netherlands, which introduced the ‘Experiments for Decentralised

Sustainable Electricity Production’, which allowed new energy services to be tested at distribution grid level (Waal et al., 2020). However, the sandbox was discontinued after four years and no prolongation was planned due to the introduction of a new Energy Act, which included a legal framework for energy communities (Beckstedde et al., 2023), and also to avoid market distortions (European Commission, 2023). In the UK the national electricity regulator Ofgem has introduced ‘innovation sandboxes’, which allow companies to test new products, services and business models in real-world conditions, typically for up to two years, and require the involvement of a licensed energy supplier or distributor (Ofgem, 2018). The sandbox environment provides temporary relief from certain regulatory requirements. While it is not regionally limited within the UK, it only applies to systems within Ofgem’s regulatory scope. There are clear limits on what can be tested. Core consumer protections and regulations outside Ofgem’s control are generally excluded. Eligible innovations must be genuinely novel, demonstrate potential consumer benefit and include a well-defined trial plan. Unlicensed innovators must work with licensed companies to access certain types of support (Ofgem, 2020). In parallel, Elexon, the organisation responsible for balancing and settlement in the UK energy market, has launched its own sandbox. This sandbox is designed to test necessary changes to the Balancing and Settlement Code (BSC) and works in conjunction with Ofgem’s sandbox. This arrangement allows participants to propose innovative business models that deviate from the existing BSC rules, thus enabling the practical testing of changes to the BSC (ELEXON, 2017). Other countries in Europe that have set up sandbox environments and are actively implementing new business models in the energy sector include regions in Belgium, France, and Norway (Beckstedde et al., 2023). Beckstedde et al. (2023) have grouped the approved regulatory sandboxes across Europe into five categories: ‘local energy’, ‘flex participation in electricity markets’, ‘distribution network tariffs’, ‘connection to electricity networks’ and ‘connection to gas networks’. These categories highlight the geographical distribution but also the thematic diversity of approved projects across Europe. Nevertheless, countries such as the Netherlands have started the phasing out of sandbox environments in the energy sector showing that they may not be the most effective tool to accelerate energy market transition in all cases and contexts. In order to improve the effectiveness of regulatory sandboxes, Beckstedde et al. (2023) argue that multiple regulatory entities should be involved in the decision-making and oversight of the sandbox programme. This will ensure a more comprehensive and balanced regulatory approach. Sandboxes should be continuously evaluated and updated to assess the effectiveness and impact of the sandbox, make necessary improvements and adapt to changing circumstances or emerging challenges.

The need for supportive regulation to provide a comprehensive framework and define the boundary conditions for P2P energy trading systems is critical. At present, there is a lack of specific guidance on the design and operational scale of these systems, which hinders their wider uptake. Regulation often lags behind the rapid pace of market development, resulting in inefficiencies, barriers to innovation and restrictions on the full realisation of the potential of new energy market models (Maldet et al., 2022; Bray et al., 2018). To foster regulatory innovation, it is necessary to provide regulators with illustrative projects of the use of innovative energy market business models. These examples can help assess their impact not only on traditional energy market structures and network operations, but also on new entrants and incumbents in the sector. This evaluation can be supported by the implementation of pilot programmes. Such pilots, often conducted within regulatory sandboxes or in a simplified manner, provide valuable practical insights into the operational challenges of P2P energy trading systems and help to identify viable solutions to these challenges. The following chapter provides a comprehensive overview of the current landscape of P2P energy trading pilots, highlighting the diversity of these initiatives and the obstacles they face.

2.3.2 Implementations of P2P energy trading pilots globally

P2P energy trading pilot projects have been carried out around the world, each tailored to the specific context in which it operates and with a specific set of objectives. These objectives vary and include social, economic and technical goals, and are influenced by the unique challenges and resources of each location. Pilot projects serve as critical test beds, providing a controlled environment to assess the feasibility of innovative ideas while managing the risks associated with novel concepts. They provide insights for future decision-making and are instrumental in demonstrating the potential of a project before it is taken to scale.

The following discussion will provide an overview of both ongoing and completed P2P energy trading pilots. It will focus on identifying and examining the key challenges faced in moving these projects from the pilot stage to large-scale implementation. This analysis aims to highlight the diverse nature of these projects, showing the range of strategies and solutions adopted in different contexts to address the unique challenges and opportunities of P2P energy trading. Table 2.1 provides an overview of ongoing or completed pilot projects, some of which are discussed in more detail below.

Project name	Country	Start year	Objective	Status	Source
AGL Virtual Trial of Peer-to-Peer Energy Trading	Australia	2017	Test the applicability of DLT and incentivise uptake of DER	Ended	(ARENA, 2018)
Brooklyn Microgrid	USA	2016	Security of energy supply and integration of local RES	Unknown	(Brooklyn Microgrid, 2023)
CommUNITY	UK	2018	Empower energy end-users	Ended	(EDF, 2019)
Pebbels	Germany	2018	Optimise self-consumption of renewable energy	Ended	(Pebbels, 2023)
Piclo	UK	2015	Consumption of locally generated electricity	Pivoted	(Piclo, 2023)
Quartierstrom	Switzerland	2019	Local consumption of locally generated energy	Extended	(Quartierstrom, 2023)
SOLshare	Bangladesh	2015	Access to affordable solar energy	Ongoing	(SolShare, 2023)
Transactive Energy	Colombia	2019	Democratisation of energy	Ended	(Transactive Energy Colombia, 2023)
Uttar Pradesh Pilot	India	2020	Test feasibility of rooftop solar energy trading	Ended	(PowerLedger, 2023)

Table 2.1: Overview of P2P energy trading pilot projects.

One of the first and most prominent P2P energy trading pilots, the Brooklyn Microgrid, was launched in the United States in April 2016. Established by LO3 Energy, the Brooklyn Microgrid was designed to respond to recurring blackouts in the region and provide social benefits to the community by reducing energy costs and selling local and renewable energy (Brooklyn Microgrid 2021). The Brooklyn Microgrid operates on a permissioned blockchain, Exergy, which manages peer transactions in the market between prosumers (LO3 Energy, 2018). While the market provides social benefits to the community by reducing energy costs and selling local and renewable energy, its main goal is to respond to frequent grid failures and provide a more reliable and secure grid service (Mengelkamp et al., 2018a). In recent years, the company behind LO3 Energy has expanded its options to other regions, including testing a microgrid operation in Germany (Siemens, 2017). To date, the latest developments of the Brooklyn microgrid are not known. There is no longer an online presence for LO3 energy, so it is not clear whether the pilot is still in operation or has been discontinued.

Another P2P energy trading pilot that has also received a lot of attention is the Quartierstrom energy trading pilot in Switzerland. The main objective of the pilot was to promote local consumption of locally produced energy. Among other things, the pilot focused on exploring user

preferences for local energy trading and the type of engagement users are interested in (Ableitner et al., 2020). All 37 participating households were connected downstream to a substation. To clear transactions between participants, a discriminatory pricing structure was introduced using a double auction, where individual households can set the minimum price they are willing to accept or the maximum price they are willing to pay when selling or buying electricity (Ableitner et al., 2019). In Quartierstrom, a blockchain-based solution was proposed to enable energy trading between participants (Meeuw et al., 2020). The first phase of Quartierstrom has ended in July 2020. The project faced operational difficulties in deploying the trading system on the existing smart meter infrastructure, and in identifying a promising business model for a blockchain-based system under current Swiss legislation. The participation of multiple prosumers operating as a community over public networks is not accommodated in the regulatory frameworks of major markets posing challenges for regulatory innovation in the transition to a prosumer-centric network management approach (SFOE, 2020). During the second phase, the focus of the project shifted to replacing hardware with mass-produced devices and increasing the number of participants. The project was supported by government funding and operated in a sandbox (Energie Schweiz, 2020). The project team acknowledged that at the start of the project in 2017, they were chasing blockchain hype and had to act quickly with ready-to-use technology without being able to assess the framework conditions in detail before the start of the project. In the Quartierstrom 2.0, the trading platform and applications have now been mapped to commercially available technology (Energie Schweiz, 2020; Inside IT, 2022).

The CommUNITY pilot project, launched in Brixton, London at Elmore House, aimed to empower low-income residents by enabling them to participate in the low-carbon energy transition through P2P energy trading of locally generated solar energy. The initiative shifted from the previous status quo of selling excess electricity back to the grid to facilitating direct energy sharing between residents, thereby promoting local consumption, sustainability and achieving cost savings (Hadri et al., 2021; EDF, 2019). Similar to the projects above, the CommUNITY project tested a blockchain-based P2P energy trading platform to manage transaction (Murkin, 2021). Despite its innovative approach, the pilot faced challenges in fully testing the P2P market due to the virtual nature of the transactions and regulatory sandbox constraints. It explored different stages, including community self-consumption, battery storage integration and grid flexibility services (UKPN, 2021).

Launched in the UK in 2015, the Piclo platform was an early example of a P2P electricity trading system designed to allow consumers to choose their energy source based on criteria such as location and price. The project, run by Open Utility in partnership with Good Energy, aimed to explore the possibilities of a more decentralised and user-driven electricity market (Open Utility, 2016). Using smart meter data, the platform matched consumer demand with available supply on a half-hourly basis. The pilot demonstrated the technical viability of P2P energy trading and highlighted participants' interest in renewable energy sources. It also provided insights into consumer preferences for local energy matching, suggesting the potential for greater community engagement in energy markets (Zhang et al., 2017; Open Utility, 2016). The improvement in the efficiency of matching energy production and consumption during the pilot increased confidence in the transition to renewable energy. Challenges related to wider market integration and regulatory frameworks were identified, highlighting areas for further development of P2P energy trading initiatives (Open Utility, 2016). Piclo is still in operation, but the company has shifted its focus to providing a marketplace for trading local flexibility (Piclo, 2023).

A P2P energy trading trial with a much stronger focus on the social value of the P2P energy trading markets has been set up in Medellín, Colombia. The aim of the Transactive Energy pilot in Medellín was to enable prosumers from low-income households to trade energy with consumers from high-income households. Many affluent residents live in high-rise buildings on the valley floor of Medellín and therefore do not have roof space to install PV and generate their own electricity. Many less well-off residents live in low-rise settlements on the south-facing hillsides around Medellín with good access to the sun (Transactive Energy Colombia, 2023). The main objective of the pilot project was to enable high-income users without PV to buy energy with positive social and environmental attributes from low-income users living in low-rise buildings with PV systems through a P2P trading scheme. In total, 14 residential users of different income levels were connected to a digital platform and can choose which resident they want to trade energy with (Ortega, 2019). However, the initiative also faced challenges in terms of regulatory compatibility, technological implementation and ensuring equitable participation, highlighting the need for further research and policy development to fully realise the benefits of P2P trading in diverse urban contexts.

Founded in 2014, SOLshare is a social enterprise that introduced a P2P solar energy trading platform

in Bangladesh. The company aims to increase access to affordable PV energy in off-grid⁵ areas by enabling households with surplus solar energy to trade with their neighbours.

SOLshare's model is built around solar home systems and uses a digital platform to facilitate the trading of surplus solar energy (Agnihotri et al., 2022). Initially piloted in a Bangladeshi village, this approach has enabled the emergence of solar entrepreneurs within local communities and demonstrated the feasibility of decentralised energy trading (Fairley, 2018; Agnihotri et al., 2022). Despite challenges related to system affordability and capacity, SOLshare's innovative energy trading model has attracted international attention and funding and is still ongoing.

Further summaries of P2P energy trading pilot projects can be found in the literature (Suthar et al., 2023; Gunarathna et al., 2022; IRENA, 2020; Park et al., 2017; Zhou et al., 2020; Tushar et al., 2021). However, not all the projects referenced therein necessarily correspond to the specific definition of P2P energy trading systems as described in this thesis.

Many of the projects listed in Table 2.1 only reach a 'proof of concept' stage and were limited in time. The reasons for these are varied, but often include the end of a regulatory sandbox, the end of public or private funding or the withdrawal of various project partners. However, in order to be considered successful, it is important that pilot projects are followed up. Many are discontinued at the end of a pilot phase, and in a few cases only a second phase is carried out. The business models trialled in the pilot phases often have difficulties remaining viable in the face of changing external conditions. In the case of Piclo, they revised their value proposition to reflect strategic shifts in their business approach. A common transition observed is the shift from a 'peer-to-peer' framework to a 'producer-to-peer' model. This adaptation allows customers to select their electricity from designated commercial generators, rather than facilitating direct energy exchanges between users. A Popular example is the Dutch market platform Vandebron (Zhang et al., 2017). Other P2P energy pilot projects studied in the literature by Andoni et al. (2019), such as the Dutch Alliander and Alva pilots, are no longer available online and information about them cannot be found, or have instead moved away from P2P markets. In addition, many of the start-ups involved in these pilot projects in the past have benefited from the popularity of Blockchain and DLTs between 2017 and 2019 (Deign, 2017; Merchant, 2017). Subsequently, after the initial 'hype' faded, projects were phased out and companies involved in pilots are no longer operational. For example, a German-based P2P

⁵Off-grid refers to the installation of PV systems and smart meters for sites where there is no grid-provided electricity connection. PV installations connected with SOLshare are linked through a local private microgrid (Sajid, 2020)

energy trading platform provider that was involved in two pilots in Kettwig and Mühlheim (Zhou et al., 2020) has closed down (Crunchbase, 2023).

Pilot projects play a crucial role in evaluating new business models and technological concepts in an environment that closely mirrors real-world operating conditions. The P2P energy trading pilots discussed above tend to benefit from favourable conditions, especially when conducted within a supportive regulatory framework, such as regulatory sandboxes. Nevertheless, pilots without such a supportive regulatory environment are forced to modify their market designs to comply with existing implementation rules. As pilots are designed to minimise risk and include measures to limit dynamic change, they are not inherently the most appropriate environments for testing scalability. This is largely because the structure of a pilot is pre-determined, from predetermined market participants and pre-selected geographic locations to support from private or public funding, and thus often does not need to be commercially viable. Hence, most P2P energy trading initiatives remain at the pilot stage, with few moving beyond their initial trials. This stagnation highlights a critical gap in the understanding of the scalability and sustainable operation of these markets outside controlled environments.

Part II: Scaling-up P2P energy trading systems

Section 2.3 has shown that while pilot projects are effective for exploring new business models, they are limited in their ability to thoroughly test the scalability of P2P energy trading systems. This limitation arises because pilot projects are primarily designed to implement innovative ideas in a controlled and minimised risk environment. As a result, these projects may not fully capture the complexities and challenges of scaling up in more diverse and uncontrolled real-world environments.

The second part of the literature review aims to further explore the concept of scalability as discussed in the academic literature and consider its applicability to LEMs. It will examine the diverse nature of scalability, from theoretical principles to practical considerations. The first section examines the concept of scaling up, particularly in relation to new business models and pilot projects. The second section includes a review of different methodologies for investigating the scale-up of new concepts in the energy sector. The third section provides an analysis of the current understanding of scalability in the context of P2P energy trading systems, highlighting the existing gaps in the academic research. Finally, open research questions arising from this discussion are identified and presented.

2.4 Dimensions of ‘scaling-up’

The use of pilot projects in the energy sector is a relatively recent phenomenon and has been encouraged through the changes in the type and scale of new energy generation assets and new market actors. To date, there has been a lack of research focused on exploring methods to assess the scalability of P2P energy trading systems, with the aim of facilitating their scale-up beyond the initial pilot phase. This section seeks to fill this knowledge gap by examining concepts from other sectors and industries, that can inform the scaling up of P2P energy trading pilot projects.

Pilot projects have been widely used as a means of testing innovations in real-world settings, particularly in development interventions (Hartmann et al., 2008; Naber et al., 2017) as well as epidemiology and medical clinical trials (Thabane et al., 2010). In these contexts, pilots are typically viewed as feasibility studies conducted prior to the large-scale implementation of a novel intervention (Thabane et al., 2010). Consequently, much of the literature on scaling, particularly in relation to the scaling up of pilot projects, is published under this domain. The World Health Organization (WHO) defines ‘scaling up’ as “deliberate efforts to increase the impact of successfully tested health innovations to benefit more people and to foster policy and programme development on a lasting basis” (WHO, 2010). The WHO provides a guide for a scaling-up strategy in response to the lack of know-how on systematic planning processes to achieve a larger scale and impact. In the same context, the WHO (2016) further describes scalability as “the ability of a health intervention shown to be efficacious on a small scale and or under controlled conditions to be expanded under real-world conditions to reach a greater proportion of the eligible population while retaining effectiveness”. Similarly, the World Bank’s Global Poverty Report, which focuses on development projects, defines ‘upscaling’ as “the need to go beyond business as usual, to embrace new technologies, new institutional arrangements, and new approaches that will enable countries and communities to overcome capacity constraints and improve development effectiveness” (World Bank, 2005). Broadly speaking, these definitions can be applied to the scaling up of LEMs, although their actual implementation may change due to the inherent characteristics of electricity markets and grids, which differ from those of other sectors.

The upscaling frameworks that have been developed by WHO (2016), Hartmann et al. (2008) and Uvin (1995) present a multifaceted approach to scaling projects. These frameworks include ‘qualitative upscaling’, which allows for geographic expansion or replication in new areas; ‘functional upscaling’, which focuses on diversifying services; ‘political upscaling’, which engages with political

networks to support growth and address structural challenges; and 'organisational upscaling', which strengthens the project's structure through private and public sector funding. Similarly, the World Bank's approach includes 'spatial upscaling' to scale up or replicate projects; 'intertemporal upscaling' to extend projects to gain deeper insights; 'macroeconomic framework upscaling' to adapt the operating environment and initiate reforms; and 'international and cross-border upscaling' to strengthen international organisational linkages and facilitate knowledge sharing. Although not specific to the energy market, these collective findings provide an overview of scaling up initiatives, showing their multidimensional and context-specific nature.

A framework that is contextually closer to the scaling of LEMs is proposed by van Winden et al. (2017), based on smart energy solutions. The authors categorise scaling into 'roll-out', 'expansion' and 'replication' in order to understand how to effectively scale up smart city projects, which often involve complex interactions between technology, policy and community engagement:

- Roll-out: "Bringing a smart city solution to the consumer or business-to-business market, or applying the solution in the entire organisation"
- Expansion: "Add more partners, users, or functionalities to a smart city solution, or enlarging the geographic area in which the solution is applied"
- Replication: "Replicate (exactly or by proxy) the solution in another context by the original partners involved in the pilot project or by others"

Figure 2.6 presents a schematic illustration of the three types of scaling. The roll-out method is generally applied to pilots that are trying to scale up their business proposition, i.e. manufactured offerings like products. Expansion refers to the continuation of the project beyond the pilot stage through collaboration with other companies and partners, increasing the area or scope of a project. This is usually applied to platform-based projects and online solutions. Finally, replication is when the concept proposed by a pilot project can be replicated in a different context and understood, for example, by another organisation. The context sensitivity increases from left to right between roll-out, expansion and replication (van Winden, 2016).

In order to facilitate the scaling of pilots, certain conditions and requirements need to be met, as identified by van Winden et al. (2017), which, if not present, will reduce the likelihood of a pilot going to scale. These include the 'prospect of economies of scale', which implies the reduction of

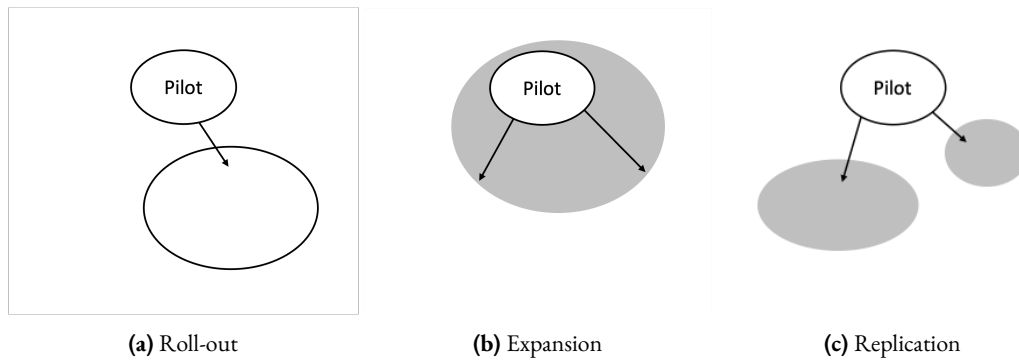


Figure 2.6: Schematic illustration of the three types of scalability of pilot projects.

fixed costs by spreading them over a larger number of users. This concept is particularly relevant for digital platforms, where the balance between supply and demand is crucial. Subsidised growth, such as incentivising users to join a platform, can help to balance these elements. 'Managing ambidexterity' is another critical factor, requiring organisations to effectively navigate the exploration stage (pilot phase) and the exploitation stage (scaling phase). Each stage requires a different set of skills, and it is crucial to manage these skills separately, while ensuring appropriate information sharing. Knowledge transfer mechanisms are essential, especially when replicating a project in a different geographical or cultural context. Successful replication can be facilitated by involving potential scaling partners or sites from the beginning of the project. 'Regulatory, legal and policy frameworks' have a major impact on the scalability of a project. These frameworks determine the conditions under which scaling takes place. Many pilot projects operate in protected niches or regulatory playgrounds that may not be replicable in the real world. However, sharing information and results on a global scale could influence long-term regulatory development. 'Data and system interoperability' is also critical, especially for IT-focused projects. The success of these projects often depends on the ability to share data and seamlessly integrate different systems. A lack of common standards and protocols, coupled with a general lack of interest in sharing data between organisations, can hinder project success. Finally, 'establishing standards for measuring return on investment' is critical but is challenging due to the immature stage of many pilot projects, especially in the clean energy sector, which is characterised by complex and fluctuating price structures and unpredictable policies.

To draw conclusions from these areas of scaling, it is important to recognise that scalability in complex systems such as energy markets or smart city solutions is not a one-size-fits-all process. Each type of scaling addresses different aspects and challenges of growth and adaptation. The choice of

scaling strategies depends on the specific objectives, resources and environmental factors of the project. For example, roll-out strategies may be more appropriate for technology-driven solutions with a clear market demand, while replication strategies may be more appropriate for community-based projects where local context and stakeholder engagement are key factors. Furthermore, the interplay between these types of scaling suggests that a successful scaling strategy may involve a combination of these methods. A project may start with a roll-out, gradually expand as it gains partners and resources, and finally replicate in different contexts as it proves its effectiveness and adaptability. It should also be noted that private and public sector organisations may have different approaches and interests in scaling up initiatives. While private sector organisations may have a commercial interest in scaling up a project or product, the public sector often has less incentive to take a project forward beyond the pilot stage.

In the context of P2P energy trading, scalability can take the form of expansion (scaling up by increasing the number of participants) or replication (scaling out to another location). These two forms of scaling are not mutually exclusive; a P2P energy trading pilot project may initially scale up before external factors require it to replicate in new locations. The next section focuses on the assessment of different scalability theories and methodologies for new innovations in the energy sector that can be applied to P2P energy trading.

2.5 Scaling theories

This chapter provides an overview of the different theoretical frameworks and methods that have been developed to analyse and improve the scalability of innovative projects, and their contribution to providing insights into the scalability challenges of the concepts studied. In particular, in the context of smart grids and P2P energy trading, Strategic Niche Management and Scalability Replicability Analysis are identified as two prominent approaches to assess the growth potential and wider applicability of pilot projects. These are explained in more detail below and their applicability to P2P energy trading systems is discussed.

2.5.1 Strategic niche management

One method frequently used in literature to assess the growth and scalability potential of sustainable energy solutions is Strategic Niche Management (SNM), which is part of this Multi-Level Perspective (MLP) of transition theory by Schot et al. (2008). The concept is based on the idea that sustainable innovations require technological niches, which are “protected spaces that allow nurturing and experimentation with the co-evolution of technology, user practices and regulatory

structures” Schot et al. (2008). This multi-level perspective is based on niches, regimes and landscapes (Geels, 2002). While at the regime level dynamically stable sociotechnical innovations can be found, landscapes are deep structural changes in a society that can be influenced by regimes but are more difficult to change (Geels, 2002). The process of nurturing niches is a bottom-up approach that starts with designing technological niches, conquering market niches and, in the long run, replacing and transforming an existing regime (Schot et al., 2008).

A study by Naber et al. (2017) developed a framework for assessing the upscaling potential of sustainable energy solutions using a comparative qualitative case study design. The authors distinguish four types of upscaling patterns: (1) ‘growth’, meaning that as an experiment continues, more participants join or market demand increases; (2) ‘replication’, meaning that an experiment is replicated in another location or context; (3) ‘accumulation’, meaning that one or more experiments are linked; and finally (4) ‘transformation’, meaning that an experiment is transformed across the levels of the MLP. This means that an experiment diffuses into the wider social environment and contributes to institutional change (Naber et al., 2017). An example of the application of SNM in the context of local energy markets is provided by Ruggiero et al. (2018). In an interview study, the authors use the concept of SNM to understand the scalability challenges of a community energy project in Finland concluding that the limiting factors for scale-up include a lack of vision on how to achieve scalability and an unfavourable policy and regulatory framework.

A graphical representation of all four upscaling patterns by Naber et al. (2017) can be seen in Figure 2.7. The authors conclude that experiments that are well managed in the context of SNM are more likely to scale successfully than others. MLP and SNM can be seen as holistic frameworks that capture the complexity of sociotechnical systems and highlight the multiple dimensions associated with transitions. However, MLP often takes an abstract approach to explaining how niches diffuse.

A common criticism of transition theory in general is that it provides limited guidance to policy-makers and managers in terms of concrete actions to promote niche technologies or accelerate transitions (Voß et al., 2009). Among other things, Genus et al. (2008) criticise the lack of attention to the specifics of each case study and the uncritical use of historical data in many transition studies. They argue that there has been insufficient attention to the politics and power dynamics within regimes and niches, neglecting issues of agency, control and influence that shape transitions. In addition, user practices, consumption patterns and everyday realities are often overlooked in

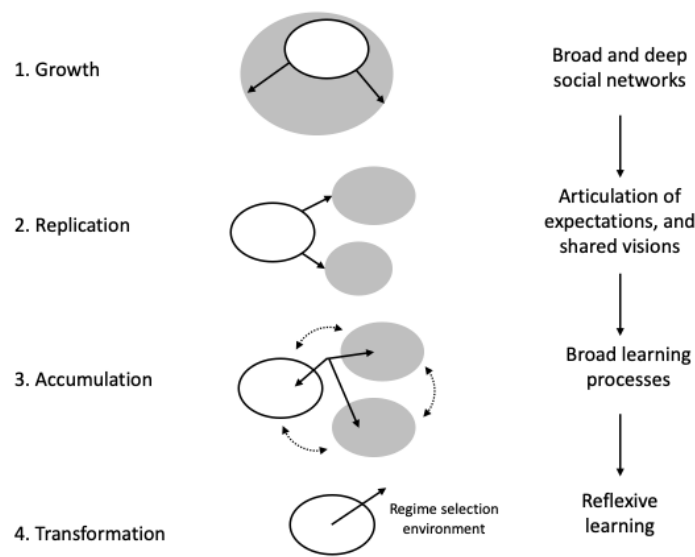


Figure 2.7: Patterns of upscaling and relations with SNM processes (adapted from Naber et al. (2017)).

transition analyses. The complex specificities of how technologies are embedded and stabilised (or destabilised) in society remain underexplored. As a result, transition theories tend to lack concrete practical guidance for policymakers on how to intentionally promote and manage niche technologies or manage sustainability transitions. By neglecting issues of power, agency and incremental dynamics in regimes and niches, transition theories are limited in their ability to inform policy aimed at accelerating the adoption of sustainable technologies and broader system transformations.

2.5.2 Scalability and replicability analysis

In contrast to the SNM, the scalability and replicability analysis (SRA) method has a more applied background, having been developed through a series of EU-funded initiatives with the aim of maximising the lessons learned from Smart Grid trials. The method focuses on assessing the potential for Smart Grid pilots to be scaled up across Europe. It does this by systematically examining key functionalities, fostering knowledge exchange and identifying regulatory barriers that could hinder wider deployment and scaling up. In practice, the SRA tool evaluates pilots under different conditions and examines various scalability factors to uncover insights that guide the wider deployment of these technologies (Rodriguez-Calvo et al., 2018). A successful SRA result indicates that a system can be scaled or replicated without compromising its fundamental performance (Menci et al., 2021). Essentially, the SRA tool aims to move from stand-alone pilots to a more integrated approach that promotes regulatory progress and collaborative knowledge

sharing, which is essential for large-scale smart grid deployment.

SRA has been applied in several EU funded Smart Grid projects such as Grid+, Grid4EU, SuSustainable, IGreenGrid, SiNGULAR, InterFlex, InteGrid, Bridge and EUniversal. The main objective of the SRA application is to assess the feasibility of scaling up and replicating solutions tested in one country across the EU. This approach aimed to cultivate a common pool of knowledge and facilitate the exchange of experiences and lessons learned between different projects. The range of projects that have implemented SRA and the contexts in which it has been used are detailed in Table 2.2.

Project	Year	Description	Source
Grid+	2012	Studied prerequisites for scalability and replicability of smart grid projects, with emphasis on technical solution characteristics. Surveyed publicly funded smart grid projects in Europe to identify factors considered in assessing potential for scaling up and out from pilots.	(Grid+ Project, 2012)
Grid4EU	2012-2016	Developed SRA methodology covering technical, regulatory, economic and stakeholder dimensions. Project demonstrating large-scale advanced smart grid solutions across six European countries. Tested functions like demand response, DER, grid supervision. Qualitative and quantitative SRA using simulations to understand effects of implementing solutions in other contexts. Aimed to provide insights on scalability and replicability for decision-makers.	(Grid4EU Project, 2014)
IGREENGrid	2013-2016	Focused on increasing hosting capacity for DER in low and medium voltage grids. Project demonstrating solutions across six EU countries. Technical and economic SRA. Technical SRA involved screening feeders, load flow analysis to determine achievable hosting capacity, and evaluating KPIs like losses.	(IGreenGrid Project, 2016)
SuSustainable	2012-2015	Focused in increasing DER hosting capacity in distribution grids. Project demonstrating solutions in Portugal, with goal of scaling and replicating in UK, Germany, Greece. Survey of functionalities and boundary conditions relevant in different contexts. Mapped technical and regulatory barriers against functionalities to develop SRA scenarios per country.	(SuSustainable Project, 2014)
SiNGULAR	2012-2015	Focused on increasing renewable energy integration in isolated grids using sensing, control methods, communications. Project demonstrating integration of renewable energy with centralised generation across five European countries. Testing advanced sensing, intelligent control, bidirectional communications in isolated grids to enable increased renewables.	(SiNGULAR, 2016)
InterFlex	2017-2019	Managing distribution grid constraints using local flexibility from storage, DERs, EVs, heat pumps to identify key factors affecting scalability and replicability of congestion management and voltage control solutions. Project across five EU countries testing integration of local energy markets and demand response. Technical SRA (system logic, ICT) and non-technical SRA (regulatory, stakeholder perspectives). Simulation tools used depending on use case. Qualitative and quantitative assessment of key functionalities under different boundary conditions to evaluate scalability and replicability	(InterFlex Project, 2019)
InteGrid	2017-2020	Focused on increasing system reliability and DER integration through flexibility management, Virtual Power Plants (VPP), load/generation aggregation to derive generally applicable recommendations on scaling up and out. Project demonstrating solutions at three sites across EU. SRA covering functional, ICT, economic, regulatory dimensions. Assessed scalability of clustered smart grid functions. Used power flow simulation and sensitivity analysis. Tested flexibility management, VPPs, aggregation to provide grid services. Evaluated scalability and replicability of functionality clusters against different dimensions.	(InteGrid, 2022)
Bridge project	2014-2020	Cooperation project among 90 Horizon 2020 smart grid/storage/digitalisation projects to harmonise SRA practices across H2020 projects and stakeholders to improve knowledge exchange. Developed common SRA methodology through surveys and review of existing project approaches. Task force surveyed projects on their SRA status and practices. Synthesised methodological guidelines based on survey findings.	(Bridge Project, 2019)
EUuniversal	2020-2023	Focused on DSO use of flexibility and interaction with new flexibility markets to assess scalability and replicability of flexibility use cases and DSO-market solutions. Project across three EU demos, testing 10 business use cases. SRA methodology covering functional, business, regulatory and stakeholder perspectives. Developing universal market enabling interface for DSO flexibility and market interaction.	(EUuniversal, 2019)

Table 2.2: Overview of applications of SRA in EU-funded projects.

As one of the first projects, Grid+ was launched in 2012 to implement the objectives of the European Electricity Grids Initiative, mainly targeting distribution and transmission grid projects. The project focused on studying the prerequisites for smart grid projects to be scalable and replicable, focusing on the technical characteristics of smart grid solutions. In addition, the work included a survey of publicly funded Smart Grid projects across Europe to assess what factors were considered when assessing the scalability and replicability of a pilot project (Grid+ Project, 2012). IGREEN-Grid, SuSustainable and SiNGULAR were all part of the same EU-funded call on the integration of variable DER in distributed energy networks. Therefore, all of their SRA evaluations were similar in their approach, as they were designed in close collaboration and had a strong focus on distribution networks (Rodriguez-Calvo et al., 2018). More recent projects, such as InterFlex, InteGrid, Bridge and EUniversal, build on the SRA methodologies proposed by the previous projects.

The key element of an SRA is the analysis of the scalability and replicability of a system, where a system is generally understood as a set of elements interacting within a similar environment or boundary conditions (Sigrist et al., 2016). Boundary conditions can have different origins, such as social, technological, economic and others. They define the environment or conditions in which a system operates. The boundary conditions are defined by the parameters of a system that affect its ability to scale (Rodriguez-Calvo et al., 2018). While both scalability and replicability potential are necessary for any system to perform well, the two concepts are inherently different but can influence each other.

The term *scalability* refers to the scaling up of an existing system, which means increasing its size, scope or range without significantly changing the environment in which it operates, mainly to respond to growing demand in one form or another. In contrast, *replicability* or scaling out refers to the ability of a system to be duplicated or replicated in a different environment, which can refer to a temporal, geographical or grid typological component (Menci et al., 2021; Rodriguez-Calvo et al., 2018; Sigrist et al., 2016). Some authors also highlight variations within the terms themselves. A system can be scaled either in density or in size. The former refers to extending the scope of a project, for example by increasing the variation of parameters or the volume of DERs, while the latter refers to implementing a project in a larger area while maintaining similar environmental conditions. In terms of replicability, a distinction is made between intranational and international replicability. The former assumes the replicability of a project in another location

while maintaining similar environmental conditions in terms of regulation but not technology, whereas in an international replication most environmental conditions will vary (Rodriguez-Calvo et al., 2018). Table 2.3 provides an overview of the definitions used for the terms scalability and replicability in SRA studies conducted on smart grid projects.

Scalability	Replicability	Source
“ <i>Scalability</i> refers to the increase in a system in relation to its size, scope, or range while ensuring that its ability to adequately meet the grid’s technical requirements is not compromised.”	“ <i>Replicability</i> refers to the capability of the proposed technical solution to be implemented within another network, location or time.”	(InterFlex Project, 2019)
“<i>Scalability in density</i>: the scope of the use case is widened in terms of variation of parameters, such as the number of consumers involved, the volume of participating distributed energy resources (DER) or the implementation degree of the smart grid solution. <i>Scalability in size</i>: the implementation of the use case is assessed for a larger area. For instance, at a regional level, boundary conditions related to regulation and stakeholders will be the same or very similar, but may involve different types of distribution networks, sub-areas of different load density, and so forth.”	“<i>Intranational replicability</i>: the implementation of the use case is analysed for different distribution areas in the country of the demonstrator. Similar boundary conditions may be expected regarding regulation, perspectives of stakeholders, or technical aspects such as voltage levels. However, different locations may involve different network architectures, different reliability levels, and so forth. <i>International replicability</i>: the implementation of the use case is analysed for areas in different countries. The boundary conditions may differ widely, including different regulation schemes, network characteristics, economic conditions or stakeholder perspectives.”	(Rodriguez-Calvo et al., 2018)
“ <i>Scalability</i> can be defined as the ability of a system to change its scale in order to meet growing volumes of demand”. A system is understood as a set of interacting elements with similar boundary conditions.”	“ <i>Replicability</i> denotes the property of a system that allows it to be duplicated at another location or time.”	(Sigrist et al., 2016)

Table 2.3: Definitions of scalability and replicability in the context of SRA.

The primary aim of SRA is to formulate rules for scaling up and replicating specific pilot projects in the European context, focusing less on technical components and more on the functional benefits of the solutions, adopting a technology-agnostic approach. In the GRID4EU SRA, each use case is evaluated against pre-defined key performance indicators (KPIs) that are relevant to either general aspects, specific functionalities or the use case itself. The process starts with a technical SRA to identify how technical constraints, such as grid topology, geographical factors, generation and demand profiles, affect scalability and replicability. Simulation tools appropriate to each use case are used for this analysis, followed by sensitivity assessments to estimate expected KPIs. This is followed by the economic SRA, which examines the impact of economic constraints ranging from electricity prices and tariffs to subsidies and incentives. Sensitivity analyses, both technical and economic, explore the impact of parameter variations on KPIs. Recognising the influence

of stakeholder behaviour on project outcomes, GRID4EU recommends conducting separate stakeholder acceptance analyses, possibly using questionnaires, to understand the perceptions and interactions between stakeholders. Depending on the contextual parameters of a case, this can be critical given the significant influence that stakeholders have on the course of a project. In addition, the assessment includes a review of the regulatory framework to identify existing barriers and potential drivers for change, which is essential to improve scalability and replicability. The culmination of these assessments leads to the formulation of scaling and replication rules, derived from factors identified in the technical and economic SRAs. Figure 2.8 shows the flowchart outlining the SRA process described above.

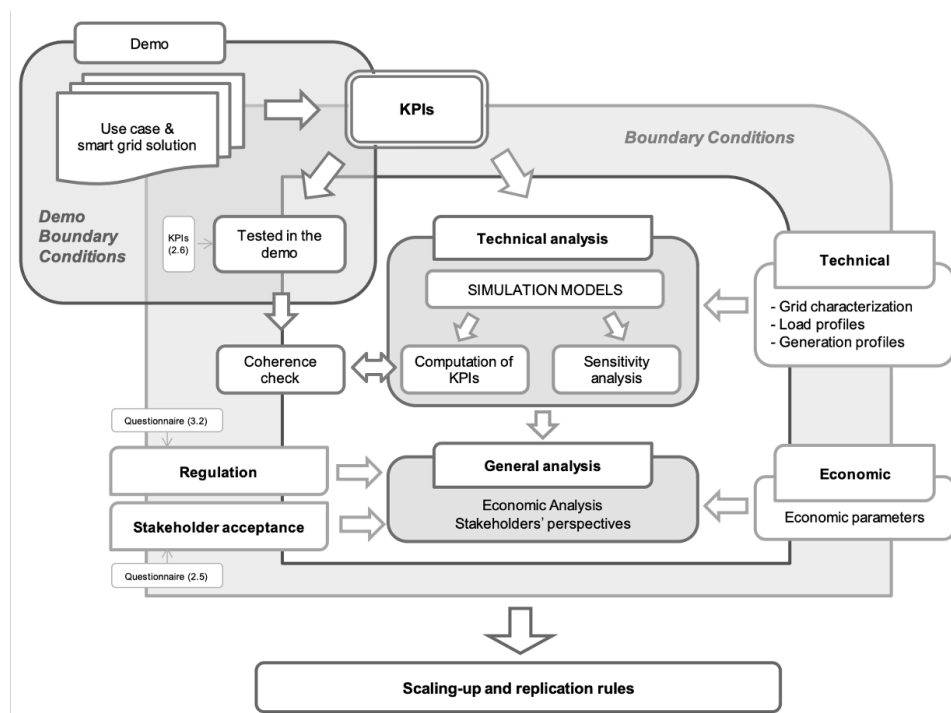


Figure 2.8: Flowchart SRA (Grid₄EU, 2014).

Based on the GRID4EU initiative, Rodriguez-Calvo et al. (2018) have developed a methodology structured around a five-step approach to perform an SRA, applied to the optimisation of distribution systems. This focus is in line with the approach of SRA methodologies applied in EU-funded pilot projects, which mainly focus on the distribution system level. This structured methodology is developed through a series of steps aimed at providing a comprehensive assessment of the potential for scalability and replication of smart grid technologies. The first step is to select appropriate simulation tools and define KPIs, including addressing the definition of the simulation timeframe based on the project objective. The second step is to define representative networks and scenarios

within the distribution system that reflect the practical challenges and opportunities of smart grid implementations, and the third step is to perform simulations to calculate KPIs under both existing and potentially changed conditions. This phase is essential for establishing baseline performance metrics, exploring how different network scenarios affect KPI results through sensitivity analysis, and assessing the feasibility of scaling based on these metrics. Fourth, adjustments to the simulation parameters, while maintaining consistent boundary conditions, are used to evaluate scalability with respect to project size. Finally, in addition to the technical assessments, the methodology includes a non-technical SRA to explore economic, social and regulatory factors that may affect the adoption of smart grid technologies. This analysis aims to identify the key drivers and barriers to technology adoption, providing a holistic view of the conditions that support scaling and replication.

By following these steps, the methodology facilitates the creation of guidelines for effectively scaling up and replicating smart grid technologies in different contexts, including considerations of size, density and geographic spread. Figure 2.9 provides an overview of this methodology and illustrates the systematic approach to developing an understanding of the scalability and replication potential of smart grid projects.

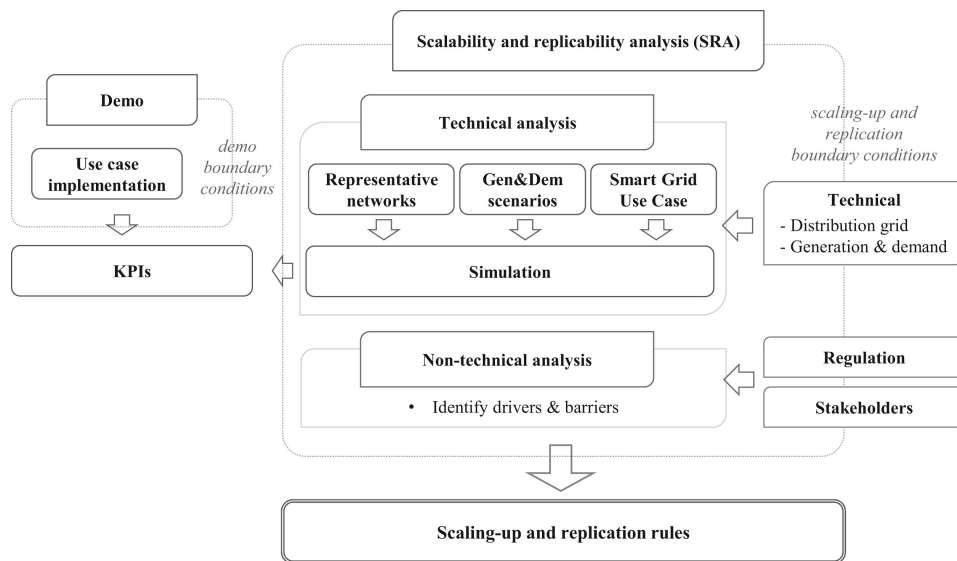


Figure 2.9: Methodology for SRA for smart grid use cases (Rodríguez-Calvo et al., 2018).

In more recent European projects such as InterFlex and InteGrid (Le Baut, 2018; InterFlex Project, 2019) the SRA as proposed by Grid4EU Project (2014) has been further simplified to (i) *pre-evaluation*, (ii) *execution* and (iii) *closure* with results and conclusions:

- (i) Collecting and analysing available data, providing detailed use case overviews, analysing key functionalities and establishing relevant KPIs. This phase also includes defining different scenarios to test the scalability of the project in terms of size and density, and its replicability in different national and international contexts.
- (ii) Conduct simulations based on these scenarios, including baseline and future projections, coupled with economic and non-technical analysis that includes cost assessment, business model and regulatory factors evaluation
- (iii) Evaluate the impact of the SRA and, based on their findings, develop specific rules and guidelines for scalability and replicability.

All SRAs discussed aim, despite their different structures, to explore the multiple aspects that influence the scalability and replication of innovative solutions in different contexts. The specific structure of an SRA is largely influenced by its focus areas, which can range from technical to economic, social or regulatory factors, depending on the objectives of the project under review. In summary, an SRA provides a comprehensive methodology for examining the conditions necessary for the successful uptake and scale-up of innovative solutions in different settings. This approach goes beyond simple technology demonstrations and advocates an in-depth examination of the barriers and facilitators to scalability and replication. By emphasising the importance of gathering and sharing evidence on these factors, SRAs contribute to a richer collective knowledge base that improves policymaking processes. This can lead to well-informed policy adjustments and the creation of incentives to promote the wider application of proven solutions.

However, it is important to recognise that the standard SRA methodology may not be appropriate for all pilots or innovations. Customisation and adaptability are often essential to address the unique characteristics of each technology and its operational context. The effectiveness and depth of insight from an SRA depends on the rigorous and consistent application of the methodology across different projects to accurately measure and understand its impact on facilitating post-pilot growth and wider adoption of solutions. While SNM provides a framework focused on developing innovations in protected environments, SRA is well suited to exploring and improving the potential for scaling pilot initiatives such as P2P energy trading systems. SNM is about creating enabling environments for innovation, whereas SRA focuses on the potential for scaling innovation by methodically assessing a range of influencing factors.

This section has shown that while pilot projects are effective for exploring new business models, they are limited in their ability to thoroughly test the scalability of P2P energy trading systems. This limitation arises because pilots are primarily designed to implement innovative ideas in a controlled and low-risk environment. As a result, these projects may not fully capture the complexities and challenges of scaling up in more diverse and uncontrolled real-world environments. The following chapter examines the scalability challenges faced by pilot projects, aiming to identify strategies for overcoming these barriers and paving the way for the wider uptake and sustainability of P2P energy trading models.

2.6 Scalability in the context of peer-to-peer trading

The previous sections have looked at P2P energy trading in academic literature, but also in terms of its practical implementation. This section narrows the focus to examine scalability in more detail. Specifically, it discusses how scalability is currently being addressed in the context P2P energy trading systems. The aim is to identify current research gaps that need to be addressed in order to support the scale-up of P2P energy trading systems and derive relevant research questions this thesis will address.

2.6.1 Current understanding of scalability in P2P energy trading

Most existing research has concentrated on the operation and analysis of energy trading markets, with a strong emphasis on market designs and mechanisms. In these studies, the term scalability typically refers to the computational scalability of the settlement procedures proposed for these mechanisms. The next section provides an overview of current research that specifically addresses computational scalability in this context.

Morstyn et al. (2019b) introduce a scalable market design for P2P energy trading, proposing a bilateral contracting network that incorporates a mix of real-time and forward markets to address forward market uncertainty. The model integrates utility-maximising preferences of different types of agents, including generators, suppliers and prosumers with different energy profiles. The design aims to streamline market processes by reducing the complexity of coordinating interactions across multiple market layers and agent types. This reduction in complexity is critical to enabling scalability as the number of participants increases. Another approach, by Morstyn et al. (2019a), presents a multi-class energy management system that protects the privacy of prosumers' data while promoting scalability in P2P markets. The method uses a distributed optimisation model that does not compromise prosumers' privacy for scalability, demonstrating that P2P markets can expand

without exposing sensitive information. Khorasany et al. (2019) address scalability by proposing an adaptive segmentation method to simplify market clearing. This method clusters market participants based on certain attributes, allowing for more manageable segments that facilitate faster agreement on prices and traded amounts of energy. This segmentation has a direct impact on computational complexity and scalability, showing that increasing the number of segments can significantly reduce the computational burden. Han et al. (2019) apply cooperative game theory to group energy customers into coalitions, which reduces the number of direct market participants and thus the computational time for market settlement. This approach maintains incentives for participation, while addressing scalability through a clustered model that accommodates more participants with a reduced computational burden. Similar studies were conducted by Yujian Ye et al. (2021), Dawei Qiu et al. (2021), Morstyn et al. (2020b), and Guo et al. (2024).

Taken together, the above studies illustrate that scalability in P2P energy trading has primarily been conceptualised in terms of computational complexity. They focus on market design, privacy, segment clustering and cooperative game theory to address scalability concerns. While addressing computational scalability is critical to the adoption of P2P energy trading systems, it addresses only one of many challenges to scaling P2P energy trading systems. A review by Capper et al. (2022b) suggests that academic discourse has largely bypassed concerns about scaling up LEMs, that is, extending the current limitations imposed on these systems by their operating environments. This oversight suggests a gap in the literature on the wider implications of scalability for LEMs and P2P energy trading systems, and points to the need for further research and analysis in this area.

2.6.2 Barriers to scalability in P2P energy trading pilots

As P2P energy trading systems evolve, understanding how to scale local energy trading markets will become increasingly crucial. However, few studies in the literature address scalability beyond computational analysis. The following section will discuss key barriers to scaling these markets.

An article by Morstyn et al. (2021) discusses the role of P2P energy trading in enabling the scalable integration of DERs into the energy system. Scalability in this context is defined as the ability of P2P energy trading systems to accommodate increasing numbers of participants and transactions without compromising efficiency or system integrity. The discussion highlights unresolved challenges in scaling P2P energy trading, such as managing network constraints and aligning local trading activities with broader system objectives. To address these issues, the authors propose a multiscale design framework for P2P energy trading that integrates local transactions with system-wide needs,

highlighting the need for cross-platform coordination mechanisms. This approach to scalability goes beyond computational efficiency, focusing on the systemic adaptability of P2P energy trading to enable whole-system integration across distribution and transmission networks and different market levels. Bonfert (2024) explore the transformative potential of Local Energy Communities (LECs) in Europe, highlighting their role in democratising, decentralising and embedding social values in the energy system, amidst economic and regulatory challenges. There is a strong focus on the scalability of LECs, highlighting the critical role of municipalities, legislation and various stakeholders in supporting their growth and wider implementation. Informed by the Foundational Economy framework, the study assesses the governance, transferability and social impact of scaling up LECs through the lens of pilot projects in the Netherlands, Belgium, Sweden and the UK. It highlights the limitations cities face in terms of authority and resources to scale up LEC innovations, the cautious approach of private firms to non-financially beneficial innovations, and the propensity of municipal enterprises to adopt such innovations with varying degrees of citizen participation. The article concludes that effective legislation is essential to remove barriers to innovation, facilitate scalability and ensure democratic participation in LECs, thereby contributing more effectively to a sustainable energy transition. Perger et al. (2022) have developed a stochastic optimisation model to help energy communities make better decisions when selecting new participants, taking into account uncertainties such as member departures and potential new entrants. The model, which extends an existing two-stage optimisation approach, allows the community to plan ahead by calculating optimal contract durations and comparing the effectiveness of the stochastic approach with a deterministic alternative.

While initial attempts have been made to investigate the scalability of P2P energy trading systems, there are still many areas that have yet to be explored through a mix of physical pilot projects or simulation environments. Pilot projects are particularly suitable for overcoming technical implementation challenges. This may include integrating physical grid hardware, securing controllable assets and responding to capacity constraints (Papadaskalopoulos et al., 2021). In order to create P2P energy trading systems that can be scaled up, there are a number of additional socio-economic and regulatory challenges that need to be addressed. Real-world P2P energy trading markets are vulnerable to disruptions such as power outages and unforeseen events that can jeopardise market operations and risk the loss of transaction data (Junlakarn et al., 2022). However, the controlled settings of pilot projects can obscure how different behaviours affect financial profitability, as regulations often restrict the use of financial transactions (Slingerland et al., 2021). At the same

time, the structured nature of pilot projects makes it difficult to test the opt-in/opt-out dynamics of the market, which can lead to discriminatory or non-transparent market designs in terms of size, type, timing and diversity of participants (Papadaskalopoulos et al., 2021).

Besides technical implementation challenges, high upfront costs and limited awareness of market concepts among private developers, along with their environmental and social benefits, are cited as significant barriers to the scalability of P2P energy trading systems (Papadaskalopoulos et al., 2021). Such high upfront costs, coupled with uncertain future revenues, make it difficult to set market prices, while fluctuating participation rates add to this uncertainty (Junlakarn et al., 2022). Business models for LEMs remain largely undefined, with a focus on market implementation and participant engagement rather than defining business models for market operators (Weinhardt et al., 2019). In addition, many virtual pilot projects have shown that savings are not significantly better than in standard operations (Plewnia et al., 2021). Building trust, setting attractive prices and demonstrating tangible benefits are crucial to engaging participants in the long run (Junlakarn et al., 2022).

The complexity of the concepts, concerns about external data security and scepticism about the impact of renewable energy generation and demand shifting can be additional barriers (Papadaskalopoulos et al., 2021). Although community building can mitigate some of these challenges, its success depends heavily on the nature and size of the community and the specific context (Slingerland et al., 2021). Furthermore, assumptions about behavioural concepts such as theoretical rationality in market design need to be re-evaluated. Ensuring trust, inclusiveness and fair distribution of benefits is crucial for the adoption of P2P energy trading markets (Papadaskalopoulos et al., 2021; Junlakarn et al., 2022).

An important factor that can influence the scaling up of P2P energy trading systems is the political and regulatory environment. Sandbox conditions can be used as a temporary workaround to these constraints, but they do not provide a longer-term solution for testing the potential of P2P energy trading systems. P2P energy trading markets need to be able to adapt dynamically to changing regulatory frameworks (Doumen et al., 2022). Sandboxes could also hinder the full testing of P2P markets under current regulation, potentially missing key insights into necessary adjustments (Junlakarn et al., 2022; Weinhardt et al., 2019). Policymakers and regulators are thus faced with the task of either fostering a dynamic regulatory environment or introducing stable but potentially complex and bureaucratic regulations (Papadaskalopoulos et al., 2021). Future regulation will need

to address how private companies work with public bodies and manage property rights, which are crucial for access to infrastructure and will also affect the ownership and processing rights of data, such as that from smart meters (Junlakarn et al., 2022).

Another factor limiting the scalability of P2P energy trading systems is their context dependency. The Quartierstrom project highlighted that it is necessary to recognise the unique contextual, situational and methodological constraints that call into question the generalisability of the results of such projects. The limitations imposed by factors such as small sample sizes and limitations on the number of participants due to technical constraints have a significant impact on the potential for scalability and the ability to apply lessons learned in different contexts (Ableitner et al., 2020). Additionally, a recurring barrier to scaling is the lack of comprehensive planning and evaluation of scalability opportunities in the early stages of design. While pilot projects are fundamentally about exploring new ideas, formulating a scalability strategy in advance is critical to increase the chances of successful expansion. Furthermore, research suggests that the particular context and group dynamics within initiatives such as community energy projects have a profound impact on their scalability (Ruggiero et al., 2018). This pronounced contextual dependency in the expansion of P2P energy trading markets requires careful consideration in future projects. Given the uniqueness of each case, the practicality of universally applying standard market scaling strategies is questionable, pointing to the need for approaches that are more tailored and sensitive to specific contexts.

Although P2P energy trading pilot projects have demonstrated successful implementation under real-life conditions, it is essential to acknowledge that these projects are typically conducted in controlled environments with favourable conditions (Doumen et al., 2022). These conditions may include the pre-selection of suitable participants, the availability of required assets, and the existence of a regulatory framework that is conducive to the project's objectives. While this may limit the ability to test the full integration of P2P energy trading markets into existing energy systems, it also helps to manage the risk associated with implementing innovative business models. Generally speaking, as pilots aim to prove the viability of the concept, they may not always consider the strategies required to expand the scope of the project beyond its initial objectives, or may be constrained by external conditions. As P2P energy trading markets seek to scale beyond the pilot stage, it is crucial to recognise that the initial favourable or unfavourable conditions may not persist. This recognition is essential to address potential challenges that could impact the effectiveness and sustainability of the project.

2.7 Summary and open questions

The previous chapters have examined scalability in the academic discourse, particularly its diverse nature, from theoretical principles to practical considerations within LEMs. Limitations in research assessing the scalability of P2P energy trading projects have been identified, suggesting a need to explore strategies that facilitate their scale up within pilot phases. This exploration included reviewing different scalability methodologies, understanding the multidimensional nature of scaling projects, and identifying current understanding and gaps when it comes to scalability in the context of P2P energy trading systems.

P2P energy trading pilots provide a unique insight into the potential and challenges of implementing new business models in the energy sector. However, their scalability to wider, uncontrolled real-world conditions remains a significant challenge. While successful in controlled environments, pilots often fail to capture the full complexity of scaling up, as they are designed to minimise risk and explore innovative ideas in a somewhat ideal environment. The scalability challenges for P2P energy trading systems are diverse and include technical, socio-economic and regulatory hurdles. Recurring themes cited as reasons for the lack of scalability of In addition, P2P energy trading systems need to be able to respond to a changing regulatory landscape (Bonfert, 2024; Slingerland et al., 2021; Doumen et al., 2022). Although pilots are often conducted in pre-defined environments with fixed boundary conditions, the reality beyond pilots is different. P2P energy trading markets must be able to function under changing participation rates, (Morstyn et al., 2021; Papadaskalopoulos et al., 2021; Junlakarn et al., 2022; Slingerland et al., 2021) while maintaining their economic and technical viability. In addition, inclusivity and equitable distribution will be key to the adoption of P2P energy trading markets (Papadaskalopoulos et al., 2021; Junlakarn et al., 2022). There is a need for business models that can accommodate high upfront costs and uncertain future revenues (Papadaskalopoulos et al., 2021; Junlakarn et al., 2022), which are currently often secondary to public and private funding sources. This will be particularly important when it comes to the acceptance of P2P energy trading systems by the stakeholders and participants involved. In addition, the high contextual dependency of P2P energy trading systems poses a unique challenge for scalability, affecting the transferability of lessons learned to different settings (Slingerland et al., 2021; Ableitner et al., 2020; Ruggiero et al., 2018).

In summary, the literature review has shown that P2P energy trading systems can respond to some of the pressing challenges facing the energy sector, such as the integration of renewable energy

sources, the democratisation of the energy system and the empowerment of energy users. However, the transition from controlled pilots to scalable deployment involves several aspects, including technical, regulatory, economic and social factors that collectively affect the scalability and uptake of P2P energy trading systems. While pilots provide a suitable environment for testing new business models, their structure often lacks the necessary considerations for assessing scalability. This thesis aims to address this gap by exploring ways to scale up P2P energy trading systems, thereby informing strategies to overcome or mitigate identified barriers in future pilots. Consequently, this research seeks to answer the following questions:

1. *How can the scalability of P2P energy trading systems be assessed, taking into account the obstacles encountered in pilot projects?*
2. *What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?*
3. *How applicable are scalability barriers identified in the broader context of P2P energy trading systems?*

The research questions outlined above are directly derived from, and aligned with, the broader research objectives presented in Chapter 1.3. These objectives provide the basis for structuring the exploration and analysis in this thesis, with each research question being addressed through the fulfilment of specific objectives. The first research question is addressed and builds on research objectives 1-3:

1. Understand the design and operation of P2P energy trading systems and analyse different market designs and objectives.
2. Understand how current policy and regulatory frameworks and other external circumstances facilitate or hinder the scale-up of existing pilots.
3. Identify the scalability challenges faced by past and present P2P energy trading pilots in different regional contexts.

These objectives collectively provide the foundational understanding required to answer the first research question. Specifically, by analysing the design and operation of existing P2P energy trading systems, identifying how external factors such as policy and regulation influence their scale-up

potential, and examining the practical scalability challenges encountered in real-world pilots, the thesis provides the empirical and conceptual basis for developing a methodology to systematically assess the scalability of P2P energy trading systems which is discussed in Chapter 2 Part II and Chapter 3 of this thesis.

The third research question is addressed by research Objectives 4-5:

4. Understand how scaling up P2P energy trading systems can affect the P2P energy trading market's performance and impact on market participants.
5. Understand the implications of scaling up P2P energy trading systems on different social, technical, economic and regulatory aspects.

The second research question seeks to identify the main barriers to scaling up P2P energy trading systems and understand how these barriers affect system performance. Objective 4 focuses on how the process of scaling impacts the technical, economic, and operational performance of the market, including the distribution of benefits among participants. Objective 5 broadens this analysis by examining the wider implications of scaling on social dynamics, regulatory frameworks, and market stability. Together, these objectives enable an assessment of the interrelated challenges that emerge as P2P energy trading systems scale up and are addressed in Chapter 4 and Chapter 5 of this thesis.

Finally, the last research question is addressed by Objectives 5-6:

5. Understand the implications of scaling up P2P energy trading systems on different social, technical, economic and regulatory aspects.
6. Identify requirements and provide recommendations for successful scaling up of P2P energy trading systems in different regional contexts.

Objective 5 provides a wider understanding the implications of scaling P2P energy trading systems by examining how social, technical, economic, and regulatory factors influence system performance across different contexts. This includes identifying which barriers are context-specific and which are more universal. Objective 6 builds on these insights by identifying requirements and formulating recommendations for how P2P energy trading systems can be successfully scaled in diverse regional settings. Both objectives contribute to Chapter 6 of this thesis.

In order to answer these research questions, the research design and the methodology used are described in the following chapter.

Chapter 3

Methodology

The following chapter aims to define a methodology to address the first research question introduced in the previous chapter: *‘How can the scalability of P2P energy trading systems be assessed, taking into account the obstacles encountered in pilot projects?’*. However, before assessing how P2P energy trading systems can be scaled up, it is important to define how scalability is defined in the context of this thesis. The term scalability refers specifically to the scaling up of P2P energy trading systems, as opposed to scaling out or replicability, as discussed in Section 2.5.2. Scaling up is the ability of a system to increase in size, scope or coverage while continuing to meet technical requirements such as balancing local supply and demand. This may involve growing from a P2P energy trading project of, for example, 10 households to a community of 100, or integrating larger volumes of traded energy, or expanding service offerings. Whether scaling refers to broader community involvement, increased energy volumes or more sophisticated market interactions depends heavily on the specific conditions and objectives of each pilot.

Due to the high context-dependence of P2P energy trading systems, the form that scaling up takes will vary significantly. For this reason, in this research the Scalability Analysis Framework is introduced, adapted from the SRA, and applied in a case-by-case manner. The specific aspects of scaling up that are examined in relation to the second research question, including changes in participant numbers, technical limitations addressed, or service extensions, are described in detail in the following chapters.

While scaling up and replicating P2P energy trading systems in other contexts remains essential for wider uptake, this research focuses primarily on scaling up within the pilot environments to explore the barriers that may need to be overcome for successful system scaling. The third research

question extends this focus by exploring whether the barriers identified for scaling up are also relevant for wider implementation, beyond the assessed pilot project contexts.

The remainder of this chapter outlines the methodological approach used to assess the scalability of P2P energy trading systems, with a particular focus on pilot project settings. Section 3.1 introduces the research design, framing the study as exploratory in nature and grounded in a pragmatic approach suited to complex socio-technical systems. Section 3.2 introduces the scalability analysis framework developed in this research, which builds on the SRA and is adapted to the context of P2P energy trading systems. It outlines how the framework addresses technical, economic, social, and regulatory aspects of scalability. Section 3.2.1 explains the rationale for using a case-based approach and highlights the value of real-world pilot data in exploring context-specific scalability pathways. Section 3.2.2 presents the structure of the scalability analysis, organised into three phases: pre-evaluation, implementation, and post-evaluation. Each phase includes steps such as defining boundary conditions, selecting performance indicators, and developing the simulation environment. Section 3.2.3 discusses the use of sensitivity analysis, justifies the choice of a local approach, and explains how input parameters were selected. Section 3.2.4 outlines the selection of the CommUNITY project in the UK and the Medellín pilot in Colombia, and explains their relevance for comparative analysis. Section 3.2.5 describes the process of model verification and validation to ensure the credibility of the simulations. Section 3.3 reflects on the assumptions and limitations of the analysis. Finally, Section 3.4 summarises the methodology and introduces its application in the case study chapters that follow.

3.1 Exploratory research design

Research design refers to the procedures for collecting, analysing, interpreting, and reporting data in a research study, and should outline the strategy for addressing the stated research questions (Creswell et al., 2017). A well-grounded design sets out clear objectives, identifies data sources, acknowledges constraints, and justifies the methodological choices made (Saunders et al., 2009).

Saunders et al. (2009) distinguish between three broad types of research design: exploratory, descriptive, and explanatory. These approaches are not mutually exclusive and may overlap or evolve throughout the course of a project. Exploratory research aims to investigate a problem or phenomenon where knowledge is limited, using flexible and iterative methods to generate new insights or develop hypotheses (Robson, 2002). Descriptive research, by contrast, seeks to provide

an accurate portrayal of events or phenomena, typically using structured methods to summarise known situations. Explanatory research focuses on understanding causal relationships, often through hypothesis testing and statistical analysis.

This thesis takes an exploratory approach to address its research questions, as the scalability of P2P energy trading systems, particularly in the context of real-world pilot projects, remains a relatively underexplored area. The intention is not to predict specific outcomes or test predefined hypotheses, but to identify key barriers and enablers, and to explore how different contextual, behavioural, and institutional factors influence the potential for scaling up.

This exploratory orientation is reflected in the choice of a case study-based simulation methodology, which allows for the examination of hypothetical scalability scenarios that cannot easily be tested in real-world settings due to technical, regulatory, or ethical constraints. By simulating different configurations and varying key parameters, this research aims to explore plausible future pathways for P2P energy trading systems under evolving market conditions.

This research recognises the complexity of socio-technical energy systems and adopts tools suited to understanding that complexity. As such, the methodology supports the development of context-sensitive, policy-relevant findings that can inform both academic debate and real-world implementation.

3.2 Scalability analysis framework

SRA provides a framework for assessing the multiple aspects, including technical, economic, social and regulatory, that define the scalability of smart grid solutions. It focuses on addressing the nuanced challenges of scaling up, taking into account the complexity and dynamic nature of real-world energy system operations. Within the SRA framework, pilot projects are instrumental in shaping the design and analytical approach of the case studies analysed.

SRA was originally developed to address scalability barriers specific to smart grid solutions, and contains elements that don't easily transfer to other contexts. Therefore, this thesis introduces a Scalability Analysis Framework that builds on the foundation of SRA, but is specifically adapted to the context of the P2P energy trading case studies examined. The research grounds the exploration of the scalability of P2P energy trading in the unique circumstances of each case, using modelling to explore how scalability interacts with the particular conditions and constraints of each case. This approach allows for a detailed examination of scalability within these pilot cases, highlighting the

critical role of context in the scaling process. The methodology aims to address research questions two and three by drawing conclusions from the case study findings.

Before detailing the design and structure of the scalability analysis used in this thesis, the following section outlines the rationale for adopting a case-based approach to address the stated research questions.

3.2.1 Opting for a case based approach

The scalability analysis in this research requires the establishment of a baseline case according to the SRA framework. This baseline serves as a reference point for scalability assessments, allowing for a contextual approach that recognises the importance of the specific nuances of individual cases. By examining specific pilots and using modelling techniques, this research seeks to understand how scalability interacts with the unique contextual factors and constraints of each case.

However, while archetypal P2P energy trading systems could theoretically provide insights into scalability by representing idealised, context-agnostic market designs, their practical applicability is limited by the lack of universally valid archetypes. Moreover, as discussed in Chapter 2.6, the inherently context-sensitive nature of P2P energy trading systems underscores the inadequacy of relying solely on archetypal designs to assess scalability. Pilot projects in different social, regulatory, financial and energy system contexts often reveal specific scalability challenges through their real-world implementations. While archetypal designs for P2P energy trading markets and pricing mechanisms can be found in the literature (e.g. Capper et al. (2022b)), no universally applicable archetypes for P2P energy trading systems have been identified. Therefore, this research focuses on exploring scaling constraints based on the contextual realities of specific cases, using modelling to investigate how scalability is affected by the unique configuration and constraints of each scenario.

The use of real-world pilots as exploratory case studies provides an empirical basis for identifying relevant parameters and scenarios to be modelled in simulations. Case studies provide detailed insights into technical configurations, stakeholder perspectives, and operating conditions that can lend feasibility and credibility to simulations investigating scalability pathways. Several examples can be found in the literature where case study data is used to inform simulation designs and set operating conditions for P2P energy trading market designs, including Shrestha et al. (2019) and Tushar et al. (2020). Feeding case knowledge into simulations allows for the systematic alteration of market variables that cannot be freely altered in real-world deployments due to ethical, practical

or regulatory constraints. The simulated environments facilitate controlled exploration of scaling effects across different contexts and constraints. In particular, for non-market-driven innovations such as community energy projects, the specific communal context and dynamics of groups participating in the market may influence the scaling process (Ruggiero et al., 2018). Therefore, this work seeks to replicate the status quo of a P2P energy trading system in order to further assess scalability parameters through modelling and simulation. The iteration between case-based knowledge and customisable simulations allows for a holistic examination of scalability challenges under different potential scenarios, in order to identify both generalisable and context-specific considerations for advancing the adoption of P2P energy trading markets.

3.2.2 Structure

In order to systematically analyse the scalability potential of P2P energy trading systems, a scalability analysis framework consisting of three phases is proposed. This framework aims to examine the scalability potential of selected case studies, as outlined in Figure 3.1. Variations of this approach have been used in studies by InterFlex Project (2019), Le Baut (2018) and Grid4EU Project (2014).

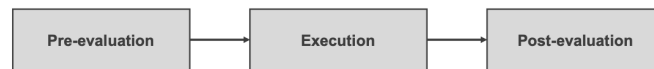


Figure 3.1: Three-step approach scalability analysis framework.

The following each phase is presented in details, describing individual steps that are conducted within each phase. The aim is to provide a general overview of the scalability analysis and its implementation. Specific methods for assessing the scalability of a case study are analysed in the following chapters, as these vary depending on the type of pilot project and its specific contextual requirements.

3.2.2.1 Pre-evaluation

The pre-evaluation phase comprises several steps that are necessary to prepare the case study for the scalability analysis. These include the creation of an overview of the case study and the definition of scalability scenarios. Performance indicators are then derived, which are necessary to carry out the scalability analysis.

Case study overview

The first step is to gain a complete overview of the case study. This involves gathering all available information about the selected pilot project. This could include gathering primary data through methods such as interviews and direct observation, as well as secondary data from project documents and reports. It is important to get an overview of both internal and external influencing factors. Internal factors include, but are not limited to, the size of the market, market design and mechanisms, project partners and participants involved, and installed assets. External factors may include the current regulatory situation, technical prerequisites, installation costs and electricity tariffs. These are just a few examples that should be considered when collecting data. The aim of this step is to have a good overview of the pilot project in order to be able to derive relevant scalability scenarios in the next step.

Definition of scalability scenarios

Having gained an overview of the pilot project, the next step is to define scalability scenarios. To do this, it is necessary to clearly define the scope and objectives of the pilot project in order to derive scalability scenarios that are relevant or feasible within the context of the pilot project. As described in previous chapters, pilot projects often face challenges in scaling up their projects due to various technical, social, economic or regulatory barriers. The aim of this step is to identify these reasons and derive scalability scenarios that can be evaluated within a simulated case study. There can be one or multiple scalability scenarios proposed, depending on the scaling parameters tested as part of those. Particular attention will be paid to the boundary conditions. Boundary conditions are the limits within which a pilot project must operate. In order to derive scalability scenarios, these boundary conditions need to be identified in order to understand which of them can remain the same or be challenged within the scalability analysis.

Identification of performance indicator

The final step in the pre-evaluation phase is to derive performance indicators. These indicators are quantifiable measures that enable structured evaluation of projects and simulations, allowing standardised comparisons across different scenarios and scaling conditions. To ensure meaningful results, performance indicators should meet SMART criteria: specific, measurable, achievable, realistic and time-sensitive (Shahin et al., 2007). In scalability analysis, locally relevant performance indicators can be taken directly from pilot projects, if available, or derived from the specific objectives of the project. These indicators, which can be both technical and non-technical, allow the

assessment of impacts under different scaling scenarios. The use of similar KPIs across projects increases the comparability and reliability of results (Rodriguez-Calvo et al., 2018).

Originally developed in a business context, several studies have used performance indicators to evaluate P2P energy markets. Okwuibe et al. (2022) used indicators such as individual and community savings, self-sufficiency and proximity indices for their LEM configurations. Regener et al. (2022) focused on economic indicators such as gross profit, social welfare and equity, and technical indices such as congestion relief and self-sufficiency. Qualitative criteria such as user acceptance were also taken into account. Similarly, Zhou et al. (2018) used economic (value tapping, participation, equity) and technical (energy balance, self-sufficiency) performance indicators and combined them into an overall performance index. Other notable studies using performance indicators include Pena-Bello et al. (2022), Prevedello et al. (2021) and Mehta et al. (2022).

3.2.2.2 Execution

In the execution phase, the scalability analysis is performed. This phase consists of three steps: collecting the data, developing the simulation environment, performing the scalability analysis and calculating the performance indicators. Each step is described in detail below.

Data collection

The scalability analysis will require data to feed into the analysis. Where possible, real-world data from pilot projects will be used, including information on user participation, electricity load profiles, DER generation capacity and asset flexibility data. Where specific pilot project data is unavailable or inaccessible, open source databases may be used to fill gaps, such as historical weather data to estimate renewable generation. Where real case study data cannot be obtained, simulated datasets could be considered as a last resort, recognising the limitations of decontextualised data. For example, load simulation models can be used to generate synthetic residential load profiles, as proposed by Labeeuw et al. (2013). Additional simulated grid models and energy resource data are available through open sources if needed to complement the case data, such as Schneider et al. (2018). However, the use of such data would limit the contextual validity of the model and the resulting insights. By collecting as much real case study data as possible and using simulated data sensibly, the model can strike a balance between authenticity and practicality. Ultimately, the aim is to ground the simulation in real-world conditions in order to explore scaling pathways in a contextualised way.

Simulation environment development

To perform the scalability analysis, a simulation environment must be created to run the defined scalability scenarios to calculate the performance indicators. Simulation environments vary depending on the case study and its context. This includes, but is not limited to, the modelling of the market design and mechanism, the trading behaviour of the participants, the simulation period, and the specific methods to be used to test the scalability scenarios. However, it is recognised that simulations cannot replicate the exact reality of pilot projects on a one-to-one basis. Assumptions and adjustments or simplifications should be clearly described and their impact on the results discussed.

Scalability analysis and calculation of performance indicators

The first part of the scalability analysis is the calculation of the baseline design. The purpose of the baseline design is to simulate the market before the scalability scenarios are run. The baseline is needed to compare the results of the scalability scenarios with the status quo. Naturally, any case study simulated as part of the scalability analysis can only approximate the actual pilot project. Because of this approximation, only the key functionalities or use cases selected for testing will be included in the scalability scenarios analysed. Where possible, the calculated performance indicators of the baseline design should replicate the performance indicator values of the real pilot project using a coherence test. However, not all pilots were able to calculate their set performance indicators due to potential implementation challenges.

The scalability analysis can be divided into technical and non-technical analysis. Depending on the scalability scenarios set, the technical analysis focuses on load flows and power distribution in the market. The non-technical analysis can provide insight into the economic feasibility of the tested scalability scenarios. The calculated results are presented and discussed in detail, taking into account the assumptions made and the boundary conditions defined. The aim of this step is to provide insights on the second research question of this thesis: *‘What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?’* By evaluating the results, the aim is to identify the main barriers that may have hindered the successful scaling up of the P2P energy trading system. An overview of the execution step of the scalability analysis can be seen Figure 3.2.

A commonly used method in scalability analysis is the use of sensitivity analysis to represent the

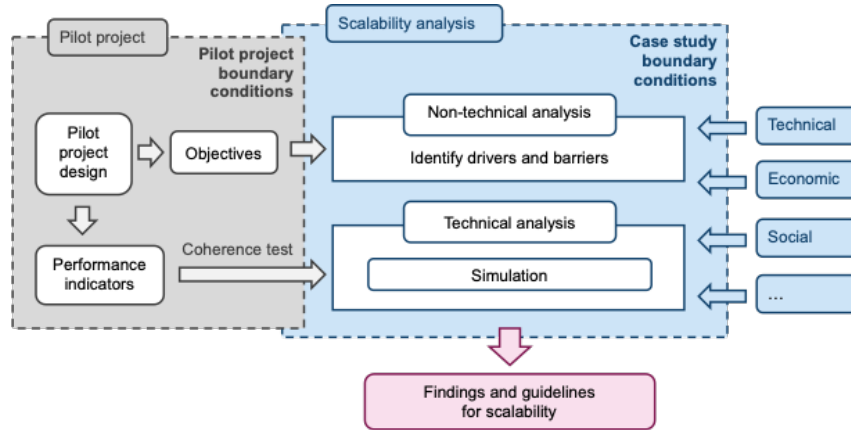


Figure 3.2: Schematic design of the execution phase of the scalability analysis.

diversity of potential scalability paths. Sensitivity analysis allows for methodical testing of the effects of changing simulation variables on model outputs. The method and its application in scalability analysis are discussed in more detail in Chapter 3.2.3.

3.2.2.3 Post-evaluation

The final phase of the scalability analysis framework is the one-stage post-evaluation phase, in which the results and impact of the scalability analysis are assessed. This phase also allows for the exchange of guidelines and recommendations for the successful scaling up of the case study that can be derived from the scalability analysis. If possible, further conclusions will be drawn to improve the scalability of the pilot being studied, but limitations of the applicability of the case study results to the pilot should be discussed. In order to carry out this evaluation in a structured way, the results and impacts are described using the five-layers of the LEM introduced in Chapter 2.1.2, namely power systems integration, ICT and data, market and transaction, social and economic value and policy and regulation. Using these five layers will allow for a more systematic analysis of results.

The aim of the post-evaluation phase is to also answers to the third research question of this thesis: *‘How applicable are scalability barriers identified in the broader context of P2P energy trading systems?’*. The scalability findings, while initially tailored to individual case studies, aim to address the broader question of the extent to which the constraints observed can be generalised. This study seeks to identify scalability guidelines that could have wider applicability, providing future projects with insights and incentives to integrate scalability and replicability considerations from the design phase. This approach is intended to provide actionable guidance and encourage future initiatives to proactively plan for scalability pathways.

3.2.3 Sensitivity analysis

A key part of assessing the scale-up potential of a case study is the use of sensitivity analysis, as it allows the effect of changing boundary conditions and other parameters on the performance of the market to be examined. Sensitivity analysis has been widely used in building energy research to evaluate design improvements, but has also been used to model P2P energy trading systems. For example, Nguyen et al. (2018) used local sensitivity analysis when simulating P2P energy trading markets.

Generally, two types of sensitivity analysis can be distinguished: local and global. Local sensitivity analysis focuses on the effect of variations in specific input parameters, while global analysis evaluates variations in all parameters on the overall performance of a model or system. Global analysis is considered to be more comprehensive but requires more computation. However, local sensitivity analysis may provide sufficient insight depending on the specific use case and design priorities (Yliruka et al., 2023).

For this research, local sensitivity analysis has been selected to assess the scalability of the selected P2P energy trading cases studies. The parameters selected for analysis, such as the number of market participants or tariff levels, were identified based on their direct relevance to the scaling-up processes studied in each case. These parameters represent key variables that influence the operational and market performance of P2P energy trading systems, as also highlighted in the scalability and replicability analysis framework by Rodriguez-Calvo et al. (2018). Testing the performance impact of incremental increases in market participation provides focused, actionable insights into the scalability limitations of the current pilots. The variation of individual parameters (e.g. number of consumers, tariff levels) facilitates a more straightforward interpretation of scale effects and constraints as relationships and influences can be directly derived.

Although a global sensitivity analysis could offer a systematic means of identifying the most influential parameters, this approach was considered beyond the scope of this study due to computational constraints and the diversity of case-specific boundary conditions. In this context, the selection of input parameters for local analysis was guided by theoretical considerations, prior literature on P2P energy market design, and the characteristics of each pilot project. This pragmatic and targeted approach enables the derivation of actionable, context-specific insights into the scalability limitations and opportunities of P2P trading systems. Testing the performance impact of incremental changes in key parameters allows for a more detailed interpretation of scale effects, as individual influences

can be directly assessed. While a global analysis might be more suitable for generalised pattern discovery, local sensitivity analysis is better suited to the case-specific nature of this research. It supports a more nuanced understanding of how particular market design elements and boundary conditions affect scalability outcomes.

3.2.4 Selection of case studies

Chapter 3.2.1 outlined that the case studies used in the scalability analysis in this research were informed by real-world pilot projects.

This study focuses on two distinct pilot projects: the ‘Medellín Peer-to-Peer Energy Trading’ pilot in Colombia and the ‘CommUNITY’ pilot project in London, UK. Both pilots, conducted in collaboration with researchers at UCL, provided crucial access to a rich mix of qualitative and quantitative data. As outlined in Chapter 2.3.2, such extensive data, often difficult to obtain, allows for an in-depth examination of these case studies.

The selection of the Medellín and London pilots was based on their shared commitment to promoting social and financial inclusion, particularly for participants from disadvantaged backgrounds. Both projects emphasise fairness and sustainability in their energy market models, making them ideal subjects for a comparative study. This research specifically targets consumer-centred pilots with a strong focus on participants involved in them.

On the other hand, the differences between the Colombian and UK pilots provide a rich basis for exploring how different regulatory environments, energy market structures and socio-economic contexts influence the implementation and outcomes of P2P energy trading initiatives. For example, the CommUNITY pilot focuses on ‘behind-the-meter’ energy trading between residents within a single block of flats in London, while the Medellín P2P Energy Trading pilot manages transactions across the city of Medellín. This geographical contrast allows an assessment of how the geographical scale affects P2P trading and its potential for expansion. In addition, the UK and Colombia have very different policy environments, with the UK having a liberalised electricity market and Colombia having a highly regulated energy sector. Comparing cases within these different regulatory regimes allows an examination of how market rules and regulations shape the scalability of P2P energy trading markets in different environments.

These two case studies, with their shared social objectives and structural variations, provide multifaceted insights into the opportunities and challenges associated with scaling consumer-centred P2P

energy trading systems. The cross-case comparisons not only facilitate the identification of scaling challenges of general relevance, but also highlight those that are specific to particular contexts. While the findings of each case study will be limited in their generalisability, the comparative approach allows for the identification of commonalities and differences across cases, which can be used to inform generalisable conclusions.

While less common in the natural sciences, there is a large theoretical framework for the selection of case studies when conducting case study research. Simons (2013) defines a case study as “an in-depth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, program or system (in a ‘real life’ context)”. However, a case-based approach is not a methodology in itself but rather ‘a design frame’ that could include a number of methods to study a particular case or cases (Thomas, 2011).

The selection of case studies is primarily driven by their relevance to the research objectives, ensuring they address the specific research questions at hand. In addition, several other key factors come into play during the selection process, including accessibility, comparability, diversity, and the richness of information. These factors collectively contribute to the analysis of cases, allowing for a deep exploration of the research questions at hand, with the ultimate goal of providing valuable and diverse insights. Stake (1995) distinguishes between three types of case studies. *Intrinsic* case studies focus on the case itself because it is inherently interesting. The case is chosen for its uniqueness, not its representative value. The aim is to gain an in-depth understanding of the particular case. In *instrumental* case studies, the selection focuses on cases that provide insight into an issue or theory. The case facilitates the understanding of something else. Often a ‘typical’ case is chosen. *Collective* case studies involve the study of several cases. This allows comparison, replication and generalisation by looking at patterns across cases. Cases may be chosen as typical examples to generalise theories or to test theories through replication.

In light of these distinctions, the research conducted to address the research questions outlined in Chapter 2.7 can be placed between instrumental and collective case studies. The aim is to gain extensive insights into scalability challenges from specific P2P energy trading pilot cases, while also extracting findings that can support general conclusions. Therefore, in this research an inductive approach was selected, which means exploring findings from a sample that can be developed into a theory, as opposed to a deductive approach, where a theory or concept is tested using specific data set (Saunders et al., 2009).

Analysing a representative sample of P2P energy trading pilot projects would go beyond the scope of this work and at the same time create uncertainties regarding its representativeness. This stems from the inherent challenge of defining a representative sample in the context of P2P energy trading. Therefore, the selected cases should be diverse enough in terms of technical, geographical and regulatory dimensions to provide a range of scaling insights, but similar enough to be able to draw generalisable findings from scalability analysis. With this approach, the barriers and enablers to scaling in each case study will be explored in depth, while identifying common challenges, requirements and pathways that may influence the scalability of P2P markets in general. It is crucial to emphasise the importance of recognising and addressing any contextual limitations. This entails a diligent consideration of the specific factors, circumstances, or constraints within each case study that might affect the research outcomes.

3.2.5 Verification and validation

In a research project, and especially when building simulation models, it is important to ensure that the model itself is 'correct'. This is particularly important if the simulated data are to be used to draw conclusions about the real world. The concern that a model is correct can be addressed by validating and verifying the model itself. Model validation can be defined as "the demonstration that a computational model, within its domain of application, has a satisfactory range of accuracy consistent with the intended application of the model". Model verification is defined as "ensuring that the computer program of the computerised model and its implementation are correct" (Sargent, 1994). Both model validation and verification are integral parts of the modelling process, which consists of the problem entity, the system to be modelled, the conceptual model, which is the mathematical, logical or verbal representation of the problem entity, and the computerised model, which is the conceptual model implemented on a computer. Figure 3.3 shows a simplified representation of the modelling process.

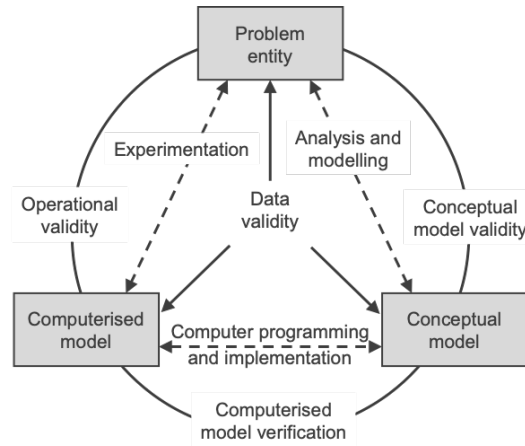


Figure 3.3: Schematic overview of the modelling process (adapted from Sargent (1994)).

Conceptual model validity involves verifying that the theories and assumptions underlying the model are consistent with current knowledge and that the model adequately represents the real system for its intended purpose. Computer model verification refers to ensuring that the computer programming and implementation accurately reflect the intended conceptual model and are correct. Operational validity means demonstrating that the outputs of the model are sufficiently accurate for its intended use in the domains to which it is applied. Data validity means ensuring that adequate and correct data are available for the model development, testing, evaluation and experimentation required to solve the problem at hand (Sargent, 1994).

Validation of the conceptual model, computer implementation and data is critical to ensure the overall credibility of the model. In this research conceptual model validity was established by grounding the model in the theoretical foundations outlined in Chapter 2 and by closely aligning modelling choices with project objectives, performance indicators, and details provided through extensive discussions with pilot project stakeholders. Basing the simulation on real pilot projects added further conceptual validity. Computer model verification involves structured walkthroughs and iterative testing to confirm that each model component works correctly. Individual components were tested manually prior to integration into the full model. Dynamic testing with varying inputs verified that model outputs were consistent with expected component behaviour. In addition, simulation models are validated against the results of real-world testing. Sensitivity analyses are also performed to account for variability in boundary conditions within the regions of interest. Data validity is assessed through rigorous data collection and analysis. Where possible, real data from pilot projects were used directly. Where data were not available, relevant synthetic

or simulated data were substituted and their use justified. Finally, operational validity is assessed by comparing model outcomes with the performance indicators identified and subjective tests comparing model behaviour with expected system dynamics under the specified boundary conditions, and through graphical analysis of model outputs.

The scalability analysis structure allows for intermediate model verification through the baseline implementation. Prior to evaluating hypothetical scaling scenarios, the initial implementation of the current pilot status as a baseline model provides a concrete checkpoint to verify the validity of the model. As the baseline implementation of the case study aims to approximate real world conditions of the pilot project, its results could be easily understood and compared with expectations, unlike the more abstract scaling scenarios. Using the existing pilot as an intermediate step facilitates a tangible verification of model behaviour and outputs before extrapolating the results through scaled simulations.

3.3 Assumptions and limitations

It is important to note that the pilot design decisions made by the stakeholders involved are taken as given when they are incorporated into the data collection and pre-evaluation phase of the scalability analysis (assuming they are not analysed in more detail as part of the defined scalability scenarios). To be more precise, the characteristics or design decisions of the pilot, such as the geographical location or the type of participants involved, are carried over into the simulation as accurately as possible to make the simulation results more relevant to the particular context. Nevertheless, such design decisions may be challenged in the final conclusion phase of the scalability analysis if they affect the scalability guidelines.

This systematic verification across conceptual, software, and data domains ensures the validity of the scalability analysis and its alignment with real-world pilot conditions. However, as noted by Sargent (1994), “a model may be valid for one set of experimental conditions and be invalid in another”. This means that the findings from the scalability analysis are primarily relevant to the specific input parameters and context in which the model was developed. The analysis relies on certain simplifying assumptions and abstractions of the pilot project, as fully capturing real-world complexity is inherently challenging. Reliance on single case studies makes generalising findings across contexts more difficult. However, a thoughtful interpretation of the model outputs in light of its assumptions and limitations allows for deriving nuanced conclusions both particular to the cases and more broadly. The simulated scenarios simplify complex real-world dynamics, with

the potential risk of overlooking or misinterpreting important factors. Although the simulation of case studies is grounded in their particular regulatory context, there are unknowns around future regulations, technologies, and behaviours which add uncertainty to potential forecasts. Furthermore, the focus of this research is on the technical and economic aspects of P2P energy trading markets. However, the field of research in general would benefit from an assessment of emergent system behaviours such as influence, learning and spillovers, as well as the impact of the social and cultural environment more generally.

A detailed discussion of the limitations associated with the findings of this thesis is provided in Chapter 6.1, exploring how these limitations may have influenced the findings and providing a deeper analysis of the constraints encountered during the research.

3.4 Conclusion

This chapter has explored the nature of scalability in P2P energy trading systems, addressing the first research question on evaluating scalability in the context of the challenges faced in pilot projects. Starting with an exploration of scalability dimensions in Section 1, the discussion extended to different methodologies for scalability assessment in Section 2, and proposed the scalability analysis framework for evaluating the scalability of P2P energy trading systems in Section 3. Section 4 analyses the assumptions and limitations of the chosen methodology. The main findings underline the complexity and context dependency of scaling up P2P energy trading systems. The chosen methodology, based on the SRA framework, highlights the importance of technical, economic, regulatory and social dimensions in shaping the scalability potential of P2P energy trading systems.

The following chapters apply the established framework to specific case studies, with the aim of unpacking the nuanced scalability constraints unique to each context. Using pilot projects to inform the case studies, this research aims to better understand the balance between achieving operational scalability and overcoming the unique constraints of each project's context.

Chapter 4

Distributional impacts of P2P energy trading: Insights from a case study in Medellín, Colombia

This chapter examines the first of two case studies analysed in this thesis. It focuses on the Medellín P2P energy trading pilot project, which was one of the first P2P energy trading pilots in Latin America. The implementation of local energy markets in the Global South is a relatively under-researched topic, despite the often more favourable environmental conditions, such as higher solar radiation and the decreasing costs of decentralised energy.

The aim of this chapter is to contribute to answering the second and third research questions defined in Chapter 2.7 by applying the scalability analysis described in Chapter 3.2. The second research question '*What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?*' is addressed in the execution phase of the scalability analysis framework. The third research question '*How applicable are the identified scalability constraints in the broader context of P2P energy trading systems?*' is addressed in the post-evaluation phase of the scalability analysis framework. The answers to this question are based on the results of the scalability analysis and are limited to the context of the pilot project. An attempt is made to interpret the results in the broader context of the Colombian energy market.

The chapter is structured as follows. In Section 4.1 the Colombian energy market is presented to give context to the operational environment of the Medellín P2P energy trading pilot project. Section 4.2 provides a detailed overview of the pilot project, emphasising its objectives and the challenges faced

during implementation. Section 4.3 describes the scalability scenarios designed to explore potential barriers and opportunities for expanding the P2P energy trading market. Section 4.4 outlines the performance indicators used to evaluate the scalability scenarios. In Section 4.5 relevant data required to assess the scalability scenarios is described and analysed, followed by Section 4.6 which defines the simulation environment required to calculate the identified performance indicators. Section 4.7 corresponds to the execution phase of the scalability analysis, presenting the results of the simulation and exploring the economic and technical implications of the case study of the different scalability scenarios. Section 4.8 concludes the scalability analysis by discussing the results of the simulation and providing scalability guidelines based on the five layers of P2P energy trading systems. Finally, Section 4.9 summarises the findings of the Colombian case study.

4.1 Introduction

Colombia's electricity needs are already largely met by renewable energy generation. Hydropower accounts for over 68% (IEA, 2020a) of the electricity produced. However, this over-reliance on a single source of electricity can affect security of supply, particularly as the effects of climate change become more apparent. Extreme droughts during weather patterns such as El Niño can cause river and reservoir levels to fall below average, leading to high energy prices and an increased risk of blackouts (Zapata et al., 2018; Henao et al., 2020; Poveda et al., 2011). As the climate crisis progresses, it is likely that these extreme weather events will occur more frequently (Cai et al., 2015). A recent crisis surrounding the construction of the country's largest hydroelectric plant, Hidroituango, reinforces this argument. Severe design deficiencies and construction errors have resulted in significant damage to the construction site (Henao et al., 2020) and subsequent flooding which led to the relocation of several thousands of people (Bedoya et al., 2018). Further, the construction and operation of hydropower stations of this size means great interference with nature and biodiversity (Poveda et al., 2011).

To mitigate the risks associated with large hydro, the Colombian government has developed a strategy to diversify the country's renewable energy generation. This strategy involves increasing the share of small-scale RES in the generation mix, such as solar and wind. The Colombian Law 1715 (2014) (Congreso Colombia, 2014) paved the way for the expansion of small-scale RES and included tax exemptions and financial incentive schemes for surplus energy from small-scale installations to help reduce greenhouse gas emissions and ensure security of supply (Rodríguez-Urrego et al., 2018). Several studies have concluded that an increased share of RES in Colombia's generation mix can

respond to some of the country's pressing energy challenges. Favourable weather conditions and the absence of seasonal changes due to its location close to the equator result in a relatively constant energy load throughout the year and great access to solar radiation throughout the country (López et al., 2020; Rodríguez-Urrego et al., 2018; Radomes et al., 2015). Falling costs of RES compared to alternative fuel-based solutions (Henao et al., 2020; Zapata et al., 2018), especially solar and wind generation (Henao et al., 2019), support this new target.

In addition to research specifically focused on grid-scale RES installations connected to the high- and medium-voltage grid (Pupo-Roncallo et al., 2019), a considerable amount of research has also focused on the issue of residential PV and the concept of energy prosumers in Colombia. A foundation was laid by Resolution 030 of the Colombian Energy and Gas Regulatory Commission (CREG), which aimed to encourage the deployment of small-scale RES installations by allowing energy end-users to produce electricity and receive remuneration for any excess electricity produced (Rodríguez-Urrego et al., 2018), effectively receiving a FiTs.

There is a substantial body of literature examining various remuneration policies that could facilitate the adoption of residential solar PV. Radomes et al. (2015) design a model based on the concept of diffusion of innovation to test incentive schemes such as FiTs and subsidies. Castaneda et al. (2018) evaluate the efficiency and effectiveness of FiTs, net-metering and capital subsidy to promote the investment into residential solar PV in Colombia. By employing a system dynamics approach, they conclude that FiT and net-metering represent the most promising alternatives. León-Vargas et al. (2019) compare the amortisation of residential solar and wind systems. The results demonstrate that, in contrast to wind energy, residential solar PV can be amortised within a period of a few years. However, this would result in higher return rates for residents in higher economic strata¹ due to higher energy tariffs paid. High-income residents would benefit more than medium-income residents while low-income residents would most likely be excluded from the benefits. Similarly, Cardenas et al. (2017) conduct a scenario analysis to predict the uptake of solar rooftop PV generation and the use of energy-efficient appliances in Colombia. In an assessment by Rodríguez-Urrego et al. (2018), the authors cite a lack of vision and regulations as key factors hindering the uptake of residential PV. Another significant challenge is the investment deficit by public entities and a lack of incentives to promote small-scale RES installations.

¹The Colombian socio-economic strata system divides residential dwellings into six strata based on the circumstances of the dwelling and area in which it is located. The aim is to provide affordable utility services to citizens based on their income level with one being the lowest and six being the highest level.

In a more recent study, López et al. (2020) employs both qualitative and quantitative analysis to assess the potential for solar uptake in Colombia. The study finds that the current regulatory framework lacks sufficient incentives to accelerate the uptake. It is essential to implement changes to the general energy market structure in order to attract investment into solar PV. The study identified household-level Power Purchase Agreements (PPAs) and regulatory mechanisms, including net metering, tax reductions, FiTs and microfinance, as potential tools for accelerating the uptake. Furthermore, a general lack of public awareness and education was identified as an additional factor contributing to the slow uptake. Similarly, as noted by León-Vargas et al. (2019), López et al. (2020) residents from higher income strata would be the primary beneficiaries due to their financial resources and the resulting first mover advantage. The authors conclude that, under the current net-metering system, PV systems without energy storage have higher rates of return. A further factor contributing to the slow uptake of solar installations is the lack of sufficient intelligent monitoring equipment, as highlighted by Rodríguez-Urrego et al. (2018). This can result in the inefficient use of existing installations.

The results of the studies demonstrate a growing interest in user-centred energy market designs. However, implementation with a particular focus on LEMs remains relatively unexplored. This research addresses the lack of evidence from developing countries by analysing the results of a completed P2P energy trading pilot project in Medellín, Colombia, and assessing its potential for scalability.

The *Medellín Peer-to-Peer Energy Trading Pilot* forms part of the Transactive Energy Colombia Initiative². It was initiated with the objective of testing the technical and socio-economic implications of applying user-centric models in the Colombian energy market under current regulatory conditions. The pilot's broader aim, similar to the challenges described in the studies above, was to increase the uptake of DER and contribute to an inclusive energy transition that benefits low-income households. The pilot ran between 2019 and 2021 and was led by EIA University in cooperation with University College London, EPM, a local utility company and one of the largest in Latin America, ERCO, a DER company, and NEU, a digital energy retailer.

The Medellín Peer-to-Peer Energy Trading Pilot has encountered obstacles due to the stringent energy market policies and regulations currently in place. This has made it challenging to gather the necessary evidence to drive the uptake of such initiatives in the future. This evidence is vital

²<https://www.transactive-energy.co/>

for the continued development of P2P energy trading systems and the effective engagement of key stakeholders. When physical pilots reach their limits due to their restrictive environment, simulation and modelling techniques can provide further insight. In the following sections, the scalability analysis described in Chapter 3.2 is applied to the Medellín Peer-to-Peer Energy Trading Pilot.

4.2 Case study overview

The Medellín Peer-to-Peer Energy Trading Pilot project was designed as a virtual P2P energy trading market. All participants in the pilot were connected to a digital platform that allowed them to engage in energy transactions. Electricity was supplied through the public distribution network. The objective of the pilot was to test the operation of a P2P energy trading market with participants from different social backgrounds, with a focus on delivering electricity bill savings for low-income households.

The topography of Medellín has a significant impact on the distribution of household types across the city. Many affluent residents live in high-rise buildings on the valley floor of Medellín, which limits their ability to install solar PV to generate their own electricity. While this pattern is specific to Medellín's urban layout and social geography, it illustrates how topography and socio-economic factors can intersect to create unique opportunities or constraints for decentralised energy production. In other cities, both within Colombia and globally, these dynamics may be very different. However, such unique characteristics highlight the need for strong context sensitivity in the design and operation of peer-to-peer energy trading systems, as discussed in Chapter 2.6. A significant proportion of the city's population, comprising those with lower incomes, live in low-rise settlements on the south-facing hillsides around Medellín, with good access to solar radiation. The pilot project was established to facilitate the purchase of energy with positive social and environmental attributes from low-income households with PV installations by high-income users without PV systems. This was to be achieved through a P2P energy trading system. The aim of the pilot project was twofold: firstly, to test the feasibility of such a scheme and secondly, to identify potential barriers to its implementation. The project was initiated with the following three objectives in mind:

- (a) Test the installation and grid connection of DERs in neighbourhoods with different physical and socio-economic characteristics to identify barriers,

- (b) test the use of smart metering, IoT, and a digital platform to analyse metering accuracy and user engagement, and
- (c) using households' generation and load data, infer how a P2P energy trading market could work with participants from different socio-economic strata and identify barriers within the current Colombian energy regulation.

A total of 13 households participated in the pilot study, representing a range of socio-economic strata within the city of Medellín. These strata are defined according to a system that classifies housing units according to their wealth³, from one (the lowest) to six (the highest). This classification is used for taxation, education and health, but primarily for the cross-subsidy scheme for public utility services (Rise, 2020). The pilot project includes three small energy prosumers (SP), representing lower socio-economic groups with low generation capacities, three large energy prosumers (BP), comprising higher socio-economic groups with medium generation capabilities, six energy consumers (C), living in higher socio-economic areas, and a community centre prosumer (CCP) with a medium-sized generation unit. Table 4.1 provides an overview of the households that participated in the pilot, including details on stratum and DER installation capacity. Due to the low uptake of rooftop PV in low-income areas, the PV systems for the small prosumers and the community centre were both funded and installed as part of the pilot project. The PV installations of the larger prosumers were pre-existing installations. This criterion was a key factor in the selection of these particular participants. Figure 4.1 illustrates the breakdown of households from different socio-economic backgrounds involved in the pilot project. The images demonstrate the stark contrasts in living conditions among the participants, with notable differences between those from different socio-economic groups.

The socio-economic strata system was originally devised with the intention of reflecting the capacity of households to meet financial obligations. Despite criticism of the accuracy of the current stratification system in reflecting the changing ability of households to pay over time (Quiñones et al., 2021), this study will use the existing system as a proxy for the socio-economic status of participants. The implications of this are discussed in further detail in Chapter 4.8. Households are therefore classified into different participant groups or types. Small prosumers are categorised as low-income households, while large prosumers and consumers are associated with high-income

³The wealth of households is not directly measured but is instead inferred based on the characteristics of the building the household lives in.

Participant type	Stratum	DER installations	Short code
Small prosumer	3	1.24 kWp PV	SP ₁
Small prosumer	2	1.24 kWp PV	SP ₂
Small prosumer	3	1.24 kWp PV	SP ₃
Community centre	4	5.58 kWp PV & 6.3 kWh battery	CCP ₁
Big prosumer	6	9.72 kWp PV	BP ₁
Big prosumer	6	4.86 kWp PV	BP ₂
Big prosumer	6	1.86 kWp PV	BP ₃
Consumer	4	-	C ₁
Consumer	6	-	C ₂
Consumer	6	-	C ₃
Consumer	6	-	C ₄
Consumer	4	-	C ₅
Consumer	4	-	C ₆

Table 4.1: Overview of households participating in the Medellín Peer-to-Peer Energy Trading Pilot with details on socio-economic strata and DER installation capacity.

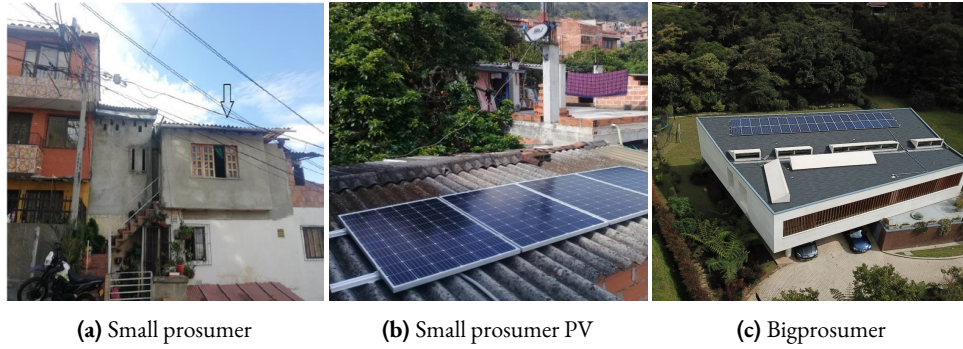


Figure 4.1: Examples of small-prosumer and big prosumer participants involved in the Medellín Peer-to-Peer Energy Trading Pilot (images provided by project coordinators).

households.

The 13 participants involved in the pilot project were provided with access to a digital platform via a mobile phone app. This platform contained information on electricity consumption and generation data, as well as transaction tracking functionality. The digital platform, developed by NEU, included a trading mechanism based on solar energy availability using hourly load data to settle transactions. Participants' energy transactions were ranked according to which participant traded the least in the previous period, in order to encourage equal participation by all participants in the pilot. The online platform was used as an approximation of a P2P energy trading market, without enabling actual monetary transactions between participants for the virtual energy exchanged.

4.3 Defining scalability scenarios

The Medellín Peer-to-Peer Energy Trading Pilot, while pioneering in its approach, encountered several challenges that limited its capacity to provide the evidence needed for advancing P2P energy trading models. The pilot encountered a number of significant hurdles, including structural challenges (e.g. housing conditions, rooftop materials, wiring, and internet access), educational challenges (e.g. lack of digital literacy, lack of understanding of basic energy concepts and energy bills, especially among low-income households), and technical challenges highlighted by the lack of national standards for smart metering (J. P. Cárdenas-Álvarez, personal communication, 19/08/2020). The lack of technological expertise resulted in higher installation costs and data reliability issues, including date and time misconfiguration, data transmission failures, and corrupted load, generation, and injection profiles. One particular issue was the malfunctioning of the energy management system for the storage unit in the community centre, which was intended to be used as a backup system in case of power outages. A notable barrier in the pilot project was the regulatory framework, which prevented the implementation of an actual monetary transaction-based P2P energy trading market.

As outlined in the preceding chapter, the pilot project had three primary objectives: to assess the installation and grid integration of DERs, to evaluate the use of smart metering and an IoT platform, and to gain insight into the potential of a P2P energy trading market among participants from diverse socio-economic backgrounds. While the first two objectives were addressed in the physical trial, providing insight into the technical feasibility of the pilot, the third objective could not be adequately addressed due to regulatory constraints. Colombia's energy regulation does not provide an environment in which new market or business models can be piloted, even for testing purposes. Instead, the pilot's designers compensated participants for their active engagement with the pilot's platform by generating digital tokens that did not have any monetary value attached to them.

In order to evolve and accommodate new energy business models, it is often required that concrete proof of concept demonstrations are provided. However, without regulatory evolution, the full realisation of these proof-of-concept initiatives remains a challenge. This creates a regulatory impasse where innovation and regulatory progress are mutually paralysed, unable to move forward. To overcome this, this research proposes the adoption of the scalability analysis framework outlined in Chapter 3.2. Using modelling and simulation, it explores potential scenarios under adjusted

regulatory conditions. This approach provides insights into the potential impact of regulatory adjustments that are difficult to obtain under current regulatory constraints.

In order to achieve the objectives set out in the Medellín P2P Energy Trading Pilot, two scalability scenarios were developed. Each scenario was designed to address a different set of barriers to scaling up the pilot. These scenarios contribute to an understanding of how the Medellín Peer-to-Peer Energy Trading Pilot could evolve and scale up, and of the impacts this would have on different participant groups. The following sections describe and justify these scalability scenarios in more detail.

Scenario I

Prior to examining the impact of scaling market participants on the performance of the P2P market, it is necessary to establish the base case market design. As previously stated, the regulatory framework in place does not permit financial transactions between residential energy users. Instead, a simplified tokenisation system was introduced as a means of gamifying the trading of electricity. The tokens had no monetary value, therefore having no impact on electricity bills. However, in order to address one of the objectives of the pilot project, namely to understand how P2P energy trading markets could benefit participants and the differences between participants from different socio-economic backgrounds, it is necessary to test the impact of financial transactions on market performance. The focus is not only on the financial implications but also on the broader socio-economic benefits of transitioning to a P2P energy trading market. Scenario I therefore explores scalability through scope expansion, by modelling a version of the P2P energy trading system in which real monetary transactions are enabled. This scenario examines how the introduction of a financial settlement mechanism affects market performance, participant incentives, and the distribution of benefits across different household types. The focus is not only on financial outcomes but also on the wider social and economic implications of enabling value exchange in a user-centric energy market.

Scenario II

The second scenario examines the impact of an expanded market size on the performance of the P2P energy trading market. The number of participants is increased from the initial 13 to a total of 100, with the increase distributed between lower (strata 2 or 3) and higher (strata 4, 5 or 6) socio-economic groups. This is done in order to mimic a scaled up and more dynamic market

environment. This increase is informed by the recruitment challenges faced in the pilot and seeks to understand how the market can evolve and adapt to a more diverse range of energy consumers and producers.

In a virtual P2P energy trading market, such as that used in the Medellín P2P Energy Trading Pilot, there is no theoretical limit to the number of participants that can be involved. Unlike physical markets, there are no constraints, such as being located within a low-voltage feeder or ensuring a reasonable balance between supply and demand at certain times of the day. In the Medellín pilot, participants are spread across different parts of the city and are not confined to a single area. Research by Capper et al. (2022b) shows that two-thirds of all studies simulate markets with up to 50 participants, while only one-third examine markets with 50 or more participants. In light of these findings, the decision was taken to expand the market to 100 participants in this simulation. This approach allows for the coverage of both small and large market sizes, while also enabling the identification of changes in market performance as the number of participants increases, without significantly increasing the computational complexity of the simulation. This balanced approach aims to provide an understanding of how market dynamics evolve with an expanding participant base. By including a wider range of market sizes, the simulation can more accurately reflect the different real-world scenarios and provide valuable data on how a growing market might operate under different conditions.

The objective of these two scenarios is to assess the scalability potential of this case study and identify any obstacles to scalability encountered during the pilot project. Scenario I replicates the pilot project as it was introduced in the real environment, incorporating a P2P energy trading market mechanism to test the financial performance by simulating financial transactions between participants. Building on the findings of Scenario I, Scenario II addresses the challenges faced during the pilot project, particularly the difficulties encountered in recruiting additional participants. The aim is to provide insights into how the P2P energy trading markets could be scaled up and expanded in a way that addresses these practical challenges. In both scenarios, a detailed analysis will assess the market's response to varying market design choices and participation shares.

4.4 Identifying performance indicators

In line with the scalability analysis framework, market-related performance indicators have been evaluated in order to assess the pilot project's success in meeting its stated aims and objectives. This section outlines the performance indicators selected for this case study. The study differentiates

between two categories: ‘economic performance indicators’ and ‘technical performance indicators’. The selected performance indicators are designed to cover both the operational and economic aspects of the case study.

4.4.1 Economic performance indicators

The economic performance indicator is used to assess the distribution of electricity costs within the community. This is calculated using the average electricity bill per participant. To calculate the average electricity bill, the total electricity bill for each participant is calculated by deducting the income received from selling energy to either the retailer or other participants from the costs incurred from purchasing energy from the retailer or other participants as seen in Equation 4.1. The resulting figure is the monthly electricity bill for each participant. A positive bill value indicates that the participant has incurred a net cost for their electricity consumption. Consequently, a negative bill value indicates that the participant has generated more income from exporting energy than the cost incurred for importing it, thereby qualifying for a monthly compensation payment. The results of this performance indicator will provide insight into the financial impact of the P2P energy trading market on individual participants, offering a measure of the economic benefits or costs associated with engaging in this trading system.

$$Total\ electricity\ bill = \sum_{t=1}^{744} (E_{P2P \rightarrow P_{im}} \times p_{p2p}) + (E_{G \rightarrow P_{im}} \times p_g) - \quad (4.1)$$

$$(E_{P_{ex} \rightarrow P2P} \times p_{p2p}) + (E_{P_{ex} \rightarrow G} \times p_{fit})$$

$$p_g \in p_{stratified}, p_{sc} \quad (4.2)$$

$$p_{fit} \in p_{spot}, p_{sc} \quad (4.3)$$

where $E_{P2P \rightarrow P_{im}}$ is the energy imported or purchased from the P2P market, $E_{G \rightarrow P_{im}}$ is the energy imported or purchased from the grid, $E_{P_{ex} \rightarrow P2P}$ is the energy exported or sold on the P2P market and $E_{P_{ex} \rightarrow G}$ is the energy exported or sold to the grid. The results are summed over the 744 time steps, corresponding to 24 trading periods over 31 days.

In the base case, meaning in the absence of a P2P market, all imported energy $E_{P_{im}}$ is billed at a rate of p_g , while all exported energy $E_{P_{ex}}$ is billed to the price p_{fit} . As outlined in Chapter 4.6.3, Equation 4.2 stipulates that the tariff for grid-imported energy can fluctuate between the stratified

cost for the specific participant (subsidised or taxed) or the standard electricity tariff rate, denoted sc . In accordance with Equation 4.2, the FiT can be calculated using either the spot market price or the single cost of electricity.

In order to assess the typical performance of a market participant, the overall market performance is disaggregated and allocated to the individual participant, as per Equation 4.4, where N represents the number of participants in the market:

$$\text{Avg. electricity bill} = \frac{\sum_{n=1}^N \text{Total electricity bill}}{N} \quad (4.4)$$

The equation can also be used to calculate the average energy bill for a specific participant type (e.g. high-income consumer, high-income prosumer and low-income prosumer) or stratum. This allows for a more detailed analysis of market performance and the impact of the P2P market on different participant groups.

4.4.2 Technical performance indicators

In this case study, the absence of specific technical requirements relating to the electricity network, such as peak power output, grid congestion, or constraints, means that the technical performance indicators are limited to evaluating community self-consumption and self-sufficiency. These indicators are focused on evaluating the extent to which participants in the P2P energy trading market can meet their own energy needs through the energy they generate, thereby reflecting the degree of independence from external energy supplies. Together with the economic indicators, they can provide information about the efficiency of a P2P energy trading market. Their technical significance in P2P markets, where transactions are not directly related to physical electricity transactions, is limited. However, they do provide information about the balance between demand and supply, which allows for insights to be derived about the size of the market and participants operating in it.

Community self-consumption is defined as the proportion of electricity generated by PV installations that is consumed directly by participants in the market. This metric is useful for determining the energy usage from the PV array by participants. The equation for calculating community self-consumption is depicted in Equation 4.5.

$$\text{Community self-consumption} = \sum_{n=1}^N \sum_{t=1}^{744} \left(\frac{E_{P_{ex} \rightarrow P2P}}{E_{P_{ex} \rightarrow P2P} + E_{P_{ex} \rightarrow G}} \right) \quad (4.5)$$

Community self-sufficiency is a measure of a community's ability to fulfil its own energy requirements using the energy traded on the P2P energy trading market, rather than depending on external grid imports. The calculation for community self-sufficiency is presented in Equation 4.6.

$$\text{Community self-sufficiency} = \sum_{n=1}^N \sum_{t=1}^{17520} \left(\frac{E_{P2P \rightarrow P_{im}}}{E_{P_{ex} \rightarrow P2P} + E_{P_{ex} \rightarrow G}} \right) \quad (4.6)$$

It should be noted that the calculations do not take into account the individual self-consumption of each participant, as this data was not separately metered during the pilot project. Consequently, the focus is on the collective performance of the community as a whole within the P2P market, rather than on individual energy usage and generation patterns.

4.5 Data collection

Prior to outlining the P2P energy trading market simulation environment and addressing the defined scalability scenarios, it is crucial to gather the data that will feed into the scalability analysis. This includes an understanding of the prevailing policy and regulatory landscape, as well as energy demand and PV generation profiles. Collecting this information is essential as it provides key input parameters for the simulation. These elements must be fully understood before setting up the simulation environment.

4.5.1 Policy and economic data

The residential energy tariffs in Colombia are a combination of average cost prices and a non-trivial system of targeted subsidies and taxes. The simulation environment is based on the current tariff design to ensure the most accurate representation of real-world conditions. However, it is important to note that the characteristics of the tariff design may limit the development of new and innovative business concepts in the energy market. Further details and variations to the current tariff design tested in the scalability scenarios can be found in Chapter 4.6.

Colombian residential energy customers with a consumption of less than 55 MWh/month are subject to fixed tariffs, which are set by the CREG. The fixed tariffs are based on a base tariff, also known as the Single Cost of Electricity (SC), which is calculated on a monthly basis. This calculation takes into account various costs, including those associated with generation, trans-

mission, distribution, marketing, losses and restrictions (CREG, 2007). The SC represents the foundation upon which the cross-subsidy scheme is built. The cross-subsidy scheme entails a 20% contribution or tax charge for customers in strata five and six, in addition to the SC. This contribution is transferred as a subsidy to customers in strata one, two and three, who receive a reduction between 15% and 60% on top of their energy tariff (CREG, 2007). The subsidised tariff is applicable for energy consumption below a fixed monthly limit, after which the SC is used. The subsidy's limit is determined by the city's altitude above sea level (for Medellín this is 130 kWh/month). The limit is introduced to prevent households with high energy consumption from moving to lower strata just to benefit from subsidies intended for low-income users with lower monthly energy consumption. Customers in stratum four are liable for the SC, with no additional contribution or subsidy. Figure 4.2 provides a schematic overview of the current tariff design in Colombia.

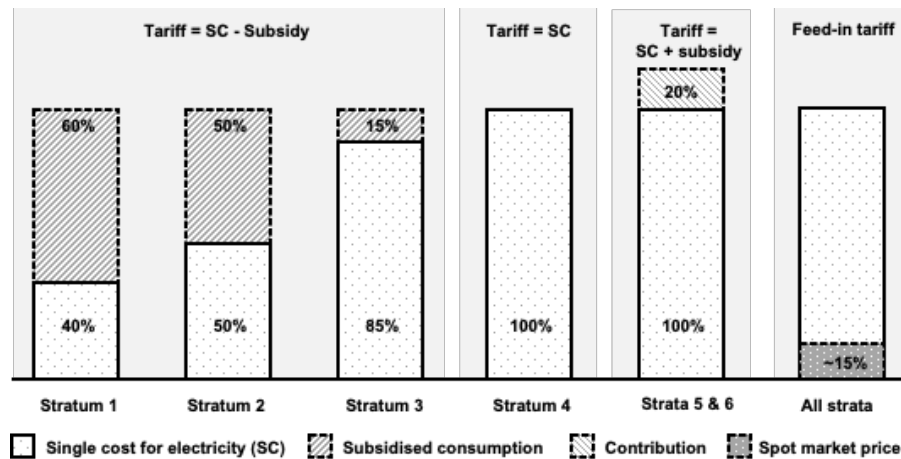


Figure 4.2: Overview of electricity tariffs and stratification system in Colombia (adapted from López et al. (2020)).

The initial rationale behind the implementation of the stratification system was to guarantee an equitable distribution of resources and promote social justice among households. However, the system has since been subjected to criticism, primarily for its perceived economic infeasibility. In particular, the additional revenue generated by the taxes paid by customers in strata five and six is insufficient to finance the subsidies granted to households in strata one, two and three. The Colombian government is therefore required to make up the difference. This indicates that the stratification of electricity tariffs requires external subsidies in both the short and long term or even higher taxes on residents from strata five and six. For instance, in 2017 the government had to add USD 488 million to public spending to maintain the subsidies (MinHacienda, 2019).

The regulatory framework governing the implications for households generating their own electricity has only recently been established. The regulation, published in 2018, defines the generation of electricity for non-commercial purposes (CREG, 2018). CREG Regulation 030 sets out the conditions for net metering for small self-generators in Colombia. In the event that a household's monthly net energy export is less than the monthly net import, the energy retailer is obliged to pay each household the SC price for their exported energy, minus marketing fees. However, for any amount of energy exported above the household's import level, the household will receive the spot market price plus losses and restrictions, which is a significantly lower rate than the standard tariff. To illustrate, if a household consumes 100 kWh and exports 130 kWh during one month, the household will be paid the SC price for the first 100 kWh and the spot market price for the remaining 30 kWh. Energy imported and exported are settled on a monthly basis, resulting in energy users receiving their bills on a monthly basis. This concept is also referred to as 'net metering' in Colombia. These regulations are intended to encourage the production of energy for self-consumption and discourage the production of energy for sale to third parties. Additionally, they aim to prevent households from oversizing their generation capacity, for example, by not using all available roof space for solar PV systems, and to limit this to the household's maximum import capacity.

4.5.2 Energy demand and PV generation profiles

As outlined in Chapter 3.2, where possible, real energy load data from participants in the pilot project should be used. In this case study, the project coordinators made available the real load data from households that participated in the pilot project. The electricity load data from the installed meters was provided in the form of multiple CSV files, which were subsequently loaded into a PostgreSQL database. The use of real load data in the simulations significantly improves the accuracy and realism of the model, as it reflects the actual energy consumption and generation profiles of households. This approach can improve the reliability of the findings and support more effective energy system planning and policymaking (Ge et al., 2016).

The project participants were provided with supplementary metering infrastructure from NEU, in addition to the existing meters supplied by EPM. The new meters were able to record both electricity inflows and outflows and will be referred to as 'energy import' and 'energy export' in the following. It should be noted that the precise energy consumption and generation profiles of the participating consumers were not available, as the installed electricity meters only measured energy inflow and outflow. Information on the self-consumed energy of the prosumers behind the

meter is not available. Some prosumers had separate meters installed to measure PV generation, but the data from these meters was not included in the simulation due to its poor quality. The electricity meters collected data in hourly increments, providing detailed insights into electricity load patterns measured in kilowatt hours (kWh) for each hour.

Due to some data issues encountered during the pilot project, as outlined Chapter 4.3, there were significant amounts of missing data in the provided dataset. A comprehensive data cleansing and analysis process was conducted on the load data, offering valuable insights into data quality and other load characteristics. Figure A.1 in Appendix provides an overview of the missing values in the energy import and export datasets.

Once loaded into the database, all datasets were subjected to a data cleansing process to identify and remove any missing data points, duplicates, irregularities or outliers. Missing data values were filled in using advanced data imputation techniques, while duplicates were removed. Any missing energy export data points were filled using linear interpolation, with the nearest mean used as a reference point. Similarly, missing energy import data were cleaned using historical average imputation, as outlined by Peppanen et al. (2016). This method was deemed appropriate given that the temperature and radiation intensity in Medellín remain consistent throughout the year, as illustrated in Figure 4.3. Medellín is classified as having a tropical rainforest climate (Medina et al., 2021), characterised by high precipitation and temperatures year-round, with an average annual temperature of 22 °C and minimal temperature fluctuations.

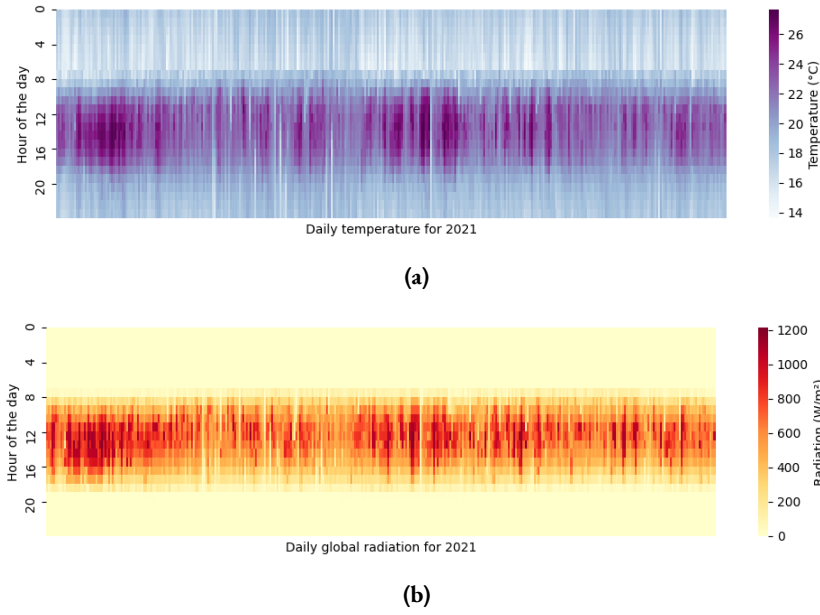


Figure 4.3: Daily temperature (a) and global radiation (b) in Medellín in 2021.

The data collection phase was concluded at the end of the pilot programme in December 2021. Further analysis of the impact of poor data quality during certain periods of the pilot can be found in the discussion section of this Chapter. Further details on participants' load profiles can be found in Appendix A.2.

4.6 Definition of simulation environment

The preceding sections provided an overview of the pilot project and its contextual characteristics. This section builds on that foundation by introducing a simulation environment designed to conduct a scalability analysis, addressing the barriers faced by the scalability scenarios. The link to the simulation environment and code is provided in Appendix A.1.

4.6.1 Simulation period

The first critical step in configuring the P2P energy trading market is to determine an appropriate simulation period. It is essential to strike a balance between simulation time and computational resource requirements by identifying a period that provides reliable results while keeping computational resources at a minimum.

In the context of this case study, market performance is influenced by a number of factors, including daily load profiles, variations between weekdays and seasonal differences that affect weather conditions and, consequently, energy generation and consumption. It is worth noting that Medellín

experiences minimal seasonal fluctuations, as illustrated in Figure 4.3. Given the stability of the climate, a one-month simulation period was deemed sufficient to evaluate market performance. This period effectively captures hourly and daily variations in load patterns and provides insight into longer-term P2P energy trading market performance, addressing the gap in the short-term focus of existing studies Capper et al. (2022b). The simulation uses participant load data from August 2021, selected for its good data quality.

4.6.2 Market participants and load profiles

All 13 households included in Table 4.1 who took part in the real-pilot project were considered for the simulation. In P2P energy trading markets, where transactions occur directly between individual households within a small group, understanding the influence of each participant on the market is crucial. It is essential to analyse participants' load profiles in order to identify distinct load behaviours or patterns, and thus assess their collective impact on the overall market dynamics.

Figure 4.4 and Figure 4.5 illustrate the load profiles of participating households over the selected simulation period. It is evident from the plots that there is considerable variation between participants. However, there are also similarities between households within the same or similar socio-economic strata. For instance, in July 2021, low-income prosumers imported an average of 68 kWh, high-income consumers imported 208 kWh, and large prosumers imported 461 kWh, reflecting that higher energy demand is linked to higher income groups. Energy export outputs also differ greatly given the different installation capacities among participant groups.

While these load profiles are not representative of each participant group, they provide valuable insight into the load characteristics of market participants and their energy needs. It should be noted that P2P energy trading markets do not necessarily operate in fully representative communities with customer profiles that have been specifically selected. As previously highlighted in Chapter 2.7, P2P energy trading systems are highly contextual. It is therefore important to consider the different load characteristics and assess their impact on the performance of the study. Using real load profiles of households involved in the pilot can increase accuracy and realism by reflecting actual consumer energy use patterns and behaviour. This approach improves the reliability of results and supports effective energy system planning, policymaking and stress testing under different conditions.

Finally, in order to assess the market's scalability potential in line with Scenario II set out in Chapter 4.3, additional participant profiles were required. It should be noted that access to residential

energy customers' load profiles in Colombia, and Medellín specifically, is limited. Accordingly, load profiles for prosumers in stratum two and three, and consumers in stratum four, five, and six, were generated using a Markov chain model in accordance with the methodology proposed by Toffanin (2016) and Labeeuw et al. (2013). The model considers a number of key parameters, including total annual consumption, load magnitude distribution, daily peak load magnitude distribution, time of use of daily peak load distribution, and autocorrelation. The model was limited to intraday and intra-week patterns due to the absence of distinct seasons in Medellín. Further details about the algorithm and load profiles created can be found in Appendix A.3.

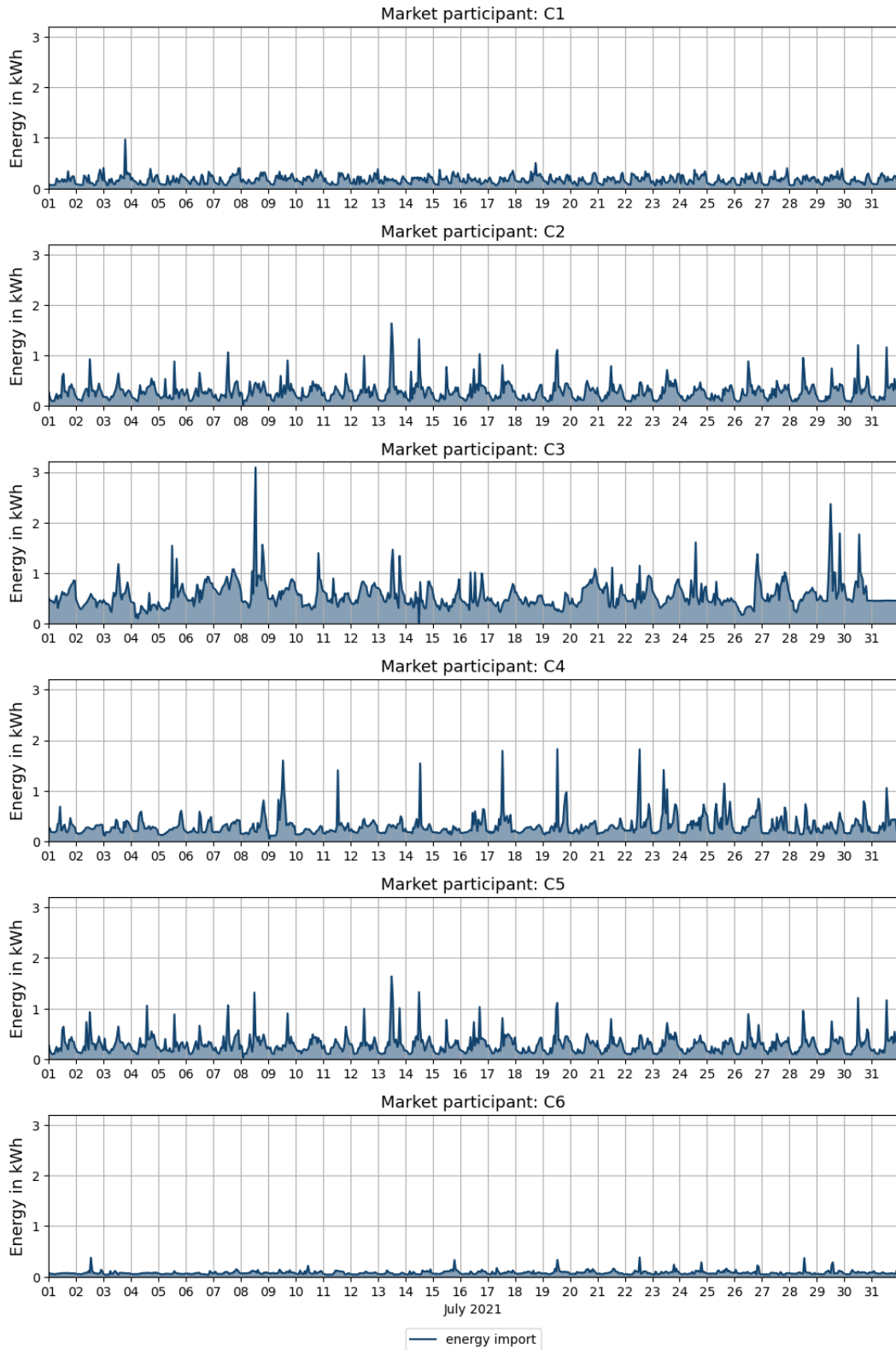


Figure 4.4: Energy import load profiles for market participants C1-C6 during the simulation period in July 2021.

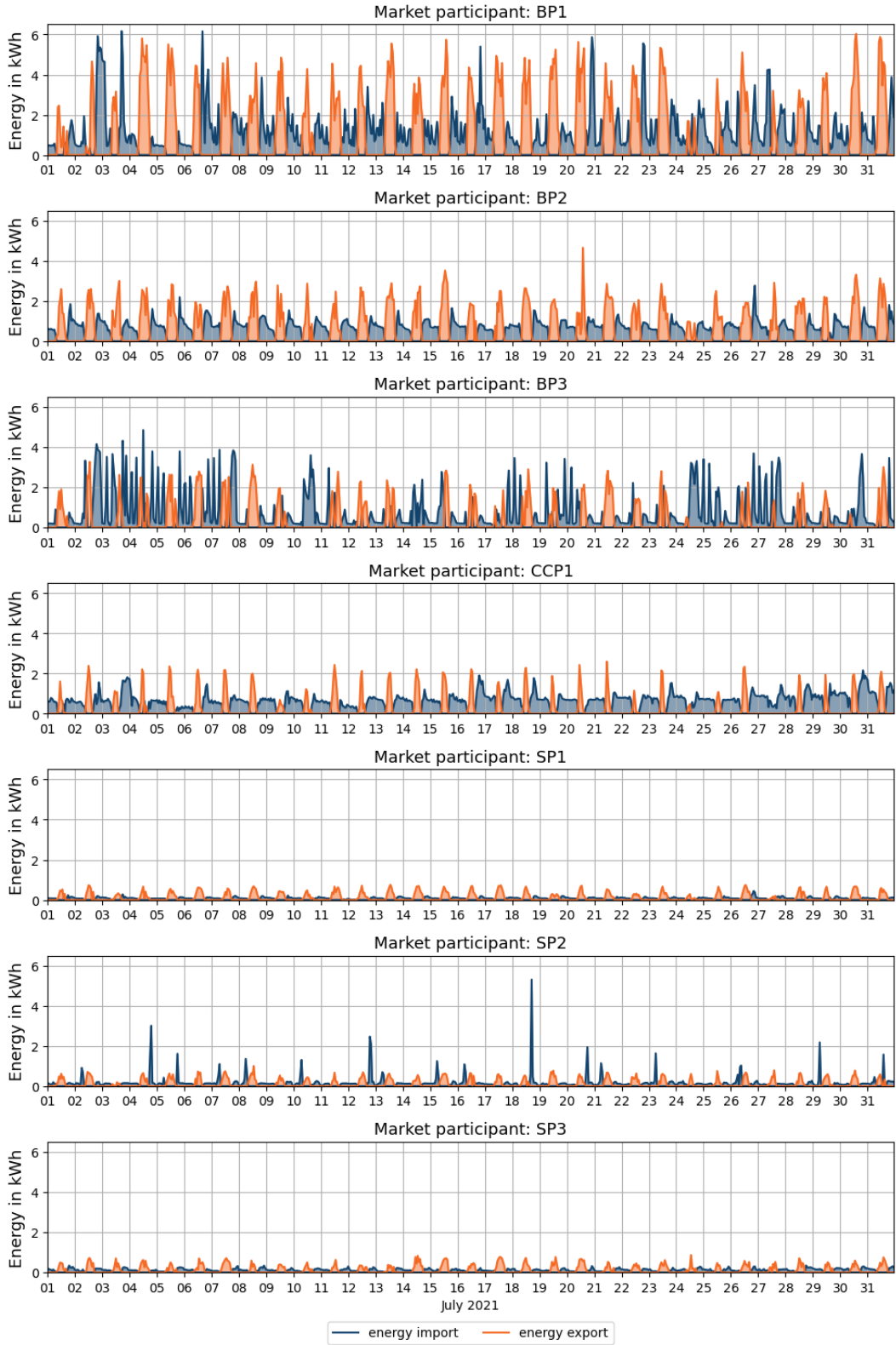


Figure 4.5: Energy import and export load profiles for market participants BP1-BP3, CCP1, and SP1-SP3 during the simulation period in July 2021.

4.6.3 Electricity tariff design

This chapter presents the tariff design used for the simulation of the P2P energy trading market. It reflects existing Colombian residential energy tariffs as well as a number of alternatives that could be used to scale beyond current restrictions of the regulatory environment. The revised tariff designs, based on the challenges discussed in Chapter 4.5.1, allow for the evaluation of the performance of the P2P market under varying external factors that cannot otherwise be tested in a real-world setting. Two tariff variations are proposed for both the ‘base case’ and the ‘P2P market’ operation, detailed in Table 4.2. The following sections will describe and justify these variations.

Tariff	Base case w/ high FiTs	Base case w/o high FiTs	P2P market w/ strata	P2P market w/o strata
Energy import (price/kWh)	Strata tariff	Strata tariff	Strata tariff	SC tariff
Energy export (price/kWh)	SC tariff with net metering limit (then spot market price)	Spot market price	Spot market price	Spot market price

Table 4.2: Proposed electricity tariff design for simulation environment for base case and P2P market operation.

The ‘base case with high FiTs’ tariff design is consistent with the current Colombian tariff design. The tariff design maintains the stratified tariff for energy import and applies a FiT equivalent to the SC price for energy exported, while the total exported energy is lower than the imported energy. Any exported energy in excess of net imported energy in a monthly period is paid at the spot market price. A detailed explanation of this tariff design can be found in Chapter 4.5.1 above.

The ‘base case without high FiTs’ tariff design modification alters the FiT to align with the spot market price, rather than the SC. This change means that households would no longer receive the highly subsidised SC price for their exported energy. This adjustment aligns with recent trends in more advanced economies where support for residential solar PV through high FiTs is being reduced or phased out (Candas et al., 2019). Additionally, this tariff design could facilitate new energy business models which often require near-real-time metering.

In the P2P market simulation, two tariff designs are considered to accommodate different market dynamics and regulatory scenarios. The first variation, ‘P2P market with strata’, is based on the ‘base case without high FiTs’ tariff design. The existing tariff framework, which defines the upper

and lower price limits for energy transactions, is retained. The upper limit for energy imports is set at the respective stratum tariff of each participating household. The lower limit for energy exports is set at the spot market price. To illustrate, participant C₁, a consumer in stratum four, submits a bid to the market indicating a willingness to pay 0.08£/kWh for energy consumption. Should the energy demand be successfully met in the market, the participant will be charged the market price. However, in the event that the market demand cannot be met, the participant is subject to the tariff price of 0.11£/kWh applicable to stratum four. This tariff design reflects the necessity for more granular metering and billing data in order to accurately match supply and demand in a dynamic P2P market environment. Adapting the 'base case with high FiTs' is not a viable option, as it requires monthly settlement.

The second tariff design, 'P2P market without strata', addresses the feasibility concerns of the stratification system outlined in Chapter 4.5.1. The current model is facing challenges due to an imbalance in tax contributions and subsidies across income classes. In particular, the higher income strata (5 and 6) have higher tax contributions than the lower income strata (1, 2 and 3), which require greater subsidies. In the 'P2P market without high FiTs' tariff design, all market participants operate under a unified pricing structure. The upper price limit for energy imported is set by the SC price, which represents the maximum price per kWh when no energy is traded on the market and instead is purchased from the retailer. Conversely, the lower price limit for energy exported is limited by the spot market price, representing the minimum price per kWh when energy cannot be sold on the market and instead needs to be sold to the energy retailer. This tariff design aims to evaluate the potential of P2P energy trading to create a more balanced and economically viable market, providing an alternative to the traditional stratification system.

All proposed tariff designs align pricing with Colombia's current electricity prices. The SC tariff is set at 594 Colombian pesos (equivalent to 0.11£/kWh). The spot market price is set at 92 Colombian Pesos (equivalent to 0.02£/kWh), which is in line with the market rate during the data collection period. The SC tariff incorporates a number of elements, including generation, transmission, distribution, commercialisation, losses and restrictions. These are outlined in more detail in Chapter 4.5.1. The FiT includes the same components, except the commercialisation element. For the sake of simplicity, the FiT does not include the commercialisation component, given the relatively minor impact and the already complex nature of these elements.

While there are some suggestions for reforms of stratification systems in the literature, none are

explicitly designed for P2P energy trading markets. By comparing and contrasting different tariff designs, the objective is to assess the potential of P2P energy trading markets in expanding the current residential energy market operation and the existing stratification system. Furthermore, this assessment of tariff designs is not only about the economic feasibility but also considers the broader implications for social equity and environmental sustainability. The potential of P2P energy trading markets to democratise energy access and foster a more inclusive energy landscape, particularly in diverse socio-economic contexts like Colombia, is a key aspect of this evaluation.

4.6.4 Market mechanism

Given the difficulties encountered in implementing a full P2P energy trading market in the Medellín Pilot, this chapter puts forward a proposal for a P2P market clearing mechanism. The aim is to assess the potential impact and dynamics of a fully operational P2P energy trading market that allows real monetary transactions among participants.

In contrast to other P2P energy trading pilots, which were primarily focused on providing grid services and managing grid constraints, the primary objective of the Medellín P2P energy trading pilot was to connect households from diverse socio-economic backgrounds. The project facilitated the virtual exchange of energy in a P2P market, aiming to promote financial and social benefits, particularly for low-income households.

Chapter 2.2.1 examined market mechanisms that are commonly found in existing literature. It considered their adaptability to diverse market operations and objectives. The double auction mechanism, a common choice in similar studies as highlighted by Mengelkamp et al. (2017) and Chapman et al. (2019), was selected for this study. One of the key advantages of this mechanism is that it allows participants to exercise control over their trading preferences and to set prices flexibly. This is not typically offered by system-based pricing mechanisms. In a double auction, both buyers and sellers set their maximum or minimum prices for energy transactions. This results in a market clearing price that accurately reflects the collective preferences of all participants. This method is also a well-established practice in the wholesale energy market.

The double auction mechanism used in this study operates on an economic dispatch system that uses uniform pricing to optimise the social welfare of all participants involved. Market participants submit bids at their maximum willingness to pay for electricity and offer their minimum acceptable selling price. In this context, social welfare refers to the overall well-being or economic benefits derived from energy trading activities. The optimisation function is defined in Equation 4.7 - 4.10,

where p is the price of energy per kWh, x is the energy supply by sellers S and energy demand of buyers D , with the agent j selling to the agent i :

$$\max_{x_i^D, x_j^S} \sum_{i \in \mathcal{I}}^{N_D} p_i^D x_i^D - \sum_{j \in \mathcal{J}}^{N_S} p_j^S x_j^S \quad (4.7)$$

$$\text{subject to } \sum_{j \in \mathcal{J}} x_j^S - \sum_{i \in \mathcal{I}} x_i^D = 0 \quad (4.8)$$

$$0 \leq x_i^S \quad (4.9)$$

$$0 \leq x_j^D \quad (4.10)$$

Once the market is settled, all transactions are cleared at the Market Clearing Price (MCP). In instances where there is a multiplicity of prices, a unique MCP cannot be determined. In such cases, the MCP is selected randomly within the range of the lowest bid price and the highest ask price. Each bid and offer $p_{i,j}$ submitted by the market participants is a random value between a lower bound p_l and an upper bound p_u which are defined by the FiT and the strata or SC price (depending on which tariff design is studied) according to Equation 4.11.

$$p_l \leq p_{i,j} \leq p_u \quad (4.11)$$

This type of randomised bidding by participants in the market is also referred to as a zero-intelligence trader. The concept of zero-intelligence traders is employed in economic and financial models, particularly in the analysis of markets and trading behaviours. They are essentially theoretical agents (traders) that make decisions randomly, without any strategic planning, foresight, or consideration of market conditions or outcomes. This approach is frequently used to approximate trading behaviour of peers in P2P energy trading markets as it is able to model lower-bound system efficiency (Vytelingum et al., 2010; Guerrero et al., 2018). This study adopts an ex-post approach to energy trading, whereby physical energy transactions precede monetary exchanges. While this method simplifies the analysis by eliminating the need to account for uncertainties in trading and forecasting variability, its practical applicability is still open for discussion. Further implications are discussed in the limitation Chapter 6.1. In contexts where managing grid constraints is not the primary focus, this ex-post trading approach can serve as an effective method for settling energy

transactions.

In the event of an unfulfilled energy demand or surplus within the market, these are settled with the grid in accordance with the prevailing tariff design prices. The electricity supplier assumes the role of a ‘supplier of last resort’, guaranteeing the consistent fulfilment of energy needs for all participants. This function is critical in ensuring a reliable and continuous energy supply for all involved in the P2P market. When energy transactions are settled with the grid, electricity is typically provided by the local retailer, in this case EPM. The retailer margin is reflected in the SC price, which incorporates various price components, including a retailer fee.

It is important to note that, as part of the P2P energy trading market design, participating households were not charged for their involvement in the pilot project, as external funding was available. However, in a commercial implementation beyond the pilot setting, it is likely that the model would transition toward a subscription-based approach, as proposed by Sandys et al. (2018).

4.7 Scalability analysis and calculation of performance indicators

This section presents the results of the scalability analysis, which includes the calculation of the identified performance indicators outlined in Chapter 4.4. The results⁴ are presented in two parts, each corresponding to the two scenarios described in Chapter 4.3. The first part presents the results of Scenario I, which compares the base case with the P2P market operation. The second part presents the results of Scenario II, which examines the impact of increased market size on the P2P energy trading market’s performance.

4.7.1 Scenario I

This section presents the results of the P2P market analysis. The performance of the P2P energy trading market is evaluated using the performance indicators introduced in Chapter 4.4. This assessment compares the outcomes between the base case and the P2P market design. The chapter begins with an analysis of the economic performance of the P2P market, followed by an analysis of the technical performance.

⁴It is important to note that the results of this scalability analysis are illustrative rather than directly applicable to the real world, as the simulation environment is only an approximation of the real pilot conditions and includes assumptions and simplifications. These results, which may differ from the actual results of the pilot, are intended to provide nuanced insights into specific design choices and their potential impacts. This simulation serves as a tool for understanding and extrapolating the impact of different design choices in a controlled, hypothetical context.

4.7.1.1 Economic analysis

Table 4.3 illustrates the electricity bills of all participants over the course of the simulation period. It compares the tariff designs of the base case with high FiTs with those of the P2P market, with and without the stratification system. The data demonstrates that the introduction of the P2P market results in a notable reduction in energy bills for high-income consumers. Consumers in the market have the option to purchase energy from the P2P market at a lower price point, rather than from the energy retailer at the higher strata-specific price. The reduction in energy bills is more pronounced in the P2P market without strata. Participants, especially those previously located in the higher-income stratum 6, e.g. C2-C4, now pay the SC price without the additional taxes. Furthermore, the removal of stratification encourages greater competition between prosumers, leading to a greater reduction in energy bills for consumers in the market.

Participant	Base case w/ high FiT	P2P market w/ strata		P2P market w/o strata	
	Total energy bill (in £ equiv.)	Total energy bill (in £ equiv.)	Bill changes (%)	Total energy bill (in £ equiv.)	Bill changes (%)
(HI) C1	14.02	12.16	↓ 13	11.97	↓ 15
(HI) C2	27.47	22.33	↓ 19	18.88	↓ 31
(HI) C3	55.33	46.47	↓ 16	39.4	↓ 29
(HI) C4	29.92	24.24	↓ 19	20.32	↓ 32
(HI) C5	23.12	19.42	↓ 16	19.15	↓ 17
(HI) C6	6.23	5.36	↓ 14	5.25	↓ 16
(HI) BP1	10.08	59.57	↑ 491	45.49	↑ 351
(HI) BP2	6.86	35.43	↑ 416	27.59	↑ 302
(HI) BP3	31.36	47.5	↑ 51	39.67	↑ 26
(HI) CCP1	27.29	39.84	↑ 46	39.94	↑ 46
(LI) SP1	-1.55	0.8	↑ 152	1.81	↑ 217
(LI) SP2	-3.73	2.2	↑ 159	7.88	↑ 311
(LI) SP3	-1.46	2.49	↑ 271	3.75	↑ 357

Table 4.3: Comparison of the energy bill between the ‘base case with high FiTs’ tariff design (SC price for energy exported as long as monthly net energy export is lower than net energy import, after which the spot market price is paid for energy exported) and the P2P market with and without the stratification system in place. ↓ indicate a decrease in the total energy bill, while ↑ indicate an increase in the total energy bill. (HI) indicates for high-income and (LI) indicates low-income participants.

By contrast, for prosumers engaged in the P2P market, energy bills are set to rise under both P2P market tariff designs. This increase is due to the fact that, as a result of the FiT, prosumers are no longer able to benefit from the more favourable SC price. The impact is more pronounced in cases where monthly net energy exports are lower than net energy imports, as all exports are compensated at the higher SC price in line with the FiT rate. To illustrate, high FiT rates result in negative energy bills for low-income prosumers, whereby they are compensated for their energy consumption at the end of each month. Furthermore, a comparison of the P2P market with the existing stratification system reveals that high-income prosumers experience a higher increase in

their bills, while low-income prosumers see a smaller increase. In contrast, in the P2P market without the stratification system, this trend is reversed: low-income prosumers tend to face a higher increase in bills, whereas the increase is lower for high-income prosumers. The reason for this trend in the P2P market without a stratification system is that all low-income prosumers are charged the less favourable SC price for their imported energy, which removes the advantage of previous subsidies. Meanwhile, high-income prosumers benefit as they are no longer subjected to additional taxes on top of their standard SC rate.

Table 4.4 compares the ‘base case without high FiTs’ tariff design, where all participants are compensated at the spot market price for their exported energy, with the P2P market scenarios, both with and without the stratification system. In the stratified P2P market, there is a reduction in energy bills for all participants, with the greatest relative reduction seen in low-income prosumers. In contrast, the reduction in energy bills in the P2P market without stratification is more substantial, although this advantage predominantly favours high-income participants. It is worth noting that participant SP2 experienced an increase in their energy bills. Following the removal of the stratification system, this participant now pays 50% more per kWh for energy imports from the grid. For comparison, for participants SP1 and SP3 only pay 15%, as shown in Figure 4.2. This is why they are less affected by the removal of the stratification system.

Participant	Base case w/o high FiTs	P2P market w/ strata		P2P market w/o strata	
	Total energy bill (in £ equiv.)	Total energy bill (in £ equiv.)	Bill changes (%)	Total energy bill (in £ equiv.)	Bill changes (%)
C1	14.02	12.16	↓ 13	11.97	↓ 15
C2	27.47	22.33	↓ 19	18.88	↓ 31
C3	55.33	46.47	↓ 16	39.4	↓ 29
C4	29.92	24.24	↓ 19	20.32	↓ 32
C5	23.12	19.42	↓ 16	19.15	↓ 17
C6	6.23	5.36	↓ 14	5.25	↓ 16
BP1	64.24	59.57	↓ 7	45.49	↓ 29
BP2	39.6	35.43	↓ 11	27.59	↓ 30
BP3	54.73	47.5	↓ 13	39.67	↓ 28
CCP1	42.71	39.84	↓ 7	39.94	↓ 6
SP1	2.35	0.80	↓ 66	1.81	↓ 23
SP2	3.79	2.20	↓ 42	7.88	↑ 108
SP3	4.03	2.49	↓ 38	3.75	↓ 7

Table 4.4: Comparison of the energy bill between the ‘base case without high FiTs’ tariff design and the P2P market with and without the stratification system in place. ↓ indicate a decrease in the total energy bill, while ↑ indicate an increase in the total energy bill.

The decision to focus on absolute energy bills was driven by the significant discrepancies in total energy consumption observed across different participant groups, which directly impact the overall cost of energy. For example, participant SP1, as illustrated in Table 4.4, realises a 66% reduction in

costs upon transitioning to a P2P market. This change equates to a savings of £1.55, resulting in a total energy bill of £0.80. Conversely, participant BP1 experiences a smaller percentage decrease of 7% in their energy bills, but this equates to a larger monetary reduction of £4.67, leading to a new total bill of £59.57.

The differences between absolute and relative values demonstrate the value of presenting absolute energy bills as a means of illustrating the variations within the market. This approach offers a clearer perspective on market dynamics and the financial impact on various participant groups, placing them in a more accessible context. These variations raise a crucial question: is the compensation provided through the P2P market sufficient to motivate customers to actively choose P2P trading over remaining in the current status quo? This key consideration, focusing on the factors influencing customer decisions to transition to a P2P market, will be explored in more depth in the discussion chapter.

Using the dataset from above, Figures 4.6 and 4.7 provide a visual representation of the total costs and savings. These figures are organised by participant type within the market, with values averaged per participant to demonstrate the impact of the changing operational environment on different groups. The figures represent high-income consumers (participants C1-C6), high-income prosumers (participants BP1-BP3 and CCP1), and low-income prosumers (participants SP1-SP3). This breakdown provides a clear insight into how each participant group is affected by the transition to P2P energy trading under various market conditions.

Figure 4.6 (a) and (b) illustrate the impact of high FiTs on the P2P market, with and without the stratification system. It is evident that low-income prosumers experience the highest increase in energy bills. However, in absolute terms, this increase is lower than that observed among high-income prosumers.

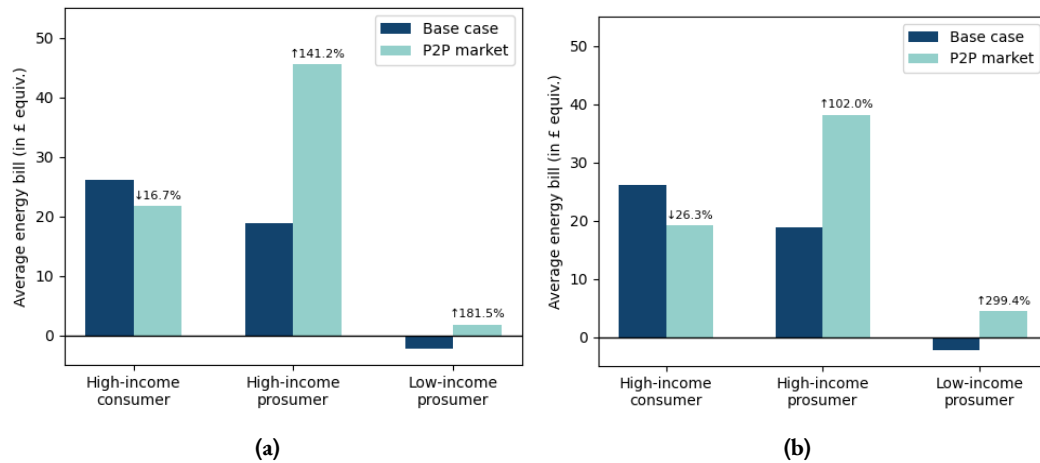


Figure 4.6: Average costs per participants and the equivalent changes in electricity bill (savings ↓ when positive values and additional costs ↑ when negative values) comparing the base case with high FiTs and the P2P energy trading market with (a) and without (b) the stratification.

On the other hand, Figure 4.7 provides an overview over the results for the base case market operation with the spot market price as FiT. Here, in Figure 4.7 (a), all groups of market participants realise savings. However, when the stratification system is removed, as shown in Figure 4.7 (b), only low-income prosumers experience a slight increase in their energy bills.

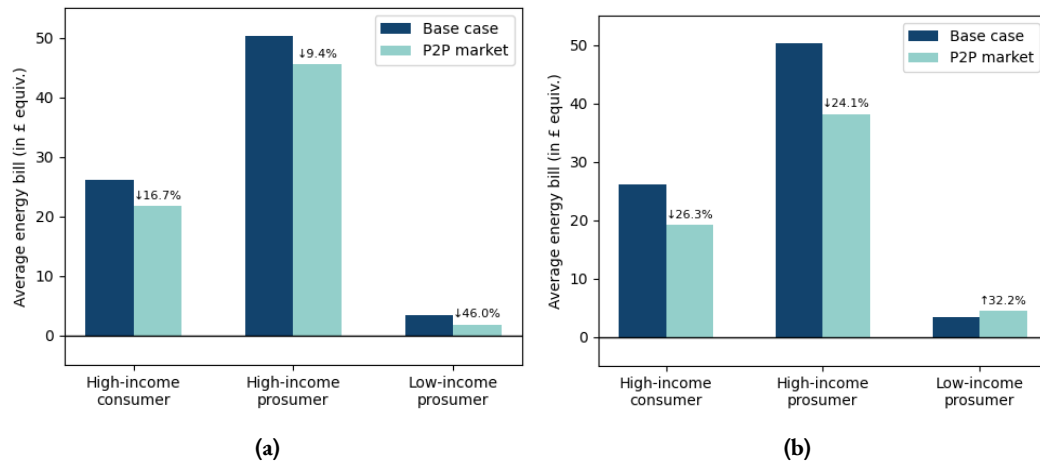


Figure 4.7: Average costs per participants and the equivalent changes in electricity bill (savings ↓ when positive values and additional costs ↑ when negative values) comparing the base case without high FiTs and the P2P energy trading market with (a) and without (b) the stratification.

In conclusion, the establishment of a P2P market based on the current status quo with high FiTs appears to offer significant advantages primarily to high-income consumers. This market scenario results in higher energy costs for both low- and high-income prosumers. Therefore, in light of

these particular circumstances, the shift from the base case to a P2P energy trading model may not be a compelling proposition for prosumers. However, given Colombia's potential direction towards reducing or eliminating FiTs, as explored in Chapter 4.6.3, the P2P market could be a viable alternative. This model is capable of reducing monthly energy bills for the majority of participants, even in the absence of a stratification system. This suggests that the P2P market could offer tangible financial benefits in a dynamically changing tariff landscape.

The Scenario I result also demonstrates the sensitivity of the P2P energy trading market to the characteristics of its participants and their associated strata. This impact is particularly evident in the increase in energy bills for low-income prosumers, as illustrated Figure 4.7 (b), which is the result of including a participant from Stratum 2. Regardless of which tariff design is compared, both in the base case and in the P2P market, high-income prosumers are the clear winners, as they consistently achieve savings in the P2P market. In contrast, the gains and losses of both high- and low-income prosumers are more nuanced and depend heavily on tariff structures and the resulting competitiveness in the market.

In addition to the strata tariff and the existing tariff design, the load profiles and characteristics of the participants also have a significant impact on the performance of the market. These aspects, which are crucial to understanding market performance, will be examined in more detail in the following analysis.

4.7.1.2 Technical analysis

The market's performance is contingent upon the volume of energy that can be traded on the P2P market. For consumers, it is important to purchase as much energy as possible from other participants. For prosumers, it is crucial to consider both the amount of energy they can purchase on the market and the potential to sell to other participants, with the objective of maximising social welfare. In the P2P market, both with and without the stratification system, the community achieves a self-consumption rate of 25% and a self-sufficiency rate of 14%. This indicates that a quarter of the energy generated by the participants' PV systems is used within the market, and 14% of their total energy consumption is supplied by these systems. As previously mentioned the self-consumption value calculated here only includes community self-consumption and does consider individual self-consumption.

Figure 4.8 and Figure 4.9 show energy traded by each participant in the P2P market with and without the stratification system in place respectively. The figures illustrate the volume of energy

imported or exported to or from the grid, as well as energy imported or exported to or from other participants in the P2P market. It is worth noting that prosumers with greater generation capacity have the ability to export more energy to their peers in the market, representing a more financially advantageous transaction. In contrast, smaller energy prosumers can export approximately half of their generated energy to other participants, relative to their total energy exported. The figures also demonstrate that pure consumers in the market can derive benefits from purchasing energy from their peers. By contrast, both large and small prosumers import only a small proportion of their energy requirements from other market participants. This pattern is particularly evident among participants who import more energy than they export over the course of a month. This suggests that their installed capacity may be insufficient to meet daytime electricity demand when solar energy is available, or it could indicate that these participants have particularly high energy consumption in the evenings, when solar energy is not being produced. This observation highlights that the balance between energy import and export for prosumers is closely tied to their installed capacity and consumption patterns, particularly in relation to the timing of energy production versus usage. The introduction of flexible energy storage or demand response mechanisms could enhance the benefits to prosumers in the market. However, it should be noted that these solutions require significant up-front investment and may present an initial financial barrier, especially for low-income participants or those already facing high up-front costs for renewable energy installations.

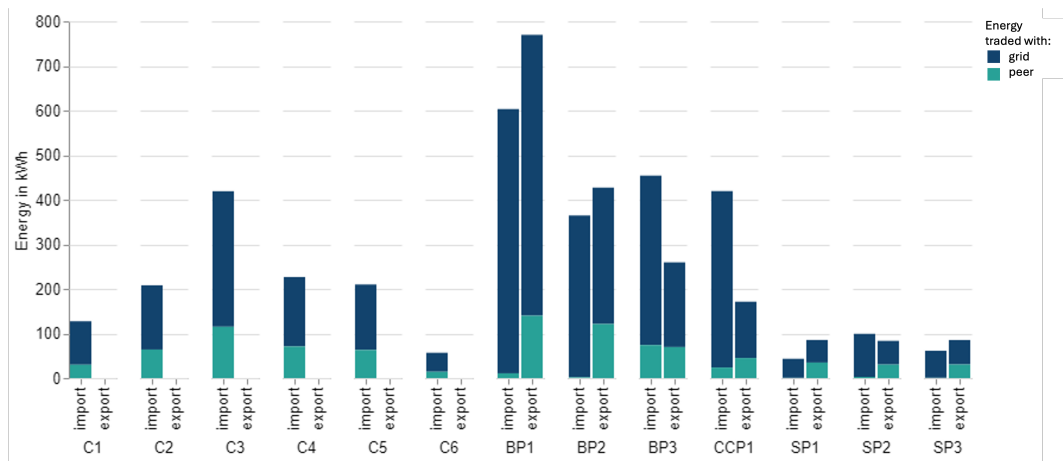


Figure 4.8: Energy import and export traded in the P2P market with the retailer or other participants in the market with the stratification system in place.

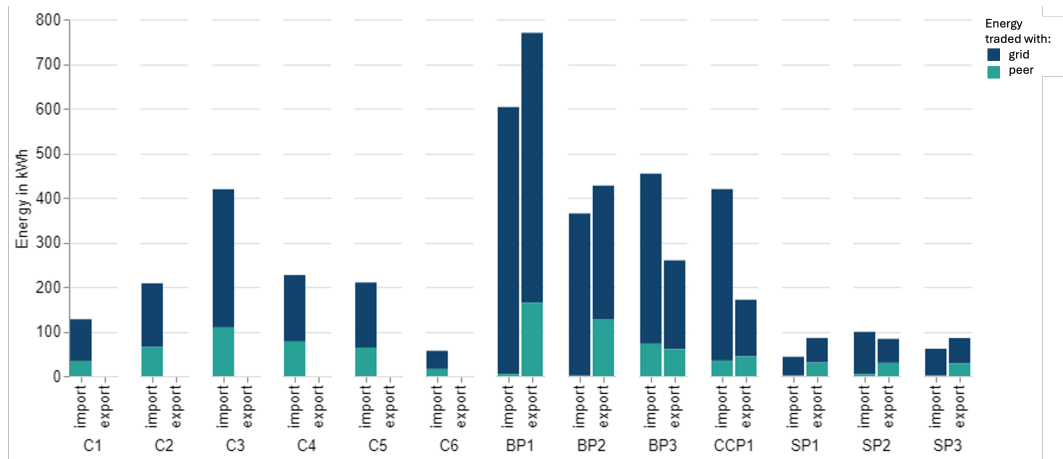


Figure 4.9: Energy import and export traded in the P2P market with the retailer or other participants in the market without the stratification system in place.

4.7.2 Scenario II

In Medellín, a significant proportion of lower socio-economic areas are situated on the southern slopes, with convenient access to solar radiation. Many wealthy residents from higher socio-economic strata reside in high-rise buildings on the valley floor of Medellín, which limits their ability to install PV systems to generate their own electricity. Derived from the objectives of the pilot project, Scenario II tests how the market would develop if additional participants were added in accordance with the original strategy of the project coordinators. The objective is to demonstrate how the inclusion of a greater number of low-income prosumers and high-income consumers can impact market performance. The market configuration is scaled up from the market design described in Scenario I to include 100 participants, 50 from the low-income strata (2 or 3) and 50 from the high-income strata (4, 5 or 6). No additional high-income prosumers are added to the market. A sensitivity analysis is performed to illustrate the impact of the additional inclusion of new participants on market performance, using the performance indicators specified in Chapter 4.4.

4.7.2.1 Economic analysis

In general, low-income prosumers benefit most when there are few prosumers in the market, which reduces competition, while there are many high-income consumers to purchase the energy sold. The opposite is also true. The market is most attractive for high-income consumers when there are few other consumers who increase competition and instead many prosumers who provide cheaper energy. The following figures present a comparison of different tariff designs defined in Chapter 4.2. The coloured fields in the heatmap indicate the percentage bill changes of the market

from a community perspective.

Figure 4.10 compares the ‘base case with high FiTs’ with the P2P market with the stratification system (a) and without the stratification system (b). In both Figures 4.10 (a) and (b), it is evident that the market or the community as a whole generates savings when there are more consumers than prosumers participating. Both high- and low-income prosumers can sell a significant portion of their excess energy to consumers, enabling most consumers to reduce their electricity costs, albeit to a limited extent. Conversely, it would be more beneficial for consumers if there were a greater number of prosumers in the market, as this would reduce competition. However, this results in increased costs for low-income prosumers and a reduction in the overall market welfare. Separate figures for energy bill changes by different participant groups can be found in the appendix in Table A.5. The figures demonstrate that the overall bill changes for high-income consumers and prosumers are more favourable in the P2P market without stratification than with stratification. However, the opposite is true for low-income prosumers, where the removal of stratification leads to a higher increase in energy bills. This is due to the fact that the stratification system reduces the energy bill for low-income prosumers and increases the energy bill for high-income consumers.

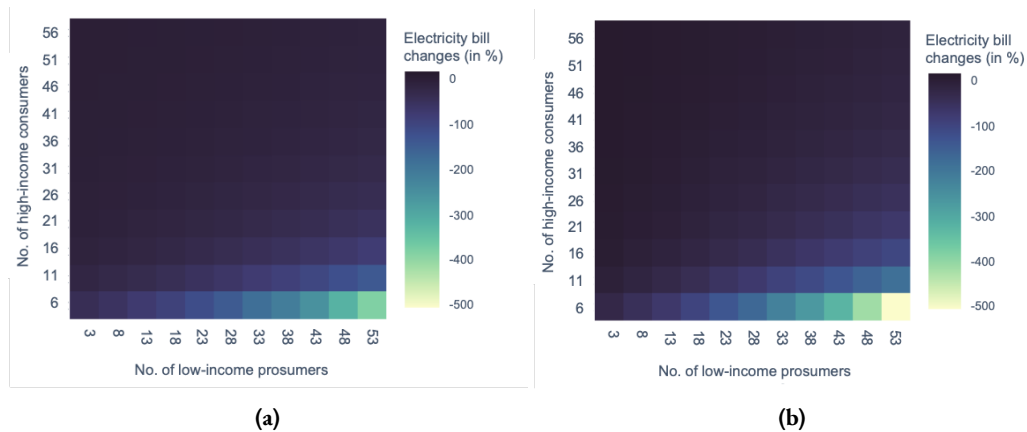


Figure 4.10: Energy bill changes for the entire community (savings when positive values and additional costs when negative values) comparing the base case **with** high FiTs with the P2P market with the stratification system (a) and without the stratification system (b).

Figure 4.11 shows nuanced results for the optimal balance between high-income consumers and low-income prosumers from the perspective of the community. Specifically, Figure 4.11 (a) demonstrates that the overall social welfare of the community is enhanced when the market comprises approximately twice as many prosumers as consumers. This shift in the optimal number of partici-

pants within the market is attributed to the increased savings accessible to low-income participants. Consequently, the overall influence of low-income participants on the market dynamics becomes more pronounced. A higher proportion of prosumers in the market contributes to better market performance.

In contrast, the findings depicted in Figure 4.11 (b) are more closely aligned with those in Figure 4.10. It is typically the case that greater savings are realised when the number of high-income consumers exceeds that of low-income prosumers. However, it should be noted that the tariff structure currently under consideration allows low-income prosumers to benefit from reduced energy bills. This necessitates a greater number of high-income prosumers than low-income prosumers in the market. From a community welfare standpoint, a market with a lower participation rate but a higher proportion of high-income consumers relative to low-income prosumers is therefore deemed more beneficial. Further, detailed information on the variation in energy bill changes for different participant groups is available in the appendix in Table A.6. This table also highlights the differences in relative savings across all participant categories.

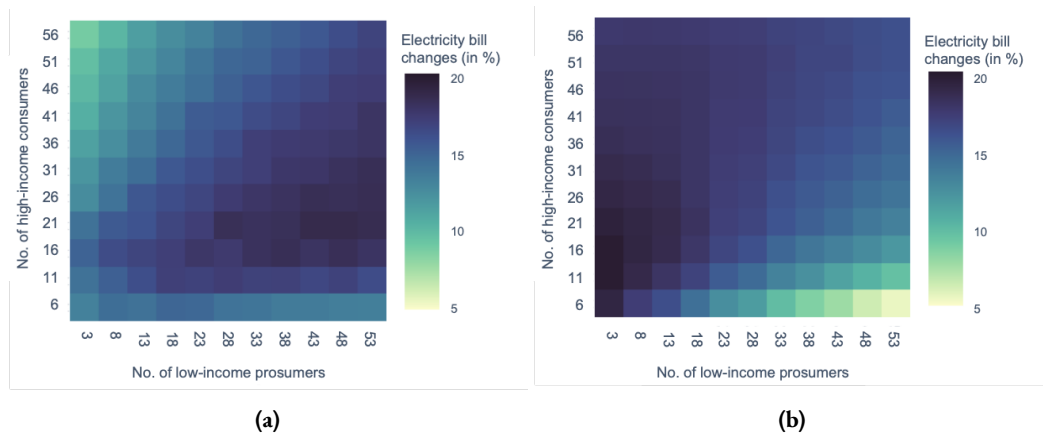


Figure 4.11: Energy bill changes for the entire community (savings when positive values and additional costs when negative values) comparing ‘base case **without** high FiTs’ with the P2P market with the stratification system (a) and without the stratification system (b).

Finally, Figure 4.12 shows the energy bill for the community averaged over one participant. The figures show that, on average, energy bills are highest when there is a low number of low-income prosumers and a high number of high-income consumers engaged in the market. The potential range of the total electricity bill is greater in Figure 4.12 (a), showing results with the stratification system in place, than in Figure 4.12 (b) without the stratification system. In light of these findings, it seems reasonable to suggest that the removal of the stratification system would result in a net

improvement in social welfare across the community. However, depending on the final objective of the case, this conclusion should be subject to further scrutiny. Table A.7 in the appendix demonstrates that the elimination of the stratification system results in a reduction in electricity costs for high-income consumers and prosumers, while simultaneously increasing costs for low-income prosumers. Given that high-income participants have a higher energy consumption, their total electricity costs have a greater impact on the average electricity costs of the community, skewing the average community bill in favour of the high-income participants.

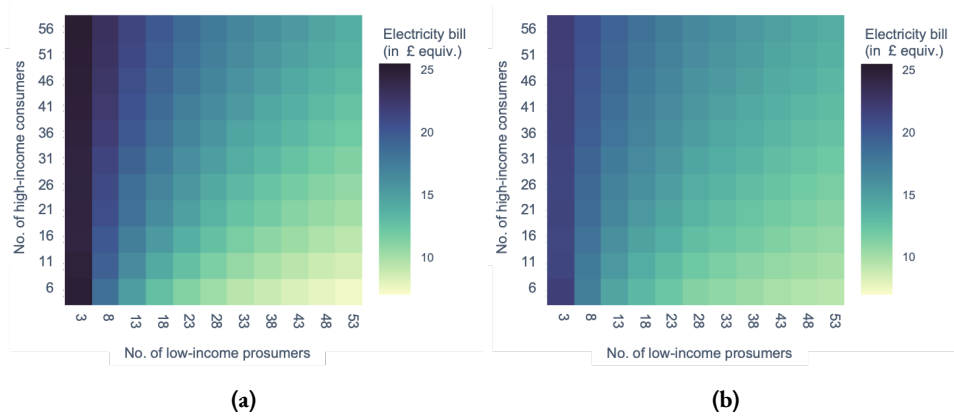


Figure 4.12: Total community electricity bill averaged over one participant for the P2P market with the stratification system (a) and without the stratification system (b).

4.7.2.2 Technical analysis

This chapter assesses the influence of diverse P2P market tariff structures on community self-consumption and self-sufficiency. It is essential to acknowledge that, due to the characteristics of the data, no information is accessible regarding individual self-consumption, specifically how much of the self-produced energy is consumed behind the meter by each participant. Figure 4.13 and Figure 4.14 illustrate the community self-consumption and self-sufficiency in the P2P market with and without the stratification system. The self-consumption of the community increases with a higher involvement of high-income consumers compared to prosumers. Similarly, self-sufficiency shows a linear behaviour, with self-sufficiency being highest when a slightly higher number of low-income prosumers than high-income consumers are involved in the market. There is no noticeable difference in the behaviour between the P2P market with and without stratification.

As the number of high-income consumers in the market grows, so too does the practice of community self-consumption. This is due to the fact that with an increase in market participants, there is a corresponding rise in the amount of energy available for sale. Nevertheless, the maximum

achievable value for community self-sufficiency is limited to 18%. This indicates that only 18% of the energy traded on the market is actually purchased by its participants. One of the reasons for this limitation is that load consumption and generation profiles among prosumers are often similar, leading to simultaneous production and consumption of energy. This lack of flexibility in the market means that most prosumers are both generating and using energy at the same times. The introduction of flexibility assets, such as battery storage, could help mitigate this issue by allowing for energy storage and later use. However, given that this is a virtual market, the economic viability of incorporating such assets is debatable. It is essential to carefully consider the practicality and cost-effectiveness of these solutions in the context of a virtual market environment.

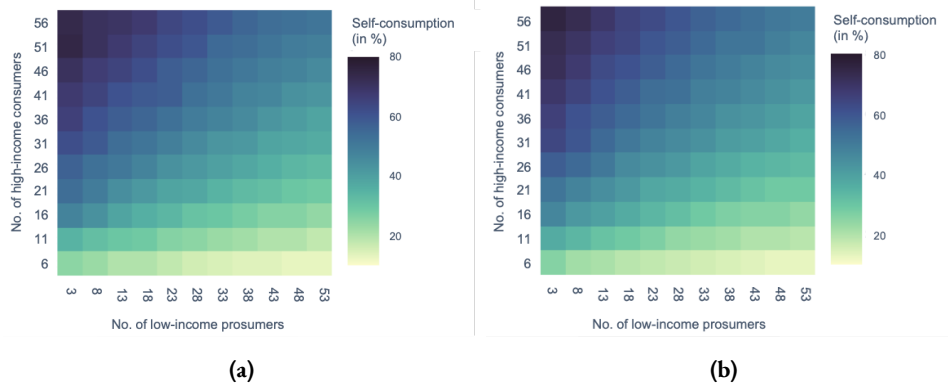


Figure 4.13: Community self-consumption with stratification (a) and without stratification (b).

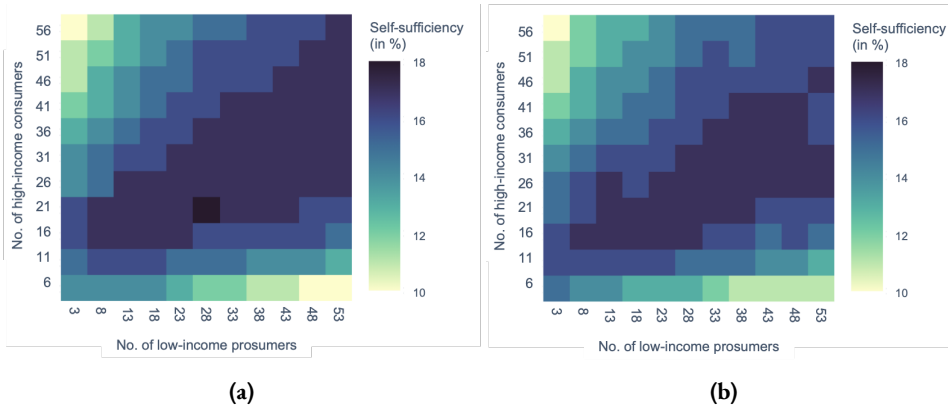


Figure 4.14: Community self-sufficiency with stratification (a) and without stratification (b).

4.8 Evaluation of results

This chapter presents the findings of the scalability analysis, with a particular focus on the implications derived from the results of Scenarios I and II. The discussion is primarily focused on interpreting the results in the context of the case study, but also on their implications for the

Medellín P2P Energy Trading Project and the Colombian energy market more broadly. The findings will be analysed using the five layers of LEM markets as detailed in Chapter 3.2. This structured assessment will provide a holistic understanding of the progress and areas for growth in P2P energy trading systems and identify layers that require further development.

A notable finding is that the results challenge the initial assumptions of the pilot project coordinators that low-income prosumers, rather than high-income consumers, would be the primary beneficiaries in this energy market. Instead, the market design introduced has resulted in high-income consumers generally receiving higher savings through the introduction of a P2P energy trading market with monetary transactions. Both Scenarios I and II demonstrate that, irrespective of the tariff design implemented, consumers typically derive the greatest financial benefits from the P2P market in comparison to other types of households. The financial benefits of low-income prosumers are more susceptible to fluctuations in external factors, such as the prevailing tariff structure or the market size and the nature of participants involved in the market. These external conditions can significantly impact their capacity to benefit from participating in P2P energy trading.

The results of the scalability analysis demonstrate that, given the current design and configuration of the market, the existing tariff structure and regulatory framework, the introduction of a P2P energy trading market is not a viable proposition.

4.8.1 Social and economic implications of the P2P market

The findings of this study indicate that, under the prevailing circumstances, operating within a stratification system with high FiTs and transitioning to a P2P energy trading market does not present a significant financial benefit to the community as a whole. However, should FiTs be reduced or phased out, a P2P market could become a more attractive alternative to the existing tariff structure. It is also important to note that even with the removal of the stratification system, a P2P market can still generate savings for the majority of participants, although low-income prosumers benefit the least.

One of the key insights to emerge from the analysis is the sensitivity of the overall welfare of the community to participation shares of different household types in the market. For instance, when contrasting the 'base case without high FiTs' with the 'P2P market with strata', the social welfare of the market enhances as the number of participants rises, on the condition that there is a balance between low-income prosumers and high-income consumers. Conversely, in the absence of a

stratification system, the market functions optimally with lower participation rates. These findings highlight the impact of different tariff designs on the social welfare of the community, as illustrated in Figure 4.11b.

The findings of this study indicate that the greatest benefit to the community may not always align with the greatest benefit to individual participants or specific participant types. For instance, a market that is most advantageous to high-income consumers may offer the least benefit to low-income prosumers, and vice versa. This highlights the importance of market design and tariff structure in determining the overall community welfare.

The study also prompts consideration of the market's performance in dynamic conditions, such as shifts in participation rates, energy demand or consumption patterns. While the modelled market did not account for participants joining or leaving dynamically, the varying market sizes provide insights into potential shifts in performance when the market expands or shrinks in size.

While this study considers different market participation rates and financial savings as an indicator for market adoption, it should be noted that the adoption of a P2P energy trading market is influenced by a range of factors beyond financial incentives. These factors include social and environmental considerations, as well as the ethical implications of introducing new energy trading models in vulnerable communities, which were outside the scope of this study.

On the other hand, energy users may be willing to pay a premium for energy if it aligns with their environmental objectives, such as using green electricity or reducing reliance on traditional energy sources. Social and environmental factors are becoming increasingly important considerations for those deciding whether to participate in the P2P market, as Cárdenas-Álvarez et al. (2022) shows. Their survey of residential energy users in Medellín revealed that non-monetary attributes of energy, such as sourcing solar power and purchasing energy with social attributes, can motivate customers to pay a premium for their energy.

It is also important to consider the ethical implications of introducing P2P energy trading in socially disadvantaged communities. These communities often face challenges related to poverty and limited access to basic services such as education and healthcare. It may not be feasible or practical to expect these households to engage in energy trading and invest in DERs. It is essential to carefully consider the social and ethical implications of implementing new energy trading models in vulnerable communities.

4.8.2 **Market design and transactions**

The P2P energy trading market presents a viable alternative to Colombia's current tariff structure, particularly in the event of a reduction or phase-out of high FiTs. Even without the stratification system, the P2P market could still offer savings to the majority of participants, although low-income prosumers might benefit to a lesser extent.

The proportion of different participant types involved in the market is a key factor in determining the overall performance of the market. As illustrated in Figure 4.11a an increase in market participation rates tends to enhance social welfare under a stratification system. However, without stratification, the market performs best with fewer participants, as illustrated in Figure 4.11b. This demonstrates that the tariff structure has a significant impact on the optimal market size for the community. It is important to recognise, however, that the ideal market size for overall community benefit may differ from what is most beneficial for specific groups of participants.

This consideration also prompts the question of what level of understanding of energy market or economic theory can be reasonably expected from participants in a P2P market. Such a market requires active agents capable of making informed decisions based on internal and external market factors. Regardless of whether decisions are made manually or automatically, some level of participant involvement is required. In the case of automated decision-making, participants need to set their input parameters or preferences. If decisions are made manually, this could be time-consuming and would likely require a significant level of knowledge and understanding of energy markets and economics. These requirements could present a significant barrier to market participation, particularly for low-income households.

An additional consideration in the design of P2P energy markets is the role and financial sustainability of the incumbent energy retailer. In a P2P energy trading market, the incumbent retailer (e.g. EPM) may experience a reduction in volumetric revenue, even though it continues to provide essential services such as grid access, balancing, and supply of last resort. If P2P energy trading markets reduce retailers' income without a commensurate decrease in their responsibilities or infrastructure costs, this could pose a major institutional barrier to adoption. The design of P2P energy trading systems should therefore consider fair compensation mechanisms for retailers, potentially through capacity-based or service-based charges that reflect their ongoing role in maintaining reliable energy access.

4.8.3 Policy and regulatory implications

The socio-economic strata are a key factor in both the outcome of the study and the interpretation of the results. They are used as indicators of overall household welfare, with lower strata corresponding to low income households and higher strata corresponding to high income households. However, it is important to recognise that these strata do not directly reflect the quality of life of households in Medellín.

A study by Chica-Olmo et al. (2020) evaluated the Colombian government's use of socio-economic strata to classify households in Medellín, assessing the accuracy of this approach in reflecting the quality of life of these households also considering income levels. The findings indicate that there is a discrepancy between the existing socio-economic stratification system and the self-reported quality of life in Medellín. This discrepancy indicates a need for a revision of the system to ensure municipal public policies effectively improve the conditions of the most disadvantaged households. Originally designed to classify dwellings, it has evolved into a framework that categorises individuals into distinct socio-economic classes. This shift in application raises questions about the system's fairness and effectiveness in reflecting the true socio-economic diversity of the community.

While the stratified system is beneficial in terms of tax and subsidy distribution, provided that households are correctly assigned to their respective socio-economic strata, it is counterproductive in supporting the adoption of innovative business models in the energy sector. Should Colombia adopt a more European-style liberalised market structure and redesign its current residential energy tariff structure, LEMs or P2P energy trading could become viable options for some energy consumers or prosumers. Colombia's energy sector is currently at a crossroads in terms of liberalisation. The current rigid tariff structures are no longer aligned with the emerging energy landscape shaped by DERs and digitalisation. However, a fully liberalised and competitive market at the residential level could lack the protections necessary to ensure that low-income households are not left behind.

For example, France operates a hybrid energy market where end-users can choose between regulated tariffs set by authorities and free-market offers from retailers. Additionally, France provides a "first necessity tariff" for households below a defined income threshold (Le Premier Ministre, 2004). This approach allows for the coexistence of innovation and social protections, illustrating how differentiated tariffs can enable the emergence of new energy business models while maintaining equity. Drawing parallels, such hybrid models highlight potential design directions that could

reconcile Colombia's goals of innovation and inclusion without suggesting a full departure from its existing stratification system.

In Colombia, the net metering policy has the potential to accelerate the adoption of PV energy, as evidenced by the Netherlands. However, it can have a counterproductive effect on the development of business models such as P2P, as it is primarily aimed at individual self-consumption. In order to promote other business models, it would be beneficial for such policies to also have a time component, in order to promote the simultaneous generation and consumption of solar power.

4.8.4 Digital infrastructure and data availability

A critical barrier to the scalability of the P2P energy trading system in Medellín was the weakness of its underlying digital infrastructure and the quality of available data. While many technical and economic findings could be explored through simulation, the pilot project revealed a range of issues that would seriously limit the real-world operation of such a market.

Most significantly, the pilot suffered from substantial data gaps. As illustrated in the appendix in Figure A.1, the time series data for many households contains large periods with missing or irregular values. These gaps were caused by factors such as intermittent internet connectivity, device disconnections, and limitations in accessing participants' homes to install or troubleshoot metering equipment. In some cases, devices remained offline for weeks or months, resulting in a loss of real-time visibility into household energy flows.

This problem was compounded by the limited metering setup: only one import and one export meter per household were installed. While sufficient for basic net metering, this setup does not capture behind-the-meter self-consumption, nor does it distinguish between when a household uses its own generation versus exporting to the market. This limitation can pose challenges to both the settlement process and the ability of participants to interpret and understand their own consumption and trading behaviour.

The absence of data at critical times had direct implications for the settlement process. In a P2P energy trading market, transactions depend on time-aligned import and export records from both trading parties. If data is missing for one participant, the transaction cannot be validated or settled. This not only leads to financial uncertainty but also undermines the perceived fairness and transparency of the system. In the Medellín pilot, no systematic fallback or error-handling protocol

was in place to deal with missing data. This meant that whenever metering data was unavailable, trades simply could not be settled. The result is not only a failure in market functioning, but also a potential loss of trust among participants, especially if they are unable to verify whether they were correctly compensated.

Even in cases where all data was available, the lack of real-time data transmission could limit the market's ability to operate in a responsive or dynamic fashion. In contrast to traditional systems where aggregated data may be sufficient for monthly billing, hourly or sub-hourly settlement in P2P markets demands near real-time data. Without it, price signals lose meaning. These conditions make P2P energy trading highly sensitive to infrastructure constraints, especially in low-income or digitally underserved communities.

The pilot project has highlighted the potential for poor data quality, emphasising the need for robust data management strategies. Accuracy is of critical importance, as it directly impacts market operations and participant settlement. Implementing effective data cleansing and imputation techniques, as well as investing in high-quality metering infrastructure, can help mitigate the risks associated with data quality issues.

4.8.5 Integration into the existing power system

The selected case study did not prioritise grid integration. The integration of DER on the low-voltage grid in Colombia is still in its infancy (UPME, 2023), leaving sufficient capacity for further installations. Consequently, the focus of the P2P energy trading market has been on virtual energy trading, with the objective of achieving economic and social benefits for participants. However, the installation of solar panels and other small DER in Colombia is expected to increase with small scale PV reaching 1,132 MW by 2036 up more than 1000MW compared to 2022. This transition is likely to cause grid capacity issues that could be addressed in the future by markets such as P2P.

The simulated study was conducted in an ex-post market to streamline the simulation setup and mitigate potential uncertainties in energy demand and customer reactions to price changes in the P2P energy trading market. In a real-world setting, it is likely to function as an ex-ante market, using forecast data to facilitate energy transactions on a peer-to-peer basis. In Chapter 2.2, a range of potential market mechanisms were presented for consideration as part of a market design to address these issues. A key challenge will be the development of a robust framework for addressing instances where a household fails to deliver the contracted energy volume. It is vital to establish the

consequences for the participant, including whether penalties or additional costs will be applied. It is also necessary to determine the extent to which a prosumer can realistically be expected to bear responsibility.

The increasing integration of DER assets on the electricity grid will have an impact on the social fairness of the market. Network congestion is typically caused by wealthier households with larger energy loads. This increases the cost of maintaining the grid, which is usually borne by all customers, but distributed across all customers in an even manner. A P2P market could provide an alternative by enabling better energy balancing through trading and potentially providing relief to low-income households. As the Colombian energy sector develops, grid constraints will emerge and market designs will need to address these challenges. As a result, congestion costs are likely to be adjusted, primarily affecting households with high energy consumption.

4.9 Summary and conclusion

The Medellín Peer-to-Peer Energy Trading Pilot Project was designed to assess the viability of P2P energy trading in Colombia, with a specific emphasis on facilitating engagement of participants from a diverse range of socio-economic backgrounds in energy transactions, thereby leveraging Colombia's substantial solar energy potential. However, the pilot faced several challenges during its implementation, limiting the project coordinators' ability to fully assess the scalability potential of P2P energy trading systems.

This chapter assessed the scalability potential of the Medellín Peer-to-Peer Energy Trading pilot project. The chapter aimed to address two key research questions using the scalability analysis framework outlined in Chapter 3.2: *'What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?'* and *'How applicable are scalability barriers identified in the broader context of P2P energy trading systems?'*. To address these research questions, two scalability scenarios were developed based on the pilot project's characteristics and the Colombian energy market context.

The first scenario involved modelling a P2P energy trading market to assess its performance under different tariff structures. This allowed for financial transactions between participants for their energy exchanged, a functionality that was absent in the pilot project due to regulatory constraints. The performance of the P2P energy trading market was benchmarked against a 'base case' scenario, representing a scenario in which energy trading between energy users was not in place. The

economic analysis demonstrated that the introduction of a P2P market could result in a reduction in energy bills, particularly for high-income consumers in scenarios without stratification. The majority of participants experience a reduction in energy bills when transitioning from a high FiTs base case to a P2P market. The greatest savings are observed in scenarios without a stratification system, where high-income participants benefit the most due to the absence of additional taxes and the lower costs associated with P2P energy trading. A self-consumption rate of 25% and a self-sufficiency rate of 14% within the P2P market indicate that a quarter of the energy generated by participants is consumed within the market itself, with only a small proportion of the total energy demand met by local generation. Prosumers with larger generation capacity were able to export a higher amount of energy, leading to a financially advantageous outcome.

A second scenario was developed to assess the implication of scaling up the P2P energy trading market in size while also varying the share of participant type involved. The objective of this scenario was to assess the scalability potential of the P2P market by introducing additional high-income consumers and low-income prosumers into the market. This scenario was derived from the contextual features of the pilot project, in which the project coordinators sought to provide low-income prosumers with a financial incentive to engage in energy transactions with high-income consumers. In particular, the market configuration comprised an equal number of low-income prosumers and high-income consumers, with the objective of assessing economic and technical outcomes. The key findings from this scenario are as follows: low-income prosumers benefit when they are in the minority, as this reduces competition to sell energy, while high-income consumers benefit when they are in the minority, as this reduces competition to buy energy. From an economic standpoint, high-income participants tend to perform better in a market without socio-economic stratification due to lower costs and greater flexibility. Conversely, low-income prosumers face higher costs without the price controls provided by stratification, which underscores the role of market structure in economic inequality.

The results demonstrate that under the modelled market design and current tariff structure, high-income consumers frequently receive greater financial benefits than low-income prosumers. This indicates the necessity for market restructuring to guarantee a fair distribution of benefits. The analysis indicates that, in the absence of substantial regulatory changes, P2P energy trading markets are unlikely to be financially sustainable, given the limitations of community-wide benefits under the current stratification system with high FiTs. However, removing the current stratification

could potentially increase the attractiveness of the market by offering savings to most participants, although low-income prosumers would still be at a disadvantage relatively compared to high-income consumers. However, the electricity bill for low-income prosumers would reduce further. Market performance depends on the mix of participants and the size of the market. The optimal configurations for community welfare do not always coincide with the best outcomes for individual groups, highlighting the complex interplay between market design and social justice.

Chapter 5

Barriers and benefits to scaling up P2P energy trading: A case study of a UK housing estate

This chapter explores the scalability potential of the second of two case studies analysed as part of this thesis. Similar to the Medellín P2P Energy Trading Pilot, the UK pilot analysed here implements a real-world trial of a P2P energy trading market in a disadvantaged community. However, unlike the Colombian pilot, which spanned an entire city, the UK pilot is taking place within a single block of flats, presenting a unique set of challenges in a physically constrained environment.

Some challenges encountered during the pilot, particularly in achieving higher participation rates, limited the pilot's ability to thoroughly test market operations and consequently affected the scope and applicability of its findings. By applying the scalability analysis framework presented in Chapter 3.2, this study seeks to overcome some physical trial limitations by adjusting the pilot parameters in a simulated environment. This chapter aims to provide insights that will contribute to answering the second and third research questions defined in Chapter 2.7: *'What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?'* and *'How applicable are scalability barriers identified in the broader context of P2P energy trading systems?'*. The former question is addressed in the 'execution' phases of the scalability analysis framework while the latter is addressed in the 'post-evaluation' phase of the scalability analysis framework. The answers to these questions are primarily based on the results of the scalability analysis and are limited to the case study. An attempt is made to interpret the case study

results in the specific context of the pilot project and the UK energy market.

Before examining the particulars of the pilot, which encompasses the pre-evaluation, execution and post-evaluation phases of the scalability analysis framework, an overview of the UK local energy market landscape is presented in order to provide a context for the subsequent analysis.

5.1 Introduction

In line with its Pathway to Net Zero strategy, the UK government has pledged to decarbonise its buildings sector by 2050 (UK Government, 2021a). With almost 25 million dwellings (DLUHC, 2021), the UK's built environment is responsible for approximately 25%¹ of the UK's total greenhouse gas emissions (House of Commons, 2022). The majority of these emissions are the result of heating using fossil fuels, with a significant proportion also arising from electricity consumption, which indirectly contributes to emissions during generation.

In addition to the necessity of retrofitting homes to enhance energy efficiency, there is an increasing requirement for households to use RES to meet their electricity demand. For example, the Mayor of London's Solar Action Plan has set a target to install over 2GW of solar capacity by 2050 (Greater London Authority, 2018). Buildings have a crucial role to play in achieving this target. A study by UCL Energy Institute (2020) found that the capacity target could be met by installing PV systems on a third of a million homes or alternatively on the roofs of around 4,000 large warehouses in London.

Solar energy is now recognised as the world's most cost-effective source of electricity (IEA, 2020c). It offers numerous benefits that extend beyond achieving net-zero targets. It helps to reduce household electricity bills and plays a vital role in minimising environmental impact and moving towards a sustainable energy future.

However, an analysis of solar adoption indicates a discrepancy between household types. The 2021 English Housing Survey, broken down by tenure type, reveals that solar PV was installed on 6% of owner-occupied homes, 4% of local authority dwellings, and only 1% of privately rented properties, totalling 1.2 million installations overall (DLUHC, 2022). This discrepancy in PV system installation rates highlights a broader issue of unequal access to the benefits of solar energy, which is influenced by factors such as financial resources and property ownership. The benefits of solar energy, including lower electricity bills and greater energy independence, are more accessible

¹This figure includes buildings and infrastructure and relates to consumption emissions.

to homeowners than to renters or social housing residents. This issue is further compounded by the ‘landlord-tenant divide’ (Eyre et al., 2019). Landlords may be reluctant to invest in measures such as PV systems, given that the direct financial benefits, particularly in terms of reduced energy bills, will primarily accrue to tenants. This can result in a lack of interest from landlords in energy efficiency measures, which presents a significant challenge in improving the energy efficiency of rented dwellings. However, the presence of a PV system in a rented property does not guarantee that tenants will benefit from cheaper electricity bills, as there is currently no standardised regulation on how landlords can sell the electricity they generate to tenants.

While 65% of households in the UK are owner-occupied, the private and social rented sectors still represent a significant proportion of the housing market at 19% and 16% respectively (DLUHC, 2023). To achieve a just energy transition, it is important to ensure that individuals from all social backgrounds have access to renewable energy technologies, which will enable them to reduce their energy consumption and bills. In the absence of targeted policies, there is a risk that the benefits will be concentrated among wealthier households (UK Government, 2021b). Governments need to focus on targeted policies that are tailored to the specific needs of different households. Ofgem, the UK’s energy regulator, places great emphasis on the importance of inclusivity in these initiatives. While forecasting a range of benefits from changes to the energy system over the next few years, such as a more cost-reflective and flexible energy system, Ofgem also warns that vulnerable groups could miss out (Ofgem, 2019). It is therefore essential to guarantee that the advantages of the shift towards greener energy production are available to all customers, particularly those who are most vulnerable.

In 2017, the UK government announced plans to invest £160 million to install solar panels on 800,000 council homes over five years. The objective is to reduce residents’ electricity bills (Beth Howell, 2024). By the end of 2023, six years later, there were approximately 1.4 million PV installations across the country. Of these, approximately 15.6% were in social rented properties, representing only around 225,000 installations, according to MCS data (MCS, 2023). In 2022, the UK government allocated a further £1.5 billion from the Social Housing Decarbonisation Fund and the Home Upgrade Grant scheme to facilitate the upgrading of approximately 130,000 social housing and low-income properties in England. These upgrades will encompass external wall and loft insulation, energy-efficient doors and windows, heat pumps, and the installation of solar panels (BEIS, 2022). In response to the growing interest in customer involvement in

energy generation, Ofgem published a discussion paper on non-traditional business models in 2015 (Ofgem, 2015). This paper examines the obstacles these models encounter, including market entry costs and regulatory compliance, in the context of the low-carbon transition and consumer engagement.

There have been several instances where local PV installations have demonstrated the potential to reduce energy consumption and carbon emissions in social housing units. For example, Energy Local has introduced a new pricing structure whereby participants receive a reduced rate on electricity used during periods of high local generation (Repowering London, 2023). This model provides an incentive for energy usage that aligns with local production peaks, thereby enhancing efficiency. Another project, conducted by SolShare in a social housing unit, focused on a hardware-based solution. By integrating a PV system with battery storage, they achieved a reduction of 60-70% in grid energy consumption (Allume Energy Pty Ltd, n.d.).

In 2014, the UK government launched the Community Energy Strategy, with a particular focus on social housing (DECC, 2014). The strategy's objective is to foster stronger communities by actively engaging local residents in energy projects, thereby fostering a sense of unity and empowerment. The strategy suggests that community energy initiatives can play a pivotal role in fostering social cohesion while also offering avenues for skill development, including work experience and training in energy and climate change sectors. From an economic standpoint, the strategy aims to equip communities with the ability to generate their own income from renewable energy sources and to participate in larger energy projects. However, as highlighted in the report by DECC (2014), there remains a need for more comprehensive quantitative data to fully understand the social impacts and weigh up the costs and benefits of community energy initiatives.

Brixton Energy Solar 1 is a project that was initiated as part of the government's Community Energy Strategy. The project was carried out at Elmore House and is managed by the Brixton Energy Co-op, an initiative by Repowering London² that installed PV systems on social housing estates (Brixton Energy, n.d.). The objective was to enhance local energy resilience and address fuel poverty. The project was structured in such a way that the profits generated by the co-op through the sale of PV energy were reinvested back into the community. However, residents of Elmore House were not able to benefit directly from reduced energy bills through the consumption of PV energy. Instead, the profits were indirectly reinvested into the community through energy advice

²<https://www.repowering.org.uk/>

sessions, work experience opportunities and a range of community events. Reductions in energy bills were limited to communal areas such as lighting and lifts. In order to maximise the benefits for residents, the CommUNITY pilot project was launched in 2019. This project, which formed part of Ofgem's 'Innovation Link' sandbox between 2019 and 2021 (Johnson et al., 2022) enabled residents of Elmore House to actively participate in and benefit from the electricity generated by their rooftop PV system. A distinctive feature of the CommUNITY project was the ability of residents to trade energy in the form of electricity within their building block, a practice that is typically prohibited under current regulations (Ofgem, 2023b). Due to its innovative nature, the project encountered a number of implementation challenges, further detailed in the following chapter.

5.2 Case study overview

The CommUNITY pilot project (**Community Urban Neighbourhoods Internal Trading of energy**) was launched in March 2019 with the objective of enabling energy users from low-income and socially disadvantaged groups to engage in the low-carbon energy transition. The pilot project was conducted at Elmore House in Brixton, London. Elmore House is a multi-apartment building constructed in the 1960s, comprising 62 units. The building is owned by the local council and managed by a third party. It consists mainly of social housing (60%), with the remainder being privately rented or owner-occupied. As part of the previous Brixton Energy Solar 1 initiative, a PV array was installed on the building's rooftop. The 37kWp PV installation was community-owned, with revenue generated from the PV system used to finance its installation and reinvest in the community (Repowering London, 2020). Figure 5.1 shows the building and its PV rooftop installation.

Prior to the CommUNITY pilot, the electricity generated by the solar panels at Elmore House was mainly used to power communal areas such as lighting and lifts. Over 90% of the electricity generated was sold back to the grid under a Power Purchase Agreement (PPA)³ (Hadri et al., 2021). In the context of Elmore House, the PPA facilitated the sale of excess solar energy back to the grid.

The initiative facilitated resident engagement in P2P energy trading with a community pool,

³PPAs are commonly used in renewable energy projects to ensure a steady revenue stream for the generator and a fixed cost for the buyer, thereby supporting the long-term viability of renewable energy initiatives. A PPA is a long-term contract between a power producer and a buyer, often a community or corporate entity. PPAs are used to provide a stable and predictable price for the electricity generated, allowing both parties to hedge against volatile market prices (Solar Energy UK, 2023)



Figure 5.1: Elmore House Brixton (EDF, 2019).

ensuring that each participant benefited equally from the output of the rooftop solar panels. This was made possible by virtually assigning an equal share of the PV output to each participant. By focusing on direct participation in the consumption of PV energy, the project moved away from the traditional model of funding community development through the sale of energy to the grid. Figure 5.2 illustrates the market design before and after the implementation of the sandbox and P2P market, demonstrating the transition from a reliance on the traditional grid to a more integrated, community-focused energy model. Figure 5.2a shows the operation of the community energy market, with the blue line indicating energy flows and the green line representing financial transactions. There is no direct physical link between the PV energy generator and the energy users inside the physical boundary of the building. Figure 5.2b shows the energy market operation once the P2P energy trading market has been implemented. The CommUNITY platform facilitates communication between PV generators, suppliers and energy users in the market, enabling the exchange of transaction, generation and consumption data. Additionally, the platform allocates virtual energy transactions to energy users in the market, as indicated by the blue dotted line.

The primary objective of the pilot project was to encourage energy users to consume more local and low-carbon energy, while also reducing their electricity costs (EDF, 2019). In order to achieve this, the pilot aimed to engage with energy users who typically do not have the financial resources or living conditions to actively engage with new energy systems. The pilot set out to achieve the following four key objectives (Hadri et al., 2021):

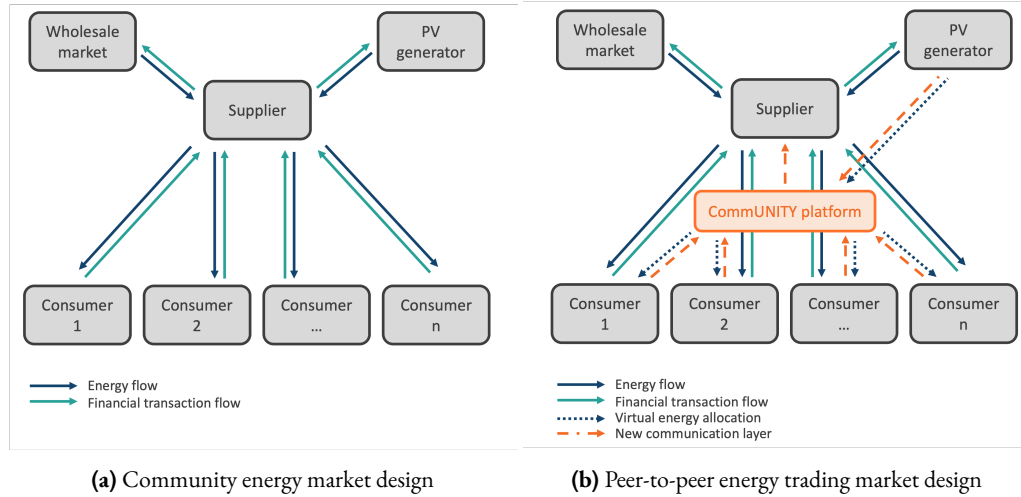


Figure 5.2: Business model design for (a) community energy market and (b) and P2P energy trading market design (adopted from Hadri et al. (2021)).

- (a) Empower energy users by enabling direct transactions between market participants, giving them direct control over their generated energy.
- (b) Promote innovative technology by designing and developing a P2P energy trading market, complemented by a customer app to engage with participants, promoting technological interaction and literacy.
- (c) Improve sustainability by testing new business models aimed at reducing energy users' energy bills and providing access to local renewable energy.
- (d) Ensure market fairness by developing a sustainable business model that is scalable and replicable in other communities.

The CommUNITY project introduced a 'virtual' P2P energy trading market. A virtual market design was necessary due to the nature of the physical metering arrangement, which include a separate landlord grid connection point and individual tenant grid connection points. The PV system was connected to the landlord's grid connection point. 'Virtual' energy trading means that the electricity generated by the PV system is not consumed directly by the tenants of Elmore House. However, due to the proximity of the two connection points and the physical flow of electricity, it is likely that the energy generated by the PV system is consumed by tenants in the building. A platform-based solution was implemented that connects all participants via an app that enables energy trading and allows households to view their electricity generation and consumption profiles. EDF was responsible for monitoring participants' electricity consumption through installed clamp

meters⁴ as well as the PV generation output (Hadri et al., 2021).

The CommUNITY pilot project was structured in three distinct phases, each focusing on a specific aspect of the energy market, with the objective of exploring different business models. The initial phase concentrated on the design of the P2P energy trading market, with the objective of increasing community self-consumption, reducing electricity bills and testing the feasibility and scalability of the market. This phase established the foundation for subsequent phases. The second phase introduced a community battery storage system. This addition aimed to increase the community self-consumption of the energy generated by the PV, thereby improving both the efficiency and practical utility of the PV energy generated. The final phase involved exploring the provision of flexibility services to the grid as an additional revenue stream. Taken together, these phases aimed to explore business models of community energy solutions.

It is important to highlight that all three phases of the CommUNITY project were conducted within a regulatory sandbox, which enabled operations outside the usual energy regulations. While this enabled technical experimentation and innovation, it also posed a number of regulatory and coordination challenges. Although the necessary hardware was successfully installed, the project did not progress to a stage where the P2P energy trading market was operating at a sufficient scale or level of maturity to produce meaningful system or market-level insights. Therefore, while the second and third phases introduced relevant insight from a practical implementation perspective, they could not be meaningfully evaluated in the absence of an operational P2P trading environment. As such, this study focuses exclusively on the first phase of the pilot project. The analysis centres on the early-stage design and implementation barriers that prevented the pilot from scaling into a functioning trading system.

The following section outlines these challenges. It aims to identify and articulate the limitations encountered in the pilot and to derive scalable scenarios relevant to the pilot project.

5.3 Defining scalability scenarios

The CommUNITY pilot project, which aimed to explore alternative business models in the community energy sector, encountered several challenges, particularly in achieving the desired market size. One notable limitation was the requirement that households had to be customers of the utility partner, EDF, in order to participate. This requirement had the effect of significantly

⁴A clamp meter can be used to estimate energy consumption by measuring the current flowing through a conductor, such as the wire inside an electric cable, to which the clamp is applied.

limiting the number of participants in the pilot. Of the 62 eligible households at Elmore House, only 13 were EDF customers and only four of these chose to participate in the pilot, resulting in a low participation rate of 6%. It is important to note that, although all residents had the opportunity to switch to EDF for the duration of the project, none chose to do so. This may be due to a number of factors, including a lack of interest or the perceived inconvenience of switching (Johnson et al., 2022). While this study does not include a detailed analysis of consumer decision-making or switching behaviour, this is a critical barrier to the scalability of P2P energy trading systems in liberalised markets such as the UK. Consumers must actively choose to participate in such novel market models, and if participation requires switching suppliers or navigating complex procedures, adoption rates may remain low. This highlights the importance of minimising friction in enrolment processes and aligning P2P energy trading models with existing retail market structures to support wider scalability.

The market performance of the CommUNITY project was evaluated with the participation of only four households. The level of participation resulted in a higher share per participant than would be expected in a typical residential environment, with the installed PV capacity of 37kWp split between the participating households. As a result, the pilot does not accurately reflect the potential of a P2P energy market in a typical residential setting. This discrepancy limits applicability of the market results in providing insights into the operation of P2P energy trading markets under normal or scaled conditions. Furthermore, the low participation rate in the pilot makes it challenging to analyse its effects on market participants. It is therefore essential to understand the impact of changing participation rates on the redistribution of benefits among participants with different characteristics, which highlights the importance of testing the P2P energy trading market with a larger, more representative group of households. Such testing is essential to effectively assess the scalability and practicality of P2P energy trading markets as an alternative to the standard community energy market operation.

To facilitate participation in the pilot, no additional fees or upfront payments were required. The pilot was designed to remove financial barriers to participation, with operating and capital costs covered by a combination of public grants and research and development expenditure by participating companies. While this approach is practical in a pilot setting, it raises questions about the future viability and scalability of such non-traditional business models (Johnson et al., 2022). While government funding or subsidies are often a prerequisite for the launch of such projects, it

is crucial to develop business models that are economically viable in the long term⁵.

In order to gain further insights into the scalability challenges faced by the CommUNITY pilot project, this study defines two scalability scenarios, which are outlined in the following.

Scenario I

The objective of the first scenario is to gain insight into how the level of participation affects the performance and feasibility of P2P energy trading markets. This scenario examines the effect of an increase in the number of participants in the P2P energy trading market at Elmore House. It assesses market performance with a higher participation rate, focusing on the redistribution of financial benefits between participants with different characteristics. The objective is to gain insight into how the financial benefits of the P2P energy trading market are distributed among participants and how this distribution changes as the number of participants increases.

Scenario II

The second scenario is designed to assess the financial viability of the CommUNITY energy business model. It will examine potential revenue streams and cost structures to ensure that the long-term commercial viability of such projects can be achieved in a market-driven environment. The scenario will focus on analysing the performance of the P2P market established in the pilot to assess the impact of a more participatory approach to community energy trading on the residents of Elmore House and other key stakeholders.

The scalability scenarios are tested over a one-year period. There are two factors that influence this decision. Firstly, it should be noted that UK household electricity consumption and generation are subject to significant fluctuations in line with weather patterns. A year-long simulation allows for the capture of seasonal variations and provides insight into the impact of weather on household energy consumption and PV energy generation. By analysing a full cycle of seasons, the simulation can approximate real-world conditions where household energy dynamics shift with changing weather conditions, providing a realistic representation of how these dynamics affect energy consumption. Secondly, the full year time horizon allows the assessment of the financial

⁵An example of the over-reliance of non-traditional business models on external funding and subsidies in the energy sector are the Community Energy projects across Europe. These initiatives grew for years on highly subsidised feed-in tariffs, which protected them from the competitive energy market. With the steady reduction and eventual phase out of these FiTs in several countries across Europe, many Community Energy projects missed the opportunity to adapt their business model to the new market conditions. As a result, many community energy projects were no longer viable. The growth of these new business models declined (Sweeney et al., 2020).

viability of the P2P market, as introduced in Scenario II, by allowing results to be extrapolated over an operating year. This supports an assessment of longer-term economic performance.

It is important to note that this differs from the Medellín case study presented earlier in the thesis, where only a one-month period was analysed. In that case, the choice of a shorter time frame was justified by the relative stability of the local climate and the absence of significant seasonal variations, meaning that a shorter period was sufficient to capture representative energy use patterns. The decision to use different time frames reflects the specific environmental and contextual characteristics of each case study.

The following section outlines the performance indicators that will be used to assess the outcome of the scalability analysis.

5.4 Identifying performance indicators

This study uses a combination of economic and technical indicators to evaluate the performance of the community at both the individual and aggregated levels in comparison to the base case. The calculation of these indicators is crucial for assessing the scalability scenarios previously defined. This encompasses not only operational profitability but also the capacity to cover upfront costs over the lifetime of the project.

Figure 5.3 shows a sequence diagram outlining the interaction between the different actors and objects in the market to support the explanation of the performance indicators discussed in this section. A detailed description of the market design and mechanism will follow in the subsequent chapters.

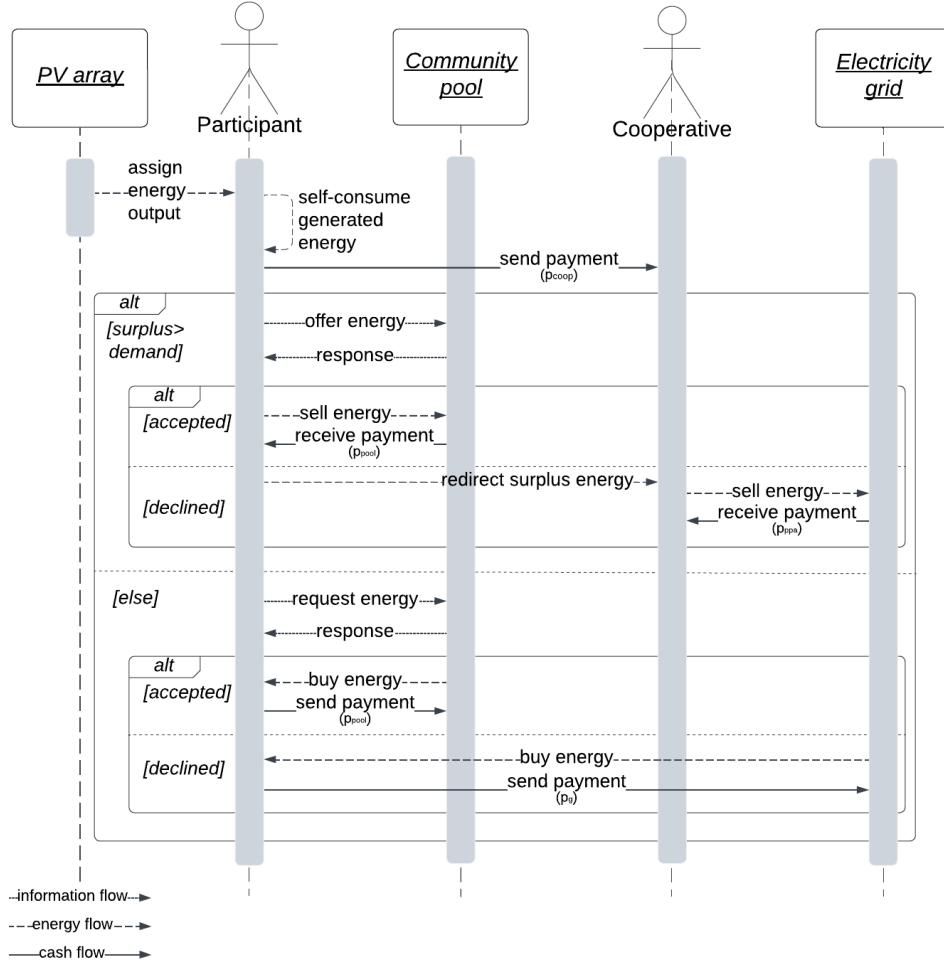


Figure 5.3: Sequence diagram CommUNITY market.

5.4.1 Economic performance indicators

The calculation of benefits enables the assessment of the baseline market design in comparison to the P2P energy trading market design. Benefits are defined as the sum of *savings* and *earnings*. Equation 5.1 defines the total benefits per participant B_P . Equation 5.2 defines the aggregated benefits for the community as a whole, where n is the number of participants involved.

$$B_P = \sum_{i=1}^{17520} \underbrace{(E_{PV \rightarrow P} \times (p_g - p_{coop})) + (E_{POOL \rightarrow P} \times (p_g - p_{pool}))}_{\text{savings}} + \underbrace{(E_{PV \rightarrow P \rightarrow POOL} \times (p_{pool} - p_{coop}))}_{\text{earnings}} \quad (5.1)$$

$$B_{P_{agg}} = \sum_{n=1}^N (B_P) \quad (5.2)$$

The benefit for each participant is calculated on an annual basis for each half-hour period, resulting in 17,520 trading periods. $(E_{PV \rightarrow P} \times (p_g - p_{coop}))$ calculates the savings by consuming the generated PV energy $E_{PV \rightarrow P}$, where p_g is the current grid price and p_{coop} is the price charged by the cooperative. If the generated energy is offered to the participants free of charge, $p_{coop} = 0$. $(E_{POOL \rightarrow P} \times (p_g - p_{pool}))$ calculates the savings as a result of consuming energy from the pool market $E_{POOL \rightarrow P}$ rather than purchasing energy from the electricity grid, where p_{pool} is the price for energy exchanges within the community. Similarly, $(E_{PV \rightarrow P \rightarrow POOL} \times (p_{pool} - p_{coop}))$ represents the earnings from selling PV energy $E_{PV \rightarrow P \rightarrow POOL}$ to other participants in the community pool at price difference of $(p_{pool} - p_{coop})$.

Similarly, the cooperative benefits from the market by selling energy to participants and the electricity grid. Equation 5.3 calculates the total earnings for the cooperative over a one-year period.

$$B_{COOP} = \sum_{t=1}^{17520} ((E_{PV \rightarrow P} \times p_{coop}) + (E_{P \rightarrow G} \times p_{ppa})) - Cost_{O\&M} \quad (5.3)$$

$(E_{PV \rightarrow P} \times p_{coop})$ are the earnings from selling PV energy to the participants in the market $E_{PV \rightarrow P}$ at price p_{coop} . $(E_{P \rightarrow G} \times p_{ppa})$ are the earnings from selling any energy that was not consumed within the community $E_{P \rightarrow G}$ back to the electricity grid at the PPA rate p_{ppa} . Costs associated with the operation and maintenance of the market $Cost_{O\&M}$ are deducted from annual earnings.

To gain insight into the profitability of the P2P market from the perspective of cooperative financing and market operation, the Net Present Value (NPV) can be calculated. The NPV represents the difference between the present value of cash inflows and the present value of cash outflows over a specified period of time. Equation 5.4 shows the standard NPV calculation.

$$NPV_{coop} = -I_0 + \sum_{a=1}^{PV \text{ lifetime}} \frac{B_{coop}}{(1+i)^a} \quad (5.4)$$

The annual cash flows are equal to the cooperative benefits B_{coop} , as calculated in Equation 5.3. I_0 is the total initial investment costs, which includes costs of installation and market setup, i is the discount rate which is set at 3% and a defines the lifetime of the project. In this case the lifetime of the P2P market is set to be equal to the lifetime of the PV installation set to 25 years. Setting the market duration equivalent to the lifetime of the PV installation allows for a realistic estimate of the costs incurred. P2P markets can theoretically last for the current lifetime of the PV system, in which case they will likely require an investment in new PV modules.

To effectively measure the performance of the market across different market sizes, a key metric, the equality index (EI), is used. This index measures the distribution of income among market participants and is derived from the Gini coefficient, as referenced in (Zhou et al., 2018). Calculating the equality index offers a valuable insight into the income distribution within the market, a crucial aspect in evaluating market fairness (Regener et al., 2022; Zhou et al., 2018)

The EI is particularly valuable in ensuring the fairness of the P2P energy market. It enables the assessment of whether the benefits of the market, as defined by Equation 5.1, are distributed fairly to all participants, irrespective of their individual energy consumption or generation profiles. It is important to ensure that the market does not favour certain participants disproportionately, as this can lead to imbalances and potentially discourage participation. In this context, $n, m \in N$ represent the participants in the market. The income is calculated according to benefits B_P outlined in Equation 5.1.

$$EI = 1 - \frac{\sum_{n=1}^N \sum_{m=1}^N |B_{Pn} - B_{Pm}|}{2N \sum_{n=1}^N B_{Pn}} \quad (5.5)$$

5.4.2 Technical performance indicators

Energy self-consumption (SC) represents the proportion of electricity generated by the PV array that was consumed by the market, either through self-consumption or trading of energy on the community pool. SC can be used to assess the efficiency of a production source. High self-consumption rates indicate that the demand for electricity from the grid is reduced, which can lead to lower energy bills and a reduced carbon footprint. In P2P energy trading markets, self-consumption rates are typically higher due to the ability to trade surplus energy with neighbouring households, thereby optimising the benefits derived from the PV array.

$$SC_{agg} = \sum_{n=1}^N \sum_{t=1}^{17520} \left(\frac{E_{PV \rightarrow P} + E_{PV \rightarrow P \rightarrow POOL}}{E_{PV \rightarrow P} + E_{PV \rightarrow P \rightarrow POOL} + E_{PV \rightarrow G}} \right) \quad (5.6)$$

Self-sufficiency (SS) is a measure of a community's ability to meet its own energy needs through local sources of energy, rather than relying on energy imports from the grid.

$$SS_{agg} = \sum_{n=1}^N \sum_{t=1}^{17520} \left(\frac{E_{PV \rightarrow P} + E_{POOL \rightarrow P}}{E_{PV \rightarrow P} + E_{POOL \rightarrow P} + E_{G \rightarrow P}} \right) \quad (5.7)$$

Each of these indicators provides a unique perspective on the performance of the market, contributing to an understanding of its viability and sustainability. In particular, the economic indicators, such as Net Present Value and Benefits, directly address the need to ensure that the P2P market is both operationally viable and able to recoup initial investment. Technical indicators, such as self-consumption and self-sufficiency, provide insight into the efficiency of energy use within the community, which is critical to long-term sustainability. The aim of this study is to provide valuable insights into the potential for P2P markets to operate successfully in a market-driven environment without heavy reliance on government subsidies by evaluating these performance indicators.

5.5 Data collection

The simulation is rooted in the real pilot project, which provides the conceptual foundation for the model. However, due to data protection constraints and the unavailability of certain information from the pilot, some data could not be obtained directly. As a result, this simulation is based on a combination of existing datasets, assumptions and necessary simplifications. Each of these elements is explained in detail and supported by evidence to ensure clarity and validity. The market mechanism and logic underlying this simulation will be set out in full to enhance the reproducibility of the results. In addition, the methods used and conditions required for the simulation will be outlined in full to provide a clear framework for the analysis and interpretation of the simulated results.

5.5.1 Electricity demand and generation profiles

In the process of scaling the market size for the CommUNITY project, the selection of appropriate energy load profiles for residential customers was crucial. Given that only four customers were actively involved in the pilot and their data access was restricted due to GDPR, this study

opted for a publicly available dataset. UKPN's Low Carbon London project (UKPN, 2015) is a dataset comprising half-hourly meter readings from 5,567 London households, recorded between November 2011 and February 2014. The dataset includes residential smart meter data and dynamic time-of-use data, and was collected to test the impact of different low carbon technologies on London's electricity distribution network.

In order to ensure the accuracy and relevance of the data, the dataset was filtered to include only those households that use a flat energy tariff. The data from 2013 was used to create a model of the annual energy consumption of participants in the P2P energy trading market. Households with more than 10% missing values in their electricity meter readings were excluded from the analysis, leaving 4,387 distinct electricity meter IDs for consideration. Households with an annual consumption above 10,000 kWh were excluded from the study as they are unlikely to be representative of 1 to 5 occupant household in a block of flats. This resulted in a final dataset comprising 4,274 distinct electricity meter IDs. The rationale behind this exclusion is based on the assumption that such high energy consumption would be atypical for small to medium-sized households without significant additional loads, like electric vehicles. However, higher rates of annual electricity consumption are possible if electric heating is used instead of, for example, gas boilers⁶.

Figure 5.4 illustrates the distribution of annual electricity consumption among the selected households. The data indicates an average energy consumption of 3,624 kWh and a median of 2,974 kWh, with a standard deviation of 2,715 kWh.

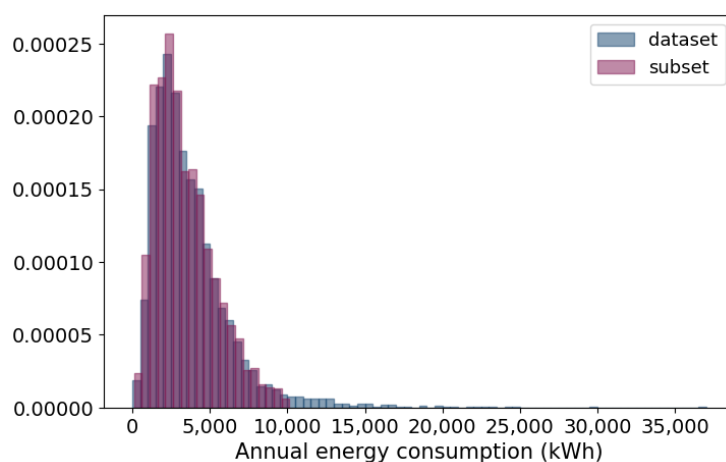


Figure 5.4: Normalised histogram of annual electricity consumption (bin size 500 kWh)⁷.

⁶No information was available on the type of heating used by residents in Elmore house.

⁷Each bin displays the bin's raw count divided by the total number of counts and the bin width, so that the area under the histogram equals to 1.

As the number of participants in a P2P energy trading market grows, the diversity of energy load profiles increases, which in turn affects trading activity on the market. When multiple individual load profiles are aggregated, the resulting combined load profile may exhibit characteristics that differ from those of the individual profiles. In the context of Elmore House, where there are no large energy-consuming devices such as electric vehicles or heat pumps to provide flexibility, the diversity of load profiles, along with energy generation profile, is a key factor in determining the amount of energy that can be traded at any given time. To effectively represent and measure the impact of increasing participation on the aggregated load profile, both the load factor and the coincidence factor can be measured (Bayliss et al., 2012).

The load factor is calculated by dividing the average load of all participants by their peak load over a specific time period T as seen in Equation 5.8. A higher load factor indicates a more balanced load profile, which optimises the usage of the infrastructure, in this case the network. A load factor of 1 represents a flat load profile, maximising the efficiency of the system.

$$\text{Load factor} = \frac{\text{average load over a period } T}{\text{peak load over a period } T} \quad (5.8)$$

The coincidence factor is defined as the ratio between the aggregated peak load of n households and the sum of the individual household peak loads, as defined in Equation 5.9. The coincidence factor is a measure of the probability that all participants will reach their peak load simultaneously. A lower coincidence factor indicates a lower probability of all participants reaching their peak load at the same time. A coincidence factor of 1 indicates that all components will peak at the same time.

$$\text{Coincidence factor} = \frac{\text{peak load of } n \text{ households}}{\sum \text{peak load of individual household}} \quad (5.9)$$

Figure 5.5 show the daily load and coincidence factor calculated for the data subset used in this simulation. The colour shades represent the distribution while the dark line shows results for the median values. It can be seen the load factor increases with a higher level of aggregation. It increases rapidly for the first 20 participants in the market and then levels off, meaning that usage of the infrastructure doesn't improve much more after that. At the same time the coincidence factor decreases with a higher level of aggregation. This means that the probability of all participants reaching their peak load at the same time decreases with a higher level of aggregation and also levels

off at around 40 participants. In a P2P energy trading market setting, this implies that not all households have their peak demand at the same point in time.

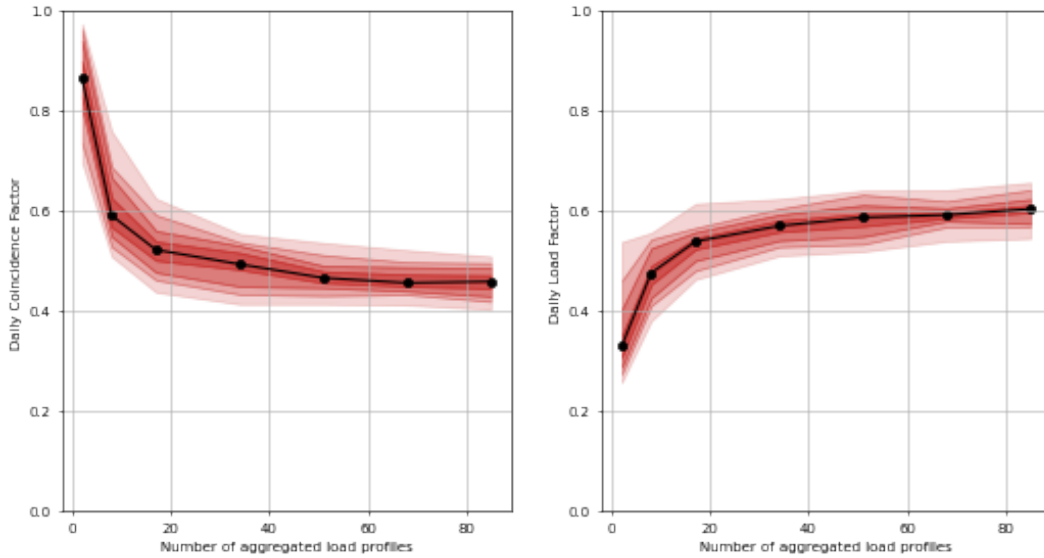


Figure 5.5: Distribution of daily coincidence and load factors of load profiles used for the simulation.

Despite Repowering London providing actual PV generation data for the 37 kWp installation, this was not used in subsequent analysis due to concerns regarding the quality of the data values. Instead, a synthetic annual electricity generation profile was constructed using the Python pvlib library (Holmgren et al., 2018). This entailed the creation of a model for a 1 kWp array with a standard inverter, which was then extrapolated to the scale of the installation. The site parameters, including latitude, longitude and a building height of 26 metres, were specifically adapted to reflect the location of Elmore House. Further details, including a PV tilt of 35° and an orientation and azimuth of -30° , were incorporated into the model. The model also accounts for the impact of air temperature on PV panel efficiency. The PVGIS model (Huld et al., 2012) was used to obtain plane-of-array (PoA) irradiance data specific to the site⁸. As the energy load profiles used for this simulation were from 2013, weather data from that year were used as parameters such as temperature, humidity and solar radiation can influence energy consumption patterns (Staffell et al., 2018). Figure 5.6 illustrates the resulting load profile, which has been resampled to show daily variations over a full year.

⁸Poa irradiance refers to the solar radiation received by the panel at its installed angle.

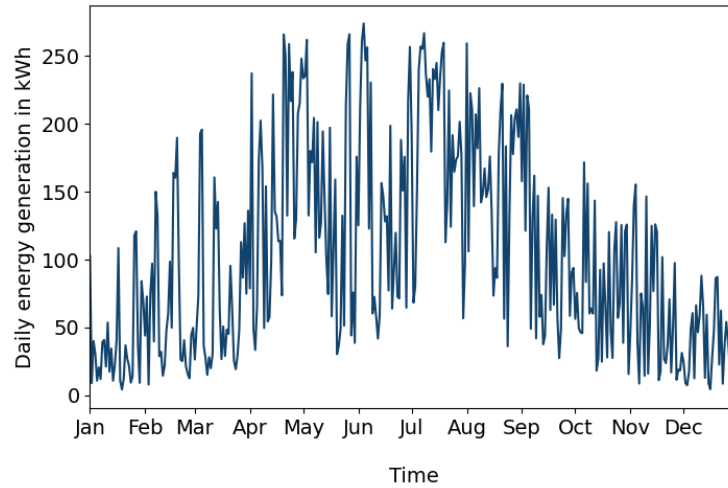


Figure 5.6: Generation profile of the 37kWp PV system.

5.5.2 P2P market pricing and costs

Although the pilot project was carried out before the impact of the energy crisis (Ofgem, 2021) and was therefore not directly affected by the subsequent increase in electricity and gas tariffs, this study has adjusted the tariffs to reflect current market rates. The objective of this adjustment is to evaluate the performance of the P2P energy trading market in the context of the prevailing market conditions. By simulating a scenario aligned with today's energy market conditions, the study aims to provide insights that are more applicable and potentially more valuable to current stakeholders.

For the simulation, the grid electricity tariff p_g was set at a fixed rate of £0.34/kWh in accordance with the Energy Price Guarantee from 1 October 2022 (Ofgem, 2023a). Three different rates for the cooperative price p_{pool} were tested, with the lowest rate set at £0.00/kWh, the highest at £0.10/kWh and the middle rate at £0.05/kWh. In the CommUNITY pilot, the energy consumed by each participant from their allocated share of the PV system was provided free of charge by the cooperative (The allocated share of the PV system is calculated by dividing the size of the PV system equally by the number of participants). It is likely that in future scenarios, the cooperative will opt to charge a price for this energy that is still lower than the average market price. All cooperative rates remain lower than the highest community pool rate (£0.12/kWh, see below), ensuring that self-consumption continues to be the most cost-effective option. This approach enables a local sensitivity analysis to assess how varying price levels impact both individual and system-level performance under different tariff scenarios.

The price set by the cooperative, p_{coop} , for the consumption of PV energy, is below the price set by the community pool, p_{pool} , as self-consumption is a more cost-effective option than transactions in the community pool. Three different tariffs are proposed for the community pool price p_{pool} to reflect the actual conditions of the CommUNITY pilot. Participants may sell the energy on the market to other participants at no cost or charge a price of approximately £0.12/kWh, as defined by the pilot coordinators. To reflect potential price range, a step of £0.06/kWh was selected. As the p_{coop} increases, the p_{pool} prices that are below the p_{coop} price fall away as it is unlikely that self-consumption is more expensive than community self-consumption. Finally, the PPA price p_{ppa} for energy exported to the grid was set to reflect at a range of values between the current Smart Export Guarantee (SEG) tariffs and industrial-scale PPAs. The SEG, a successor to the FiT scheme, differs in that it requires all licensed energy companies to offer an SEG scheme, with prices set on a voluntary basis (Energy Saving Trust, 2022). The highest fixed SEG tariff was chosen for the simulation. Meanwhile, PPA tariffs were set based on current market rates, ranging from £50 to £200/MWh.

A local sensitivity analysis was conducted to assess the impact of these different price ranges on market performance. The above-mentioned tariffs for the different price components are combined and analysed in three tariff design options. The objective of this analysis is to help stakeholders gain a deeper understanding of the potential risks and opportunities associated with different pricing scenarios in the current energy market. Table 1 provides an overview of the tariff designs and rates used in this simulation.

Tariff design	Tariff rates in £/kWh			
	p_g	p_{coop}	p_{pool}	p_{ppa}
Option 1	0.34	0.00	0.00	-
			0.06	0.05
			0.12	0.10
				0.20
Option 2	0.34	0.05	-	0.0
			0.06	0.05
			0.12	0.10
				0.20
Option 3	0.34	0.10	-	0.0
			-	0.05
			0.12	0.10
				0.20

Table 5.1: Tariff rates and designs tested in the P2P market. Tariffs design options that were present in the CommUNITY pilot are highlighted in **bold**.

Including the upfront installation and ongoing maintenance costs in the viability calculation is essential to ensure the financial sustainability of the P2P energy market. The cost of PV installation has been obtained from the Department for Business, Energy and Industrial Strategy (BEIS, 2014). These costs are based on the average per kWp for installations between 10-50kWp in 2021/2022, with a rate of £1016 per kWp. In addition, operation and maintenance costs $C_{O\&M}$, which are critical to the continued operation of the market, are included in the cooperative's cash flows at an annual rate of £30 per kWp (F. Wight, Repowering, personal communication, 27/04/2023). The $C_{O\&M}$ cost figures, although not from a published source, were provided by Repowering's project coordinator and provide valuable insight into the practical cost implications of running such projects.

Including these costs is crucial for the financial analysis and aligns with the study's objective of evaluating the long-term economic viability of community energy projects. This approach guarantees that the P2P energy trading market is not only operationally viable, but also able to recoup its initial investment over its operational lifetime. The assessment of these costs therefore plays a pivotal role in determining whether such projects can operate sustainably without significant reliance on government funding or subsidies, in line with the second primary objective of the study.

5.6 Definition of simulation environment

The previous chapters described the pilot project and its contextual characteristics. Building on this foundation, this chapter introduces the simulation environment designed to conduct the scalability analysis by addressing the barriers faced by the scalability scenarios.

5.6.1 Market size

In order to assess the impact of increasing market sizes on the P2P energy market and the overall feasibility and viability of a P2P energy trading system, the simulation explores a range of market sizes. The simulation begins with a market size of just two participants, reflecting the smallest possible scale of interaction within a P2P market. Thereafter, the number of participants is increased in each subsequent simulation run in a structured pattern of 2, 4, 8, 16, 32 and finally 64 participants, which approximates the total number of flats in Elmore House.

This increase in market size enables the simulation to capture a wide range of participant interactions and market dynamics. By starting with a minimal participant base and increasing it

systematically, the study can observe changes in market performance, participant benefits and overall energy distribution. Furthermore, testing up to 64 participants provides a realistic scenario that closely matches the actual number of households in a typical block of flats such as Elmore House. This ensures that the simulation results are practically relevant, providing actionable insights for the implementation of P2P energy trading systems in similar residential contexts.

A random sample is selected from the pool of 4,274 available electricity meter IDs for each market size. The random sampling approach is adopted primarily due to a lack of original load data. Without access to actual load data from pilot project participants, sampling from a broad and diverse pool allows for a more representative and unbiased selection of load profiles. This method ensures that the simulation results are not biased by a particular subset of data that may not accurately reflect the energy consumption patterns of the wider population.

To further increase the reliability and robustness of the simulation outcomes, each simulation run is conducted 100 times, with annual load profiles randomly assigned to market participants in each iteration. This repetition allows a wide range of possible scenarios and outcomes to be captured. The aggregation of these repeated runs helps to smooth out anomalies or outliers, ensuring that the conclusions drawn are not the result of chance but are representative of broader trends and patterns. A detailed overview of the market simulation setup, including the rationale behind these methodological choices, is provided in Figure B.1 in Appendix B.

5.6.2 Market mechanism

The following section outlines the P2P market design used in this simulation, which has been adapted from the original CommUNITY pilot project design. To begin with, all participating households in the market are assigned an equal share of the PV system, meaning the total installed PV capacity is ‘virtually’ divided by the number of participants⁹. The more participants join the market the smaller the share each participant gets assigned becomes. When energy is generated this means that the generation output is divided equally between the number of participants in the market.

Each market participant is initially permitted to self-consume energy generated from their assigned PV share at the price p_{coop} . In the event that any surplus energy is available, it can be sold to other participants in the market through a community pool at the price p_{pool} . Similarly, any energy

⁹In contrast to the operation before the launch of the CommUNITY pilot project, the P2P energy trading market no longer takes into account the energy consumption of the landlord. In this simulated environment too, the total capacity of the plant is also divided equally between the participants excluding the landlord.

demand not met by the PV can be purchased from the community at the same price. In the event that the required energy cannot be sourced from the community pool, each participant has the option to purchase excess demand from the grid at the standard grid price p_g . Surplus PV generation that cannot be sold in the community pool is redirected to the cooperative¹⁰ that sells the community surplus energy to the grid at the given PPA rate p_{ppa} .

Algorithm 1 P2P market clearing

```

if  $\sum D > \sum G$  then                                ▷ if total market demand exceeds total generation
   $l = \text{length}(D)$ 
  sort  $D$  in ascending order
   $g_{\max} = \sum G \div l$                                 ▷ maximum generation volume each household can trade
  for all  $g$  in  $G$  do
     $\text{payment}_g = g \times p_{\text{pool}}$                         ▷ will be negative because income
  end for
  for all  $d$  in  $D$  do
    if  $d \leq g_{\max}$  then
       $\text{payment}_d = d \times p_{\text{pool}}$ 
       $l \leftarrow l - 1$ 
       $g_{\max} \leftarrow (\sum G - d) \div l$ 
    else if then
       $d \leftarrow d - g_{\max}$ 
       $\text{payment}_d = g_{\max} \times p_{\text{pool}} + d \times p_g$ 
    end if
  end for
else if then                                          ▷ if total generation exceeds total market demand
   $l = \text{length}(G)$ 
  sort  $G$  in descending order                          ▷ because negative values
   $d_{\max} = \sum D \div l$                                 ▷ maximum demand volume each household can trade
  for all  $d$  in  $D$  do
     $\text{payment}_d = d \times p_{\text{pool}}$ 
  end for
  for all  $g$  in  $G$  do
    if  $g \leq d_{\max}$  then
       $\text{payment}_g = g \times p_{\text{pool}}$ 
       $l \leftarrow l - 1$ 
       $d_{\max} \leftarrow (\sum D - g) \div l$ 
    else if then
       $g \leftarrow g - d_{\max}$ 
       $\text{payment}_g = d_{\max} \times p_{\text{pool}} + g \times p_{\text{ppa}}$ 
    end if
  end for
end if

```

¹⁰The cooperative in the pilot project is the project partner Repowering London. It takes the role of the community energy development organisation and is effectively managing the energy community.

Algorithm 1 illustrates the logic that is applied to clear the market once bids have been submitted. This is done in the event that the total energy demand exceeds the energy supply, and vice versa. The following description outlines the procedure to be followed in the event that there is more energy demand than supply in a trading period. The procedure for the opposite scenario is the same.

Once all generated energy has been self-consumed, participants may place bids in the P2P market, indicating their energy demand $d \in D$ or energy surplus $g \in G$, where $G = \{g \in \mathbb{R} | g < 0\}$. If the sum of the energy demand bids exceeds the sum of the energy surplus bids, the total number of demand bids l is calculated and bids are sorted in ascending order¹¹. To calculate the total energy surplus available per participant demanding energy, the total energy surplus, is divided by the number of participants l . This figure g_{max} represents the maximum amount of energy each participant looking to cover its demand on the market can buy from participants selling energy in the market. Each participant selling energy on the market will be compensated with $payment_g$ for their energy surplus bid by multiplying the surplus bid g with the price of the community pool p_{pool} . This will result in a negative value as it generates an income for the participant selling energy.

For participants that are placing demand bids on the market, the cost that occur in the form of the $payment_d$ are calculated by checking if a demand bid d is less than the maximum supply per participant g_{max} calculated. If this is the case, the $payment_d$ the participant has to make is calculated by multiplying the demand bid d with the price of the community pool p_{pool} . After that step the total number of demand bids l is reduced by one and g_{max} is recalculated to add the remaining surplus from the participants share to the pool. However, if demand bid d requested by the participant is larger than the maximum supply per participant g_{max} , the demand bid is recalculated as the difference between the demand bid and the maximum supply per participant. The $payment_d$ the participant has to make is calculated as the sum of the maximum surplus bid g_{max} multiplied by the pool price p_{pool} and the remaining demand d multiplied by the grid price p_g . This process is repeated for all demand bids in each trading period before the next trading period starts.

By implementing this approach, the market mechanism ensures an even distribution of energy

¹¹If the sum of the energy surplus bids exceeds the sum of the energy demand bids, then bids are sorted in descending order as values are negative.

among all participants in the most efficient way. This strategy not only optimises the communities' self-consumption, but also contributes to optimising the participants' bills, ensuring that trading energy in the P2P market results in savings.

In the P2P energy trading market, settlements are conducted every half hour, in alignment with the operational framework established in the actual pilot project. This half-hourly settlement period not only mirrors the configuration of the pilot, but also aligns with the operational realities of energy data management. In the UK, smart meters, which are integral to the system, transmit data at half-hourly intervals. This consistent data transmission allows the market to be cleared with the most up-to-date information, ensuring that the market operates on the basis of the most recent consumption and generation figures.

The shorter clearing period also results in a closer match between actual energy generation and consumption, which is an important aspect given that this market model does not incorporate uncertainties. The ex-post nature of the market settlement means that energy is first generated and consumed, and only then is it accounted for in terms of billing through the P2P market, the grid and the cooperative. Such a mechanism removes the need for participants to forecast their energy consumption, thus eliminating potential discrepancies between predicted and actual consumption. This lack of predictive responsibility ensures that participants are only billed based on their real-time energy consumption, thereby increasing the fairness and accuracy of the market.

5.7 Scalability analysis and calculation of performance indicators

This chapter applies the scalability analysis framework to analyse the defined scalability scenarios by calculating the performance indicators described in Section 5.4. The results¹² are presented in two parts, covering Scenarios I and II. The first part analyses the impact of increasing market size on the overall performance of the P2P energy trading market, with a particular focus on the individual and community benefits achieved. The second presents the results of the financial viability of the community energy business model under different pricing strategies.

¹²It is important to note that the results of this scalability analysis are illustrative rather than directly applicable to the real world, as the simulation environment is only an approximation of the real pilot conditions and includes assumptions and simplifications. These results, which may differ from the actual results of the pilot, are intended to provide nuanced insights into specific design choices and their potential impacts. This simulation serves as a tool for understanding and extrapolating the impact of different design choices in a controlled, hypothetical context.

5.7.1 Scenario I

This section presents the results of increasing market participation. The results are split into two parts: technical and economic analysis. The technical analysis includes the impact of increasing participation rates on the distribution of load and PV generation among participants, as well as the impact of market size on self-consumption and self-sufficiency rates. The economic analysis focuses on the financial benefits to participants under changing participation rates in relation to household characteristics such as load. It also considers the equality of savings and benefit distribution.

5.7.1.1 Technical analysis

The volume and timing of energy trading on the P2P energy trading market is contingent upon the load profiles of market participants. As demonstrated in Chapter 5.5.1, the coincidence factor and load factor fluctuate in response to changes in market size. This example will examine how energy generation and consumption patterns evolve as market size increases.

Figure 5.7 shows the participants' annual energy consumption and who it is supplied by, from self-consumption, from the community pool or from the electricity grid. The aggregated energy consumption in Figure 5.7a shows that with increasing market size more energy needs to be purchased from the grid while energy self-consumed or bought from the community pool will eventually reach a maximum as energy produced by the PV system is limited. The data in the figure also shows that with increasing market size, the distribution of annual load increases on an aggregated level ranging from around 150,000kWh to over 200,000kWh at a market size of $n=64$. Figure 5.7b shows the mean individual energy demand. While distribution is higher at the beginning when participation in the market is low, it decreases as the market size increases.

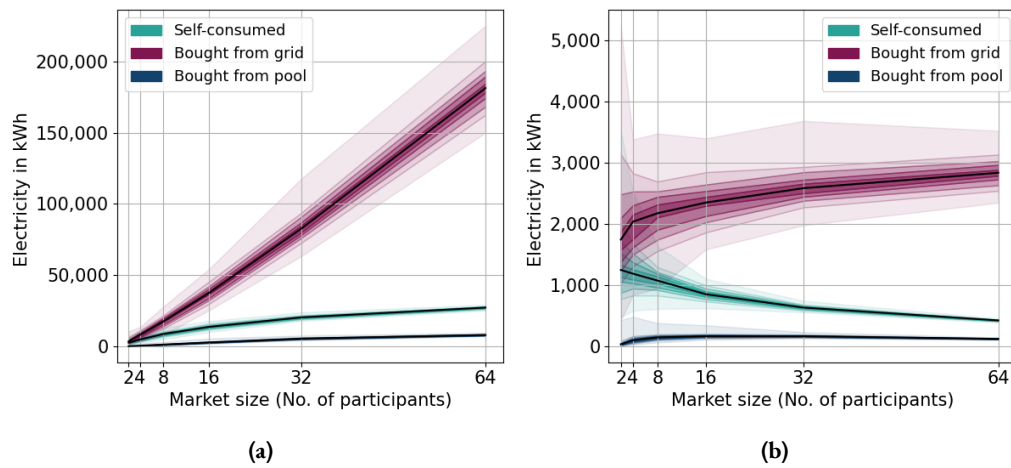


Figure 5.7: Distribution of supply type of energy consumed (self-consumption, community pool or grid) for 100 simulation runs showing (a) aggregated market energy consumption (b) and mean individual market participant's energy consumption.

Figure 5.8 shows the annual energy generation and consumption of the PV system. It shows how the energy is either consumed by participants, sold to the community pool or sold to the electricity grid. As can be seen in Figure 5.8a, at small market sizes a large proportion of the electricity generated must be sold back to the electricity grid, given the low level of consumption. As the number of participants increases, the proportion of electricity consumed from the PV panels also rises in line with this growth. As the number of participants increases, the proportion of electricity consumed from the pool will eventually reach a maximum and then decrease. This is because each participant's share of the PV system is reduced to a size such that most of the energy can be self-consumed. The impact is particularly evident when examining PV energy consumption on an individual basis in Figure 5.8b. In markets with a small number of participants, such as $n=4$, the majority of generated PV energy is sold directly to the grid due to a discrepancy between the total demand of market participants and the total energy produced by the PV system.

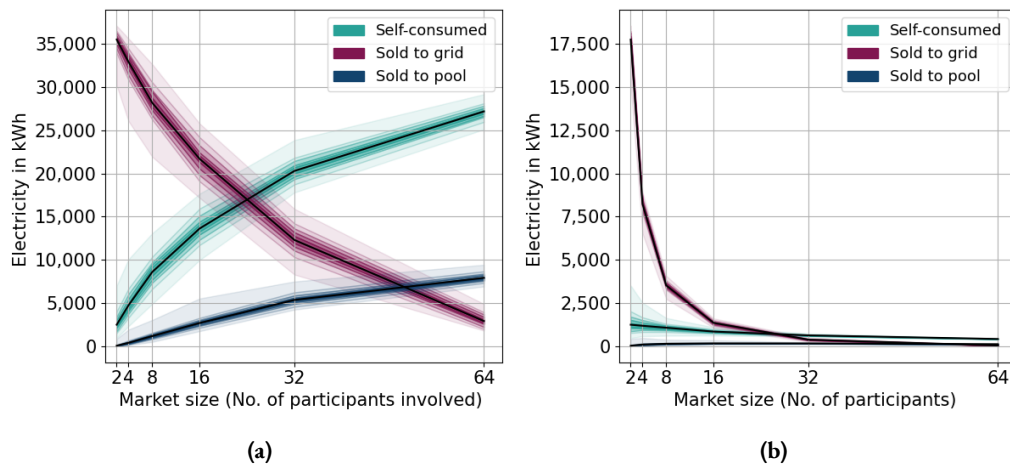


Figure 5.8: Destination of generated PV energy (self-consumption, community pool or grid) for 100 simulation runs showing (a) aggregated market energy generation (b) and mean individual market participant's energy generation.

While the metering infrastructure in CommUNITY does not reflect the physical boundaries of Elmore House, self-consumption and self-sufficiency remain key considerations in the CommUNITY pilot, given that energy is generated and consumed locally. Figure 5.9 illustrates the virtual energy imported and exported in the P2P energy trading market for different participation rates. As the market size increases, the self-consumption rate increases accordingly. Specifically, for $n = 2$, the self-consumption rate is 7% and gradually increases to 92% for $n=64$ as can be seen in Table 5.2. In contrast to alternative market designs, where increasing participation often leads to an increase in generation capacity, the distribution of PV capacity among participants results in a decline of community self-sufficiency from 42% to 16% as seen in Table 5.2.

	Market size					
	2	4	8	16	32	64
Community self-consumption	0.07	0.14	0.26	0.43	0.68	0.92
Community self-sufficiency	0.42	0.40	0.36	0.30	0.24	0.16

Table 5.2: Mean community self-consumption (SC) and community self-sufficiency (SS) rate of P2P market at different market sizes.

Figure 5.9 shows the energy load profile of the community for different market sizes. The figure demonstrates the substantial oversizing of the PV system in comparison to the actual community requirements for low participation rates, where the majority of energy produced must be fed back into the grid. In addition to contributing to a more balanced load profile, a higher level of self-

consumption will facilitate a more rapid return on investment for the system, as self-consumption of energy is typically more cost-effective than grid consumption.

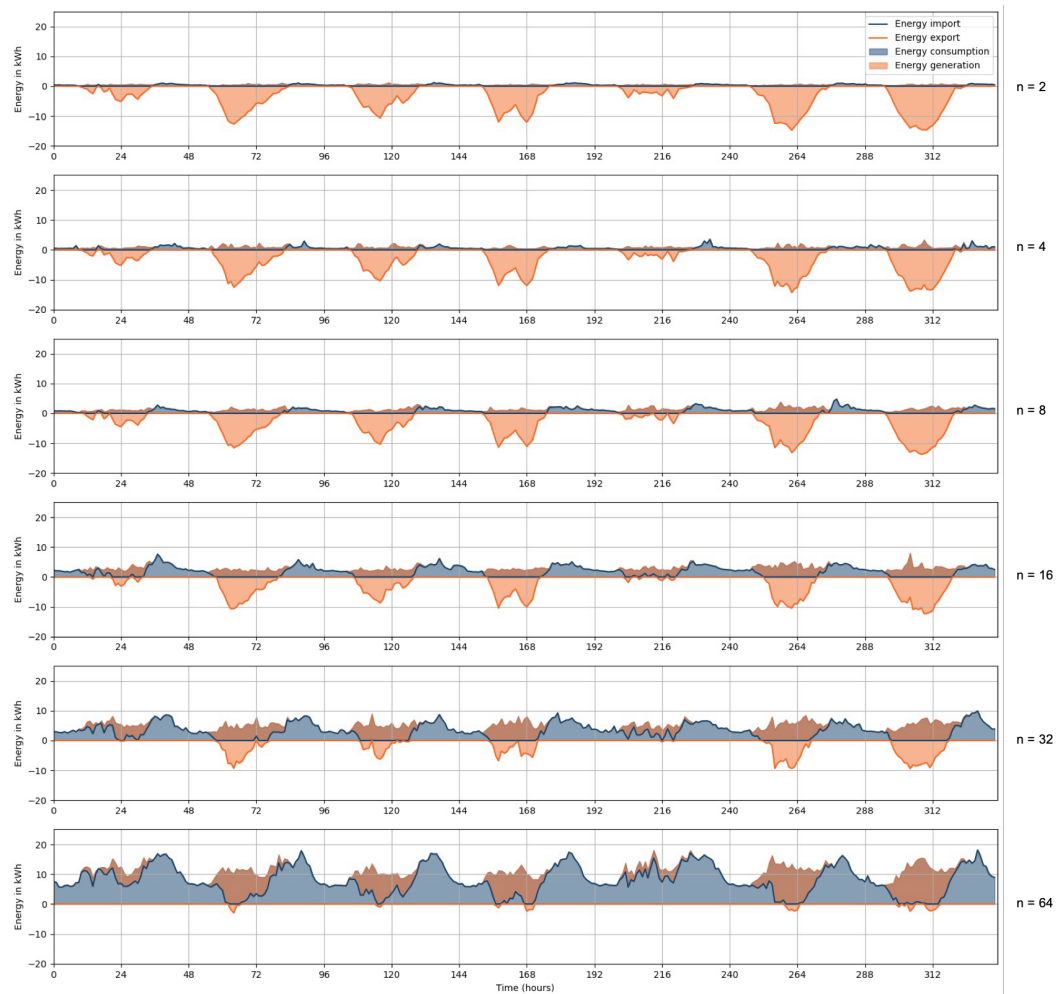


Figure 5.9: Sample week of virtual energy imported and exported in the P2P energy trading market participation rate n .

The total demand of the households within the building is visible to the network operator at the point of meter supply to the house, irrespective of the size of the market. This is dependent on the type of metering or monitoring in place. It is therefore unlikely that the community will export energy back to the grid. Implementing demand response, energy efficiency measures and exploring energy storage options can help increase self-consumption and self-sufficiency. Battery storage could be used to store excess energy generated during peak hours and discharge it during evening peaks. However, this requires high up-front costs to establish the market and will result in longer payback periods for the cooperative, making the investment less attractive.

5.7.1.2 Economic analysis

The following analysis examines the financial benefits associated with different market sizes, both for the community and for individual participants. These benefits are closely linked to the load profiles discussed above and are significantly influenced by the choice of tariff structures. To demonstrate how the financial outcomes vary with different tariff settings, the sensitivity of these benefits under different pricing scenarios is explored.

Figure 5.10 shows the community's total benefits at varying market sizes and p_{coop} prices, calculated using Equations 5.2 and 5.1. These figures demonstrate the cumulative economic benefits from energy savings and earnings in contrast to scenarios without P2P energy trading. The higher the price p_{coop} , the lower the absolute benefit. As the market size increases, the individual benefits of the markets accumulate as seen in Figure 5.10a. In contrast, since the share of the PV system assigned to each participant decreases with increasing market size, the individual participant's benefit decreases, which is illustrated in Figure 5.10b. Depending on whether the community or the individual perspective is considered, the benefit first rises or falls faster and then more slowly.

The community pool price p_{pool} has no impact on the annual benefit on from a community perspective, as the energy sold by the community is also consumed by the community and therefore balances itself out. However, marginal differences may occur on the individual level.

In this market design, which is confined to a physically limited area with a maximum achievable market size, there is an inherent contrast between community and individual benefits. As the market expands, each participant's share of the PV system decreases, leading to a decrease in individual benefits despite an increase in collective benefits.

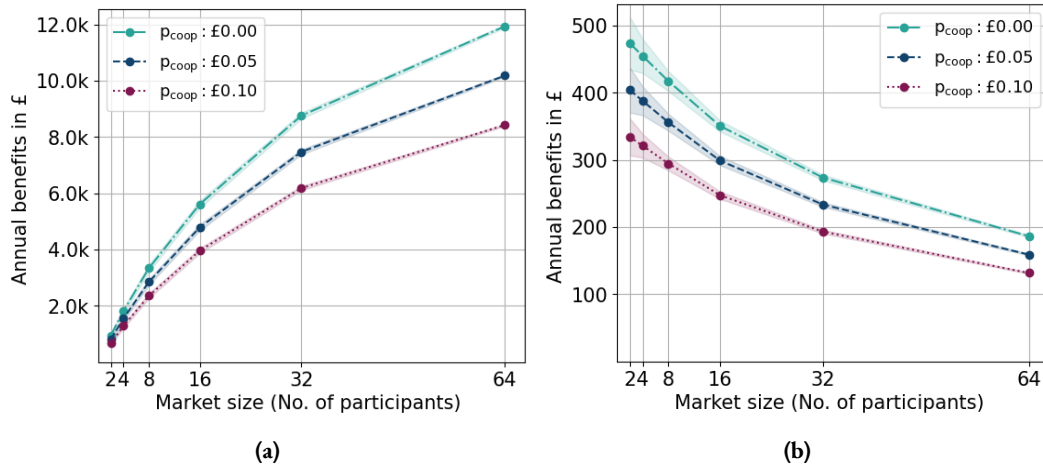


Figure 5.10: Benefits of P2P market at different price sensitivities aggregated over the community (a) and average over an individual participant (b). Shaded area indicates the 95% confidence interval.

To gain insight into how varying pool prices p_{pool} affect the distribution of benefits, it is instructive to examine the equity index. According to Equation 5.5. The index measured the distribution of benefits among participants in the market. Significant inequality can influence perceptions of fairness within a community and impact market adoption.

Figure 5.11 shows the equality index for an expanding market size with varying pool price points p_{pool} . In smaller markets, each participant's allocation of the PV system is relatively large, resulting in higher absolute benefits and smaller differences in benefits between participants. This initially results in a higher equality index. However, the index reaches its lowest point around a market size of $n=8$, indicating the most unequal distribution of benefits. As the market size increases, the equality index increases again. This is due to the reduced share of PV per participant, which becomes proportionally smaller relative to their total energy consumption, leading to a more even distribution of benefits across participants.

Although greater load homogeneity (as seen in Figure 5.5) between participants typically increases the overall equality index, it doesn't always lead to the most beneficial outcome for the community as a whole. Surprisingly, a higher p_{pool} price leads to a more equitable distribution of benefits. Despite the uniformity in the communities pool's buy and sell price, the savings accrued by participants vary significantly. When selling energy, a participant's benefit is calculated as the total energy sold multiplied by the difference between the community pool price p_{pool} and the cooperative's price p_{coop} . Conversely, savings from purchasing energy are derived from the energy bought in the community pool, multiplied by the difference between the grid price p_g and the

community pool price p_{pool} . As p_{pool} increases, individual benefits, particularly savings from purchased energy, decrease, however leading to a more equitable distribution of benefits across participants. A detailed summary of these dynamics is presented in Appendix B, Table B.1.

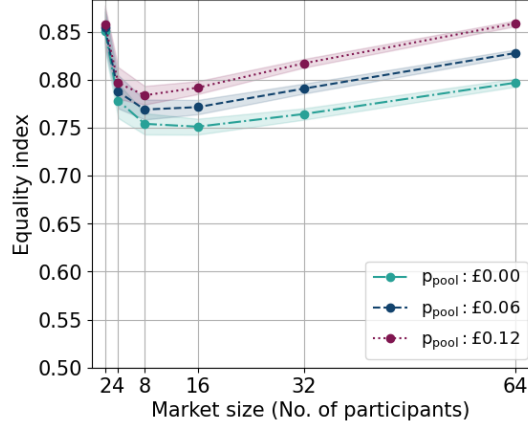


Figure 5.11: P2P market mean equality index at different price rates for p_{pool} . Shaded area indicates the 95% confidence interval.

While the equality index indicates how the benefit is distributed for different prices for p_{pool} it fails to indicate how different household characteristics impact the benefits for the participants. A common way to categorise households is by the amount of their annual load, which can be considered an indicator for household size. For the following analysis, participants in the market were categorised into low, medium and high annual load according to the distribution of annual load profiles as seen in Figure 5.4 to understand how their savings differ from each other. Low annual load includes all participants in the lower quartile of the distribution of load profiles (0-1939 kWh). Medium annual load includes all participants with annual energy consumption within the interquartile range (1939-4511kWh) while high annual load considers all participants that fall into the upper quartile range of the distribution (4511-10000kWh). Figures 5.12 - 5.14 show the savings of participants in the market for different prices of p_{coop} and p_{pool} .

Figure 5.12 illustrates the annual benefits of participants in the P2P market, for $p_{coop} = 0.0$, meaning participants don't pay the cooperative for PV energy self-consumed. Annual benefits are equal to electricity bill savings experienced through the participation in the P2P market. For smaller markets, savings are relatively consistent across different load ranges, averaging between 41-47%. As the market size increases, overall bill savings decrease for all load ranges. Notably, this reduction is more pronounced for households with higher annual energy consumption. At a market size of $n = 64$, these households experience an average bill reduction of 12-13%, whereas those with

lower energy consumption see savings of 24-31%. Households with medium annual loads also see a decline in relative savings as the market expands, with minimal variation at different pool price ranges p_{pool} , decreasing from approximately 42% at a market size of $n = 2$ to around 18% at $n = 64$. In contrast, households with high and low annual energy loads show different savings in response to different p_{pool} prices. For households with low annual demand, a higher p_{pool} price leads to greater savings. Conversely, for those with high annual demand, an increase in the p_{pool} price leads to lower savings.

While the discrepancies are minimal, they can be attributed to the fact that households with low energy consumption tend to sell more of their electricity on the pool market, thereby generating greater profits. This is in contrast to households that donate energy to their neighbours.

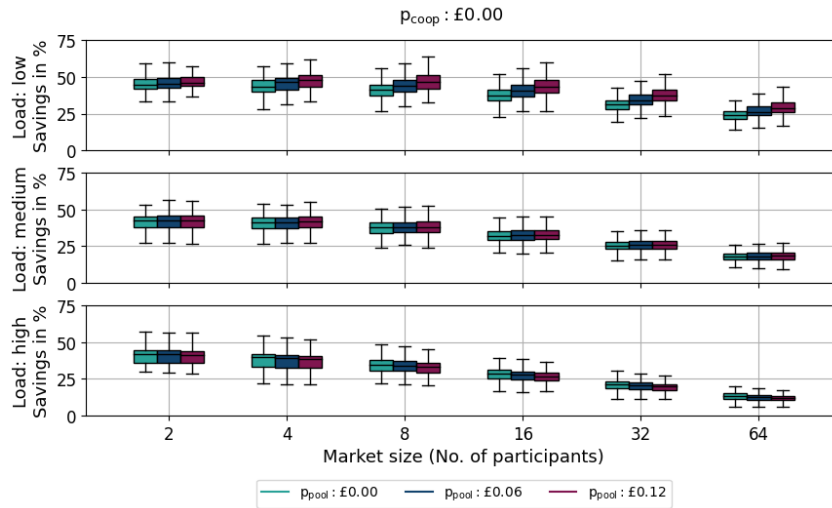


Figure 5.12: Distribution of annual electricity bill savings in relation to annual load for $p_{coop} = £0.00$.

Figures 5.13 and 5.14 demonstrate a similar trend for p_{coop} prices at £0.05 and £0.10, respectively. With increasing p_{coop} , the overall relative savings for participants decrease. At a p_{coop} of £0.05, savings initially range from 35-40% and then decrease to between 10-24%. Similarly, for a p_{coop} of £0.10, initial savings of 29-32% drop to an average of 9-18%. A detailed summary of mean values is available in Appendix B, Table B.2.

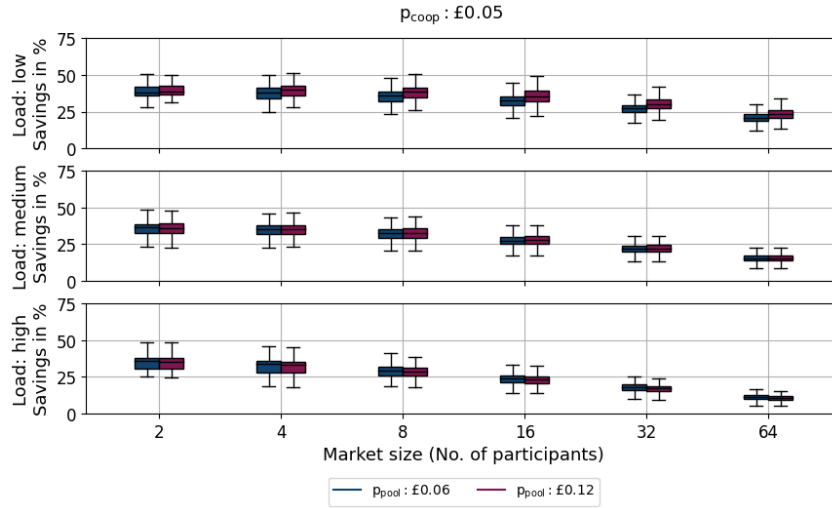


Figure 5.13: Distribution of annual electricity bill savings in relation to annual load for $p_{coop}=£0.05$.

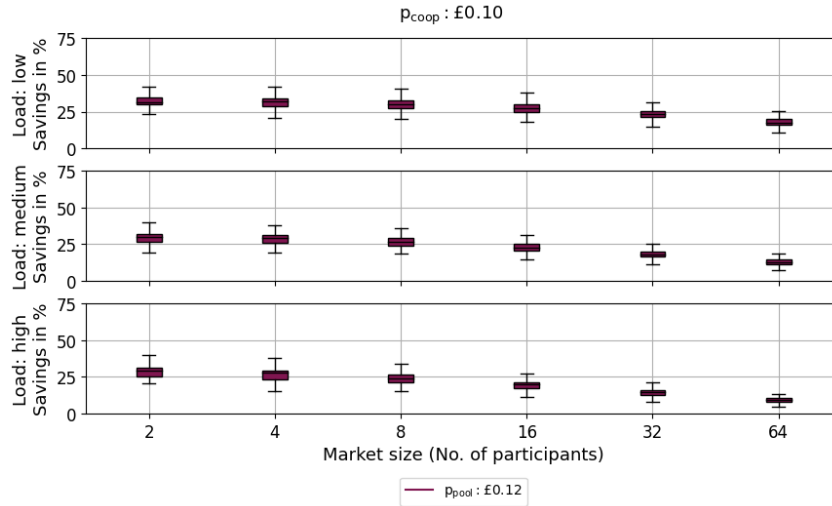


Figure 5.14: Distribution of annual electricity bill savings in relation to annual load for $p_{coop}=£0.10$.

5.7.2 Scenario II

Scenario II assesses the financial viability of the P2P energy trading market from the perspective of the cooperative. While a cooperative involved in such a project will not act on a purely commercial basis, it is essential to ensure that the upfront costs are recouped over the lifetime of the hardware installations to guarantee the long-term sustainability of the model.

5.7.2.1 Economic analysis

In the CommUNITY market, where participants do not incur any upfront costs and only benefit from savings, it is essential to provide sufficient financial incentives to the cooperative responsible for establishing and managing the P2P market. The NPV calculation is used to determine the

profitability of the cooperative's investment. Figure 5.15 illustrates the NPV for different p_{coop} prices, showing the profitability of the market for the cooperative when $NPV \geq 0$. This figure also explores the NPV under different p_{ppa} rates, assessing the financial viability under different market settings.

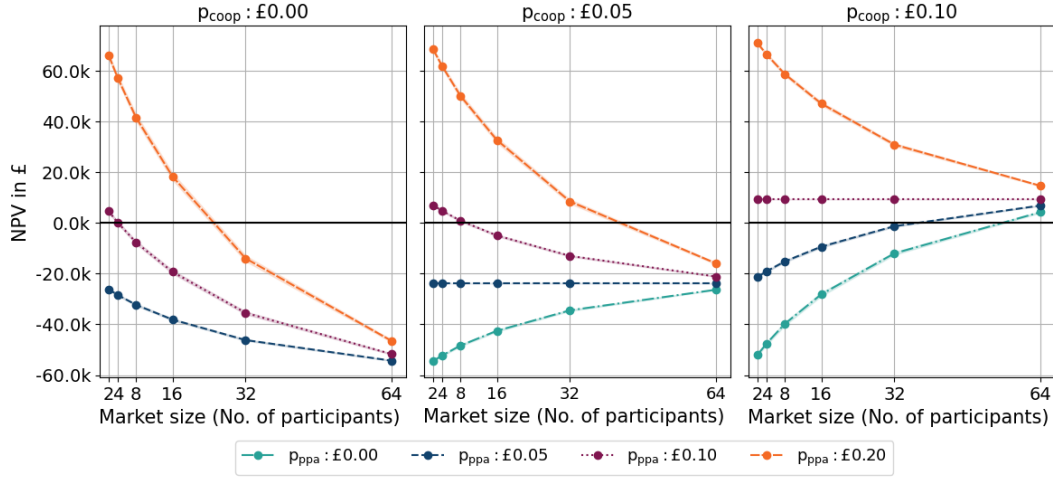


Figure 5.15: Mean NPV of cooperative under different price sensitivities.

The objective of the project is to optimise savings for community participants while ensuring the investment is financially viable. To assess the impact of an increasing number of participants on market profitability, it is essential to distinguish between two scenarios: when $p_{coop} > p_{ppa}$ and if $p_{coop} < p_{ppa}$.

Where p_{ppa} is greater than p_{coop} , increasing the market size reduces the NPV of the cooperative. For $p_{coop} = £0.00$ the market is profitable up to about 4 participants for $p_{ppa} = £0.05$, about 25 participants for $p_{ppa} = £0.10$. At $p_{ppa} = £0.05$, the market does not make enough money to break even. As p_{coop} increases, the possible market size at which the investment pays off for the cooperative increases. For $p_{coop} = £0.05$ this is 8 for $p_{ppa} = £0.10$ and 43 for $p_{ppa} = £0.20$. For $p_{coop} = £0.10$ and $p_{ppa} = £0.20$ the NPV remains positive as the market size increases. As p_{coop} and p_{ppa} increase, the size at which the market implementation remains profitable increases. Increasing the number of participants therefore decreases the NPV of the cooperative. The cooperative has to choose between greater profits or greater distribution of savings to the participants in the community. Given the business model of CommUNITY, the latter is more likely.

In the case where p_{coop} is greater than p_{ppa} , the opposite behaviour can be observed. Increasing

the market size increases the NPV. Where $p_{coop} = £0.05$ and $p_{ppa} = £0.00$, the NPV increases with higher market participation rates, but remains negative even at the largest market size. Where $p_{coop} = £0.10$ the NPV becomes positive at around 55 participants for $p_{ppa} = £0.00$ and 37 participants for $p_{ppa} = £0.05$, where $p_{coop} = p_{ppa}$ the NPV remains constant for different market sizes.

In the case of CommUNITY, the rates set for p_{coop} and p_{ppa} are £0.00 and £0.05 respectively. This means that the project would not have been profitable if it had continued for 25 years. Increasing participation in such market conditions would have increased losses for the cooperative.

In order to determine the appropriate size of the market, it is important to consider what the savings in electricity bills should be for the market participants compared to the profit for the cooperative. A higher profit for the cooperative may also mean that money can be reinvested to support other areas of community life. In addition, the profits can be reinvested in setting up more P2P energy markets in other communities or blocks of flats.

Fixed costs have been assumed in calculating the net present value. However, it can be assumed that the capital cost of installing solar systems will continue decrease in the future, as historical developments have shown (IEA, 2020b). At the same time, the rates for p_{coop} and p_{ppa} will strongly depend on the electricity price development in the national and international energy markets. Rising electricity prices mean rising PPA rates. In this case, the cooperative has to offer a p_{coop} that is lower than the given p_{ppa} to compensate the energy users' electricity bills. Conversely, if electricity prices fall, the cooperative's PPA rate will also fall. To compensate for the lost profits, the cooperative can increase its p_{coop} to bring it above the p_{ppa} . These dynamics specific to the electricity market must be taken into account when designing P2P energy trading markets based on the CommUNITY principle. It must also be taken into account that an investment with high returns and short payback periods may be more attractive, especially in cases where third parties are involved in the financing.

5.8 Evaluation of results

This section presents the findings of the scalability analysis, with a particular focus on the specific context of the case study. Furthermore, the discussion is extended to interpret these findings in the broader context of P2P energy trading, both within the pilot and across the UK. The analysis is structured using the five levels of LEMs outlined in Chapter 2.1.2, which helps to improve our

understanding of the progress made and identifies key areas for further research into P2P energy trading systems, as well as pinpointing specific tiers that merit further investigation.

5.8.1 Power systems integration

This study did not focus extensively on the integration of the energy systems, as this was addressed during the CommUNITY pilot project. However, the design and performance of the overall P2P energy trading system was significantly influenced by the physical infrastructure at Elmore House, with the electrical infrastructure playing a key role.

In the CommUNITY pilot, the metering infrastructure at Elmore House was not configured in accordance with the physical boundaries of the building. Each flat was equipped with a dedicated meter, with additional meters installed for the landlord and the PV system. This setup required a virtual approach to energy trading, as electricity generated by the rooftop PV system had to be routed through the public grid before it could be used by the residents. A single grid connection for the entire building would have facilitated more efficient use of PV-generated electricity and streamlined P2P market operations by allowing immediate use of on-site generated electricity and exporting any surplus to the grid. While these challenges were successfully avoided during the pilot phase due to the experimental nature of the project, there are potential regulatory and financial implications to consider when scaling this model. These may include grid usage fees or other related costs, depending on the regulatory context. It is therefore essential to make further regulatory adjustments to ensure the seamless integration of these systems.

A limitation of this study is that the economic analysis does not take into account the capital and operating costs associated with the electrical configuration required to implement a private wire system, beyond the installation and operating costs of the PV array itself. In a real-world deployment, upfront costs might have include rewiring and metering infrastructure to support dedicated energy flows between participants, as well as ongoing costs for billing, data handling and system maintenance. While the pilot operated under virtual market conditions, a fully physical implementation would likely require significant investment in electrical infrastructure. The absence of these costs means that the NPV and financial viability projections for the cooperative and participants may be overoptimistic. Future work should seek to include these cost components, using cost benchmarks from existing community energy projects with private wire systems, to provide a more comprehensive assessment of economic viability.

The intermittent nature of PV generation often results in a mismatch between peak energy gen-

eration and consumption times. Residential energy consumption typically peaks in the early morning and late evening while solar energy generation peaks around midday. Using electricity directly from the PV system, rather than exporting it to the grid, can significantly reduce costs for households. However, the study's deterministic analysis did not take into account potential shifts in energy demand by users in response to the availability of cheaper solar power, or buying at the lower community pool rate rather than purchasing electricity from the utility. Research with seven low-income households in the UK (Fox, 2023) found that solar installations led users to adjust their electricity use to match solar production times, resulting in cost savings and alleviating concerns about high energy bills. This behavioural adjustment shows that households are able to shift demand to PV generation hours, which can further reduce energy bills. However, the degree of benefit may vary depending on seasonal changes in solar energy output and the daily routines of households.

Integrating additional battery storage could allow low-cost solar energy generated during the day to be stored for use in the evening, extending the benefits of solar power beyond daylight hours. However, the economic viability of implementing such solutions, particularly in disadvantaged communities, requires careful assessment. The significant upfront costs and longer payback periods associated with battery systems could reduce the overall attractiveness of a P2P energy trading market. It is crucial to balance the benefits of increased energy efficiency and reduced grid dependency against the potential financial burden of battery installation, taking into account the perspectives of both residents and the managing cooperative.

5.8.2 ICT and data

The ICT and data layer was not specifically addressed as part of this study. However, as described in Section 3.2, the scalability analysis framework intends to use real data from the pilot projects to ground the study results in real conditions; however, as mentioned above, the available PV production data was of low quality due to missing data, which reduced its usefulness for this study.

The CommUNITY pilot project faced significant hurdles related to the quality and availability of PV generation and consumer load data, which are crucial for the operation and assessment of the P2P energy trading market. These issues highlighted the need for reliable data flow, as the effectiveness of wider market operations depends heavily on high-quality, timely data. This emphasises the importance of sophisticated data management systems capable of supporting

dynamic P2P transactions and ensuring accurate billing and settlement.

5.8.3 Markets and transactions

This scalability analysis focused on evaluating the impact of increasing the number of participants on the performance of the P2P energy trading market. One of the key insights from the simulation is the inverse relationship between market size and individual benefits. As the number of participants increases, the allocation of solar energy per participant decreases, reducing the individual benefit while increasing the collective benefit. This situation presents a significant challenge in balancing the interests of individual participants, the wider community and the managing cooperative. It is essential to determine the ideal market size, which requires careful consideration of these multiple interests to ensure an equitable distribution of benefits and financial sustainability for the cooperative. While the impacts of this have been demonstrated in the study, further research is required to understand the socio-economic consequences of such market behaviour under real-life conditions.

The study also sheds light on potential engagement challenges within the P2P energy trading market, especially in economically disadvantaged communities. Factors such as the complexity of the trading platform, data reliability, and general participant willingness to engage can influence user engagement levels. The research assumes that all households receive an equal share of the PV system's capacity and have equal rights to the generated electricity within the community pool, with adjustments made based on individual consumption levels. Although this promotes fairness, it does not account for the varying energy needs associated with different household sizes, suggesting that future research should consider more nuanced energy allocation methods that reflect household demographics. Additionally, the study notes that market transactions were settled ex-post, limiting participants' ability to adjust their energy usage in response to price changes. This method was deemed appropriate due to the limited availability of flexible energy assets, aligning with the constrained capability of households to adjust their energy consumption dynamically.

5.8.4 Social and economic values

This study examines the social and economic impact of market size, a fundamental aspect of the scalability analysis. Market size plays a significant role in shaping the economic dynamics of the P2P energy trading market. Participating households can reduce their electricity bills by using locally generated solar energy and engaging in energy trading within the community. However,

the potential financial benefits are influenced by various factors, including the pricing strategy of the cooperative, market size, and the energy consumption profiles of participants.

Those with lower energy needs typically receive greater financial benefits by selling their excess solar energy at higher prices within the community pool. Conversely, those with higher energy needs benefit from buying energy at lower prices. However, increasing the size of the market has the effect of reducing the benefits to participants. This is because the market share of solar energy available to each participant is reduced, which in turn reduces the individual gains that can be made. It is therefore important to ensure that the market is scaled in a sensible way, in order to guarantee a fair distribution of benefits across all levels of consumption. The equality index shows that the distribution of benefits becomes more equal as the market expands.

The size of the market also has an impact on the economic viability of the P2P energy trading market from the perspective of the cooperative. From an economic standpoint, the cooperative must maintain competitive solar energy rates in order to attract participants, while also covering operating costs and recouping investments. The study identified a strong dependency between the cooperative's viable operation of the P2P energy trading market and its pricing policy. In particular, the fees charged for community solar consumption and the revenue generated from excess energy sold to the grid enable the cooperative to sustain its operations and support the community's energy needs without external subsidies. The study demonstrated that a P2P market could operate at a commercial scale without relying on external funding or subsidies. While operational and maintenance costs were considered in the simulated environment, other cost structures, such as interest rates required for potential upfront investments, metering and private wiring system costs, could result in higher overall project costs if implemented in the real world.

Finding the right balance between the interests of individual participants and the community as a whole is essential. The size of the market needs to be such that the benefits it offers are meaningful - neither too marginal to matter to individuals, nor so significant as to overshadow the collective good. In addition, the effort and cost of joining the market, although not addressed in this study, are important considerations that affect the overall attractiveness and accessibility of the market. As the market grows, existing participants may resist further expansion due to the dilution of their benefits. A strong governance model is therefore needed to balance and protect the interests of both energy users and cooperatives, and to ensure the fair and sustainable operation of the market.

5.8.5 Policy and regulation

One of the key challenges identified in the study is the temporary nature of the market operation under sandbox conditions, which limits its sustainability beyond the project phase. This highlights the urgent need for policy and regulatory reforms to facilitate the continuation and scalability of P2P energy trading systems. Such reforms should include adapting policies to enable P2P energy trading more broadly, allowing entities such as cooperatives to act as electricity suppliers. This approach is inspired by the ‘Tenant Electricity’ model in Germany, which supports the direct consumption of locally produced energy and promotes community-based energy solutions (BMWK, 2017). A particularly relevant innovation within this model is the use of a virtual summation meter, which enables the legal and administrative separation of internal and external energy flows without requiring a physical private wire system. This virtual boundary is permitted when all participating tenants and the generation unit are equipped with intelligent metering systems. This regulatory flexibility allows local energy sharing to take place even when rewiring is not technically feasible or economically viable (Bayernwerk Netz, n.d.). Adopting a similar approach in the UK could enable the recognition of virtual P2P markets, like the one trialled in the CommUNITY project, thereby reducing implementation barriers and supporting broader deployment of tenant-focused energy trading schemes.

To ensure the long-term success and scalability of P2P energy trading models, it’s vital to have a stable regulatory framework. The experience of the phase-out of FiTs has shown how policy changes can undermine business models that rely on government subsidies, highlighting the need for reliable and consistent policy support in the energy sector (Braunholtz-Speight et al., 2020). Short-term policies, while potentially stimulating initial adoption and innovation, often create uncertainty and risk that discourage sustainable business practices and long-term investment in renewable energy technologies.

In a submission to the Secretary of State, the NGO Power for People have called for the creation of a supportive framework for community energy schemes. This would entail requiring regulations to ensure that small energy producers receive a stable tariff for their electricity, based on current market rates. It also proposes a local energy supply mechanism to enable community renewable energy schemes to sell directly to local energy users (Power for People, 2024).

The South West Energy Hub, funded by the Department for Energy Security and Net Zero, is supporting the potential installation of solar panels on social housing as part of government-funded

initiatives (South West Energy Hub, 2021). However, they've encountered significant hurdles, particularly with the SEG, that affect the financial and administrative feasibility of these projects. While solar PV could offer significant economic and environmental benefits, in line with the UK's net-zero ambition, barriers such as complicated metering processes and inadequate SEG rates are preventing widespread uptake in social housing in the UK. To address these issues, proposals such as the Social Housing Generation Guarantee, the establishment of Energy Service Companies by Residential Social Landlords and the introduction of tenant service charges have been put forward. Each of these solutions presents its own set of challenges in terms of recouping investment, managing operations and ensuring tenant participation. Specific policy reforms are therefore essential to facilitate the uptake of renewable energy in social housing, thereby increasing energy independence, reducing costs for tenants and contributing to wider environmental objectives.

5.9 Summary and conclusion

The CommUNITY pilot project, launched at Elmore House in Brixton, had the objective of empowering socially disadvantaged groups by involving them in the low-carbon energy transition. The project aimed to test the implementation of a P2P energy trading market by using the existing 37kWp PV installation on the roof of the building, which had previously supplied mainly communal areas. This market was designed to enable direct energy transactions between residents, moving from a model that relies on selling electricity back to the grid to one that promotes local energy consumption and supports community development through reduced electricity costs and increased engagement with renewable energy technologies.

This chapter addresses several critical issues related to scalability and practical implementation challenges applying the scalability analysis framework proposed in Chapter 3.2 to a case study based on the CommUNITY pilot. One significant challenge was the limited participation due to the requirement that participants must be customers of a specific utility company, which resulted in lower than optimal participation rates. This chapter considers the implications of such barriers and explores scenarios to assess and improve the scalability and economic viability of the market. The objective of this study was to simulate increased participation in order to answer two research questions: *'What are the main barriers to scaling up P2P energy trading system and how do they affect the performance of these system?'*, and *'How applicable are scalability barriers identified in the broader context of P2P energy trading systems?'*. To answer these research questions, two scalability scenarios were developed and analysed.

The initial scenario examined the influence of participant numbers on the performance of the P2P market. This scenario examined the impact of increasing the number of participants in the P2P energy market on the distribution of financial benefits among different groups of residents. The objective was to determine whether a larger participant base would result in a more equitable distribution of financial benefits from energy trading, thereby affecting the scalability of the model's performance and social welfare impact. The analysis revealed that as the market size expands, while the total energy demand from the grid increases, the proportion of energy that is self-consumed or sourced from the community pool reaches a saturation point due to the limited capacity of the installed PV system. In terms of PV system output, smaller market sizes result in a higher proportion of energy being sold back to the grid due to insufficient local demand. However, as market size increases, a greater proportion of the electricity generated by the PV system is consumed within the community, thereby maximising the use of locally produced energy and reducing reliance on the grid. The findings indicate that while an expansion in market size within the P2P model can enhance overall energy efficiency, it also diminishes the individual benefits derived, reflecting a trade-off between collective gain and individual returns. As the market participation rate rises, each participant's share of the PV system becomes smaller, reducing their direct benefits from self-generated solar energy. The results underscore the importance of pricing strategies in determining participant benefits. Higher pool prices typically result in a reduction in individual savings, as participants are required to pay a higher price for the energy they consume from the community pool. The savings experienced by participants with different annual energy needs were influenced by both market size and pricing structure. For example, households with lower energy consumption benefited more from higher pool prices, because they could sell excess energy at higher rates. In contrast, high-consumption households benefited less under the same conditions. In smaller markets, benefits are distributed more evenly among participants due to a relatively larger share of PV systems per participant, resulting in a higher equality index. However, as market size increases and the individual share decreases, equality initially decreases, indicating a less equitable distribution. This then begins to increase again as benefits are distributed more evenly across a larger pool of participants.

The second scenario was designed to assess the economic sustainability of the CommUNITY business model under market-driven conditions. This scenario explored possible revenue models and cost structures that could support the long-term viability of the project without relying on external funding. By analysing the financial performance of the established P2P energy trading

market, this scenario aimed to determine whether such a model could provide ongoing benefits to participants, with a particular focus on the potential for a self-sustaining system that could be replicated in other communities. The profitability of the cooperative, represented by the NPV, was analysed for different cooperative prices and PPA rates. The findings showed that the financial viability of the market for the cooperative hinges significantly on these price settings. Generally, the NPV is positive (indicating profitability) when the cooperative price is set higher than the PPA rate, suggesting that the market can sustainably support the cooperative's operational costs and investment returns under these conditions. The analysis also delved into how changes in the number of market participants affect the cooperative's profitability. Interestingly, the relationship between market size and profitability varied depending on the relative values of the PPA rate and the price the cooperative would charge participants for the electricity consumed. When the cooperative price is greater than the PPA rate, larger market sizes tend to increase the NPV of the cooperative, improving profitability. If the cooperative price is lower than the PPA rate increasing the market size tends to decrease NPV of the cooperative, indicating that a smaller market might be more financially sustainable in such pricing scenarios. The study suggests that for a viable business model, and if such a market were to be replicated in other locations, the cooperative would need to carefully balance P2P energy market pricing rates and the size of P2P energy trading markets. Although higher cooperative tariffs may allow for larger market sizes and ensure that the cooperative can recoup upfront investment costs, overall P2P market prices must remain competitive with standard electricity prices in order to attract and retain participants.

The analysis also highlights that external economic factors, such as national and international electricity price trends, could significantly impact the cooperative's pricing strategies and the overall financial performance of the P2P energy trading market. Rising electricity prices may allow for higher PPA rates, whereas falling prices might require the cooperative to adjust its cooperative price upwards to maintain profitability.

The economic analysis of Scenario I underscores the complex interplay between market size, pricing mechanisms, and participant characteristics in determining the financial viability and equity of P2P energy trading markets. It highlights the necessity of carefully considering both community-wide benefits and individual participant impacts when designing energy markets to ensure that they are both economically viable and fair. The findings suggest that achieving a balanced approach that maximises both individual and community gains may require dynamic pricing strategies

and market structures tailored to the specific characteristics of the participant base. This detailed understanding of economic outcomes is crucial for policymakers and project planners aiming to scale up community energy projects sustainably and equitably.

The economic analysis of Scenario II highlights the balance required in setting market prices to ensure the cooperative's profitability while promoting a sustainable and expanding P2P energy trading market. It also highlights the need to consider external economic conditions and their potential impact on market dynamics. The findings from this scenario provide critical insights for the cooperative on how to strategically manage market size and pricing to achieve financial viability and effectively support community energy goals.

While the simulation scenarios provided valuable insights into the economic and social dynamics of P2P market scaling, they do not fully capture the real-world constraints that limited participation in the actual pilot. Notably, the UK's competitive energy market framework posed a major barrier: participation in the pilot required customers to switch to a single supplier, which deterred many potential residents and ultimately limited active participation to only four households. Furthermore, the absence of a shared metering or private wire setup meant that the energy flows had to be modelled virtually rather than implemented physically. These constraints not only reduced the effectiveness of the pilot in practice but also highlight critical barriers to wider replication. Future implementation efforts must account for the interoperability of P2P models with existing supplier frameworks and assess whether physical or virtual private wire systems are viable within the regulatory context.

The evaluation of the CommUNITY project's integration of a P2P energy trading system within a disadvantaged community revealed several insights and challenges. Key issues included the need for metering infrastructure reconfiguration to optimise local energy use, the importance of reliable data and user-friendly interfaces for efficient market operation, and the complex dynamics of balancing individual and community benefits in the market. Additionally, the project highlighted the critical role of supportive regulatory environments to ensure the sustainability and scalability of innovative energy models like P2P trading. Addressing these challenges is essential for democratizing access to renewable energy and achieving equitable economic benefits in similar projects.

Chapter 6

Global Discussion

This chapter discusses the findings of the individual chapters in the broader context of this thesis. The aim is to draw meaningful conclusions that can drive further research and understanding in this area. In the following the case studies on the Medellín P2P Energy Trading Pilot and the CommUNITY project are referred to as the Colombian and UK case studies respectively.

The chapter begins by examining the limitations identified of the research to set the stage for a nuanced discussion of the findings. This is followed by a discussion of the research questions defined in Section 2.7. The first research question, *‘How can the scalability of P2P energy trading systems be assessed, taking into account obstacles encountered in pilot projects?’* is discussed with a particular focus on the scalability analysis framework developed in this thesis. The second research question, *‘What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?’*, is explored, drawing on the findings of the Colombian and UK case study Chapters 4 and 5. The focus of this chapter lies on the third research question, namely *‘How applicable are scalability barriers identified in the broader context of P2P energy trading systems?’* and discusses the implications of the findings within the research on P2P energy trading systems beyond contextual constraints. The chapter concludes with a discussion of potential policy and regulatory reforms that could support the expansion of P2P energy trading.

6.1 Limitations

Before discussing the results in detail, it is important to acknowledge the limitations that affect the interpretation of the results. Various limitations arise that are inherent to the use of modelling approaches to explore the behaviour of energy systems and include the use of simulated environments and deterministic analysis, as well as data limitations. In addition, the approximations

and simplifications in the economic and financial models, as well as in the regulatory and policy frameworks, may not accurately reflect real-world conditions. Contextual limitations also pose challenges in generalising findings across settings due to the specific regulatory, economic and social contexts of the case studies.

6.1.1 Simulated environments and deterministic analysis

While modelling and simulation are widely recognised as necessary for the design of P2P energy trading systems and are therefore widely used methods in P2P energy trading research, they have several limitations, as detailed in Chapter 3. Like all models they fall short in capturing the complex interdependencies that exist in real-world conditions. This duality - both an advantage and a disadvantage - highlights the strengths and weaknesses of this approach. While simulated environments incorporate contextual data from real-world pilots, they cannot replicate the exact conditions of the real world (Bose et al., 2021). As a result, careful trade-offs were necessary to balance the complexity of the analysis with the relevance of the findings. The simulation replicates only a subset of the total system to provide insights into system performance, recognising that a more comprehensive model would be overly complex and less practical. This inherent limitation must be considered when interpreting the results of this thesis.

To model different scalability scenarios, this research uses deterministic analysis, which, while based on a static model structure, dynamically simulates market behaviour across time steps. This method allows for controlled adjustments of variables within the constraints of the simulation environment. However, at the same time it lacks the ability to capture the unpredictability of real-world energy systems. The deterministic framework assumes static conditions and overlooks the variability and uncertainty that characterise actual market behaviour. This limitation can lead to discrepancies between simulated outcomes and what might occur in a more dynamically responsive system. However, in the context of this work, deterministic analysis provides an exploratory approach that allows for the development and analysis of defined scenarios.

To address some limitations of deterministic modelling, local sensitivity analysis is used to assess how changes in specific input parameters affect the calculated results. By systematically exploring different scenarios and their sensitivities, local sensitivity analysis improves the understanding of how different variables interact. It explores the implications of the model's static assumptions and helps to better understand the impact of real-world variability within the constraints of deterministic analysis.

6.1.2 Impact of simplified market behaviour on economic and technical performance indicators

A significant limitation affecting the results of the economic and technical performance indicators is the simplified modelling of P2P energy trading market behaviour. The model assumes that participants do not respond to energy prices, effectively treating the electricity load as inflexible. While dispatchable DER assets such as batteries were not integrated in any of the case studies evaluated, the model does not take into account potential changes in electricity consumption behaviour in response to price signals through demand shifting, which could alter load patterns and consequently the performance of P2P energy trading markets.

This simplification may overlook the complex interactions between pricing mechanisms and consumer choices that are critical to the effectiveness and efficiency of P2P energy trading systems. By failing to consider how consumers might adjust their energy use in response to price fluctuations, the model risks underestimating or misrepresenting market dynamics. Incorporating models that reflect consumer behaviour - such as price sensitivity and adaptive consumption practices - could lead to a more accurate representation of market behaviour and provide deeper insights into the scalability and sustainability of P2P energy trading systems. However, testing passive participant behaviour provides a useful base case against which more complex dynamic user behaviour could be compared.

In addition to the simplified assumptions regarding demand flexibility, the UK case study highlighted another behavioural constraint that could affect the effectiveness of P2P trading models. Some households were unwilling to switch electricity suppliers in order to participate in the scheme. This reluctance to change providers, even when potential economic benefits were available, points to a broader challenge in encouraging participation and scaling up such initiatives. It suggests that market designs which require participants to adopt a new supplier may encounter resistance, especially in low-income or risk-averse communities. Future models should therefore consider not only technical and economic factors but also social and behavioural barriers that may influence the uptake and long-term viability of P2P energy trading systems.

6.1.3 Dependence on input data accuracy and availability

The simulation-based approach used in this study is dependent on the accuracy and availability of input data. Although some original data was provided by the project coordinators, the study encountered limitations in terms of data completeness and reliability, particularly in areas such

as participant engagement and energy use patterns. The need to base simulations on available datasets, coupled with assumptions about market operations and participant behaviour, introduces an additional layer of abstraction from the real-world scenarios being modelled. While these methodological choices are pragmatic, they may not fully capture the complexities of P2P energy trading, potentially biasing the results towards scenarios where data was more readily available or assumptions had to be made.

While the scalability analysis framework aims to incorporate real data to inform simulated case studies and explore the potential scalability of P2P energy trading systems, the lack of necessary data in some cases led to the use of synthetic data, which inherently limits the accuracy and contextual relevance of the results. To deal with missing data points, data imputation techniques were used to estimate unavailable values, although this approach also introduces potential inaccuracies. This challenge of limited data availability and reliance on synthetic data is a common issue faced by researchers in the field of energy systems (Heuninckx et al., 2023).

6.1.4 Social dynamics and stakeholder engagement

The inherent dynamics of P2P energy trading systems, driven by technological advances, variations in stakeholder engagement and social dynamics, add significant complexity to scalability analysis. While this thesis considers stakeholder roles and perspectives, its primary focus on scalability excludes the exploration of individual and community motivations, trust levels, and engagement strategies.

Social dynamics are critical to the success of user-centric business models such as P2P energy trading systems. The successful implementation and long-term robustness of these systems depends on the effective understanding and integration of human factors into the models (Ruggiero et al., 2018). Future research should delve deeper into these aspects, exploring the nuances of stakeholder interactions and their impact on system effectiveness. Recognising and addressing these limitations in future studies will improve the scalability and practical applicability of the findings for P2P energy trading systems.

In addition, the methodological framework used in this study does not take into account the evolving political and economic landscapes that influence energy markets. The rapidly changing energy environment, exemplified by recent crises and policy changes, poses a challenge to maintaining the relevance of the study's findings over time. For example, the recent energy crisis and resulting regulatory interventions are difficult to predict. Assumptions based on current conditions may

not hold in the future, limiting the long-term applicability of the analysis.

6.1.5 Financial sustainability and investment considerations

Finally, the financial sustainability of P2P energy trading markets under market-driven conditions remains an open question, particularly for projects initially supported by public grants and research funding. The methodological approach of simulating market operations without fully considering economic viability or exploring alternative financing mechanisms may overlook critical aspects necessary for the long-term success of P2P energy trading initiatives.

Whether and how investment costs were considered in the case studies depended on the derived objectives of the pilot projects: While the Colombian case study focused on operational costs and savings for participants, the UK case study also considered investment costs and the operational business model of the cooperative, as this was part of the scaling objective.

In summary, P2P electricity markets are an interplay of technical, economic, regulatory, legal, social and environmental issues that define the complexity of these systems. In this thesis, the scalability of these systems has been considered in isolation in relation to individual key objectives of the pilot projects, so the results do not reflect a complete roadmap for how these systems can be scaled in the future. However, the results of the two case studies can provide insight into individual parameters that are necessary for the successful scaling of P2P energy trading systems. The next section summarises the key findings and discusses them in the context of the defined research questions.

6.2 Assessing scalability challenges of P2P energy trading systems

This section explores key themes that emerged from the two case studies analysed in this thesis, highlighting critical factors that shape the scalability of P2P energy trading systems. While the Colombian and UK case studies are grounded in different social, regulatory and technical contexts, their combined findings provide valuable insights into the broader challenges and opportunities associated with scaling such systems. The themes discussed in the following subsections are not necessarily common to both case studies, but reflect recurring patterns and issues that are central to the debate on P2P energy trading. These include the need to assess scalability beyond the temporary structures of regulatory sandboxes, the trade-offs between individual and collective benefits within energy communities, and the importance of measuring how benefits are distributed

among participants. Other themes include the role of local context in shaping market and tariff design, the physical and topological constraints that influence system architecture and participant reach, and the impact of regulatory and tariff frameworks on the long-term viability of business models.

By addressing these interconnected aspects, this section examines key structural, behavioural, and institutional factors that are relevant to the design and evaluation of scalable P2P energy trading systems.

6.2.1 The need for scalability assessment beyond regulatory sandboxes

The literature review has shown that most studies on the scalability of P2P energy trading markets have primarily focused on the settlement of decentralised transactions. The emphasis has been on managing the decentralised nature of these markets and accounting for different product categories and trading preferences among various types of participants in competitive market settings. Examples of this can be found in studies such as Morstyn et al. (2019b), Khorasany et al. (2019), and Han et al. (2019).

While this line of research addresses a core component of P2P energy trading market functionality, it tends to conceptualise scalability mainly in terms of transaction complexity, not in terms of scaling up market size for example accommodating a growing number of participants as outlined in Chapter 2.6. In this thesis scalability refers to the ability of market mechanisms to handle increasing numbers of participants without compromising performance or efficiency. Only few studies have looked into scaling up P2P energy trading markets, specifically focusing on extending the number of participants or assets that form a market (Perger et al., 2022; Luo et al., 2019; Wu et al., 2019).

A common method used to test the practical implications of scaling up P2P energy trading markets was by conducting small-scale pilot projects, where possible within regulatory sandboxes. However, both pilot projects and regulatory sandboxes are seen as temporary solutions to enable P2P energy trading experiment testing and are limited in testing actual scaling up of P2P energy trading markets. While regulatory sandboxes offer a controlled environment to test the practical applicability of new market models, they are primarily designed to trial innovative business concepts with a strong focus on risk containment including risks that may arise from changes in market participation.

The analysis of the literature review and the specific scalability challenges encountered in pilot

projects discussed in Chapter 2 have shown that there is a general lack of advanced planning for scaling up P2P energy trading systems. This is attributed to the fact that pilot projects are often limited in scope and duration, making it difficult to test their adaptation to changing market and environmental conditions. In addition, due to the highly localised nature of P2P energy trading markets, scalability challenges are often dependent on the specific environmental and contextual factors in which they are implemented, limiting the ability to transfer lessons learned from one project to the other.

The strong contextuality of P2P energy trading case studies is not a unique finding to this thesis. Research conducted by Wilkins et al. (2020) studied participants' motivation in participating in a P2P energy trading market. Specifically, the authors highlighted that findings are limited to the particular context of the study. Additionally, their research showed, that local context in P2P energy trading markets is a key success factor, with local activists needed to support the recruitment of participants to the market. Hahnel et al. (2022) studied pricing decisions of participants in a P2P energy trading market in Germany and the UK. The authors found that while decisions were influenced by the same factors, such as political orientation, place attachment, and climate change beliefs, the results showed that nation-level differences emerged when preferences were publicly visible, highlighting the context-specific nature of pricing structures and trading preferences across regions. Similar limitations to generalisability of findings with regard to participation in P2P energy trading markets were also found by Georgarakis et al. (2021) and Cárdenas-Álvarez et al. (2022). Other factors that might impact generalisability of results include the share of DER installations (Pena-Bello et al., 2022).

Pilot projects can provide valuable groundwork by generating evidence to inform policy development. However, they often fall short when it comes to exploring the dynamics of scaling up P2P energy trading markets. To address this gap, this thesis proposed a methodological approach, the Scalability Analysis Framework introduced in Chapter 3.2, which builds on the findings of the pilot project by transferring them into a simulation environment. This enables the systematic testing of key parameters that would be difficult or otherwise not possible to assess under real-world conditions. The framework builds on the Scalability and Replicability Analysis (SRA), originally applied in the context of EU smart grid projects, and was further adapted to reflect the specific characteristics and requirements of P2P energy trading systems. This allows scalability scenarios to be derived in close alignment with the objectives and contextual settings of the pilot

projects assessed. The proposed framework serves as a tool to complement empirical findings from pilot projects, supporting more informed policymaking and long-term planning by addressing the technical, economic, social, and regulatory dimensions of scalability. This strong contextual focus of the scalability analysis, in both the design of the analysis itself and the selection of scalability scenarios allows for a more detailed examination of certain aspects of the pilot projects, providing insights into future scaling up potential. At the same time, the direct and indirect input parameters can be adapted to the characteristics of the pilot project, such as the definition of the performance indicators and the duration of the simulation.

In this thesis, the scalability analysis was performed ex-post on the completed pilot project. However, the inclusion of scalability analysis in the planning phase of P2P energy trading pilots can contribute to a more robust scalability strategy in addition to empirical data collection as highlighted by Ruggiero et al. (2018). Recent public funding programmes such as European Horizon Calls (Horizon Europe, 2023) have shown that the inclusion of scaling-up strategies is becoming a critical component for successful participation and securing funding. Given the fact that pilot projects have not yet been rolled out, and the regulatory environment is still imprecise, it is all the more important to demonstrate that LEM and P2P energy trading systems can also respond to changing market conditions in the long term. Applying the scalability analysis framework alongside a pilot project would allow P2P energy trading systems to be simulated and tested under varying conditions with reduced risk and cost. This could contribute to the refining of scaling up strategies and mitigate potential risks without the need for extensive physical testing (Adams et al., 2021).

This research extends the current understanding of scalability in P2P energy trading by moving beyond the computational focus found in much of the literature (Morstyn et al., 2019b; Khorasany et al., 2019). While previous work has primarily focused on algorithmic efficiency and settlement mechanisms, this thesis highlights the broader institutional and contextual challenges affecting the ability to scale pilot projects. By introducing the Scalability Analysis Framework, this thesis complements the existing technical literature with a more holistic perspective on scalability taking into account regulatory uncertainty, local market conditions, and policy needs. In doing so, it responds directly to the gap identified by Capper et al. (2022b), namely that academic discourse has largely bypassed concerns about scaling up LEMs. This positions the framework not as a replacement for empirical testing, but as an addition to the planning and evaluation of scalable

P2P energy trading systems.

6.2.2 Understanding the distribution of benefits in P2P energy trading markets

This subsection explores into how benefits are distributed among participants in P2P energy trading systems. It examines the inherent trade-offs between individual gains and collective welfare, highlighting how market design, participant characteristics, and governance structures influence these dynamics.

6.2.2.1 Trade-off between individual and collective benefits

One of the central themes that emerges from the analysis of the Colombian and UK case studies is the distribution of benefits among participants and stakeholders in P2P energy trading systems. A key insight is the recurring trade-off between individual and collective benefits, where market design choices influence whether welfare is maximised for individual participants or the wider community.

Most P2P energy trading models are designed to optimise social welfare, but differ in how they define and distribute this welfare. The literature has explored different optimisation approaches, with some models prioritising individual financial gains, while others focus on the collective welfare of participants. Zhou et al. (2020) emphasise the need to assess both individual and societal impacts of P2P energy systems and call for a more nuanced assessment of distributional outcomes. Guerrero et al. (2017) and Morstyn et al. (2019b) introduce mathematical frameworks in which the objective functions vary between maximising individual utility or total system welfare. However, much of this work remains theoretical, often disconnected from real-world implementation, and limited in its exploration of how these trade-offs play out in practice.

The Colombian and UK case studies presented in this research provide insights into how these trade-offs manifest themselves beyond the modelled objective functions. While both cases modelled objective functions that prioritised collective welfare, the actual distribution of benefits differed depending on local market conditions, participant characteristics and governance structures. In addition, both cases revealed distributional differences between participant groups, such as households with different consumption levels or socio-economic profiles, highlighting the need for fairness considerations in the design of scalable P2P energy trading systems. This suggests that the trade-off between individual and collective benefits is not only a function of the design of settlement mechanisms, but is also shaped by case-specific factors such as network topology, participant

heterogeneity and market governance.

The distributional dynamics observed in both case studies highlight how participant characteristics and market design shape the distribution of benefits in P2P energy trading systems. In the UK case study, differences in outcomes emerged based on both household energy consumption levels and the underlying tariff structure. Households with higher consumption levels tended to experience declining savings as the P2P market price increased, while low-consumption households benefited more under higher price scenarios. These different responses to price dynamics highlight how market price, consumption level and market size interact to produce an uneven distribution of benefits. In addition, the financial viability of the cooperative operating the market itself depended on these dynamics, particularly the price at which it could sell electricity to participants or export surplus to the grid.

In the Colombian case study, distributional differences were shaped by the type and proportion of participants. The analysis showed that prosumers benefited more when the market had a higher share of consumers, and vice versa, indicating a structural interdependence between user groups. Furthermore, the income level of prosumers also played a role, with significant differences in savings between high- and low-income participants, despite the market's initial intention to promote equitable redistribution.

An additional factor influencing the distribution of benefits is the physical configuration of the system. In the UK pilot, the topological design, specifically the shared use of a community PV system, meant that increasing the number of participants diluted the energy share available to each household, thereby reducing individual benefits. This effect, while manageable in simulations, is more challenging in real-world settings where households can dynamically enter and exit the market, introducing variability beyond purely financial considerations. These include issues of governance, trust and system stability that need to be addressed to maintain the balance between individual and collective outcomes.

The results illustrate that the design of P2P energy trading markets can disproportionately benefit certain groups of participants, depending on their characteristics and role within the market. While this outcome is not uncommon in market-based systems, where those who contribute more or behave strategically are often rewarded accordingly, the results also highlight that such benefits are not solely based on merit. They are influenced by a range of contextual and structural

factors, including market size, price dynamics and the composition of participants. This underlines the importance of integrating fairness considerations into market design, in particular to avoid disadvantaging socially or economically vulnerable households.

To address these distributional imbalances and enable long-term scalability, a robust governance structure is essential. This includes clearly defined roles, transparent rules and mechanisms to monitor and manage participation. In the Colombian case study, the market design allowed for dynamic scaling because it did not impose fixed limits on the number of participants. However, the results showed that individual benefits were highly sensitive to the composition of the participant base. To maintain equitable outcomes, the market operator would have to actively manage the mix of consumers and prosumers participating in the scheme. This illustrates a broader trade-off in P2P energy trading systems, namely achieving collective welfare often requires balancing the interests of individuals, user groups and the community as a whole.

In practice, collective energy management does not always align with individual optimisation goals. While P2P energy trading systems are often framed around community-level benefits, such as shared savings, increased self-sufficiency and reinvestment in local infrastructure, individual participants may prioritise financial returns and energy autonomy, seeking to maximise the value of their own DER within shorter investment cycles (Ecker et al., 2018; Hahnel et al., 2022). This divergence is reflected in the optimisation logic embedded in many P2P market models, applying objective functions aimed at maximising welfare across the entire community as detailed in Chapter 2.2.1. While such an approach is conceptually aligned with community-centred energy principles, it raises practical concerns regarding participant engagement and long-term commitment, especially when benefits are perceived as unequally distributed. As noted by Ecker et al. (2018), strong autarky aspirations among homeowners can reduce the willingness to trade energy within a community, especially if trading compromises personal energy independence. Further, Hahnel et al. (2022) assessed trading preferences within P2P energy trading markets in a representative sample of German homeowners and identified distinct user groups with divergent motivations. The two largest groups were price-sensitive prosumers, who responded strongly to financial incentives, and autarky-focused prosumers, who prioritised energy independence over potential trading gains.

This dynamic between individual and collective optimisation has only been explored sporadically in the literature. For example, Fina et al. (2022) tested the economics of a P2P energy trading market

considering participants with different levels of technology penetration. The authors demonstrated that customers equipped with higher levels of technology (e.g. PV, battery, heatpump, etc.) achieved better savings compared to those with lower levels of penetration. They also highlighted that the optimisation was carried out for the community as a whole, rather than for individual households. However, they noted that individual savings could have been higher if optimisation had been carried out at the individual level. Mehta et al. (2022) analysed the community sizes that would lead to profitable operation of DER assets in an energy community. The authors showed that the ratio of customer types involved, and in particular their installed PV capacity, has a significant impact on individual profitability when participating in a local energy market.

The case studies in this thesis further illustrate how contextual factors influence these optimisation outcomes. In the Colombian pilot, DER installations were either pre-existing or externally funded, which minimised financial risk for participants and arguably made it easier to accept a community-based optimisation framework. Similarly, in the UK pilot, a local cooperative funded and operated the infrastructure, creating a dependency between the cooperative, the participants and the market operator. These differences in funding structures shaped both the distribution of benefits and participants' expectations of returns, highlighting how the source of capital investment can influence the viability and perceived fairness of collective optimisation models. Abada et al. (2020) have shown that shared investment in DER can outperform individual investment in DER, however, this study was conducted within an energy community rather than a P2P energy trading market, not considering individual ownership and trading preferences.

There is a rich body of literature specifically addressing the difference between community and individually owned assets such as Hogan et al. (2022), Minuto et al. (2022), and Reis et al. (2021). Most analyses fall into the category of community energy markets rather than P2P energy trading markets where the focus on individual participants is more pronounced. Further research is needed to fill this gap. Factors such as asset ownership in a P2P energy trading market may also dictate the type of optimisation objective chosen.

In general, P2P energy trading pilots are still at an early stage and have mainly focused on demonstrating technical feasibility. As these projects move towards scaling up, addressing the trade-offs between individual and community benefits is crucial to ensure the long-term sustainability of P2P energy trading systems. These trade-offs can be both of economic and social nature (Adams et al., 2021). This requires a careful balancing of incentives and objectives to align the interests of

all stakeholders. Implementing compensation mechanisms that address inequalities in benefits ensures that no participant or group is disproportionately advantaged or disadvantaged.

6.2.2.2 Measuring distribution of benefits

P2P energy trading has been widely promoted as a means to incentivise the democratisation of access to renewable energy and to encourage greater participation and engagement in energy markets by actors who are otherwise not considered in the design of traditional energy systems. A key assumption behind these schemes is that they can deliver more equitable outcomes for participants compared to traditional market models. This research has examined the extent to which these benefits are fairly distributed among participants. This sub-section outlines how the distribution of benefits in P2P energy trading can be assessed and discusses findings from the case studies conducted in Colombia and the UK.

Distributive equity, a key dimension of energy justice, refers to the equitable distribution of costs and benefits resulting from energy transitions. In the context of P2P energy trading, this includes savings on energy bills, revenues from selling surplus energy, and improvements in self-consumption or self-sufficiency. However, due to the decentralised and user-centred nature of these markets, the way these benefits are distributed can vary significantly depending on individual household load profiles, generation capacity, market design and the pricing structure in place, as shown in Chapter 4 and 5.

In Colombia, the distribution of benefits was assessed on the basis of the predefined social groupings of participants, using the country's socio-economic stratification system. In the UK case study, the Equality Index (EI) was used to measure the distribution of benefits. This measure, derived from the Gini coefficient, was used as a quantitative indicator of distributive justice. The EI captures how evenly benefits are distributed across participants, with values close to "1" indicating high equality and values close to "0" indicating significant inequality.

In the UK case study, simulations showed that EI followed a U-shaped curve as market participation increased. At very low participation levels ($n=2-8$), each participant received a large share of the PV output, resulting in a rapidly decreasing EI. As the market expanded ($n=16-64$), equality increased due to a reduced PV share per participant, as the decreasing influence of PV allocation relative to total load led to more homogeneous relative benefits.

The EI used in Zhou et al. (2018) is used to quantify how fairly financial benefits are distributed

among participants in a P2P energy trading system. It measures income inequality across prosumers. The index is used alongside other economic indicators to compare different trading mechanisms, highlighting trade-offs between total system efficiency and distributional fairness helping to identify market designs that are not only profitable but also equitable and socially acceptable. In a paper by Regener et al. (2022), the EI is used to quantify the fairness of benefit distribution among participants in different P2P energy market designs. It is calculated based on each participant's gross profit increase from P2P trading compared to a baseline case (e.g., conventional grid interaction). The index is used to compare market setups and highlight how design choices impact equity, excluding factors like system size to focus purely on trading-related fairness.

A key novelty of this research lies in its explicit focus on the fairness of benefit distribution in P2P energy trading markets. Existing literature has primarily focused on maximising social welfare through optimisation models and ensuring privacy and data protection as mechanisms to safeguard consumer interests (e.g., (Morstyn et al., 2019b; Han et al., 2019)). However, the distribution of benefits among participants, and the potential inequities that arise, have received comparatively less attention. This is a critical gap, as strong inequalities in how financial gains or savings are allocated can undermine community cohesion, reduce trust among participants, and ultimately impede the acceptance and scaling of P2P energy sharing mechanisms. By applying quantitative fairness metrics, such as the EI derived from the Gini coefficient, this research advances the understanding of how market design choices impact equity, and lays the groundwork for integrating fairness as a core design principle in P2P energy trading systems.

Recent literature has increasingly focused on fairness in P2P energy trading, introducing innovative approaches to assess and enhance equity among participants. One such study by Wang et al. (2021) presents a novel fairness assessment method that links economic benefits to participant reputation. The study proposes fairness indicators for both buyers and sellers, measuring cost or income per unit of energy and reputation. These indicators are used to derive a fairness factor that quantifies how well benefits align with participant contributions. This approach ensures that more trustworthy participants are rewarded fairly, addressing a key gap in earlier studies that primarily emphasised efficiency or privacy without formally accounting for benefit distribution. Similarly, the paper by Lei et al. (2023) introduces a shareholding-based mechanism to assess fairness in P2P energy trading. This mechanism allows participants, especially those with lower incomes, to access and benefit from shared DERs proportionally to their investment. Energy equity is measured

using the Gini coefficient and the weighted Wilson coefficient, both of which quantify how evenly benefits are distributed among participants. The results demonstrate a significant improvement in fairness, with reduced inequality in benefit distribution, indicating that the mechanism promotes energy equity without sacrificing overall efficiency.

In summary, assessing the fairness of P2P energy trading markets is vital to understanding their scalability, social acceptability, and potential to contribute to a just energy transition. By moving beyond system-level efficiency and integrating fairness metrics into market design, this research provides a foundation for more inclusive and resilient P2P energy trading systems.

6.2.3 Impact of local context on market and tariff design

This subsection explores how local contextual factors, such as geographical topology, socio, economic conditions, and regulatory frameworks—affect the design and implementation of P2P energy trading markets. It compares the distinct environments of the Colombian and UK case studies to illustrate how local characteristics shape market structures, tariff designs, and the scalability of P2P energy systems.

6.2.3.1 Local topology and typology as constraints on market design

While the academic literature on P2P energy trading has made significant progress in exploring different market mechanisms and optimisation strategies, most research to date has been conducted in isolation from the physical and institutional realities of energy systems. Much of the existing work focuses on theoretical models, often disconnected from the constraints and complexities observed in actual pilot implementations. Even where case studies are used, market mechanisms are often simplified to fit existing regulatory frameworks or technical constraints, limiting the lessons that can be learned about scalability and long-term viability. In this section some implications of local topological and typological characteristics on the P2P energy trading systems are discussed.

The topological characteristics of the region, in particular the geographical location of the pilot projects, are closely linked to the typological characteristics of the market in both case studies. In Colombia, the focus of the pilot is strongly linked to the topography of Medellín, in particular the distribution of high- and low-income prosumers within the city. The pilot involves a ‘virtual’ P2P energy trading market where participants are all connected by a distribution network. Due to the physical properties of electricity, energy produced by low-income prosumers in one part of the city is not directly consumed by high-income consumers in another part of the city. This dynamic implies that the DNO has a central role in the P2P energy trading system, with the

potential responsibility to manage grid flows to avoid congestion. While this would make the DNO a direct operational participant in the market, such intervention is not currently necessary as the penetration of renewable energy in Medellín remains relatively low and the scale of installations does not yet have a significant impact on the distribution network.

In addition to the topological aspects, the market typology in Medellín is characterised by a high degree of diversity among participants in terms of social background, consumption patterns and generation capacity. This heterogeneity introduces a degree of complexity and uncertainty in predicting how the market will behave as participation increases. As the P2P energy trading system scales, these differences are likely to influence the distribution of benefits, the evolution of trading behaviour, and the technical and economic performance of the system. As a result, the market mechanism chosen to govern transactions may need to be adapted over time as the growing diversity of participants challenges initial assumptions about fairness, efficiency and operational stability.

In contrast, the UK pilot is located in a geographically constrained area where the boundary conditions for market scaling are defined by external factors, namely the number of flats in the building. While buildings in the multi-apartment sector may vary in size, layout and occupancy, they generally share a common structural typology, making it possible to adapt the market model to similar settings with minimal modification. Although the pilot coordinators also refer to a ‘virtual’ P2P energy trading market in the context of CommUNITY, the physical proximity of producers and consumers is inherent in the setup, but this proximity is not fully reflected in the settlement process due to a metering infrastructure that does not match the physical configuration.

While in principle the public electricity network could allow for a P2P energy trading market expansion beyond a single building, in the case of the UK pilot, the technical installation of the PV system constrained this possibility. Specifically, the PV system was configured to feed all generated electricity directly into the public grid, with the electrical meter placed accordingly. At the time of installation, future integration of the PV into a P2P energy trading setup was not anticipated, and thus the system was not wired to support behind-the-meter trading between flats. In a prospective scenario, the electrical configuration might be designed differently to allow direct sharing of PV generation among participants, potentially bypassing the involvement of the DNO as an intermediary in the market. However, if private wiring is not feasible, for example, due to building codes or technical constraints—regulatory adjustments would be required to allow PV

electricity to be treated as behind-the-meter assets even when technically connected through the public grid. The topological characteristics of the UK case study are similar to those of the German tenant electricity model (BMWK, 2017). However, the high degree of autonomy of the individual participants in the P2P energy trading market increases complexity and uncertainty.

In both cases, the main focus in the implementation of the pilots was on technical feasibility, i.e. installation of DER and connection via ICT. There was less emphasis on scalability and business model viability. Neither pilot project defined a clear scaling strategy and consequently no specific analysis was carried out on this aspect. Furthermore, due to their highly innovative nature and reliance on external funding sources, the research projects did not prioritise financial viability assessments. It is important to recognise the differences between the pilots in order to interpret the case study findings accurately. The following sections explore the common themes that emerged from the case study findings.

6.2.3.2 Role of local regulation and tariff design in market implementation

Much of the literature reviewed on P2P energy trading markets has proposed market and pricing mechanisms that are not bound to a particular geographic location or pricing restrictions, instead market and pricing mechanisms are proposed and tested that are not linked to pre-existing policies and pricing structures.

Research conducted in this thesis has shown that tariff policies fundamentally determine whether P2P trading provides financial benefits to participants. In the specific case of the Colombian pilot project regulated tariffs prevented flexible price formation, making P2P trading economically unviable for certain participants. Specific regulated subsidy structures removed financial incentives for some consumers, reducing the attractiveness of P2P participation. This research tested different tariff structures to compare their impact on financial benefits for participants. In the case of Colombia Without tariff reform, P2P markets cannot scale beyond pilot conditions.

In both studies examined in this thesis, tariff design was found to be a critical factor influencing the benefit of P2P energy trading systems to individual participants and the community. The tariff structure determines the financial incentives for participants, the revenue streams for market operators and the overall economic viability of the system.

Colombia's socio-economic stratification system, which classifies households according to their income levels and assigns energy tariffs accordingly, had a significant impact on market performance.

High-income participants were often charged higher tariffs, which influenced their performance in the market. In contrast, benefits of low-income households were more responsive to changes in tariff structures due to their reliance on government subsidies and rebates. Findings have shown that a more level playing field in the tariff structure design, with the stratification system phased out, can lead to more equal distribution of benefits in P2P energy trading markets and reduce the complexity of the market operation as a whole. While achieving a more level playing field can be a desired outcome it might not ultimately be the best result given the socio-economic characteristics of market participants.

In the UK case study, there was also a strong link between market performance and the tariff structure implemented. The results highlight the sensitivity of participant benefits to pricing strategies. Higher community pool prices tend to reduce individual savings, as participants have to pay more for energy purchased from the community pool. In addition, participants with different annual energy needs experienced different levels of savings, influenced by both market size and pricing structure. The profitability of the cooperative, as measured by net present value, was assessed under a range of cooperative prices and PPA rates. The results showed that the financial sustainability of the market for the cooperative was highly dependent on these pricing configurations. With PPA prices currently experiencing a slight increase in the UK (Solar Power Portal, 2024), the business case for the cooperative improves.

The stratification system is a key element of Colombian energy policy to redistribute wealth across different residents, however is already seen by many as outdated and presents a distorted picture of actual subsidy needs (López et al., 2020). Concrete proposals from the government on how the stratification system can be harmonised with new energy business models are not yet known.

Further, Colombia's net metering policy, which limits the benefits of PV installations to self-consumption, also constrain market growth by reducing the attractiveness of PV installations. High FiTs discourage the development of innovative business models, as they provide a greater incentive for households to sell excess energy back to the grid rather than participate in P2P energy trading. A report by Cárdenas Álvarez et al. (2023) suggests that tariffs should be structured to reflect the benefits these projects provide to the electricity system. Access to external financing can strengthen community commitment, and support schemes can mitigate financial risks. As seen in Europe, community initiatives benefit from incentives such as energy subsidies, access to credit, low or zero-interest loans linked to membership, and educational programs that include coaching

and training (Cárdenas Álvarez et al., 2023). To test new policies, proposals have been made to establish regulatory sandboxes in the Colombian energy sector (Ramírez-Tovar et al., 2023; España et al., 2020), similar to those implemented in the UK and the Netherlands. However, no specific actions have been taken yet.

The UK currently lacks clear guidance on how tariffs should be structured for a P2P energy trading market. While network charge reductions and other interventions could be considered, there is still no consistent policy framework for the implementation of such markets, such as the single-supplier rule Watson et al. (2020). In addition to tariffs, other regulatory interventions or subsidies play a crucial role in determining whether a P2P market can develop successfully. These factors are important in shaping the viability of business models within the sector. Policy stability is essential, despite the inherently dynamic nature of the energy market, which is constantly evolving with new innovations that require policy responses. There is a strong risk associated with regulatory changes that can affect revenues mechanisms such as feed-in-tariffs and tax exemptions and new pricing mechanisms (Leisen et al., 2019). A notable example of the impact of policy intervention is the removal of feed-in tariffs in the UK, which led to the cancellation of many community energy projects due to their reduced viability. This situation highlights the dual challenge of policy and business model design, and emphasises the need for models that can succeed without relying on subsidies. This research demonstrates how tariff structures and regulatory policies create systemic constraints on market scalability. Policymakers must align tariff frameworks with market incentives to ensure the feasibility of P2P trading beyond experimental pilots.

6.2.4 Policy implications

Results of this research have shown that depending on the P2P energy trading system design and the local context, different policy and regulatory frameworks are needed to support the scalability of these systems. The case studies in Colombia and the UK have highlighted the importance of regulatory support in the initial stages of pilot projects. Regulatory sandboxes can provide a safe space and quarantine risk for testing innovative business models and technologies, but they are often limited in scope and duration. Policymakers need to consider the long-term implications of these projects and provide a clear pathway for scaling up successful pilots. The lack of regulatory support can hinder the development of P2P energy trading systems, as seen in the Colombian case study, where the absence of a regulatory framework prevented the implementation of innovative tariff structures. In the UK, the lack of diversity among suppliers participating in the pilot and high barriers to entry hindered progress. Policymakers need to create an enabling environment

for P2P energy trading systems by providing clear guidelines and support mechanisms for project developers. This includes establishing regulatory sandboxes, providing financial incentives, and streamlining the permitting process.

Findings of the case studies also showed that a particular market design and market configuration can lead to greater inequality between participants, rather than promoting equality. In Colombia, the stratification system often hindered equitable access, while in the UK the focus was on balancing individual and community benefits. Policymakers need to prioritise equity and ensure that the benefits of P2P energy trading systems are distributed across the community to avoid exacerbating existing inequalities in energy access and technology. P2P energy trading can accelerate the adoption of renewable energy by providing innovative financing and distribution methods for green energy.

Findings from both case studies have also shown that a supportive electricity tariff environment can influence the distribution of benefits among participants. As highlighted by Hall et al. (2021), new energy business models are targeting different groups of consumers, differentiated by demographics, income, education, trust, and willingness to innovate. The new, more complex energy contracts associated with these business models go beyond the existing regulatory framework. Younger consumers are more likely to adopt these models, motivated by mistrust of energy companies, concerns about bills, or enthusiasm for new technologies (Hall et al., 2021). Environmental motives are less influential than saving money and gaining independence from large suppliers. Without regulatory intervention, the benefits of low-carbon innovation will accrue mainly to affluent, educated, and engaged consumers, exacerbating socio-economic inequalities. Recognising these challenges in regulation will be key to ensuring fair access and protection for all consumers.

Furthermore, the integration of DER through P2P energy trading has a significant impact on grid stability, especially in regions with low penetration of DER. It is crucial to provide appropriate incentives for intelligent flexibility. A study by Capper et al. (2022a) has shown that traditional imbalance charges, such as those currently used in the UK, do not adequately incentivise P2P market participants to minimise their energy imbalances. There is a need to introduce tailored balancing mechanisms that encourage P2P energy trading markets to adjust load in line with grid requirements.

Finally, the development of policies and regulations for P2P trading benefits from multi-stakeholder

engagement. Both case studies highlight the need of involving consumers, producers, grid operators, and technology providers in policy development to ensure a comprehensive framework that reflects all perspectives. The experiences of the Colombian and UK pilot highlight the importance of adapting international practices to local contexts in order to create more effective frameworks. Scaling up P2P energy trading systems requires careful consideration of the policy and regulatory implications. By addressing the unique challenges and opportunities of these systems, policymakers and regulators can lay the foundations for a more sustainable and equitable energy future.

Chapter 7

Conclusion and future work

LEMs and P2P energy trading systems offer promising solutions to incentivise the integration of more DER into the energy system by enabling energy exchange at community level, promoting energy equity and supporting the deployment of renewables. Despite the growing number of pilot projects, most P2P energy trading systems have yet to move to commercial implementation. The end of regulatory sandboxes or the end of a funding period are some of the reasons that limit the ability of project developers to test the viability and scalability of P2P energy trading systems. In most cases, regulatory support such as sandboxes is critical for the initial evaluation of the pilot, but these often lack the supporting structure and longevity to support and test the scaling of a project beyond the concept stage. In addition, the predetermined structure of pilots, including fixed participants and a strong attachment to a particular site, limits the ability of pilots to fully test scalability.

This thesis sought to address scalability challenges of P2P energy trading systems by overcoming the current limitations of pilots in operational environments through a simulation-based approach. Scalability in this research is understood as the ability of P2P energy trading systems to accommodate increasing numbers of participants and transactions without compromising efficiency or system integrity. This research aimed to make two key contributions: firstly, to provide an in-depth understanding of the challenges and implications of scaling up these systems across different dimensions, supported by simulated and real case study evidence; and secondly, to assess the scalability potential of two pilots using a methodological framework that combines empirical data and deterministic modelling to explore different market configurations and derive insights for scalable system designs.

This chapter summarises the key findings of the research. Section 7.1 will give an overview of the key findings of this thesis. The chapter concludes with a discussion of potential future research directions in Section 7.2.

7.1 Summary key findings

The following sections will discuss the research questions defined in this thesis and present the findings that address them.

Research question 1: *How can the scalability of P2P energy trading systems be assessed, taking into account the obstacles encountered in pilot projects?*

Due to the strong emphasis on locality and consumer focus, P2P energy trading systems are highly dependent on their contextual environment, which needs to be taken into account when assessing their scalability potential. The screening of the literature has shown that while pilots for P2P energy trading systems often succeed in controlled environments, they struggle to capture the complexities of scaling up due to technical, socio-economic, and regulatory challenges. These systems might adapt to changing conditions, such as varying participation rates and regulatory shifts, while ensuring inclusivity, equitable distribution, and sustainable business models to maintain stakeholder acceptance and scalability. The academic literature has traditionally assessed scalability of P2P energy trading systems through technical and algorithmic performance metrics, often with a narrow focus on computational feasibility and optimisation mechanisms. While these approaches provide valuable insights into system performance, they generally overlook the complexities introduced by real-world implementation such as regulatory limitations, social equity concerns, and participant behaviour.

To address the first research question, a scalability analysis framework has been proposed that grounds the assessment in the contextual realities of specific pilot projects in Medellín, Colombia and Brixton, UK. The analysis includes the definition of scalability scenarios and performance indicators based on detailed case studies, allowing for an in-depth examination of scalability within its operational environment. While the framework does not replace pilot projects, it complements empirical evidence and can support policymakers in making informed decisions. In addition to conventional indicators focused on technical and financial viability, this thesis adopts a more innovative approach by integrating quantitative fairness metrics into the scalability assessment. Specifically, the Equality Index was used to measure the distribution of financial benefits among

participants in scalability scenarios. This contributes to a more holistic lens on scalability, capturing not only efficiency and system performance, but also the equity implications of market size scaling.

The two pilot projects selected for analysis the Medellín P2P Energy Trading Pilot and the ComUNITY pilot respectively located in Medellín, Colombia, and London, UK. The real-world data from these pilots provided empirical insights that grounded the simulation models in actual operating conditions, where data quality or availability made it possible. The results of the scalability analysis on these two case studies provided insights into the second research question:

Research question 2: *What are the main barriers to scaling up P2P energy trading systems, and how do they affect the performance of these systems?*

The literature identifies a range of barriers to scaling P2P energy trading systems, including technical limitations (e.g. lack of interoperability or smart metering infrastructure), regulatory uncertainty, and low levels of user engagement or digital literacy. While many studies focus on algorithmic or theoretical models, fewer works systematically examine how these barriers interact with real-world implementation constraints, such as market design, participant diversity, or the influence of local socio-economic conditions. Moreover, little attention has been paid to how these barriers impact the actual performance of P2P energy markets when scaled in size.

This thesis addressed these gaps through detailed simulation-based scalability analysis of two real-world pilot projects in Colombia and the in the UK. In both cases, structural and behavioural constraints were identified that limited the potential for scaling up.

The Colombian P2P energy trading pilot struggled with scalability due to several challenges, including technical, educational and regulatory barriers. Structural issues such as inadequate housing and limited internet access, as well as a lack of digital literacy and understanding of basic energy concepts, made it difficult to implement the pilot. In addition, technical barriers such as the lack of national smart metering standards and malfunctioning energy management systems, combined with a restrictive regulatory framework, prevented the implementation of monetary transactions on the market. As a result, participants were remunerated with non-monetary digital tokens, limiting insights into the financial aspects of P2P energy trading. To address these challenges, two scalability scenarios were developed. Scenario I introduced a hypothetical P2P energy trading

market with financial transactions to explore the socio-economic impact on participants from different backgrounds. Scenario II expanded the participant base from 13 to 100, simulating a more diverse market to explore how increased participation affects market dynamics and adaptability. Both scenarios aimed to identify potential parameter sets which could impact the performance and hence the scaling up of P2P energy trading systems.

The CommUNITY project faced several challenges in scaling up its P2P energy trading market, mainly due to restrictions on participant eligibility and low household engagement. A major limitation was the requirement that households had to be EDF customers, which significantly limited the pool of potential participants. Of the 62 eligible households at Elmore House, only 13 were EDF customers and only four chose to participate, resulting in a participation rate of just 6%. This low level of engagement, coupled with the provision of financial incentives that removed upfront costs, raises questions about the future scalability and economic viability of the business model. Two scenarios were developed to better understand these scalability challenges. Scenario I explores how increasing participation affects the financial outcomes and viability of the P2P energy trading market, focusing on the redistribution of benefits among participants with different characteristics. Scenario II assesses the long-term financial viability of the CommUNITY business model, examining revenue sources and cost structures to determine its sustainability in a market-driven context. These scenarios aim to provide insights into scaling up P2P energy markets within a broader community energy framework.

Trade-off between individual, group and community

A key finding observed in both case studies was the trade-off between individual and community economic benefits, but also between groups of participants with particular attributes. This tension complicates scalability, as market mechanisms often prioritise community welfare over individual optimisation. In the Colombian case study, behaviour in some scenarios tested was different from that envisaged by the pilot project designers. Where possible, pilot designers should anticipate the types of participants expected in a P2P energy trading market in order to adapt appropriate policies, such as the market mechanism or tariff optimisation.

This finding is particularly relevant as individual participants typically seek financial gain and energy autonomy, whereas community-based models emphasise collective energy sharing and local reinvestment. In the Colombian case study, external funding minimised the financial burden on

participants, while in the UK case study a cooperative model covered upfront costs, influencing optimisation priorities and benefit distribution.

Impact of tariff design

In addition, tariff design is critical to the scalability of P2P energy trading systems. In the Colombian case study, the system of socio-economic stratification played an important role, as it imposed higher tariffs on wealthier households and provided subsidies to lower-income households, which affected market performance and created an unequal distribution of benefits among participants. A more level playing field in tariff design could lead to a more equitable distribution of benefits.

In contrast, the UK case study showed that tariff design, in particular community pool prices and PPA tariffs, directly affected the financial outcomes of both individual participants and the cooperative. This highlighted the sensitivity of market performance to pricing strategies and showed that tariff structures can have a significant impact on the economic viability and attractiveness of P2P energy trading systems. Tariff structure and pricing policies have a significant impact on participant benefits and market sustainability, highlighting the need for a consistent policy framework.

The simulations showed that technical viability alone is not sufficient to support scalability. For instance, in both case studies, the distribution of benefits became more unequal as market size increased, and business model sustainability was found to be highly sensitive to changes in participant composition and tariff design. These findings provide empirical evidence that common scalability barriers, such as limited engagement, fixed market structures, and price sensitivity have measurable impacts on market outcomes.

Research question 3: *How applicable are scalability barriers identified in the broader context of P2P energy trading systems?*

This research question was addressed by interpreting the types of scalability barriers observed in the case studies in light of broader implementation challenges for P2P energy trading. Rather than seeking to generalise findings, the analysis explored how specific barriers such as regulatory ambiguity, the absence of supportive tariff structures, limited digital infrastructure, or participant disengagement, can reveal deeper misalignments between the design intentions of P2P systems and the environments in which they are implemented.

The thematic analysis in Chapter 6 showed that the applicability of specific barriers varies depending on local topologies, governance structures, and socio-economic characteristics. Nonetheless, common patterns such as the trade-off between individual and collective optimisation goals, and the sensitivity of market performance to tariff design are likely to be relevant in other P2P implementations, even if their manifestation differs. The results of both case studies highlight the need for more flexible regulatory adaptations to facilitate the integration of innovative energy trading models. The different socio-economic and infrastructural contexts of Colombia and the UK highlight the need for policy frameworks that not only encourage technological innovation, but also ensure equitable market access. This suggests that while scaling strategies must be tailored to local contexts, certain structural and regulatory requirements, such as clear settlement rules, adaptable pricing structures, and participant diversity management, are universally important for successful P2P energy trading scale-up.

This research emphasises that identifying scalability barriers requires attention to both system design and the evolving context in which the system is embedded. Rather than assuming a fixed set of barriers that can be transferred across settings, this thesis proposes that scalability must be understood as a process shaped by ongoing negotiation between market rules, participant needs, technical possibilities, and policy constraints. Consequently, the inherent variability of P2P energy trading markets may itself act as a barrier to wider adoption and scalability, as stakeholders may find it difficult to predict the personal benefits of engagement. While certain types of barriers may recur across cases, their specific relevance and impact are shaped by local conditions, making scalability less about replicating fixed models and more about adapting to context-specific challenges.

7.2 Future research

The concept of P2P energy trading systems gained traction alongside the popularity of blockchain technology. The initial driver for these systems was the decentralisation and democratisation of energy markets. While community energy projects in general were already part of the energy systems landscape, the novel focus of P2P energy trading systems was on individual control over energy consumption and generation. However, unlike blockchain and financial markets, energy markets include both physical and virtual components. As trading periods shorten and transactions occur on lower voltage levels on the grid, the interdependence between these components increases, creating unique challenges for P2P energy trading systems.

Recent global events, including the COVID-19 pandemic and the energy crisis, have significantly

affected the dynamics of energy supply and demand, leading to a renewed emphasis on resilient energy markets (Zapata-Webb et al., 2023; Tubelo et al., 2022; Huebner et al., 2021). The resulting high energy prices have forced several suppliers out of business, prompting governments to introduce temporary price caps to alleviate the increased costs faced by households and businesses (Ofgem, 2021; Bolton, Paul and Stewart, Iona, 2024). Due to the interconnectedness of European and global energy markets, the European energy crisis also had global repercussions. Although the electricity markets in Europe have largely recovered from the effects of the energy crisis, these events mean a shift in focus away from simply creating greater autonomy for end consumers. Instead, the focus is now on ensuring the security and resilience of electricity grids and energy markets.

Early pilots, such as those in Colombia and the UK, focused mainly on the virtual aspects of trading. Lessons from the energy crisis have shown a greater need for demand response and flexibility. At the same time, the energy crisis has highlighted the importance of DER and the need for its full integration into the energy market, strengthening the case for P2P energy trading systems. By decreasing reliance on fossil fuels sourced outside the country, these systems can enhance the resilience of regional or national electricity grids. In addition to financial and social benefits, future P2P energy trading projects will likely need to demonstrate that they can provide grid-benefitting services. It is necessary to assess the ability of P2P energy trading systems to support grid resilience through demand response and flexibility services, evaluating how these systems can integrate more DER to enhance both local and national energy stability.

This research has explored scalability constraints by scaling up pilot projects through case studies, although further research is needed to fully understand the impact of dynamic scaling on participants. While initial studies have examined short-term changes in market size, future research should focus on how markets evolve over time as participants enter and exit. This includes identifying thresholds at which a market may become inefficient, influenced by factors such as network capacity and financial sustainability.

Focusing future analysis on specific regions could provide deeper insights into scalability by reflecting local regulatory, economic and social conditions, making findings more actionable for that context. Although not covered in this thesis, limiting scalability analysis to a specific region could also improve understanding of the replicability and ‘scaling out’ potential of P2P energy trading models.

As P2P energy trading remains largely isolated from existing energy markets, future research should explore its integration into broader energy systems. Key areas for successful scaling include aligning with national energy security strategies, establishing technical interoperability standards, and adapting regulations to support innovation while maintaining grid stability. Effective scaling will require a balanced integration of social, technical, regulatory and economic factors, emphasising a local and consumer focus for a better integration into the current energy infrastructure.

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Appendix A

Colombian pilot project

A.1 Data and code availability

Data and code is available at: https://github.com/AnnaGoriz/Colombia_casestudy

A.2 Energy import and export metadata

Table A.1 provides an overview of the start and end date of the data collected from participant for both energy import and export data. Data collection ended at the end of the pilot project. According to the pilot project coordinators the different start dates for the data collection were due to encountered challenges such as, access to homes, malfunctioning of the hardware, no internet connection and others.

Participant	Data collection start date	
	Energy import	Energy export
SP ₁	2020-08-11	2020-08-11
SP ₂	2020-02-18	2021-03-27
SP ₃	2020-02-17	2020-02-17
CCP ₁	2020-02-24	2020-02-24
BP ₁	2019-10-30	2019-10-30
BP ₂	2020-02-10	2020-02-12
BP ₃	2019-10-30	2019-11-26
C ₁	2020-02-22	-
C ₂	2020-01-31	-
C ₃	2019-12-09	-
C ₄	2019-12-04	-
C ₅	2020-10-18	-
C ₆	2020-02-20	-

Table A.1: Metadata for participant load data in the Medellín P2P Energy Trading Pilot project.

Figure A.1 shows the missing values in the energy import and export datasets for each participant

in the Medellín Peer-to-Peer energy trading pilot for the duration of recorded data, indicated by white space for the import and export load profiles, respectively.

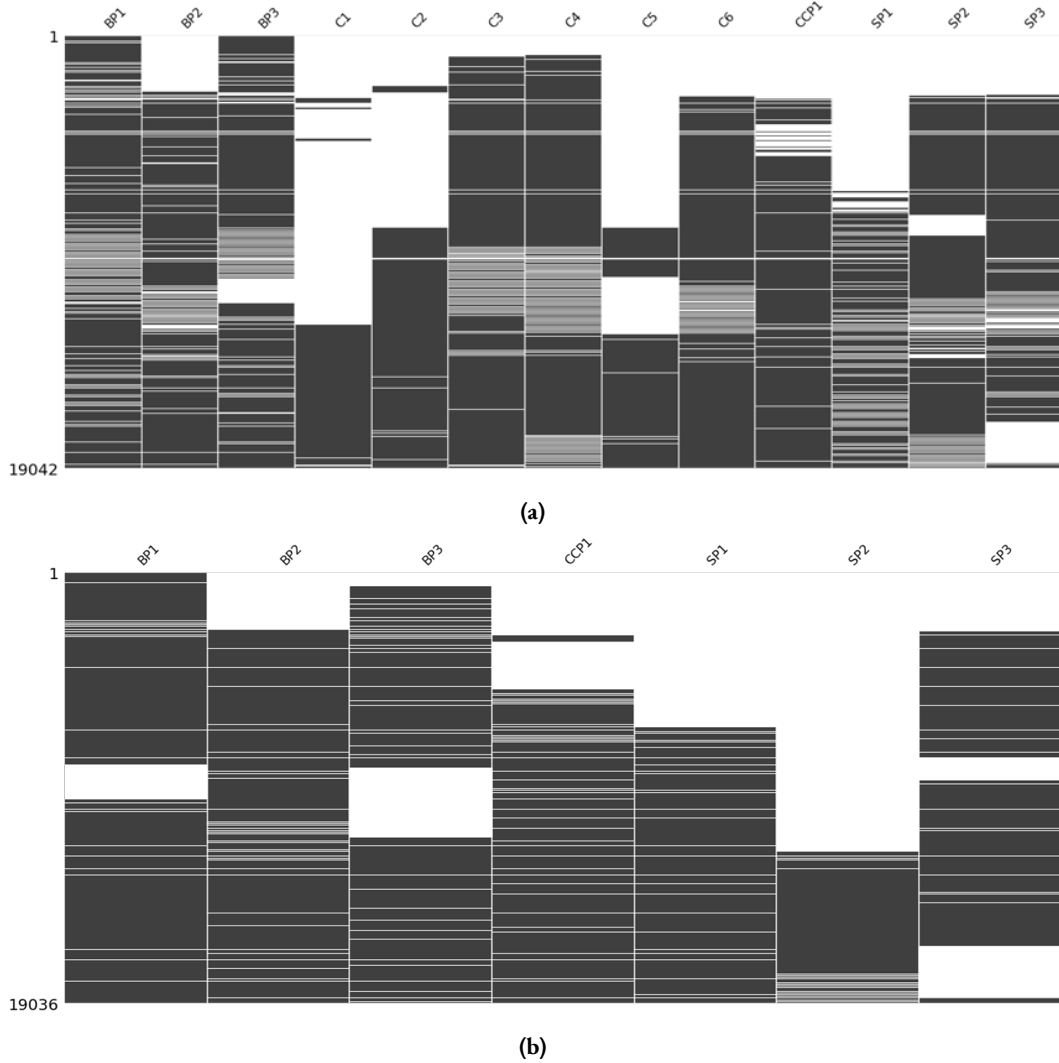


Figure A.1: Number of the missing data points for the participants of the Medellín P2P Energy Trading Pilot, indicated by white space for the import and export load profiles, respectively (a and b).

A.3 Markov-chain model for load profile generation

To allow testing of the local energy market synthetic load profiles have to be generated. The proposed algorithm adopted from Toffanin (2016) and Labeeuw et al. (2013) uses a mixture of machine learning techniques and Markov-chains to generate synthesised load profiles.

The aim of the algorithm implemented as part of this research is to gain insight into and anticipate the way in which households consume and generate electricity. The aim of the algorithm is to analyse the data to identify patterns in energy consumption and to construct realistic load profiles

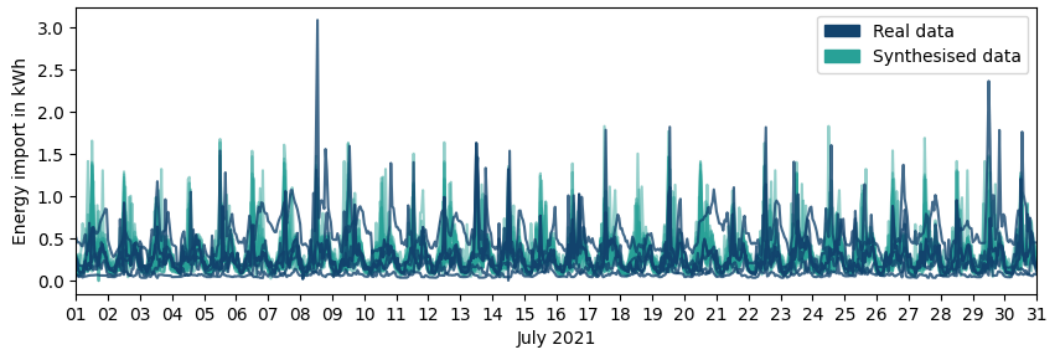
that can be used to assess increasing market participation. Household electricity consumption is highly variable, with patterns that change throughout the day, throughout the week and from season to season. The algorithm addresses this challenge by breaking down raw household data into load patterns that can be used to generate additional load profiles. The first step is to organise the load data from one group of participants into a format that can be processed. With the data prepared, the next step focuses on identifying patterns in energy use by grouping the load data into clusters. A cluster is a set of similar data points that allows the algorithm to find typical trends in energy use. The clustering process starts by grouping similar weeks together; weeks with similar energy behaviour are treated as part of the same cluster. From there, the analysis is broken down to a daily and hourly level to assess how energy use varies throughout the day. Once these patterns have been identified, they are used to create load profiles for additional market participants. The algorithm does this by calculating the probability of moving from one energy pattern to another.

For a more detailed description of the model, the reader is referred to Toffanin (2016) and Labeeuw et al. (2013). Given that the weather pattern in Medellín does not exhibit a strong seasonal pattern, the model is only intra-day time-inhomogeneous model is built using six key steps:

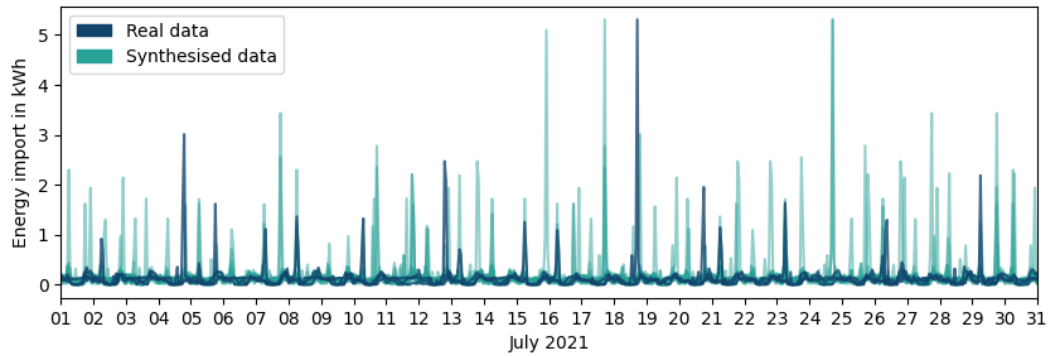
Measures		High-income consumers		Low-income prosumers	
		Real data	Synthesised data	Real data	Synthesised data
Energy import	Median	0.22	0.25	0.09	0.11
	Mean	0.28	0.29	0.11	0.12
	Min	0.01	0.02	0.00	0.00
	Max	3.09	1.77	5.31	5.31
Energy export	Median	-	-	0.25	0.18
	Mean	-	-	0.28	0.25
	Min	-	-	0.00	0.00
	Max	-	-	1.14	1.19

Table A.2: Comparison of the real data and synthesised data for high-income consumers and low-income prosumers.

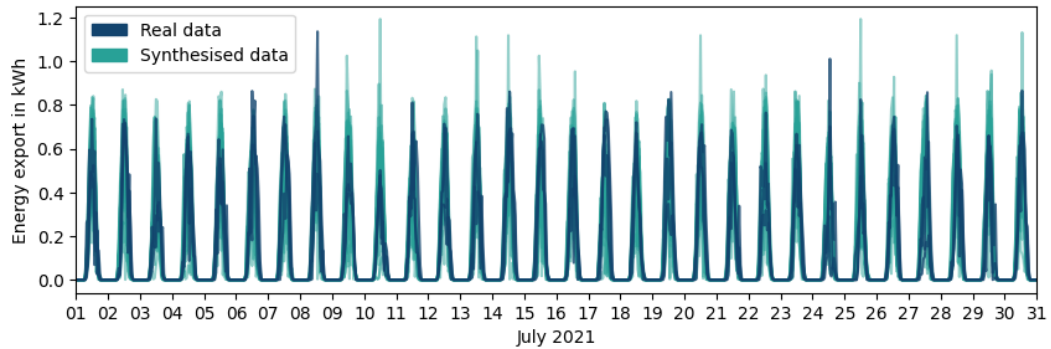
In Figure A.2 the synthesised data is compared to the real data for the month of July 2021. Figure A.3 shows a density plot of the synthesised data values. It can be seen that the synthesised data is able to capture the general shape of the real data.



(a)



(b)



(c)

Figure A.2: Comparison of real data and synthesised data for the month of July 2021, where (a) shows Energy import in kWh for high-income households comparing real data ($n=6$) and synthesised data ($n=20$), (b) shows Energy export in kWh for low-income households comparing real data ($n=3$) and synthesised data ($n=20$), and (c) shows Energy export in kWh for low-income households comparing real data ($n=3$) and synthesised data ($n=20$).

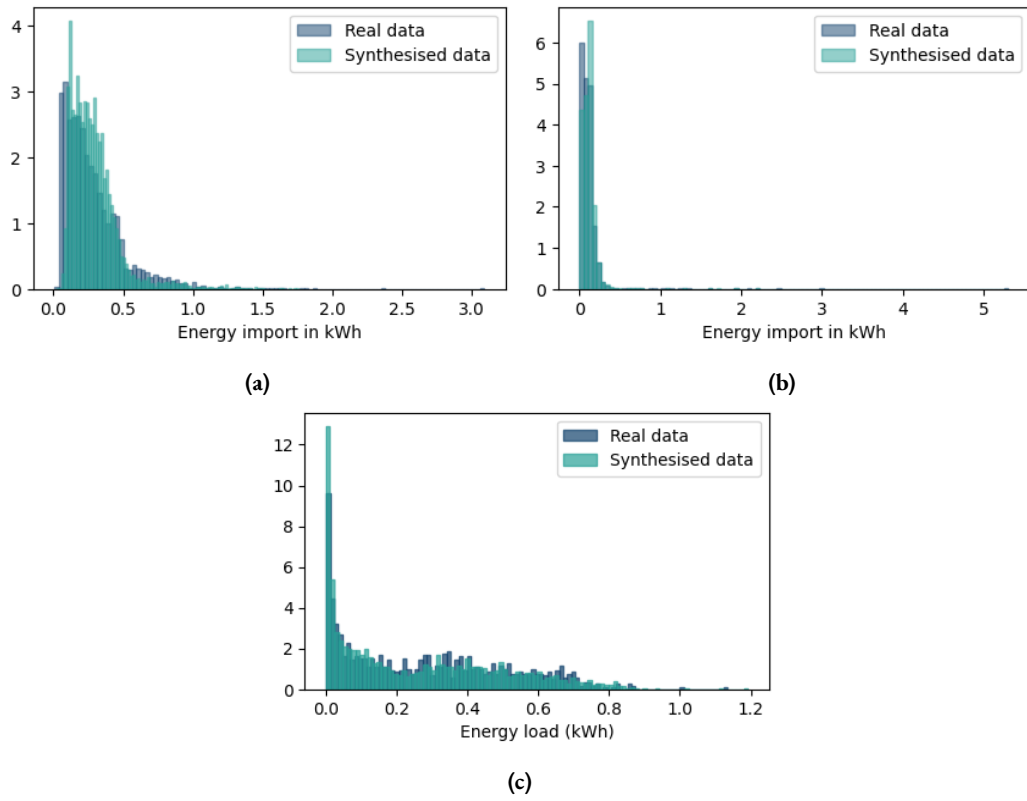


Figure A.3: Density plot of load values showing real data and synthesised data for the month of July 2021, where (a) shows energy import in kWh for high-income households comparing real data ($n=6$) and synthesised data ($n=20$), (b) shows energy import in kWh for low-income households comparing real data ($n=3$) and synthesised data ($n=20$), and (c) shows energy export in kWh for low-income households comparing real data ($n=3$) and synthesised data ($n=20$).

A.4 Results

Table A.3 show the average energy import and export price per kWh for both ‘base case with high FiTs’ and ‘base without high FiTs’. Table A.4 show the average energy import and export price per kWh for P2P market both with and without a stratified tariff scheme.

Participant	Base case w/ high FiTs		Base case w/o high FiTs	
	Energy import price (£)	Energy export price (£)	Energy import price (£)	Energy export price (£)
C1	0.11	-	0.11	-
C2	0.13	-	0.13	-
C3	0.13	-	0.13	-
C4	0.13	-	0.13	-
C5	0.11	-	0.11	-
C6	0.11	-	0.11	-
BP1	0.13	0.09	0.13	0.02
BP2	0.13	0.1	0.13	0.02
BP3	0.13	0.11	0.13	0.02
CCP1	0.11	0.11	0.11	0.02
SP1	0.09	0.07	0.09	0.02
SP2	0.06	0.11	0.06	0.02
SP3	0.09	0.08	0.09	0.02

Table A.3: Overview of average energy import and export price (in £ equiv.) for base case tariff designs.

Participant	P2P market w/ strata		P2P market w/o strata	
	Energy import price (£)	Energy export price (£)	Energy import price (£)	Energy export price (£)
C1	0.10	-	0.09	-
C2	0.11	-	0.09	-
C3	0.11	-	0.09	-
C4	0.11	-	0.09	-
C5	0.09	-	0.09	-
C6	0.09	-	0.09	-
BP1	0.13	0.03	0.11	0.03
BP2	0.13	0.03	0.11	0.03
BP3	0.12	0.03	0.1	0.03
CCP1	0.11	0.03	0.11	0.03
SP1	0.09	0.04	0.11	0.03
SP2	0.05	0.04	0.11	0.03
SP3	0.09	0.04	0.11	0.03

Table A.4: Overview of average energy import and export price (in £ equiv.) for P2P market tariff designs.

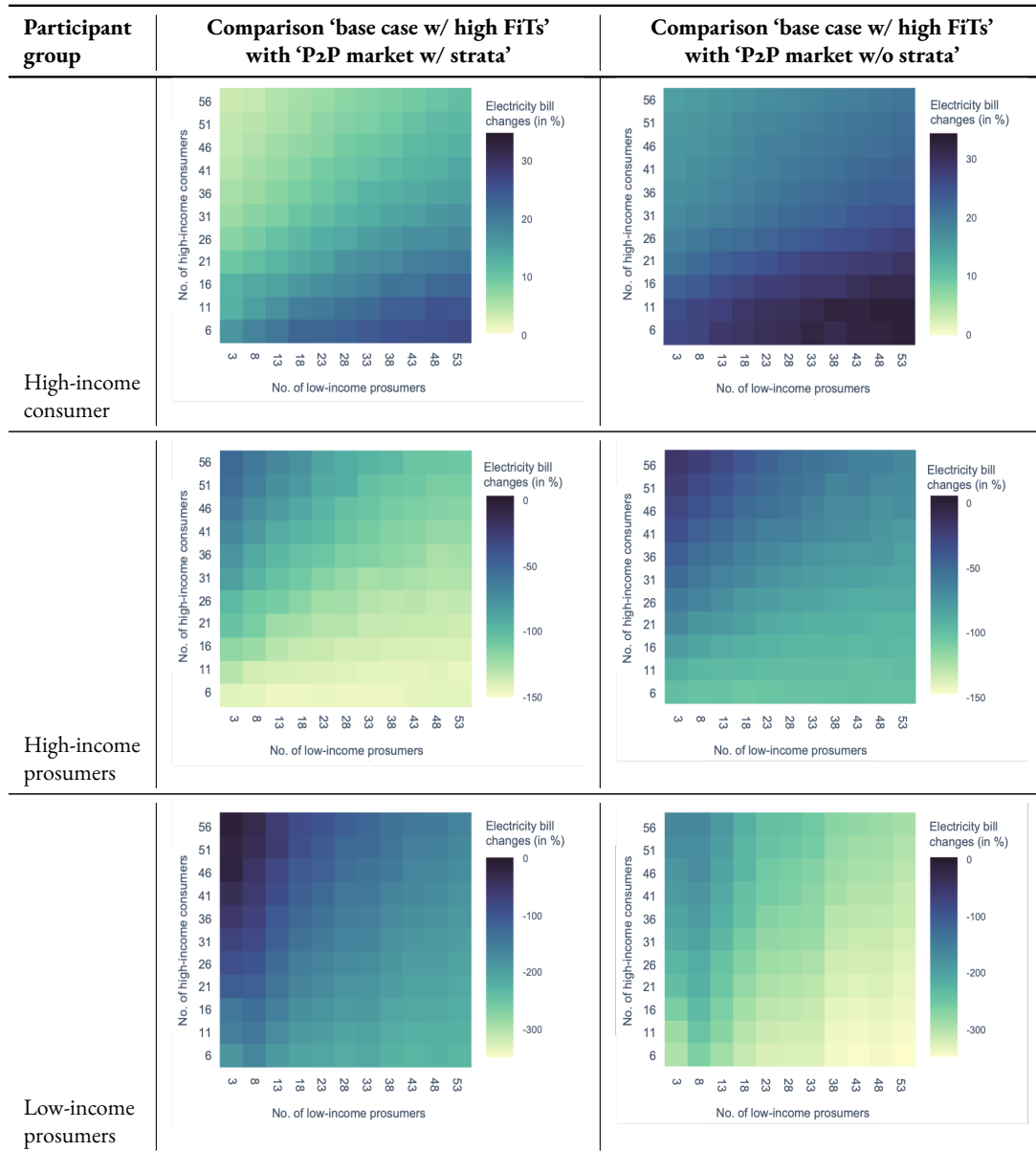


Table A.5: Energy bill changes for each participant group (savings when positive values and additional costs when negative values) comparing the 'base case with high FiTs' with the 'P2P market with strata' and 'P2P market without strata'.

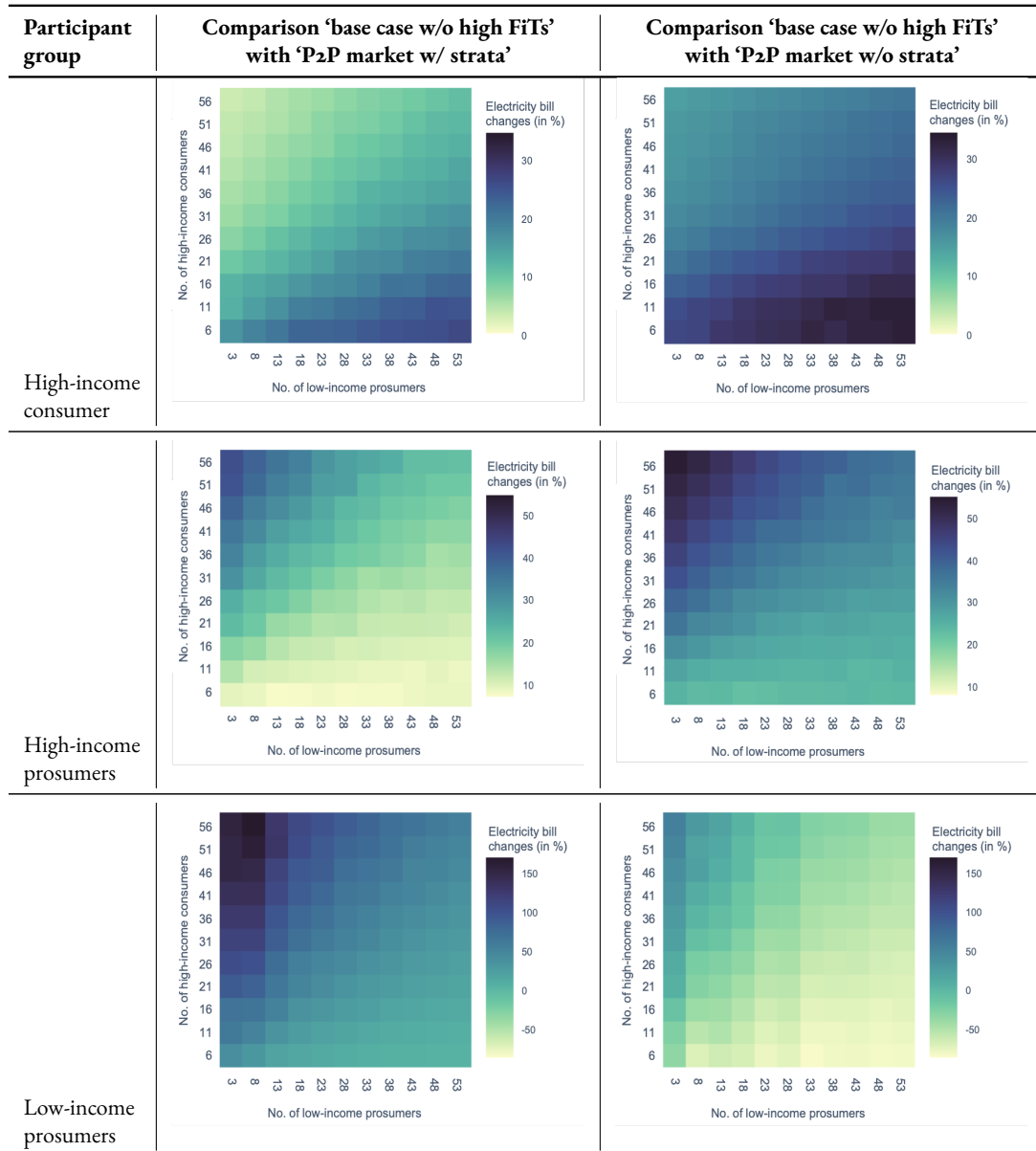


Table A.6: Energy bill changes for each participant group (savings when positive values and additional costs when negative values) comparing the 'base case without high FiTs' with the 'P2P market with strata' and 'P2P market without strata'.

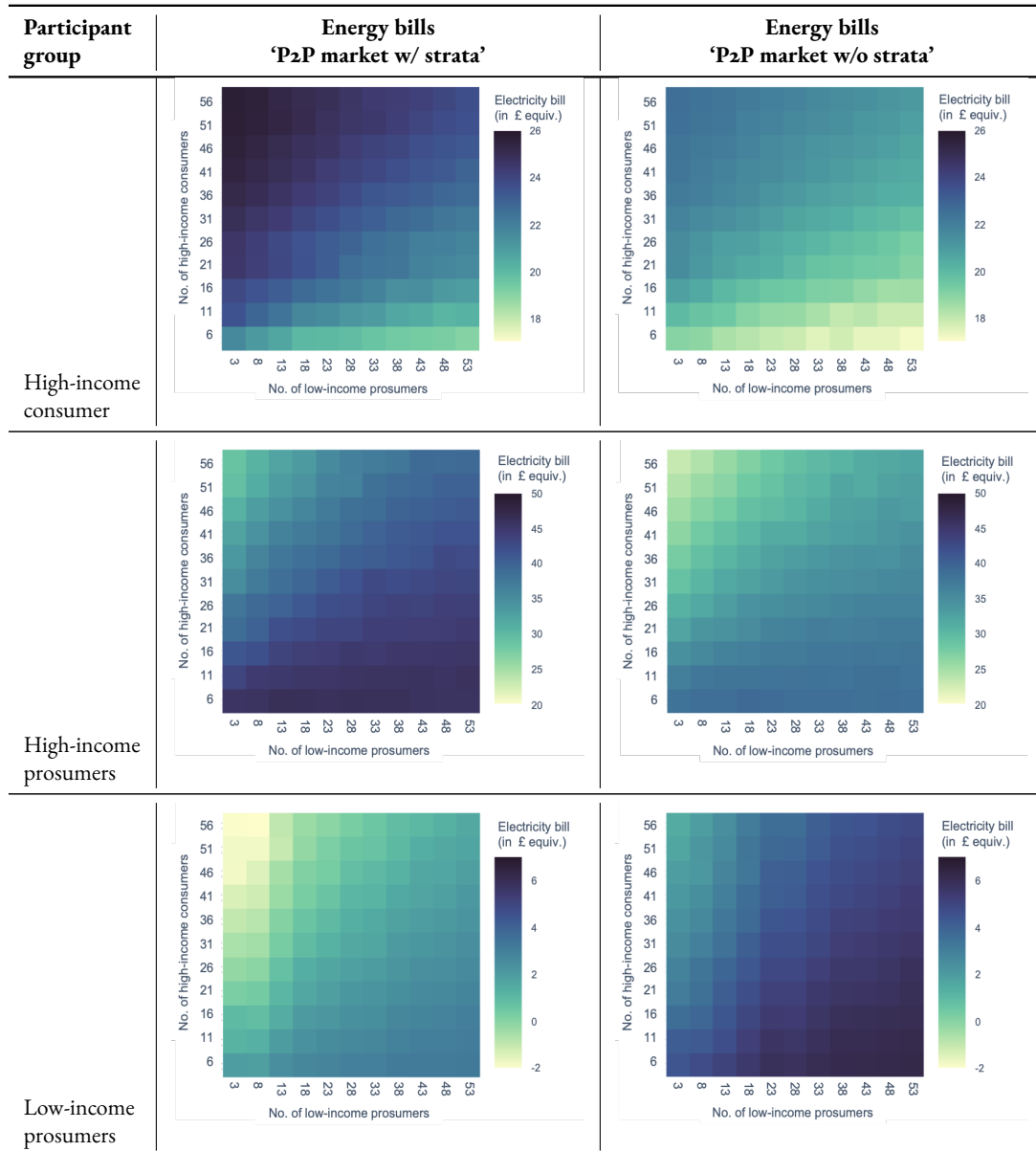


Table A.7: Total average electricity bill per participant for each participant group for the 'P2P market with strata' and 'P2P market without strata'.

Appendix B

UK Pilot Project

B.1 Data and code availability

Data and code is available at: https://github.com/AnnaGor12/UK_case_study

B.2 Flowchart simulation setup

B.1 shows a flowchart of the market simulation setup. t is the trading period with the maximum number of trading periods T_{max} , f is the number of households participating in the market where F_{max} is the maximum size of the market with f_{start} being the starting market size and f_{step} being the number of participants added to the simulation with every run. s is the simulation run with the maximum number of simulation runs S_{max} .

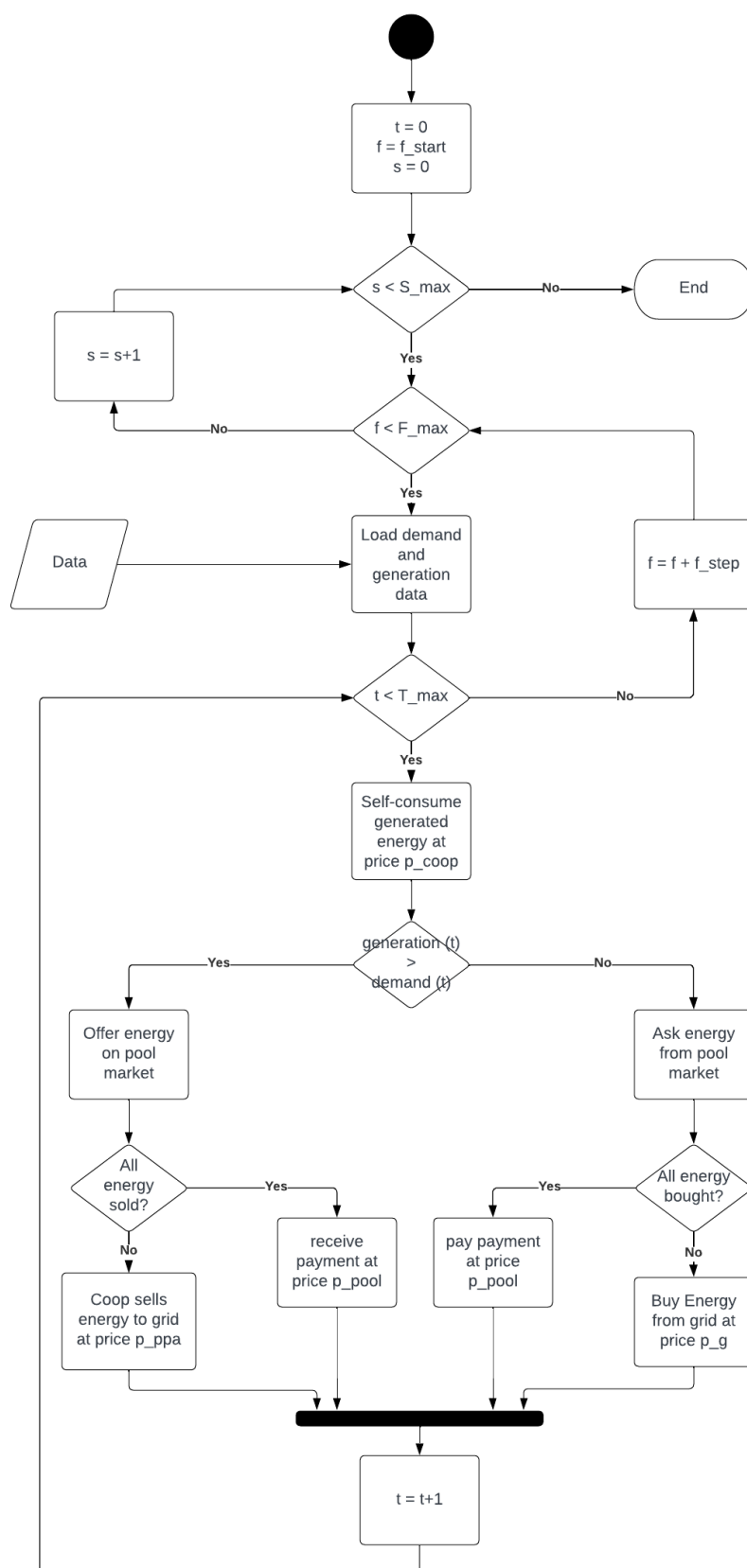


Figure B.1: Flowchart of market simulation setup

B.3 Results

KPI	Tariff (£)	Market size (No. of participants)					
		2	4	8	16	32	64
Community benefit (£)	p_{coop} : 0.00	947.46	1,819.08	3,339.09	5,610.95	8,760.42	11,935.98
	0.05	808.13	1,551.57	2,848.04	4,785.81	7,472.12	10,180.69
	0.10	668.80	1,284.06	2,357.00	3,960.67	6,183.82	8,425.40
Individual benefit (£)	p_{coop} : 0.00	473.73	454.77	417.39	350.68	273.76	186.50
	0.05	404.07	387.90	356.01	299.11	233.50	159.07
	0.10	334.40	321.02	194.63	247.54	193.24	131.65
Equality Index	p_{pool} : 0.00	0.85	0.78	0.75	0.75	0.76	0.80
	0.06	0.85	0.79	0.77	0.77	0.79	0.83
	0.12	0.86	0.80	0.78	0.79	0.82	0.86

Table B.1: Mean community benefit, individual participant benefits and equality index of the P2P market at different market sizes

Tariff (£)	Annual load (£)	Tariff (£)	Market size (No. of participants)					
			2	4	8	16	32	64
p_{coop} : £0.00	low	p_{pool} : £0.00	45.44	43.99	41.19	37.29	31.42	24.32
		£0.06	46.26	45.85	43.97	40.93	35.11	27.51
		£0.12	47.07	47.71	46.75	44.56	38.8	30.69
	medium	p_{pool} : £0.00	41.76	40.85	37.65	32.25	25.61	18.22
		£0.06	41.85	41.12	37.99	32.56	25.9	18.34
		£0.12	41.94	41.39	38.34	32.87	26.19	18.45
	high	p_{pool} : £0.00	41.88	38.19	34.13	27.72	20.72	13.03
		£0.06	41.59	37.64	33.39	26.92	19.92	12.45
		£0.12	41.3	37.09	32.64	26.11	19.12	11.87
p_{coop} : £0.05	low	p_{pool} : £0.06	38.90	37.83	35.60	32.41	27.41	21.28
		£0.12	39.71	39.69	38.38	36.05	31.10	24.46
	medium	p_{pool} : £0.06	35.64	34.89	32.17	27.56	21.89	15.56
		£0.12	35.72	35.16	32.51	27.87	22.18	15.68
	high	p_{pool} : £0.06	35.67	32.49	28.98	23.51	17.54	11.02
		£0.12	35.38	31.94	28.24	22.71	16.74	10.44
p_{coop} : £0.10	low	p_{pool} : £0.12	32.345	31.67	30.00	27.53	23.41	18.23
	medium	p_{pool} : £0.12	29.51	28.92	26.69	22.87	18.18	12.90
	high	p_{pool} : £0.12	29.46	26.78	23.84	19.30	14.36	9.00

Table B.2: Mean bill savings in % at different market sizes and price sensitivities

Tariff p_{coop} (£)	Tariff p_{ppa} (£)	Market size (No. of participants)					
		2	4	8	16	32	64
0.00	0.05	4159.21	1048.05	-4377.42	-12486.60	-23728.25	-35063.09
	0.10	46988.09	40765.77	29914.83	13696.48	-8786.83	-31456.51
	0.20	132645.85	120201.22	98499.34	66062.63	21096.00	-24243.35
0.05	0.00	-35405.46	-32703.39	-28222.14	-21960.05	-13973.39	-5756.27
	0.05	7423.42	7014.33	6070.11	4223.03	968.03	-2149.69
	0.10	50252.30	46732.06	40362.36	30406.10	15909.45	1456.89
	0.20	135910.06	126167.50	108946.86	82772.25	45792.28	8670.05
0.10	0.00	-32141.25	-26737.11	-17774.61	-5250.42	10722.90	27157.12
	0.05	10687.63	12980.61	16517.64	20932.65	25664.31	30763.70
	0.10	53516.51	52698.34	50809.89	47115.72	40605.73	34370.28
	0.20	139174.27	132133.78	119394.39	99481.87	70488.57	41583.44

Table B.3: Mean Net Present Value (NPV) of the P2P market at different market sizes.