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DESIGN AND OPERATION OPTIMISATION OF COMMUNITY MICROGRIDS CONSIDERING SOCIO-TECHNICAL COMPLEXITY

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Certificate of Original Authorship

I, *Melissa Eklund* declare that this thesis is submitted in fulfilment of the requirements for the award of *Doctor of Philiosophy*, in the *Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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M. Eklund, K. Khalilpour, A. Voinov, M.J. Hossain, "Evaluating the Interplay of Community Behaviour and Microgrid Design through Optimisation Modelling in Local Energy Markets", accepted in Renewable and Sustainable Energy Reviews.

M. Eklund, K. Khalilpour, A. Voinov, M.J. Hossain, "Community Capacity Building for Microgrid Projects: An Australian Case Study", under review in Energy Research and Social Science.

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Abstract

This thesis develops a comprehensive understanding of how social aspects can be incorporated into the design and operation of community microgrids through an interdisciplinary research approach. It introduces a multi-level conceptual framework inspired by various theories and methodologies from fields such as social capital theory, energy systems engineering, and business management. The framework systematically integrates social, technical, and economic dimensions, addressing the socio-technical complexity inherent in community microgrids.

A key contribution of this research is the development of several frameworks and tools designed to enable communities, industry professionals, policymakers, and academics to navigate the complexities of community microgrids. The Social Capital Index (SCI) is introduced to assess and quantify social capital's structural, cognitive, and relational dimensions within communities. A Multi-Criteria Decision Analysis (MCDA) framework is developed to evaluate and select business models that align with both local energy markets and community dynamics. Additionally, an integrated methodology employing Mixed-Integer Linear Programming (MILP) and energy justice theory is presented to optimise microgrid operations, ensuring technical efficiency while maintaining social equity and fairness. Furthermore, the thesis proposes strategies for community capacity building, enhancing local capabilities, and informing policy decisions to support the sustainable and effective deployment of community microgrids. These interdisciplinary frameworks and tools provide valuable insights and practical solutions, empowering communities to design, operate, and govern their microgrids effectively. They also offer industry stakeholders and policymakers evidence-based guidance for creating supportive policies and developing socially acceptable energy solutions.

By bridging the gap between operational and technical aspects of microgrids, on the one hand, and the social dimensions and context of communities they serve, on the other, this research contributes to a more resilient, equitable, and sustainable energy future. The holistic approach

adopted in this thesis not only advances scientific knowledge in the field of sustainable energy systems but also provides actionable frameworks for real-world applications, ultimately fostering a more inclusive and participatory energy transition.

1 Introduction

"Behaviour change occurs in response to changes in our social or physical environment. We rarely act differently because of attitude change, we are most powerfully influenced by what actually happens to us. Change the environment, and you change the behaviour. Change the conditions under which they behave."

- Hugh Mackay

1.1 Background

The global energy system is undergoing a transformative shift driven by the dual imperatives of advancing renewable energy technologies and addressing climate change challenges [1]. As nations worldwide strive to reduce greenhouse gas emissions [2] and enhance energy security [3], the integration of renewable energy sources has become a central strategy in redefining power generation and distribution [4]. This transition is not merely technological; it embodies a fundamental shift towards sustainability and resilience in energy systems [5], necessitating innovations that can integrate intermittent energy sources like solar and wind power effectively [6].

Within this context, microgrids have emerged as a pivotal technology [7]. Initially conceptualised to improve reliability and optimise local energy sources, microgrids have grown to play a critical role in the broader agenda of creating decentralised, flexible, and sustainable energy infrastructures [3]. They enable a more localised control of energy, allowing communities to harness and distribute renewable resources autonomously, thus aligning energy production with local consumption patterns [8].

The increasing significance of microgrids requires careful consideration of their interaction with existing energy systems and the broader structure of the electric power industry. Traditionally, the energy industry has been structured around centralised systems [9], with utilities, such as Distribution Network Service Providers (DNSPs), responsible for operating and maintaining electricity networks [10], energy retailers acting as intermediaries for selling electricity to consumers [11], and emerging players like Virtual Power Plant (VPP) aggregators coordinating distributed energy resources (DERs) to provide grid service [12]. Microgrids challenge this conventional framework by introducing decentralised systems where local generation, storage, and consumption reduce dependence on the central grid [12].

DNSPs, for instance, must adapt to managing bi-directional power flows, as microgrids generate energy locally and may export surplus back to the grid, complicating grid operations and stability [1]. Energy retailers, meanwhile, face potential shifts in their role, as microgrid communities may rely less on traditional retail services, opting instead for peer-to-peer energy trading within localised systems [13]. VPP aggregators play a critical role by integrating microgrids into larger networks to deliver services like frequency regulation, demand response, or capacity markets [9]. These dynamics underscore the need for microgrid designs that align with regulatory frameworks, market structures, and stakeholder needs while maintaining technical efficiency and cost-effectiveness [14].

Examples from various regions illustrate the versatility and adaptability of microgrids in addressing diverse technical, social, and environmental challenges. In Australia, the Kalbarri Microgrid in Western Australia integrates wind and solar energy with advanced battery storage to provide reliable electricity to a remote region [15]. The MyTown Microgrid in Victoria combines community engagement and real-time energy monitoring to explore equitable and scalable energy solutions [16], while the Corryong Microgrid, also in Victoria, enhances resilience in bushfire-prone areas through a combination of centralised and DERs [17]. Similarly, the White Gum Valley Microgrid in Western Australia employs solar and battery storage within a residential development to foster shared energy generation and collaborative energy management [18].

In other parts of the world, the Redwood Coast Airport Microgrid (RCAM) in Northern California integrates solar power and battery storage with participation in wholesale energy markets, ensuring energy resilience for critical infrastructure while highlighting economic sustainability [19]. In Sweden, the Simris Microgrid operates autonomously with solar, wind, and battery storage, offering a model for renewable energy integration and local grid independence [20]. Likewise, the Aardehuizen Microgrid in the Netherlands aligns renewable energy systems with sustainable housing design, creating an energy-autonomous community that integrates social and technical systems to achieve a low-carbon future [21].

The evolution towards community microgrids represents a further refinement of this concept, where the technical solutions are intricately linked with community participation and governance [22]. These microgrids are physical infrastructures and socio-economic platforms that promote local engagement [5], energy democracy [23], and social resilience [24]. By fostering local ownership and decision-making [25], community microgrids empower communities, enhance local economic development, and contribute to a more equitable distribution of energy resources [26].

As the significance of microgrids expands in the context of global energy transitions, they exemplify the critical intersection of technological innovation and community dynamics [27]. This convergence underscores the complexity of integrating sustainable technologies within varied social landscapes [28], a challenge that is central to the evolving discourse on how best to achieve a resilient and inclusive energy future.

1.2 Research Motivation

1.2.1 Sociotechnical complexity in the design and operation of community microgrids

Designing and operating community microgrids presents a unique challenge. Unlike conventional energy infrastructures that focus primarily on technical and economic considerations [29], community microgrids operate within an intricate socio-technical landscape [30]. This landscape encompasses the interactions between social dynamics [31], such as community values [22], networks and trust [24], and the technical aspects of microgrid design and operation [32]. The successful implementation of community microgrids requires a comprehensive understanding of this socio-technical complexity [33].

This stems from the fact that community microgrids are not just technical entities providing a service; they are also socio-economic institutions woven into the social fabric of the community [34]. They involve and impact a diverse set of stakeholders - from individuals and businesses participating in the microgrid to non-participants in the broader community [35]. These stakeholders may hold different values, expectations, and capabilities [36], contributing to the socio-technical complexity of community microgrids [22].

Community microgrids are often embedded in existing social networks within the community [37], and their design and operation can affect these networks in various ways. For instance, they can strengthen social connections by fostering cooperation and shared decision-making [23], or they can cause fragmentation if certain groups are marginalised in the process [38]. Understanding these dynamics is critical for managing the social impacts and ensuring the overall acceptance and sustainability of community microgrids [39].

Furthermore, the decision-making processes within community microgrids also encompass social aspects [24]. Decisions about energy sources, distribution, pricing, and governance are not merely technical or economic choices [40]. They are also social decisions influenced by the community's social structure [41]. Community engagement in these decision-making processes can help align the microgrid's operation with the community's preferences, enhancing its legitimacy and acceptance [42]. Adding to the complexity is the need to consider different business models for operating community microgrids [43]. These business models need to balance economic viability with social acceptability [34], which requires an understanding of both the market dynamics [44] and the community's social dynamics. Different business models may entail different roles, responsibilities, and benefits for community members [45], affecting their engagement and acceptance of the microgrid [46]. Therefore, the choice and design of the business model is a critical aspect of the socio-technical complexity of community microgrids.

1.2.2 Existing frameworks and theories

The academic and practical exploration of community microgrids has been informed by a range of existing frameworks and theories from fields as diverse as energy systems engineering [47], social sciences [48], and business management [49]. These frameworks have traditionally aimed to address either the technical aspects of energy systems, such as grid stability and energy efficiency [50], or the economic and social aspects [51], such as stakeholder engagement and governance structures [52].

Significant research has been conducted on the technical optimisation of microgrids, focusing on maximising efficiency and reliability. Studies such as those by Hatziargyriou et al. [53] have laid down the engineering principles for microgrid operation, emphasising the importance of technological innovations in enhancing microgrid performance. However, while these studies provide robust technical foundations, they often do not fully incorporate the critical socio-economic dimensions in community settings.

On the socio-economic front, community development [54] and social capital theories [24], [37] have been increasingly applied to understand and enhance stakeholder involvement in energy projects [36]. Research by Walker and Devine-Wright [55] and later Wolsink [56] explored how community engagement and social acceptance are crucial for the sustainable operation of microgrids. These studies highlighted the need for frameworks that manage the technical operations of microgrids and foster social cohesion and trust among community members.

Furthermore, business models for community microgrids have been an area of growing interest [57], particularly in how they can balance economic viability with community benefits [58]. Works by Schwidtal et al. [43] and Capper et al. [43] have examined various cooperative and participatory business models, suggesting that the success of microgrids often depends on their ability to align economic incentives with community values and expectations.

1.2.3 Identifying the gaps

Given the intricacies of the socio-technical landscape in which community microgrids operate, a comprehensive and integrated understanding of these dynamics is crucial for their successful implementation and operation [22]. The motivation for this research arises from the observed gap in our understanding of these complexities and the need for tools and methodologies to navigate them effectively. Despite the significant strides in the technological advancement of community microgrids [59], the socio-technical complexity often remains under-explored [33]. The interactions between a community's social fabric and the technical and economic aspects of the microgrid are multi-faceted, challenging to measure, and can significantly influence the microgrid's success [60]. Therefore, a structured framework to assess and navigate this complexity is a crucial missing piece in current microgrid research.

This study is motivated by the need to bridge this gap by developing a comprehensive, four-tiered framework that incorporates the evaluation of social capital, business model alignment, and operational optimisation. By introducing a systematic way to quantify and align the community's social capital with the most appropriate business model, and subsequently using this alignment to optimise the microgrid's operation, the proposed framework aims to ensure the socio-technical compatibility of the microgrid. This compatibility is key to securing community acceptance, enhancing the microgrid's sustainability, and ultimately contributing to a more resilient and inclusive energy future. Additionally, this research is motivated by the potential for community microgrids to drive local economic development, promote energy democracy, and contribute to sustainability and resilience in the face of global energy and climate challenges. Understanding and effectively managing the socio-technical complexity of community microgrids can unlock these potentials, providing valuable insights for policymakers, community leaders, and energy practitioners.

1.3 Thesis Aim and Research Questions

The overarching aim of this research is to facilitate and enhance the development of community microgrids by incorporating social aspects into the decision-making process. The research objectives include the following:

1. Develop a conceptual-theoretical framework for identifying community characteristics to determine key needs and considerations for microgrid adoption (Chapter 2):

RQ1: What key community characteristics determine the engagement and successful operationalisation of community microgrids?

RQ2: How do different dimensions of social capital (structural, cognitive and relational) influence community capability and the type of microgrid system adopted?

RQ3: How can the conceptual-theoretical framework based on social capital theory be operationalised as a practical tool for guiding community microgrid projects?

2. Develop a Multi-Criteria Decision Analysis (MCDA) framework that integrates social capital for evaluating and selecting business models for community microgrids (Chapter 3):

    RQ4: How does integrating social capital into the MCDA framework enhance the evaluation of community microgrid business models?

    RQ5: What is the systematic categorisation of business models that can be facilitated by the MCDA framework to ensure alignment with local energy markets?

    RQ6: How can the MCDA framework serve as a decision-support tool to bridge operational and technical aspects of microgrids with a socio-economic context?

3. Propose an integrated methodology using social capital for embedding and assessing social factors in the operation of community microgrids (Chapters 4 and 5):

    RQ7: How can the operation of community microgrids be optimised based on the community's social fabric?

    RQ8: What are the key performance indicators that can evaluate the social capital post-optimisation?

    RQ9: How do different electricity tariffs affect social behaviour and fairness when implemented within various business models?

4. Design multifaceted strategies that enhance community capabilities and inform policy decisions, ensuring the sustainable and effective deployment of community microgrids (Chapters 6 and 7):

    RQ10: How can community capacity-building strategies be designed to effectively leverage and enhance social capital for the successful implementation and suitability of community microgrids?

    RQ11: How can the conceptual and analytical findings from the framework in previous chapters be translated into actionable policy recommendations for community microgrid implementation?

1.4 Research Methodology and Design

This thesis is inspired by the interdisciplinary nature of community microgrids and draws on various methods and theories, intending to present an in-depth analysis of community microgrids. The research design adopts a four-layered conceptual framework to address the intrinsic aspects of socio, economic and technical factors, viewed in Figure 1.1.

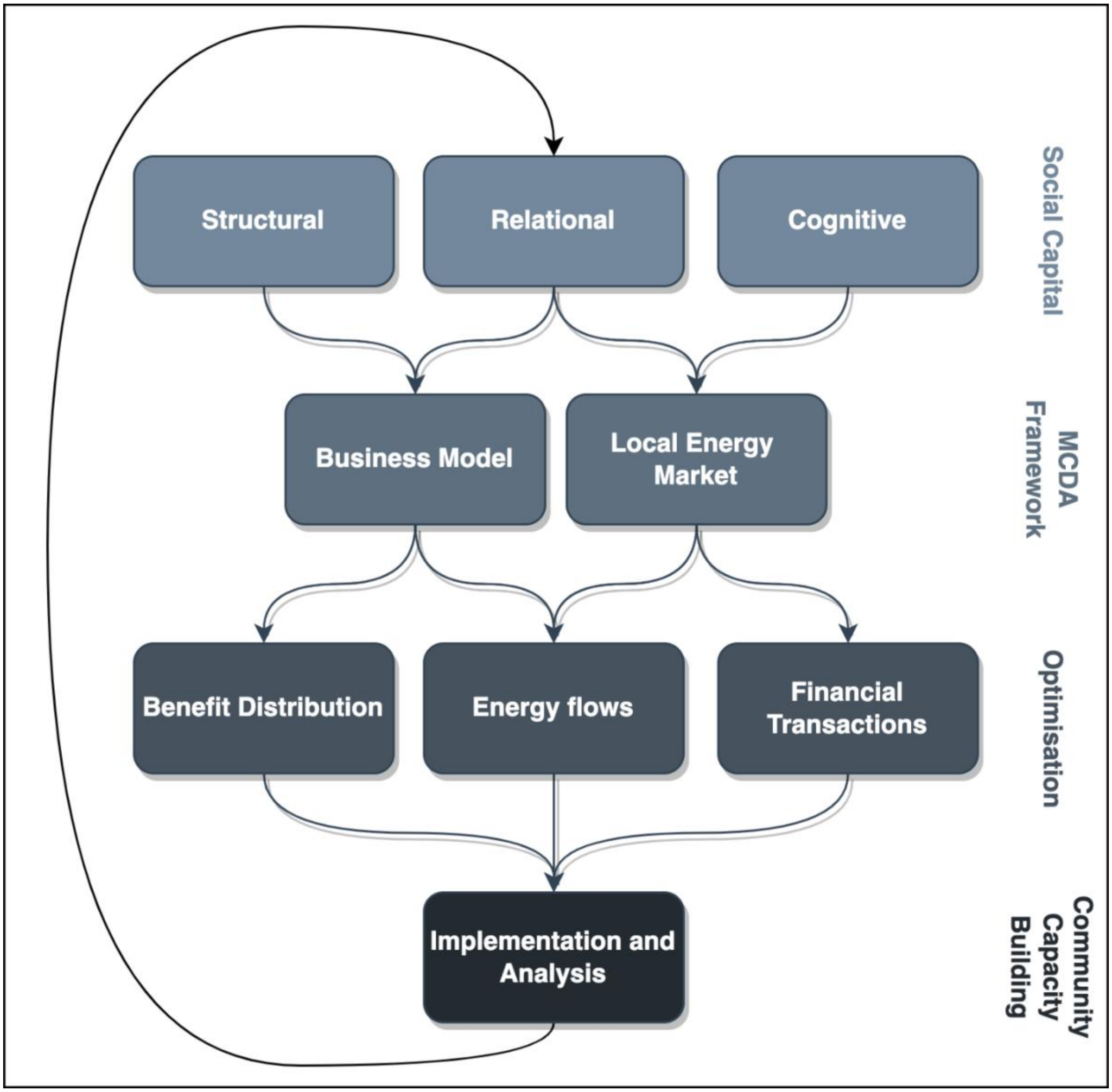

Figure 1.1. Conceptual Framework for Community Microgrid Development (CMD).

The primary level (Social Capital) of this conceptual framework focuses on identifying and evaluating community characteristics, specifically unravelling the complex social dynamics within community microgrids. This foundational layer employs a mixed-method approach [61], incorporating qualitative interviews and a quantitative survey anchored in social capital theory [62]. The social capital theory provides a framework to understand the community's structural, relational, and cognitive dimensions, ensuring a comprehensive assessment of the community's social fabric [63]. This level sets the context for understanding the social aspects critical for the subsequent levels.

The second level (Business Models) involves analysing potential ownership and governance structures for community microgrids and comparing their structural, relational, and cognitive social capital requirements with the community's measurements from the first level. Multi-Criteria Decision Analysis (MCDA) [64] is employed to evaluate and compare different business models, ensuring that the selected model aligns with the community's social capital. This level integrates the understanding of social dynamics with techno-economic and governance considerations, ensuring that the design and operation of community microgrids are socially aligned and economically viable.

The third level (Optimisation) incorporates decision-making outputs from the second level to optimise the operation of the microgrid. It focuses on understanding benefit distribution, financial transactions among participants, and energy flows. Mixed-integer linear Programming (MILP) techniques [65] are employed to ensure efficient operation, while energy justice theory [66] is applied to discuss the fairness and equity of the microgrid's operations. This level ensures that the technical efficiency of the microgrid does not come at the expense of social equity, and any significant changes in social capital are addressed by refining the business model to better fit the current state of the community's social fabric. This adaptive approach ensures that microgrid development remains dynamic and responsive to the community's needs.

The fourth level (Community Capacity Building) leverages community-capacity building theory [67] and ties together the previous levels to provide inclusive and actionable strategies. This level offers a deeper context on how the previous levels interconnect to collectively empower communities, develop community microgrids, and incorporate engagement strategies and capacity-building activities. By understanding and enhancing the community's capacity, this level ensures that the community microgrids are not only technically efficient and economically viable but also socially inclusive and acceptable to the communities they serve.

In summary, by adopting the four-levelled conceptual framework for the assessment of social capital, the evaluation of compatible business models, and the optimisation of operations, we seek to foster a more nuanced understanding of the interplay between social, economic, and technical factors in community microgrids. This understanding is expected to guide the development and operation of community microgrids that are not only technically efficient and economically viable but also socially inclusive and acceptable to the communities they serve.

To achieve these objectives, the research employs a combination of real-world and experimental case studies to test and validate the proposed frameworks. A single case study of a remote Australian community is used in Chapters 3 and 6 to provide continuity in exploring business model evaluation and community capacity-building strategies. In contrast, Chapters 4 and 5 utilise experimental case studies to examine the proposed frameworks under varying conditions, offering insights into their scalability and adaptability

1.5 Key Contributions of the Thesis

There are several major contributions in this dissertation that enhance the understanding of how social aspects can be incorporated into decision-making processes in the design and operation of community microgrids and their interrelations. The contributions to science and their impact on communities, industry, and policymakers are highlighted below.

1.5.1 Contributions to Science

This thesis employs interdisciplinary approaches to community microgrid development and implementation, contributing to scientific knowledge by introducing new methodologies and techniques. These methods incorporate innovative ways to quantify and process qualitative community knowledge, emphasising the integration of social science within the field of engineering:

- **Development of a Multi-Level Conceptual Framework:** The thesis introduces a comprehensive, multi-level conceptual framework that integrates social capital theory to the design and operation of community microgrid. This framework is novel in its approach to systematically account for social, technical, and economic dimensions affecting microgrid adoption and success. The rigorous conceptualisation of social capital within this context advances the understanding of how community dynamics influence energy solutions. It provides both qualitative and quantitative assessment and understanding of the community's social fabric through the developed Social Capital Index (SCI) and its applications.

- **Operationalisation of Social Capital in Microgrid Design:** By applying social capital theory to assess and integrate community characteristics into microgrid design and operation, the thesis provides a methodological advancement that allows for more effective and socially inclusive energy solutions. This operationalisation includes the methods for optimal business model selection and of key performance indicators for post-optimisation analysis, which are critical for evaluating the impact of social factors on microgrid efficacy.

1.5.2 Contributions to Impact Area (Communities, Industry and Policy Makers)

Furthermore, this thesis offers practical contributions to communities, industry, and policymakers by delivering enabling frameworks and tools derived from scientific contributions. These frameworks and tools are designed to be operationalised, facilitating the implementation of community microgrids and supporting informed decision-making processes. By bridging the gap between theoretical research and practical application, this work aims to empower stakeholders and promote sustainable energy solutions:

- **Frameworks and Tools for Community Empowerment:** The frameworks and tools developed in this thesis are designed to enable communities to design, operate and govern their microgrids effectively. The policy dashboard is freely available for communities, providing them with resources to enhance their energy systems and promote local engagement.

- **Enhanced Understanding and Guidance for Industry and Policymakers:** The research provides industry stakeholders with insights into the socio-technical complexities of community microgrids, helping them develop solutions that are sound and socially acceptable through various frameworks and decision-support tools. Lastly, the frameworks and tools from this thesis offer policymakers evidence-based guidance to create supportive policies that foster the development and sustainability of community microgrids.

1.6 Organisation of the Thesis

This thesis is written as a 'thesis by compilation' and comprises a collection of papers. It is structured to systematically address the complexity of the design and operation of community microgrids through a series of interconnected chapters, each contributing to different aspects of the overall research framework. The flowchart below (Figure 1.2) illustrates the organisation of the thesis, where grey boxes indicate the main contributions at various stages of the CMD framework.

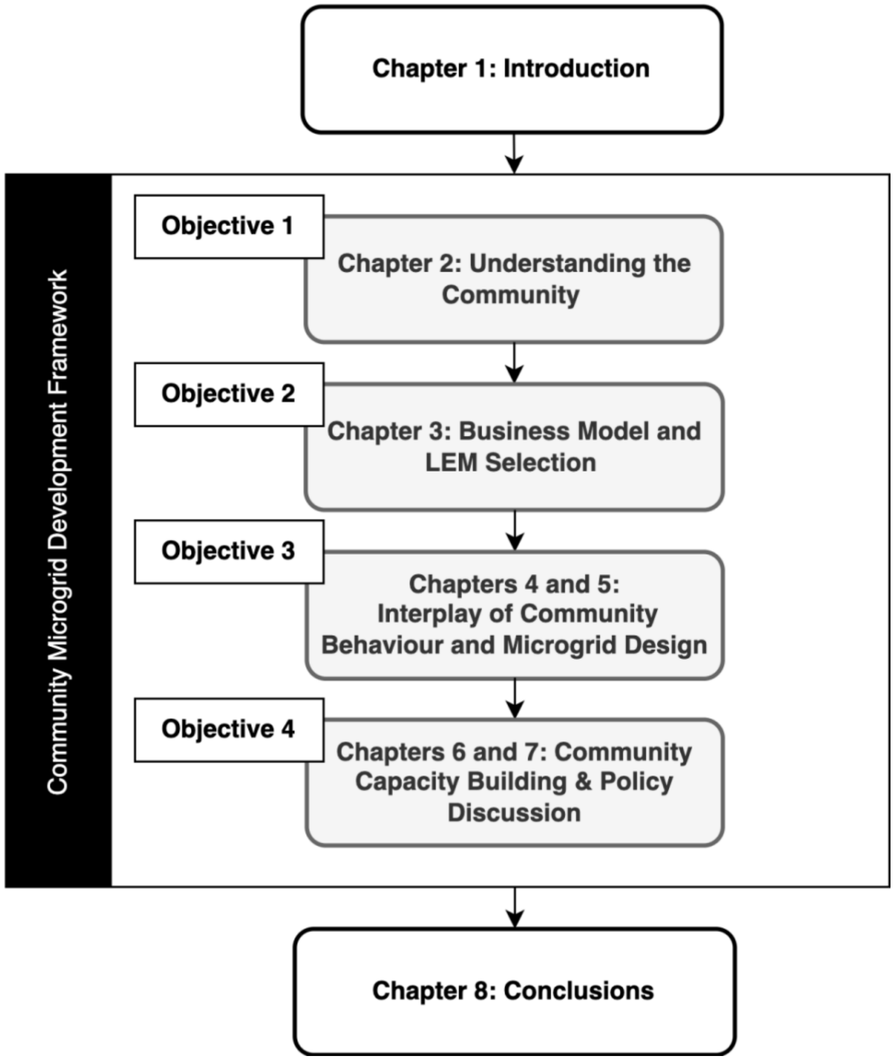

Figure 1.2. Flowchart of thesis structure where grey boxes indicate the main contributions.

Chapter 2: **Social Capital Assessment and Community Typologies**

This chapter is connected to the first level of the CMD and delves into the assessment of social capital in community microgrids. First, a comprehensive introduction to community microgrids is provided, placing them within the broader socio-technical landscape. It also provides a background on the relationships between community microgrids, energy communities, and community energy. Key technical components of microgrids are summarised, followed by an exploration of the social aspects as covered in existing literature. This review enhances our understanding and sets the foundation for subsequent chapters before exploring the dimensions of social capital, such as structural, relational, and cognitive, and presents a framework for understanding community types based on their social capital characteristics. This analysis contributes to the development of a comprehensive understanding of social dynamics in community microgrids.

Chapter 3: Business Model Evaluation and Alignment

Building on the second level of the CMD, this chapter focuses on analysing potential business models and their compatibility with local energy markets. It examines various business models and their requirements in terms of social capital, aligning them with the community's social capital assessment conducted in Chapter 2. This analysis assists in selecting the most suitable business model for the community microgrid.

Chapter 4: Evaluating the Interplay of Community Behaviour and Microgrid Design

This chapter provides the third level of the CMD and provides further refinement for assessing the optimal BM for community microgrids through an integrated methodology and MILP optimisation. The methodology builds upon the foundation of social capital theory established in Chapter 2 and BM assessment from Chapter 3. It further integrates a new set of Key Performance Indicators (KPIs) designed to enhance the analysis of community behaviour and the impact of microgrids.

Chapter 5: Fairness Analysis of Electricity Tariffs and Business Models

This chapter extends the methodologies and findings of Chapter 4, broadening the analysis to encompass a wider array of tariff structures for the business models previously evaluated. Additionally, it expands the analysis to include energy justice theory to offer new insights into community behaviour and fairness, enhancing the model developed in Chapter 4.

Chapter 6: Community Capacity Building for Microgrids

This chapter investigates the role of community engagement and capacity building in community microgrid projects. It is the fourth and last level of the CMD and builds on the three previous levels. A community capacity-building approach is developed and tested through a case study that draws on a real-world scenario to highlight the significance of these factors and provides insights into effective strategies and practices for empowering communities to participate and benefit from microgrid initiatives. The findings contribute to enhancing community involvement and fostering sustainable microgrid development.

Chapter 7: Sandboxing Tool for Policy Discussion

This chapter synthesises the frameworks developed in previous chapters and introduces a platform to facilitate policy discussion for community microgrids. The platform is also developed as a dashboard and sandboxing tool for communities and other stakeholders, enabling them to make their own decisions and providing support through an interactive and customised approach for further development.

Chapter 8: Conclusion and Future Research

The final chapter presents the conclusions drawn from the study and provides future research directions. It reflects on the findings and highlights the remaining work to be completed.

2 Understanding the Community in Community Microgrids: A Framework for Better Decision-Making

Preamble

Paper Status

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Overview

In Chapter 2, the goal is to establish the foundation for the research and develop a comprehensive approach that centers on the social fabric of communities in the design of community microgrids. This chapter introduces the first level of the conceptual CMD framework, which serves as the overarching research design framework for the thesis.

The chapter begins with a literature review, examining how social factors are included, represented, and applied in the context of community microgrids. This review serves as the basis for our theoretical exploration. Following the literature review, we conduct a qualitative analysis using Social Capital Theory (SCT). SCT helps synthesise the literature review findings, providing a framework for interpreting and integrating these insights. We then develop a conceptual-theoretical framework to guide the planning, design, and operation of community microgrids. This framework integrates social structures directly into the decision-making process and includes four key components: social capital, community capability, community type, and microgrid impact. By evaluating social capital in its structural, cognitive, and relational dimensions, we assess community capability and determine community types, influencing the microgrid's impact.

Finally, an initial step in operationalising this framework is presented through a practical tool using an SCT-based metric. This tool measures and interprets distinct social factors within communities, facilitating the classification and benchmarking of different community types.

While the primary focus of this chapter is to establish the foundational framework, it also sets the stage for understanding the socio-technical complexities of community microgrids. In the following chapters, we will explore how the framework and tool can be adapted, expanded, and integrated into various aspects of community microgrid projects.

Abstract

A community microgrid comes with the introduction of non-conventional distributed renewable energy infrastructure, affecting the behaviour of community members and their relationship with energy. The aspects of ownership, trust, collaboration and its often-discursive structure will be reflected in the cultural and social factors, such as norms and values in a community. The success of specific community microgrids is widely dependent on the community's ability to engage in various activities connected to the microgrid installation and operation. This paper conceptualises existing literature on community microgrids, focusing on the representation and inclusion of community preferences, needs and behaviour across the development stages. From this analysis, a conceptual-theoretical framework is proposed based on social capital theory for identifying community characteristics to determine key needs and considerations for microgrid adoption. The framework is divided into four components: *social capital*, *community capability*, *community type* and *microgrid impact*. Social capital, including its dimensions such as structural, cognitive, and relational capital forms the foundation of the framework and serves to evaluate the community capability and determine its type, which in turn affects its impact on the community microgrid. Finally, we present an initial step in operationalising our conceptual framework as a practical tool to guide further research in the development of community microgrids. Ultimately, this research can benefit both academia and industry by providing a comprehensive and practical approach to understanding the importance of social factors in community microgrid success.

2.1 Introduction

As the world moves towards a more sustainable future, the demand for renewable energy systems is increasing significantly [68]. This heightened demand has ignited a transformative shift towards distributed and decentralised energy systems, redefining the traditional centralised energy paradigm [1]. In this new landscape, community microgrids have emerged as a promising option for achieving localised energy balance and enhancing the integration of renewable energy sources (RES) [7]. Community microgrids are small-scale energy networks that can operate independently or in parallel with the main grid and provide reliable, sustainable, and resilient energy supply to specific communities. These systems encompass interconnected loads and distributed energy resources (DER) to enable efficient energy production, consumption, and management [69].

By incorporating diverse DERs, community microgrids enhance energy resilience and flexibility [53]. They reduce dependence on a single centralised power grid, which enhances community security against grid failures, blackouts, or natural disasters [70]. In the event of disruptions, microgrids can continue providing power, ensuring a consistent energy supply for critical facilities and essential services [71]. Additionally, community microgrids offer cost-saving advantages by reducing infrastructure costs. Through localised energy generation and distribution, the need for extensive transmission and distribution infrastructure upgrades is minimised, leading to more affordable and efficient energy systems [72]. However, realising these objectives is not a straightforward process [73].

The planning and design of community microgrids involve a complex interplay between various actors across different scales [22], each bringing their own perspectives and goals to the table [36]. These actors, with their diverse perspectives and goals, shape the organisational structure, strategy, and behaviour of the microgrid within the community [74]. As some members may benefit more from the microgrid than others, differences in perspectives and priorities may result in conflicts [38]. Additionally, the actions of individual community members can have both positive and negative impacts on the microgrid, as well as on other members of the community [24]. Positive impacts might include increased energy efficiency or bolstering communal resilience, whereas negative impacts might involve excessive energy use or resistance to necessary changes, affecting overall microgrid performance and community dynamics [24].

Previous studies such as [26], [27], [75] have emphasised the strong connection between the effectiveness of community microgrids and the social factors that influence them. Studies have also highlighted that a lack of community involvement can impede the microgrid's resilience, leading to low participation and engagement [8]. To ensure the successful integration of community microgrids, it is crucial to align the design with the behaviour and social factors of the community. For instance, tailoring the ownership and governance structures, physical design [36], and operational strategies to reflect the unique characteristics and aspirations of the community can enhance the microgrid's acceptance, participation and overall effectiveness [74]. Failure to do so can result in the microgrid not reaching its full potential and intended purpose, as highlighted in studies [56], [76].

Implementing community microgrids comes with inherent challenges due to the diverse nature of communities [77]. Each community possesses its own distinct attributes, such as geographical location, demographics, and cultural fabric, which necessitates the adoption of technical standards and practices to meet their specific needs [74]. Making it difficult to establish frameworks that suit different community microgrids [74]. The social interaction of the members within the community is a critical aspect that is often overlooked in the design and implementation of community microgrids. The success of a microgrid also depends on societal interaction, which needs to be emphasised during the design process [78].

While previous research has underscored the importance of considering social factors and their influence on community microgrids, it is important to acknowledge that research in this area remains relatively limited compared to the predominant focus on techno-economic aspects [78]. The absence of comprehensive considerations of social factors poses challenges to the successful integration of community microgrids [79]. For example, the potential for conflicts between community members, a lack of trust in the microgrid's ability to meet their energy needs, and low participation levels can all hinder the system's potential. Additionally, failing to take into account the unique social dynamics and characteristics of the community, such as community preferences and goals [25], can result in a microgrid that does not align with the needs and behaviours of its members [80].

The aim of this paper is to bridge this gap by proposing a comprehensive approach that makes the social fabric of communities central for the design of community microgrids.
In this effort, the contributions of this paper are to:

1. Introduce the Social Capital Theory (SCT) as a lens to gain insights into community structures and their roles in microgrid settings.
2. Develop a theory-based conceptual framework to serve as a guide for future planning, design, and operation of community microgrids. The framework connects social structures directly to the decision-making process, fostering a more integrated approach.
3. Present an initial step in operationalising our conceptual framework as a practical tool using an SCT-based metric that measures and interprets distinct social factors within communities, allowing for classification and benchmarking different community types.

This research takes an exploratory approach combining technical and social perspectives with the goal to design and operate community microgrids in a way that maximises benefits for the community and outside stakeholders. The first step of our research involves a literature review, using keywords that reflect the topics connected to social factors in community microgrids, such as "community microgrid", "community energy", "energy cooperatives", "energy citizens", and "community engagement". We examine the inclusion and representation of social factors and how these factors are framed, interpreted, and applied. This serves as the basis for our theory-based conceptual framework, guiding us in defining and elucidating the social factors which make up the social fabric of communities. Subsequent to the literature review, we delve into a qualitative analysis, using SCT as a theoretical lens. This provides us with a theoretical framework to deepen our understanding of community social dynamics and their influence on community microgrids. Consequently, SCT assists in the synthesis of the literature review findings and serves as a foundation for developing the framework and the first step to its operationalisation. In essence, SCT provides us with a tool for interpreting and integrating the results of the literature review and a basis for the development of our framework.

Continuing, this paper is structured as follows: Section 2 provides a definition and overview of the community microgrid concept. In Section 3, previous research on community microgrids is reviewed, with a focus on the consideration of social factors. Section 4 provides an overview of the key concepts and principles of SCT. Section 5 explores the connection between community microgrids and SCT. The conceptual framework is presented and discussed in Section 6, along with its operationalisation to inform future research and practice. Finally, in Section 7, we present our conclusions and suggest directions for future research.

2.2 Definition of Community Microgrid

The concept of microgrids has a long history dating back to the late 19th, a period characterised by a decentralised approach to power generation [1]. However, the idea of small-scale distributed generation was short-lived and largely disregarded in favour of the centralised grid structure that emerged to meet the growing electricity demand [12]. The term microgrid itself was reintroduced into the energy dialogue in the late 20th century, propelled by technological advancement, growing environmental concerns and the desire for increased energy resilience and independence [1]. As defined by the US Department of Energy (DOE) [7]: '*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode*'.

Evolving from this foundational understanding of microgrids is the construct of community microgrids a concept intertwining the principles of community energy, energy communities and microgrids. Energy communities are characterised by a group of stakeholders, usually local residents, businesses, or institutions, who collaboratively produce, consume, and distribute energy [35]. They are rooted in the principle of local and democratic participation and often operate under the guiding ethos of benefitting the community rather than maximising profits [36]. Community energy is a broader term that encompasses the efforts made by local communities to reduce energy consumption, increase energy efficiency, and adopt renewable energy generation [37]. This approach actively involves the local community in energy management to create social and environmental benefits [23]. Community microgrids are essentially microgrids tailored to match the unique energy needs, goals and characteristics of local communities [81]. They can be based in various geographical settings such as rural, remote, or urban areas, and encompass diverse types of loads that range from residential and commercial to critical and non-critical. The scale of community microgrids can vary as well, from smaller neighbourhoods and business centres to larger university campuses and municipalities [22].

Both energy communities and community energy concepts are inherently linked with community microgrids [82]. A community microgrid can serve as a physical infrastructure that enables the operation of an energy community, allowing local energy resources to be shared and managed [35]. Similarly, community microgrids can be seen as a tool to implement community energy strategies, providing localised energy systems that align with the community's goals and values [36]. However, it's important to note that while there is substantial overlap, these terms aren't interchangeable. An energy community or a community energy initiative may exist without a microgrid [83]. Technically, a community microgrid can function without the associated community engagement, although it can be argued that it would miss a significant opportunity by doing so [8].

Continuing, the concept of community in community microgrids is complex and has evolved over time [73]. A systematic review of the term "community" in community energy systems by Bauwens et al. [82] found that the meaning of the term has changed, with a shift away from the idea of community as a process that emphasises participation to being primarily defined as a physical place. This suggests that the transformative, collective, and grassroots participation aspects of energy transition in communities have been overlooked in favour of a more instrumental approach [82].

In light of these findings, the definition of community microgrids proposed by Warneryd et al. [22] provides a useful framework and is adopted in this paper. According to their definition: 'A community microgrid is technically a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries which acts as a single controllable entity with respect to the grid. A community microgrid can connect or disconnect from the grid to enable it to operate in both grid-connected or island-mode.

Moreover, a community microgrid is connected with its community through physical placement and can be owned by said community or other part.' [22].

The definitions and concepts discussed above are summarised in Table 2.1 for easy reference.

Table 2.1. Summary of key concepts and definitions

Concept	Definition	Reference
Microgrid	A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.	[7]
Community Microgrid	A community microgrid is technically a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries which acts as a single controllable entity with respect to the grid. A community microgrid can connect or disconnect from the grid to enable it to operate in both grid-connected or island-mode. Moreover, a community microgrid is connected with its community through physical placement and can be owned by said community or other part.	[22]
Community Energy	Projects where communities (of place or interest) exhibit a high degree of ownership and control of the energy project, as well as benefiting collectively from the outcomes (either energy-saving or revenue-generation)	[84]
Energy Community	Energy communities are organised groups that facilitate collective and citizen-driven actions in the field of energy, with the primary objective of advancing the transition towards clean energy while placing citizens at the forefront.	[74]

2.2.1 Assets, Actors and Activities

Community microgrids involve a range of key activities, actors and assets that contribute to their functionality and impact. These include the integration and utilisation of DER, energy exchange among community members [39], the emergence of the prosumers [85], and the operation and management of the microgrid [6]. Within this context, DER forms a fundamental component of community microgrids. DER encompass various decentralised energy generation technologies, such as solar panels, wind turbines, small-scale hydroelectric systems, and combined heat and power (CHP) units [86], as well as energy storage systems like batteries [87] and pumped hydro storage [88]. This integration of DER enables community microgrids to leverage the introduction of local RES (Renewable Energy Sources), reducing dependence on centralised fossil fuel-based power generation [32]. For example, the energy storage systems within DER play a critical role in optimising the management and utilisation of RES, enabling the storage of excess energy during low-demand periods for later use during peak demand or when renewable generation is insufficient [6]. This comprehensive approach enhances the reliability and flexibility of community microgrids, ensuring a stable energy supply [89].

Central to this concept is the role of "prosumers", individuals or entities actively participating in both energy consumption and production [85]. Community members can become prosumers by generating their own energy through DERs, which can be used for their own needs, with surplus energy potentially feeding back into the microgrid [10]. This aspect is further related to the unique potential for energy to not only be consumed but also exchanged or traded among community members [3]. Energy exchange or trading is facilitated and structured through various methods [90], often reflecting the governance and regulatory frameworks of the microgrid, as well as the community's preferences and goals [91]. It may adopt a collective model where pooled resources are redistributed among members [43]. Alternatively, it may operate on an individual level, where surplus energy is traded within the community microgrid, effectively creating a local energy marketplace [92].

Information and communication technologies (ICTs) have a central role in supporting microgrid activities. ICTs are a collection of systems and tools that facilitate information sharing, communication, and overall operational efficiency within the microgrid [93]. A central component of the ICT structure is the microgrid central controller (MCC), which coordinates the operation of the microgrid [53]. The MCC coordinates energy production from DERs, while maintain the load balance of the community, ensuring stability within the microgrid [6]. Smart meters are another component of the ICT structure, supporting the overall operation of the community microgrid [53]. Smart meters provide real-time data on energy consumption and generation of each member, which is essential for energy exchange or activities such as demand-response programs [94].

While the community microgrid's operations may include energy generation, storage and distribution, they extend to other activities which may be managed by diverse actors within the microgrid [83]. Community members, public and private organisations, utility companies, and local governments are included in the possible participants [22]. Their responsibilities can range from overseeing energy production, ensuring efficient distribution, monitoring system and performance to managing transaction and guaranteeing regulatory compliance [22]. The roles and responsibilities of these actors may vary depending on the structure and governance of the microgrid, which is further covered in Section 3.2.1. While community members can be differentiated between customers and prosumers, we continue to refer to both customers and prosumers as 'members' who participate in the community microgrid [22].

2.3 The Social View on Community Microgrids

In this section, we present a literature review on the role of social factors in community microgrids. We examine how these factors are represented, interpreted, and applied in the existing research, emphasising the contributions of collective action, local leadership, trust, and community identity throughout the microgrid implementation and development stages. These themes have been chosen for their demonstrated significance in shaping community dynamics in previous research, their prominence in the literature, and their considerable impact on the effectiveness of community microgrids.

2.3.1 The Importance of the Community and Social Factors

Cooperation and Collective Action

Community microgrids epitomise the principle of 'commons', presenting unique dynamics and challenges guided by collective action, shared resource management, and participatory decision-making. [95]. Here, 'commons' refers to the resources, that are shared, managed, and used by the community. The resource is primary energy, but it can also encompass other aspects of the community microgrid, such as DERs, the infrastructure supporting energy distribution, and decision-making processes [96]. This concept, originating form common pool resources (CPR), implies a shared responsibility for the resource's sustainability and the necessity of coordinated decision-making [97]. This concept underlines the importance of collective action and cooperation, especially in the context of RES which is managed and used by a community [98]. The extent to which a community microgrid operates as a 'commons' is directly influenced by the specific governance and ownership structures in place [49], which we further cover in Section 3.2.1.

The effectiveness of these systems, acting as a form of energy 'commons', is intricately tied to collective action and cooperation among community members. Wolsink [56] contends that collective action is necessary for the success of community energy projects as it enables community members to come together to achieve a common goal and helps to build a sense of shared purpose and commitment. Broska [24] supports this view, finding that collective action leads to community members taking ownership of the project and actively participating in decision-making.

In community microgrids, both energy sharing and trading are forms of cooperation that contribute to the overall effectiveness and success of the system [51]. While energy sharing focuses on the internal dynamics and local optimisation of energy sources within the community, energy trading may extend the cooperation beyond the microgrid boundaries, allowing the community to participate in the border energy market [90]. Yet, the 'commons' concept also brings challenges, particularly due to the inherent non-excludability of CPRs [39]. Energy consumption from CRPs in community microgrids can contribute to competitive tendencies, given the rivalrous nature of the resource use. This is due to the fact that energy used by one member can decrease the amount available for others, as the overall energy pool diminishes [99]. Such a situation might foster "free-rider" behaviour, which may lead to individuals becoming hesitant to further contribute to the community. The extreme scenario might even involve members leaving the community or hesitating to bear the costs of contributing if they believe others will benefit without contributing themselves [85]. Addressing these issues is not merely about physical connection and energy consumption patterns but involves a complex interplay of governance, cooperation and trust. If a community has a well-defined governance system, it can set clear conditions for membership and contribution, thereby encouraging fairness and minimising the risk of free-riding [96].

However, the process of managing these issues is intricate. The exclusion of a certain member could inadvertently reduce the resilience of the microgrid, disrupt its efficacy, and compromise its long-term sustainability [100]. Therefore, the community must work together, recognising the interconnectedness of the community and the critical role each member plays in maintaining the microgrid's resilience and stability.

Additionally, community members may also participate in a microgrid for various reasons, including self-interest and physical limitations [56]. As a result, barriers to participation and fair benefit distribution may arise depending on the specific community [101]. This is further validated in Sperling [102], which acknowledges that the successful implementation of community energy projects often depends on the specific context and the unique challenges faced by each individual community. Decision-making in community microgrids, therefore, hinges on balancing individual interests with the collective good [35].

Leadership

Focusing on the local members of a community, individuals can take on different roles and responsibilities desirable for community microgrids. The mindset, commitment and leadership characteristics of actors have been associated with successful community microgrid projects [73]. The constraints and opportunities for community microgrids are, therefore, highly affected by the behaviour and roles of these actors [23]. Some communities have local members with leadership roles that act as spokespersons, decision-makers, or managers for their communities. These actors have a central role in the community and require a high level of social cohesiveness [103].

Additionally, the level of support needed from external actors and stakeholders can vary based on the community's level of independence and experience [74]. As seen in Koirala et al. [51], it is important to have a network of social interactions and knowledge management in communities to support the adoption of community microgrid roles and responsibilities. However, community members often lack knowledge and awareness about community microgrids and their potential engagement in them, as highlighted in [56], [76]. This highlights the interplay between the community's capabilities and the feasibility and resilience of a community microgrid. However, the role of local leaders and institutions can also be crucial in promoting collective action and cooperation in community energy projects. Norouzi et al. [33] found that local leaders and institutions can help to facilitate communication and engagement between community members, stakeholders and partners, which can help to build trust and support for the project. They also play a key role in addressing and resolving conflicts that may arise during the implementation of community energy projects [41]. These local leaders can provide valuable resources and support that can help to ensure the long-term sustainability of the project [33].

Trust

The level of participation and engagement among community members is greatly influenced by the presence or absence of trust [37]. In this context, trust can be understood as community member's confidence in the reliability, truth, ability, or strength of different actors or conditions of institutions [48]. In particular, trust plays a crucial role in shaping the behavioural patterns and the long-term sustainability of community microgrids [27]. In other words, the ability of community members to trust each other in sharing resources, making decisions, and working towards a common goal is paramount for the system operation [104]. This mutual trust often reflects in the willingness of community members to actively participate in microgrid activities and initiatives, which consequently impacts the longevity and stability of the microgrid [35]. However, trust extends beyond internal dynamics within the community to encompass external factors, such as regulatory bodies, energy companies, and governing authorises [104]. For example, community members' trust in utility companies could manifest in the community's belief that these companies will deliver reliable service and act in the best interest of the community, such as fair pricing and rapid response to outages [103]. Trust in regulatory bodies may involve confidence in their ability to enforce fair policies that protect the community's interest [55]. Thus, to effectively implement and manage community microgrids, it is essential to understand the complexities and significance of trust in these contexts [25], [75].

Studies have demonstrated the indicate role trust plays in community microgrid projects, influencing peer expectations and the overall trust dynamic between actors [22]. Kalkbrenner and Roosen [105] found that trust played a mediating role in the effects of community energy projects. Moreover, trust can help to mitigate resistance and build support for community energy projects among community members, stakeholders, and partners. As Lennon et al. [41] argues, trust can help to overcome difficulties in achieving collective action and cooperation, which are essential components of successful community energy initiatives. Contrarily, a lack of trust among community members can result in a decline in participation and active involvement, as identified by Gangale et al. [4]. Walker et al. [27] further emphasises the importance of community engagement and active participation in decision-making processes in order to build trust and support for community energy projects. They found that communities with high levels of trust were more likely to develop and implement successful energy projects than those with low levels of trust and that a more participatory approach led to greater trust and confidence in developing community-owned projects [27].

Community Identity

The role of community identity in cooperative behaviour within energy communities and community microgrids is a topic of interest for researchers in the field. Several studies have found that norms related to the local area [75] and responsibility are major factors in shaping the behaviour of community members and are embedded in the community's identity [77], [98], [102], [105]. A strong sense of community identity and belonging, as argued by Wolsink [32], can be a powerful motivator for individuals to participate in and support community energy projects. This idea is supported by Van Veelen [52], who found that a strong sense of community identity leads to higher levels of participation and engagement in community energy projects.

However, the process of instilling a sense of community and shaping a collective identity can also present challenges, as highlighted by the study by El Gohary et al. [77]. The authors identified two main challenges: a lack of communication about the microgrid's existence and function and a lack of understanding of the basic electricity flows in the system. To address these challenges, the study argues that people need to adopt the role of energy citizens and become more democratically involved in the process. On the other hand, Kalbrenner and Rosen [105] suggest that community identity only has a positive effect on participation if it is backed by social norms and trust. The authors found that peer expectations and overall trust levels significantly impact the effect of community identity on participation in community energy projects [105]. Overall, these findings underscore the importance of trust and social norms in determining willingness to participate in community energy initiatives.

Summary

The success of community microgrids is closely related to the level of community participation and engagement throughout all stages of the process [51], including decision-making, planning [52], building, maintenance, monitoring [34], education, and governance [25]. Collective action and leadership are important factors in shaping the feasibility and resilience of a community microgrid [75], with local leaders and institutions playing a crucial role in facilitating communication and resolving conflicts. Trust is also a mediating factor in community energy projects [105], and high levels of trust are more likely to result in successful energy projects [4]. Community identity and norms related to the local area and responsibility are major factors in shaping the behaviour of community members and their participation in community microgrids [41].

2.3.2 Community and Social Factors in the Design and Planning Process

Ownership and Governance Structures

The ownership and management of community microgrids can vary greatly, from being owned and operated by utility companies, local members, third-party investors, or a combination of them [3]. Governance structures can similarly vary, encompassing energy cooperatives, corporations and no-profit associations [22]. The essence of ownership in this context extends beyond mere possession, it entails a source of control rights over the system [106]. For instance, community-owned microgrids may outsource the planning, construction, and operation of the system [49]. In such cases, even though the community has ownership, the decision-making and control might be distributed across external actors [107]. Additionally, while the community may own individual or collective DER, the physical network's ownership might still rest with the local utility company [22]. This underlines the complex nature of ownership, highlighting that different components can be owned and controlled by different actors.

Continuing, the varying governance and ownership models lead to different consequences for the community, including varying degrees of risk, return, and responsibility [58]. The study conducted by Gui et al. [34] is particularly noteworthy in this regard, as it evaluated the impact of different ownership and governance structures on community microgrid development, examining investment incentives and identifying optimal models for specific projects. Factors such as contract completeness, future demand for electricity, and level of uncertainty were found to play key roles in determining the optimal institutional structure. Moreover, the study presented a comparison of characteristics and emphasised the significance of the role of members and microgrid service providers in the choice of institutional structure. Their findings demonstrate that there is no one-size-fits-all approach to the design of control and management structures for community microgrids [34]. This conclusion is further reinforced by the work of Vandazina et al. [58], who conducted a review and classification of business models for community microgrids, emphasising the importance of selecting an appropriate model that aligns with community needs and characteristics. They present a conceptual framework that can be used to match these needs with the appropriate business model, though the paper is limited in its specificity of community characteristics. Casalicchio et al. [108] has also explored the impact of different business models on fair benefit distribution in community microgrids. However, this research falls short in considering the ways in which social factors within the community can impact this issue.

Continuously, community dynamics and power relations have been found to affect the level of participation and engagement in the ownership and governance of community microgrids [33]. This includes factors such as the composition of both producers and consumers, which can impact the feasibility of various governance and ownership models [83]. Wolsink [56] found that prosumers tend to prefer a peer-to-peer (P2P) model, while consumers with no generating capacity prefer models with low user effort or tariff incentives [56]. Additionally, the financial constraints of the community can also play a role in determining the feasibility of different ownership and governance [109]. For example, in emerging markets, communities may not have the funds to obtain full ownership of a microgrid [7], making mixed or third-party ownership more feasible options [58].

Furthermore, it is important to consider the potential challenges of communication and education on the microgrid's existence and function to ensure community members can become more democratically involved, as pointed out by [83]. Creating mechanisms for decision-making, conflict resolution, and compliance and ensuring that the governance structure is transparent and inclusive of all stakeholders [20] is crucial for the success of a community microgrid. A well-designed governance structure should provide for stakeholder coordination, negotiation, and control, reduce risks of uncertainty, and facilitate investments [14], [33]. Additionally, Wolsink [39] suggests that the socio-political layer of microgrid governance should serve as a foundation to support and encourage rather than suggesting a central and top-down control that adds to the hierarchy in power supply governance. This is particularly important as community acceptance has been shown to require high levels of member control over their systems [39], [56].

Lastly, it is important to note that both the endogenous and exogenous regulatory environment plays a significant role in the development and success of community microgrids [22]. While the endogenous regulatory framework within the community may dictate specific rules and governance structures [34], the exogenous legal and regulatory framework can either provide financial incentives or present obstacles in their development [3], [8]. In this paper, we do consider the impact of the endogenous regulatory environment on community microgrids. However, a detailed examination of the broader exogenous regulatory environment is outside the scope of this paper. Nevertheless, it is important to be aware of potential obstacles or opportunities and understand both the endogenous and exogenous regulatory environment when planning and designing community microgrids.

Technical Design and Operation

Research on community microgrid planning has primarily focused on optimising the technical and economic aspects to find the best design and operation of microgrids [110]. However, this emphasis on technical and economic optimisation has led to a lack of understanding and consideration of social aspects [78]. Studies such as [8], [34], [111] have specifically identified a lack of attention given to social objectives and community engagement and participation in microgrid design and planning. These social factors can be complex and difficult to understand, resulting in their underrepresentation in microgrid design and planning.

The use of available software tools, such as the HOMER Energy system, System Advisor Model (SAM) and Microgrid Design Toolkit (MDT), has been prevalent in microgrid optimisation. However, as noted by a review from Cuesta et al. [31], these tools often lack the capacity to incorporate social objectives such as community preferences and goals. This highlights the need for new tools and models that can account for both techno-economic and social factors in microgrid design and planning. While some researchers have attempted to incorporate social factors in the optimisation of community microgrids [80], such as considering the social value of resilience and the climate benefits of the microgrid for the community, these efforts tend to focus primarily on economic perspectives. They may neglect the social dynamics and characteristics of the community [8]. For example, Andersson et al. [112] considered the social value of resilience by quantifying the avoided outage costs and integrated the Social Cost of Carbon as a social constraint to consider the climate benefits of the microgrid for the community [112]. Even with this inclusion of social aspects, it could be argued that they are still too closely tied to an economic perspective.

When looking at research that has attempted to include the social dynamics and characteristics of the community, the methodology and characteristics typically lack documentation or do not clearly explain their impact on the technical design [78]. For instance, Suk et al. [79] developed a framework that used the community's social, technical, physical, and environmental characteristics as inputs to the technical model. The framework recognised the importance of using the community perspective to decide the importance of techno-economic parameters, but it lacked documentation of the characteristics and specification of their impact as decision-making and input parameters [79].

Summary

The ownership and management of community microgrids can greatly impact the community in terms of risk, return, and responsibility [34]. Community dynamics, financial constraints, and power relations also play a role in determining the level of participation and engagement in the ownership and governance of community microgrids [33]. The success of community microgrids relies on key aspects such as effective communication and education [102], decision-making [52], conflict resolution, and stakeholder coordination [113]. The regulatory environment can either provide opportunities or pose obstacles for community microgrids and should be taken into consideration [22]. Research on community microgrid planning has primarily focused on technical and economic aspects and lacks consideration of social aspects and community engagement. Existing microgrid optimisation tools often overlook social objectives, highlighting the need for new tools that can account for both techno-economic and social factors.

2.3.3 Identifying Research Gaps

It is clear that the social context of a community can greatly impact the effectiveness of a community microgrid, yet current research often focuses on individual social factors rather than taking a comprehensive view of the community's social fabric. An overview of this issue is presented in Table 2.2, which maps the extent to which reviewed literature integrates social factors in their analysis. A knowledge gap clearly persists with regard to these social factors, particularly on how to consider them in the design and operation stages and account for their impact on community microgrids. This narrow focus can result in microgrids that do not meet the needs and values of the community, leading to low adoption rates. For example, one key challenge is to design the community microgrid in a way that discourages free-riding or selfish behaviour and encourages active involvement and shared responsibility. This necessitates understanding the community's social dynamics and striking a balance that reflects these dynamics. To address this gap, research needs to focus on understanding and incorporating the social aspects of community microgrids in a more comprehensive manner. Considering this, SCT presents a promising direction for future research as it provides a framework for understanding the impact of social networks, norms and trust can impact community engagement and decision-making processes. While other theoretical lenses could be of relevance, we argue that SCT reduces the risk of focusing on isolated social aspects and failing to provide a complete picture of the social fabric. As seen in the next sections, we aim to contribute to the literature by investigating SCT as a foundation for better understanding and assessing the social factors in community microgrids.

Table 2.2. Overview of the social factors in the reviewed literature.

Trust	Cooperation	Collective Action	Social Norms	Attitudes and Values	Knowledge and Skills	Leadership	Social Networks	Identity	Responsibilit y	Social Cohesion	References
✓	✓	✓		✓	✓		✓		✓	✓	**[22]**
	✓										**[72]**
✓					✓				✓		**[73]**
✓	✓			✓	✓			✓		✓	**[36]**
	✓			✓	✓		✓			✓	**[8]**
✓	✓			✓						✓	**[76]**
✓	✓	✓	✓	✓	✓	✓					**[56]**
✓	✓		✓	✓	✓	✓	✓			✓	**[75]**
✓	✓		✓	✓	✓	✓		✓	✓	✓	**[26]**
✓	✓	✓			✓					✓	**[27]**
✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	**[25]**
✓		✓	✓	✓	✓			✓	✓		**[51]**
	✓	✓	✓		✓				✓		**[52]**
✓	✓								✓		**[34]**
✓		✓	✓	✓	✓	✓	✓	✓			**[24]**
✓	✓				✓		✓	✓	✓		**[102]**
✓		✓	✓			✓					**[97]**
	✓								✓	✓	**[85]**
	✓				✓						**[101]**
✓		✓	✓	✓	✓	✓	✓	✓	✓		**[103]**
	✓	✓			✓			✓	✓		**[33]**
✓	✓			✓	✓					✓	**[41]**
✓	✓	✓	✓	✓	✓		✓				**[37]**
✓	✓	✓	✓					✓			**[105]**
✓	✓	✓	✓	✓	✓		✓	✓		✓	**[4]**
					✓			✓	✓		**[77]**
✓	✓	✓	✓		✓	✓	✓		✓	✓	**[98]**
✓	✓	✓		✓	✓		✓		✓	✓	**[83]**
✓	✓		✓				✓	✓			**[39]**
✓	✓			✓	✓		✓			✓	**[113]**
	✓								✓		**[114]**
✓	✓		✓	✓		✓			✓	✓	**[115]**
✓	✓	✓	✓	✓				✓		✓	**[38]**
✓	✓		✓			✓			✓		**[23]**

2.4 Social Capital Theory

Social capital has been useful in understanding relationships and community outcomes, particularly the link between societal norms and values [62]. Researchers generally agree that social capital is multidimensional and includes factors such as trust, social cohesion, social identity, networks, norms, and values [116]. Coleman (1990) [117] viewed social capital as social structures that facilitate the actions of individuals based on the behavioural norms present in social groups [117]. Putnam (1992) [118] further developed this concept by defining social capital at the social level, focusing on communities and the networks of relationships between social groups that give rise to prosocial norms of trust, reciprocity, and cooperation. Social relations can be inward-looking, reinforcing exclusive identities and promoting homogeneity, or outward-looking, promoting links between diverse individuals [119]. Based on this, social capital can take the form of "bonding" social capital, which refers to internal social relations, or "bridging" social capital, which refers to external social relations [118], [120].

According to Nahapiet and Ghosal [121], social capital can be understood through three interrelated dimensions: structural, cognitive, and relational. Structural social capital refers to the visible social structures, networks, and rules that shape interactions within a society. It provides the foundation for other dimensions of social capital by establishing the structure for social interactions to take place. The cognitive dimension of social capital concerns shared values, beliefs, and norms within a community. It includes the social setting or cultures, shared understanding, and group interpretations or meanings. Relational social capital is intangible and refers to the nature and quality of relationships within a society. It includes assets such as trust, norms, obligations, expectations, and identities developed and utilised through relationships [121].

Building upon these foundational perspectives of social capital, research has introduced methods and tools to measure social capital. In particular, previous research on social capital has primarily relied on survey-based measures to assess the overall level of social capital within a community, focusing on the number and strength of social connections and the level of trust and cooperation [122], [123]. Over time, several measurement frameworks and tools have been developed to facilitate this. For instance, Putnam [120] proposed a state-level index comprising five categories: community organisation life, engagement in public affairs, community volunteerism, informal sociability, and social trust. This index used a total of 14 indicators, which were standardised and averaged to create a comprehensive measure of social capital [120]. Similarly, Onyx and Bullen [124] developed the Social Capital Questionnaire, which provides a neighbourhood-centric perspective. This questionnaire considers dimensions such as community participation and local safety perceptions. The World Bank [61] also introduced survey instrument tool introduced in 2004, primarily intended for measuring social capital in poverty households. Their conceptual framework consists of six dimensions; i. Groups and Networks, ii. Trust and Solidarity, iii. Collective Action and Cooperation, iv. Information and Communication, v. Social Cohesion and Inclusion and vi. Empowerment and Political Action. These six dimensions are broken down into structural (dimension i), cognitive (dimension ii.) and output measures (dimension iii.) of social capital [61], [125].

In our upcoming exploration, we will utilise the social capital conceptualisation based on Nahapiet and Ghosal’s framework [121] (see Table 2.3) to investigate how SCT can be used to identify community characteristics and key considerations for microgrid adoption. This chosen framework holds particular significance within the context of this paper as it offers advantages in simplifying the intricate interrelationships among the various dimensions of social capital. By distinguishing between structural, relational, and cognitive dimensions, this framework enables a more nuanced analysis, ultimately leading to a clearer understanding of the inherent social dynamics within community microgrids. Through this approach, we aim to shed light on the social fabric that underpins successful microgrid implementation and operation.

Table 2.3. Social capital dimensions from Nahapiet and Ghosal (1998) [121].

Social Capital Dimension	**Characteristics**	**Description**
Structural	Network structure Network ties Suitable organisation	Social structure
Cognitive	Shared narratives Shared codes and ethics	Shared understandings
Relational	Trust Norms Obligation and expectations Identification	Nature and quality of relationships

2.5 Applying Social Capital Theory to Community Microgrids

2.5.1 Cognitive Social Capital

The objectives of a community are shaped by the unique social and cultural context in which it operates. This means that different community microgrids may have different goals and priorities based on the specific needs and values of the community [8]. For example, a community microgrid in a rural area may have different objectives than a community in an urban setting [56], [74]. The rural community may prioritise energy independence and self-sufficiency [111], while the urban community may focus on reducing greenhouse gas emissions or increasing access to affordable energy [51]. Along with the geographical context, the social and cultural context of a community can also be influenced by factors such as the community history [102], demographics [3], and economic conditions [110].

The cognitive dimension of social capital, which encompasses shared values, beliefs, language, and narratives within a community [63], can play a crucial role in understanding the objectives and priorities of a community microgrid [24]. By gaining a deeper understanding of the community's shared beliefs and values, it becomes easier to identify and understand why certain objectives and priorities have been chosen. For example, the shared language and narratives of a community can provide insight into their views on the importance of different objectives [37]. The shared language and narratives of a community can also provide insight into their values and beliefs, such as the importance of local ownership and decision-making, which might be highly valued by communities as demonstrated in a study on the need for community-empowered, structures in renewable energy transitions [41]. The cognitive dimension of social capital can also help build trust and cooperation within the community. When community members share similar values and beliefs, they may be more likely to trust one another and work together to achieve the community's energy goals [63]. The shared language and narratives can also provide a sense of unity and shared identity within the community [126], which can facilitate cooperation and collaboration towards common goals [127].

Moreover, community microgrids can promote learning and knowledge-sharing among community members [51]. By providing a space for individuals to exchange ideas, experiences, and expertise, community microgrids can facilitate the formation of social networks and increase social learning [83], [128]. The development of shared knowledge and understanding can help to promote the adoption of new energy technologies, leading to the creation of shared narratives and beliefs about the benefits of renewable energy [105]. In conclusion, the cognitive dimension of social capital is a crucial factor in determining the objectives and priorities of a community microgrid. By understanding the shared language, values, beliefs, and narratives within a community, it is possible to tailor energy initiatives that effectively align with the community's unique social and cultural context, thus meeting the community's specific needs and values.

2.5.2 Structural Social Capital

The community structure is embedded in impersonal properties of the community, such as access to knowledge and information, communication linkages between actors and organisational structure for decision-making and participation [121]. Communities being entitled to decide upon their own microgrid infrastructure is shown to be essential for behavioural change and willingness to participate in community microgrids [56]. The decision-making in community microgrids directly influences the feasibility of collective action and cooperation [25], [56]. The capabilities required to achieve this will differ depending on the community structure [113].

Structural capital helps us to understand the community structure by identifying its roles, rules, precedents, and procedures. Memberships in local organisations, participation in decision making and social relationships within the community are important factors that foster cooperation [121]. Communities with democratic structures increase social interaction between their members and facilitate cooperative behaviour in community microgrids [24]. The density and connectivity of social interactions increase the accessibility of resources between members and empowerment to participate in a community microgrid [129]. This is further supported by the study conducted by Bush and McCormick [26] examining a community microgrid in Feldheim, which found that social capital played a significant role in the decision-making processes within the community due to the high level of social interaction and the number of memberships in local clubs [26].

The development of community microgrids can also have a transformative effect on the social structures of the community [83]. The creation of organisations or groups for participation in the microgrid can provide social structures and ties that foster further cooperation and trust. [27] This, in turn, can influence the establishment of networks and norms that encourage support and engagement [63]. In addition, communities with strong network ties and configurations facilitate better access to information and knowledge for individuals within the community [51], [116], [125]. It is especially important for community microgrids where individuals have different knowledge of energy systems and technology. Benefits such as information or assistance can be provided between individuals forming a solid network and communication structures [8], [22], [51], [114]. The structural dimension can therefore give information about the capabilities for empowerment and the ability to act collectively in a microgrid solution. The cohesiveness, breadth of participation and efficiency differ depending on the availability of information sharing and extracting knowledge to benefit the community and its members.

2.5.3 Relational Social Capital

The nature and quality of the relationships between community members will determine their likelihood to collaborate and the tendency to share knowledge and help each other [48]. Factors connected to the relational dimension have a strong connection to community members' behaviour [52]. Some communities may have strong social norms and obligations, and others may not be as distinctive. The level of trust within a community is a key factor in whether communities can pursue goals collectively [115]. It provides a deep understanding of the community and the level of cohesivity, which can help to prevent conflicts [39], [51], [116], [125]. Trust towards local government or businesses, such as utility owners, can further guide what type of community microgrid solution is feasible [39], [113].

Relational capital is further broken down into social connections to measure engagement within the community. Community microgrids that are able to build strong social connections among members are more likely to have higher levels of participation in energy-related initiatives [38]. The social need to be an active part of a community has especially been highlighted to be a motivator for participation in sustainable projects [24]. In addition, established cultures of cooperatives, local organisations and activities have been identified to contribute to the success of community microgrids. Cooperative behaviour can also be derived from past social interactions and identify the social distance between actors in the community [83]. Additionally, social norms, such as reciprocity and expectation of collaboration, play a crucial role in fostering cooperation among community members [37]. These norms can stimulate participation and contributions to the shared resources, which is essential for effective resource management [39]. Social norms can also help to establish a sense of shared responsibility among community members for managing these resources and facilitate communication and information sharing.

From a different perspective, community microgrids also serve as means to enhance relational social capital by creating opportunities for individuals to interact and engage with each other [37]. Community energy projects can bring together individuals from different backgrounds and perspectives, working together towards a common objective [24], thus fostering the development of new relationships and strengthening the sense of community [130].

2.5.4 Summary

The three dimensions of social capital - cognitive, structural, and relational - play a critical role in the feasibility and success of community microgrids. The cognitive dimension helps to understand the community's objectives and priorities by gaining insight into their shared beliefs and values [130], making it easier to tailor energy initiatives that align with the community's unique social and cultural context [80]. Structural social capital helps to understand the community structure, its roles, rules, precedents, and procedures [61], with communities having democratic structures and strong social ties being more likely to participate in community microgrids [24]. Relational social capital is crucial in determining the likelihood of community members to pursue goals collectively [98] and is dependent on the quality of relationships, level of trust, social norms and obligations, and level of cohesiveness [48]. By understanding these three dimensions, community microgrids may be planned and designed to effectively meet the needs and values of the community.

Furthermore, community microgrids have the capacity to impact and improve the social capital of a community [24]. By fostering cooperation and trust, it can transform the community's social structure and reinforce democratic structures and ties, resulting in a more cohesive and effective community [63]. In this way, community microgrids go beyond merely addressing energy needs, they can also strengthen the social fabric of a community.

2.6 A Social Capital-Based Assessment

This study focuses on the role of social capital in shaping the success of community microgrids. Through an analysis of previous research (Section 3) and an examination of SCT (Sections 4 & 5), we have concluded that the social fabric of a community plays a significant role in determining the adoption and success of these microgrids.

To answer the aim of this study, we have developed a theoretical-conceptual framework to provide a nuanced understanding of the community’s social fabric in relation to the planning and design of community microgrids. This framework is based on social SCT and recognises the crucial role of social capital dimensions, such as structural, cognitive, and relational capital, in shaping community microgrid success. The framework also considers governance processes, resource sharing and control, and the community's overall functioning and interests through collective action and social processes. As a result, community capability, defined as the interaction between different dimensions of social capital, is a critical factor in our framework for predicting the success of community microgrids. Additionally, we argue that ownership and management models should be designed with consideration for community type and participation. By identifying community types, specific challenges can be identified and addressed through the development of community microgrids and supporting interventions. The conceptual framework is further explained in subsequent sections below and in Figure 2.1.

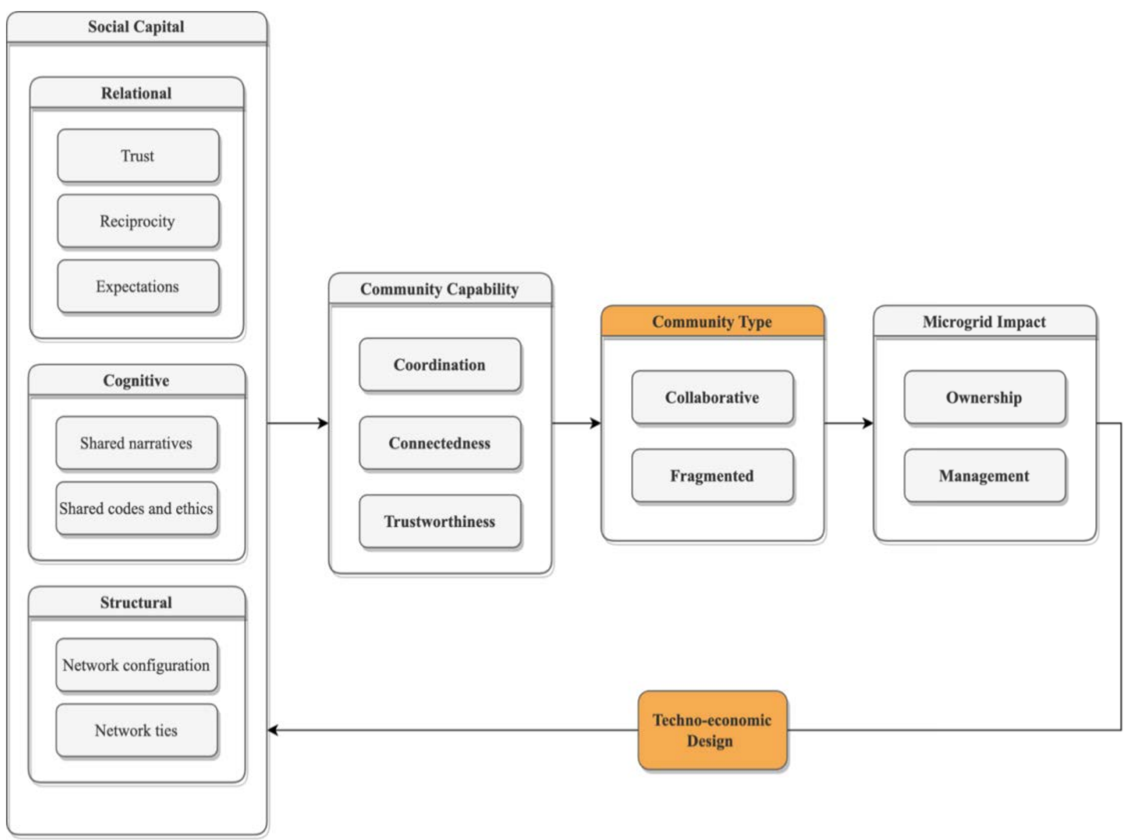

Figure 2.1. The conceptual framework linking the theoretical foundations of social capital to the impact on microgrid design.

2.6.1 Social Capital

Social capital is the theoretical foundation of our conceptual framework and provides a structured and collective understanding of the social aspects of communities. From Sections 4 and 5, we argue that by analysing the levels of cognitive, relational, and structural social capital within a community, insights connected to the community's social fabric can be extracted.

2.6.2 Community Capability

Community capability refers to the collective abilities, resources, processes, and roles of the community to work together effectively towards common goals and solve shared problems [131].. To evaluate community capability, it is important to consider the governance processes and factors that influence the sharing and control of assets and resources, as well as the functioning and interests of the community through collective action and social processes [130]. As discussed in Section 3, these considerations can provide valuable insights for the design and planning of community microgrids. Building upon this concept, George et al. [132], emphasises three interconnected elements of community capability: what communities have, how communities act and for whom communities act (Figure 2.2). This framework emphasises the importance of understanding the assets, actions, and beneficiaries within a community.

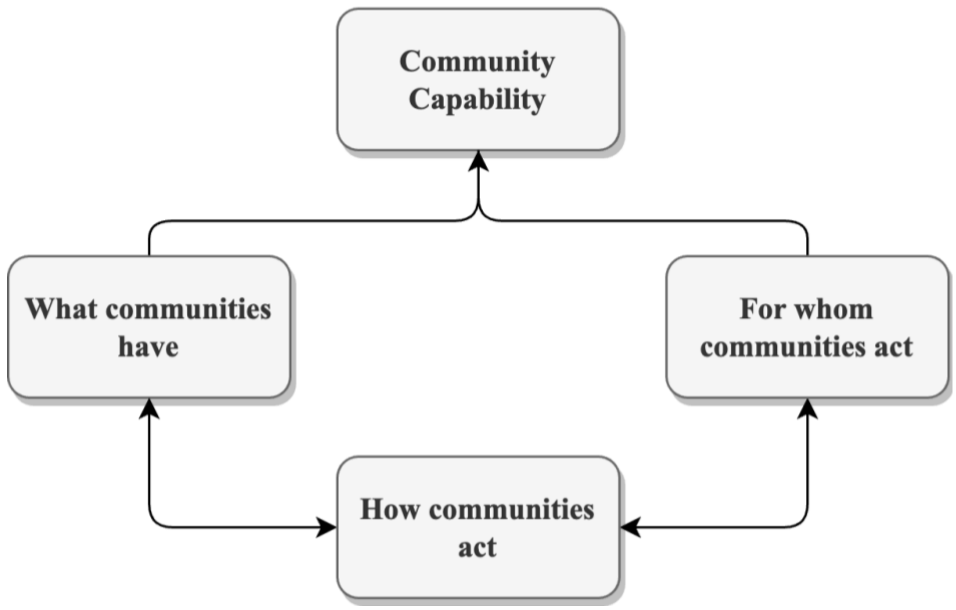

Figure 2.2. Illustration of community capability (Adapted from George et al. [132]).

To delve deeper into community capability, social capital can be utilised as a valuable tool. It offers insights into the community's effectiveness in collaborating, establishing and preserving social connections, and fostering trust and mutual understanding [37]. By assessing a community's social capital, one can obtain a better understanding of its ability to work together and attain common objectives [63]. For instance, high levels of cognitive social capital indicate the community is well-informed and capable of comprehending complex issues. High levels of relational social capital reflect strong social networks and high trust and cooperation among members. High levels of structural social capital indicate well-functioning institutions and a clear governance system. By analysing how these dimensions interact, a more comprehensive understanding of complex social factors can be achieved. This information can then be used to address any shortcomings in community capability, setting the project up for success. We categorise the capability to collaborate efficiently as "Coordination", the capability to build social connections as "Connectedness", and the capability to trust others as "Trustworthiness".

2.6.3 Community Type

In this study, we categorise communities as "Collaborative" or "Fragmented" to describe their community type. While our focus is on community dynamics, we draw inspiration from Pahl-Wostl and Knieper's [133] work on governance regimes to inform our categorisation. Their research examines different types of governance regimes, such as polycentric, fragmented, and centralised, which are based on the distribution of power and the level of coordination and cooperation within the governance system. Polycentric governance regimes are characterised by the distribution of power among various centres that effectively coordinate and cooperate with each other. These regimes promote experimentation, learning, and resilience in addressing challenges. On the other hand, fragmented governance regimes lack coordination and suffer from uncoordinated contradicting actions among decision-making centerers. The distribution of power and authority, without effective coordination can lead to inefficiency and infectives in addressing emerging challenges [133].

Within the context community microgrids, we refer to "Collaborative" as a situation where the community is functioning effectively and efficiently due to the presence of strong social capital [134]. In this case, there is high engagement and participation from community members, trust and cooperation between stakeholders, and effective communication and collaboration between actors involved in the microgrid [130]. "Fragmented" refers to a situation where the community is not functioning properly or effectively [135] due to a lack of social capital [63]. This can manifest in various ways, such as a lack of engagement or participation from community members, a lack of trust between different stakeholders, or a lack of communication and collaboration between different actors involved in the microgrid.

By analysing the social capital level present in the community, we identify whether a community microgrid is likely to be collaborative or fragmented [63]. We can use the concept of social capital to understand how well a community can adopt and utilise a microgrid, with the level of social capital within a community as a predictor of its ability to implement and operate the microgrid successfully. The level of social capital in a community is directly influenced by the strength of each dimension: Structural, Cognitive, and Relational. All three dimensions are crucial in driving the community towards a collaborative status. If any dimension weakens, it results in decreased stability and increased fragmentation within the community. It is important to recognise that the interplay among these dimensions is vital. Enhancing one dimension can positively impact the other two, fostering overall social capital and community cohesion. Figure 2.3 visually represents these intricate dynamics of social capital, emphasising the significance of each dimension and their collective influence on the community.

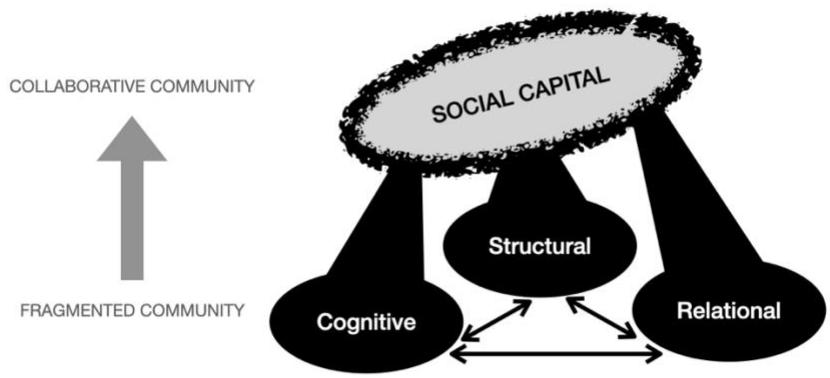

Figure 2.3. The relationship between social capital and community type.

2.6.4 Community Microgrid Impact

An important aspect to consider during this process is the ownership and governance structure of the microgrid [22]. The choice of ownership can also greatly impact the way the microgrid operates [56], as well as the level of community involvement and participation [23]. Different community types, such as "collaborative" and "fragmented", may require different ownership and governance structures for their community microgrids based on the level of social capital within the community. High levels of social capital, such as strong connections, good information flow, and trust among members, may foster cooperation and sustainable behaviour [22], [121]. Communities with these characteristics may be well-suited for community-owned microgrids [114], which can lead to greater engagement and participation from community members, as well as a greater sense of ownership and responsibility [75]. In contrast, communities with lower levels of social capital may benefit from third-party-owned microgrids, which can provide access to greater financial resources and expertise [34]. However, it is important to ensure that there is still transparency and communication between the third-party owner and the community, as well as mechanisms for community input and decision-making [8], [2]. The study by Broska [24] found a correlation between resources in social capital and locally funded community projects, which were also found to establish structures promoting cooperation and sustainable behaviour. To design effective systems that promote user acceptance, it is essential to align the ownership and governance structure with the specific needs and characteristics of the community [56]. Figure 2.4 serves as an illustration of the key elements found in cooperative community microgrids, highlighting the importance of trust, collaboration, and fair distribution of resources.

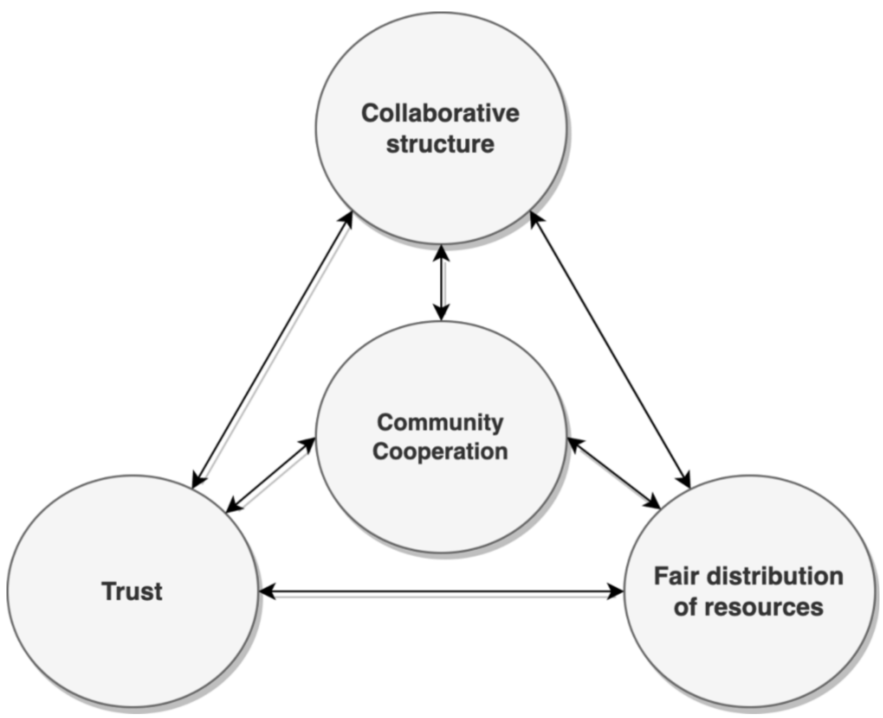

Figure 2.4. Illustration of key elements for cooperative community microgrids.

2.6.5 Techno-Economic Design

The ownership and governance structures may have a direct impact on the decision-making connected to the distribution of resources, the participation connected to the prosumer-consumer ratio and the energy flows within the community [34]. This, in turn, influences the technical design and overall feasibility of the community microgrid [114] based on the community type. For example, in a community-owned microgrid, community members may have the ability to produce and consume their own energy [114], leading to a more balanced prosumer/consumer ratio. In contrast, in a third-party-owned microgrid, the third-party owner may have more control over the energy production and distribution [34], leading to a more unequal distribution of energy resources.

Additionally, the techno-economic design also has a direct impact on the social capital dimensions and is a complex issue that requires careful consideration. On one hand, the introduction of community microgrids can promote community cohesion and foster trust, cooperation, and knowledge-sharing among members, positively impacting all components of social capital. On the other hand, it is important to acknowledge that the implementation of community microgrids can also have negative effects on the community's social capital. For example, it may lead to division and conflict if certain members feel that their interests are not being represented or if the community microgrid project is perceived as benefiting some members over others.

2.6.6 Operationalisation of Conceptual Framework: Social Capital Index

This section extends our exploration, into the practical application of our conceptual framework, as depicted in Figure 2.1, by describing the development of a potential first step towards its operationalisation in the context of community microgrids. We present the tool and its components and discuss how it can be applied to extract knowledge from data and inform decision-making in the development and implementation of community microgrids. The tool is intended to be a valuable resource for practitioners and researchers interested in understanding the social dimensions of community microgrids and promoting the success of such projects. To ensure that our tool is relevant and effective, we examined the usefulness of previous frameworks and measurement tools for assessing social capital. We also drew on the research and measurement tool developed by the World Bank [61] and in creating our tool. Through the operationalisation of our framework, we aim to bridge the gap between theory and practice and provide a more holistic understanding of social factors in communities and their importance in community microgrid development.

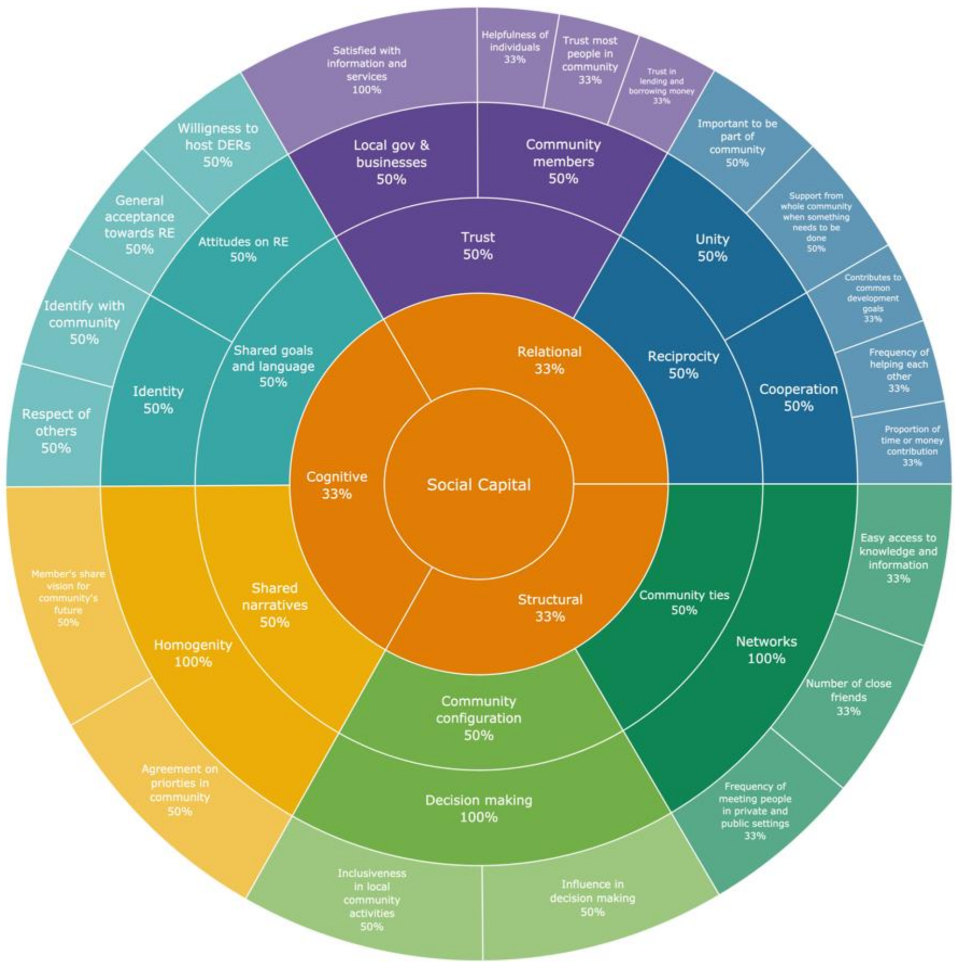

Figure 2.5. The community characteristics represent existing and potential resources that can be accessed through the community in each dimension of the social capital scale (the values are based on equal weighting, but can be variable based on user preference).

Due to the multidimensional and interdisciplinary nature of the social capital concept, we introduce a hierarchical scale of the core dimensions: structural, relational, and cognitive social capital. Each of these dimensions will be measured through a series of main and detailed indicators to derive an overall social capital index for community microgrids, as seen in Figure 2.5. More specifically, the foundation of the first two layers of our scale lies in Nahapiet and Ghoshal's established framework [63]. These layers represent the core dimensions and their corresponding factors, providing a robust theoretical basis for our model. The third and fourth layers, conversely, find inspiration in the World Bank's measurement tool. We use these layers to frame the indicators for each factor, creating a bridge to the outermost layer of the scale. The final layer is a unique amalgamation of our analysis of previous research on community microgrids and selected statements influenced by the World Bank's framework. This approach enables us to contextualise the scale, ensuring it's tailored to the context of community microgrids.

Following the World Bank's [61] survey tool methodology, our framework would utilise detailed surveys to extract data for each indicator. The outer layer of the scale offers example statements, deriving response categories suitable for the Likert scale, providing evenly distributed categories of responses across the social capital scale. We envision that these surveys would be administered by trained professionals during the preliminary stages of any prospective community microgrid project. For demonstration purposes, and to emphasise the significance of each dimension in shaping the overall social capital index, the scale in Figure 5 shows an equal weighting for all dimensions. However, we acknowledge that for any given application, the decision makers might have a different preference for the scales. For this reason, our tool is intentionally flexible, allowing researchers to adapt the scale according to their specific case. Unique weights can be assigned to each dimension or indicator as required by employing methods such as Multi-Criteria Decision Analysis (MCDA) [136]. Continuing, each dimension can be viewed independently to extract in-depth insights into key considerations of individual communities. This allows for multiple indexes between hierarchical layers to be extracted and analysed independently or together, depending on the objective. A community microgrid's overall social capital index is quantified as the sum of all direct indicators. Hence, each hierarchical layer in the scale can be seen as the percentage contribution to the overall score. The hierarchical scale provides a structured and systematic way to evaluate social capital with specific indicators for community microgrids. The scale can help map and visualise the social dynamics of the community. As a result, we can gain a better understanding of how the microgrid may be able to support and strengthen the social fabric of the community rather than undermine it. This can be especially useful for identifying any potential barriers or challenges to the successful implementation of the microgrid and developing strategies to overcome them.

This framework highlights the importance of considering the relationship between different dimensions of social capital, which are critical factors in our framework for the successful design and planning of community microgrids. To grasp the social dynamics of a community, we argue that it is essential to consider all aspects of social capital. Hence, by evaluating the social capital index, we can extract insights into the community capability, which, in turn, informs the community type, ownership and governance models that are most likely to support the community microgrid. The social capital index can thereby reveal if a community has high or low social capital and if the score is equally distributed over the dimensions or not. As an example, let us consider a community characterised by high levels of structural and cognitive capital and a medium level of relation capital. This will impact the social capital index, but still, locate the community in the higher part of the scale as a cooperative community. By further extracting the score from each dimension we might extract that the relation capital is split between high trust within the community and low trust towards the utility company. This information can provide advance warning of possible conflicts between the utility company and the community that could hinder the development of a community microgrid. However, if trusted individuals in the community have a high level of trust in the utility owner and specific knowledge in energy systems or finance, they could play a local expert role and extend trust to the whole community, which could change the outcome. The tool, therefore, offers a valuable resource for extracting knowledge and indicators of the social fabric of a community and its impact on the success of community microgrids.

To operationalise our tool into a tangible social capital index, the following steps are proposed:

1. Define indicators: Identify a set of main and detailed indicators for each dimension of social capital (structural, relational, and cognitive) based on the specific context of community microgrids. These indicators should capture relevant aspects such as network connections, trust levels, cooperation, shared values, and norms. The outer layer of Figure 5 can be used as inspiration.
2. Survey design: Develop a detailed survey instrument based on the identified indicators. The survey should include targeted questions or statements that elicit responses suitable for a Likert scale. These response categories should be evenly distributed across the social capital scale, allowing participants to provide nuanced ratings.
3. Data collection: Administer the survey to members of the community during the preliminary stages of the community microgrid project. Trained professionals should conduct the surveys to ensure consistency and accuracy in data collection.
4. Quantification: Assign numerical values to the responses provided by participants in the survey. These values can be derived by mapping the Likert scale responses to corresponding numerical scores. For example, a response of "strongly agree" could be assigned a score of 5, while "strongly disagree" could be assigned a score of 1.
5. Weighting: Consider the assumption of equal weighting for each dimension in the social capital index. Assess whether this assumption holds true for the specific context or if certain dimensions should be assigned greater or lesser importance. This step can involve further research and analysis to determine appropriate weights and refine the quantification process.
6. Calculation: Calculate the social capital index for each community microgrid by summing the scores of the indicators within each dimension The resulting index will provide an overall measure of social capital for the community.
7. Interpretation: Analyse the social capital index to gain insights into the community's social fabric and its implications for the microgrid project. Explore the distribution of

scores across dimensions to understand the strengths and weaknesses of social capital within the community.

2.7 Conclusions and Recommendations for Future Research

This research underscores the critical role that social structures and dynamics, as understood through the lens of SCT, play in the planning, implementation, and operation of community microgrids. Through a qualitative review of diverse studies, we have gained key insights into the social processes, resources, and characteristics that shape community engagement with microgrids. These insights inspired the development of a novel conceptual framework that facilitates a holistic understanding of community dynamics. Our framework, rooted in SCT, classifies communities based on their social capabilities, which are critical in their interaction with microgrids. This direct integration of social capital considerations into the design and operation processes related to community microgrids represents an innovative approach to managing these systems.

As an extension of this theoretical groundwork, we have also outlined initial steps towards the operationalisation in creating a practical tool. This tool, informed by our conceptual framework, promises to enable a systematic evaluation of unique social factors within communities, thus offering a nuanced understanding of diverse community types. This refined perspective serves to facilitate more informed decision-making in the design and planning of community microgrids.

In conclusion, this study provides a meaningful contribution to the understanding of the role of social capital in community microgrid development and serves as a useful resource for practitioners and researchers interested in promoting the success of these projects. Further validation and empirical analysis are recommended as the next steps in the line of this research to enhance its generalisability and inform decision-making in the field of community microgrid.

3 Community Microgrids: A Decision Framework Integrating Social Capital with Business Models for Improved Resiliency

Preamble

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Ethics approval

ETH22-7777 from the University of Technology Sydney

Overview

In the previous chapter, we proposed a conceptual-theoretical framework based on social capital theory for identifying community characteristics to determine key needs and considerations for microgrid adoption. In Chapter 3, we expand on this framework by operationalising it into a practical decision-support tool. The main objective is to integrate the social capital metrics established in the previous chapter with various business model archetypes, thereby creating a Multi-Criteria Decision Analysis (MCDA) framework that can guide the selection of appropriate business models for community microgrids within local energy markets (LEMs).

Focusing on business model and LEM selection was chosen because these elements are crucial for the design and operation of community microgrids. Business models determine the pathways for revenue generation, ownership structures, pricing mechanisms, and value propositions, ensuring that the microgrid is economically viable and aligned with community needs. LEMs facilitate local energy trading, optimising resource use, and enhancing energy security and resilience. By integrating social capital into the selection process, the MCDA framework ensures that the design and operation of community microgrids are tailored to fit the community based on their social capital.

First, we provide a comprehensive analysis of BM components and LEMs, categorising and examining their interdependencies. This foundational work is essential for understanding the ecosystem within which community microgrids operate. The interrelations between BM components and LEMs are then synthesised into a structured MCDA framework. This integration serves as the backbone of our decision-support tool, allowing for a structured evaluation of different business models in the context of community microgrids. Next, we strategically aligned the MCDA framework with community social capital as an evaluative element within the framework, to ensure the selection of business models is guided by the community's social fabric. Focusing on the community's behavior and economic factors, we analyse how technical and economic decisions interact with social factors, emphasising market structures due to their flexibility and direct impact on community opportunities

Finally, we apply the framework to a case study, demonstrating its utility and effectiveness in guiding the selection of appropriate business models for a specific community. The research the framework bridges the gap between the operational and technical aspects of microgrids with the socio-economic context of the communities they serve.

In the next chapter, we will provide further refinement and focus on the quantitative aspects and optimisation of business model selection, building on these findings to develop even more precise and effective strategies for community microgrids.

Abstract

This paper introduces a novel Multi-Criteria Decision Analysis (MCDA) framework for systematic evaluation and alignment of business models for community microgrids within local energy markets (LEMs). Our approach uniquely integrates social capital as a critical metric for assessing the success of these models. The framework's robustness is demonstrated through a case study application, showcasing its utility as a decision-support tool. This tool effectively bridges the gap between the operational and technical aspects of microgrids with the socio-economic context of the communities they serve. A key contribution is the establishment of a systematic categorisation of business models and LEMs facilitated by the MCDA framework. This approach emphasises the importance of analysing the synergy between business model components (ownership, revenue/pricing, activities, value proposition) and the corresponding market mechanisms, infrastructure, and ICT frameworks. The results demonstrate how the framework guides an informed and context-sensitive selection of business models, leveraging the interconnected socio-technical dynamics inherent to community energy systems.

3.1 Introduction

The transition to a decarbonised energy landscape has catalysed the emergence of community microgrids, embodying the integration of localised energy management with renewable energy sources [137]. Designed to serve the specific needs of local communities, these microgrids can either complement the main power grid or operate independently, offering a stable, renewable, and resilient energy supply [7]. The integration of interconnected loads and distributed energy resources within these microgrids allows for localised energy management, from generation to consumption, ensuring efficient monitoring and use of renewable power [69].

Despite the technological and operational progress in community microgrid development, selecting an appropriate business model (BM) remains a multifaceted challenge [43]. A BM is the mechanism by which an organisation manifests, transfers and realises value [138]. It determines the pathways for revenue generation, identifies potential customers, outlines the products or services offered and describes the financial structure that underpins the business operations [45]. For community microgrids, a BM involves the strategic planning, implementation, and management of the microgrid project and enterprise to achieve specific community objectives and goals. Hence, the design and operation are directly influenced by various components of the BM concept, including the ownership structure, revenue and pricing model, operational activities and value proposition [49]. For example, the decisions inherent in BMs can define the physical structure of the microgrid, such as the types and configurations of distributed energy resources and energy storage systems (ESS) to be included [139]. Therefore, the complexity inherent in selecting an appropriate BM for community microgrids is accentuated by the diverse objectives and characteristics of the communities they serve. These models are not one-size-fits-all; they must be intricately designed to align with the community's economic conditions, cultural context, and energy needs [58].

The scholarly exploration of BMs for community microgrids has thus far adopted various lenses, leading to a broad range of definitions, frameworks, and perspectives. Some studies have aimed to categorise potential BMs [34], while others have focused on the creation of new and emerging solutions [81], [140]. For example, F.G. Reis et al. [49] conducted an extensive overview of existing and emerging BMs in the energy community sector. They utilised the Business Model Canvas and Lean Canvas framework to classify business models into distinct archetypes based on their value proposition. Building on this comprehensive perspective, Kubli & Puranik [141] conducted a morphological analysis of 90 energy communities, identifying 25 BM design options to enable the development of customised BMs, emphasising the role of such models in the European Energy transition [141]. Additionally, other studies, such as the one from Vanadzina et al. [58] examined different BMs, considering social, technical and economic parameters, with a particular focus on ownership structures. Similarly, Gui et.al [34] discussed BMs for community microgrids through the lens of new institutional economics, focusing on ownerships and governance structures as well as the associate roles and risks and benefits.

The BM chosen for a community microgrid not only customises internal operations but also dictates the market model, establishing the engagement rules for all market participants [53]. Market models are critical as they set the procedures for how energy transactions are conducted, priced, and communicated [142]. Research on market models mainly distinguishes between the wholesale energy market (for resellers), retail market (microgrid-retailer energy exchange), and local energy market (LEM), characterised as a shared market platform for local members in a community where they can trade self-generated energy with each other [137]. Understanding the nuances of LEMs is particularly critical as they dictate the nature of these energy transactions and are influenced by the technological and social dynamics of the community. The characteristics of LEMs, such as market size, transaction mechanisms, and participant behaviour, are pivotal in shaping the microgrid's design and operational strategies [143].

While the choice of BM dictates the structural and operational characteristics of market models, they shape and are shaped by the community's behaviour. This means that social factors, such as social capital, may play a significant role in this context as they embody the relational dynamics that can influence energy trading behaviours, cooperative decision-making, and collective actions within the microgrid ecosystem [24]. Analysing the social capital of a community can help understand and harness these social dynamics to foster a more engaged and cooperative environment, crucial for the effective operation of LEMs and the overall success of the microgrid [37]. Social capital pertains to the networks of relationships among people who live and work in a particular society, enabling that society to function effectively [126]. It encompasses the trust, mutual understanding, shared values, and behaviours that bind the community members and enable them to act collectively [144]. A high level of social capital can enhance cooperation among stakeholders, facilitate the sharing of resources, and improve governance and conflict resolution mechanisms. This collective capability is particularly pertinent when considering the adoption and operation of microgrids, as these systems often require a collaborative approach to decision-making and management [42], [129]. Assessing the social capital of a community provides insights into the community's capacity for collective action, resilience in the face of challenges, and the potential for successful implementation of complex projects like microgrids [37]. Thus, integrating an understanding of social capital into the selection of business models for community microgrids can ensure that these models are economically viable, socially synergistic, and sustainable.

Although the importance of social considerations is gaining recognition, research on their integration into BMs for community microgrids is still nascent, especially compared to the focus on technological and economic aspects [145], [146]. The methods of BM selection often prioritise technical feasibility and financial returns, which can inadvertently neglect the community's cultural and social dynamics, leading to an underestimation of the levels of community engagement necessary for sustained and resilient microgrid operation [141], [145]. For instance, business models that overlook cultural sensitivities may set market mechanisms that, although economically optimal, are not socially sustainable, resulting in low participation rates and risking project viability [147]. Addressing this gap is critical; different BMs imply varied roles, responsibilities, and benefits for community members [45], significantly influencing their engagement and acceptance of the microgrid [46]. Hence, the design and choice of a BM is a pivotal facet of the socio-technical intricacy of community microgrids, which demands an economically sound and socially harmonious approach.

This paper aims to bridge this gap by proposing a decision-support framework that delivers practical recommendations for selecting the most appropriate business model for community microgrids with respect to the community’s social capital. In this effort, the main contributions are to:

1. **Comprehensive Analysis of BM Components and LEMs**: A thorough examination and categorisation of BM and LEM components and their interdependencies, which is foundational for understanding the ecosystem within which community microgrids operate.
2. **Synthesis of BM and LEM Interrelations into MCDA**: Integration of the complex relationships between BM components and LEMs into a structured MCDA framework, serving as the decision-support tool's backbone.

3. **Strategic Alignment with Community Social Capital:** Utilise the Social Capital Index (SCI) as an evaluative element within our MCDA framework to guide the selection of appropriate business models for the community.

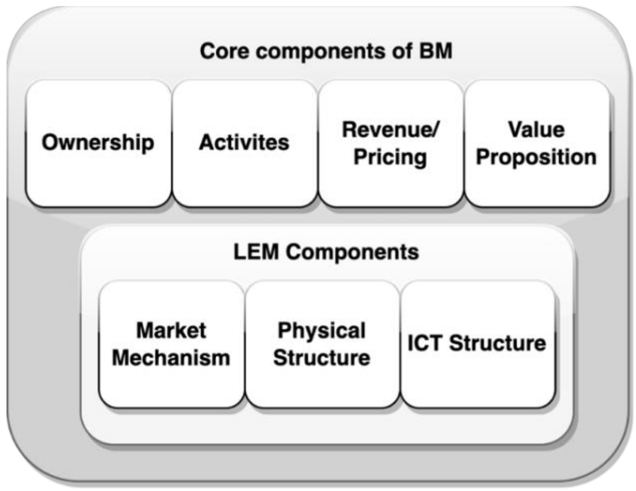


Figure 3.1. Schematic overview of the BM components in a community microgrid (BM: Business Model, LEM: Local Energy Market).

Consequently, this research introduces a new approach for aligning business models with microgrid design and LEMs for community microgrids, emphasising the importance of social capital previously introduced in [148]. We illustrate this process through a two-layered schematic model, as shown in Figure 3.1. The outer layer represents the key BM elements - Ownership, Revenue/Pricing, Activates and Value Proposition. The inner layer signifies the Market Mechanism, Physical Layer, and ICT Structure. Building on this conceptual foundation, we have constructed a comprehensive decision-support tool using Multi-Criteria Decision Analysis (MCDA), selected for its robustness and proven effectiveness in navigating multiple decision-making criteria [64]. While MCDA is an established method, the application to the socio-technical aspects of community microgrids is a less explored avenue that intersects social factors and technical operations. Hence, we tailor the MCDA framework to the nuanced requirements of community microgrids, which manifest intricate decisions that necessitate carefully balancing numerous criteria. Hence, our approach reflects the layered structure to assess and align business models in the context of community microgrids, with the SCI acting as a crucial evaluative criterion. Incorporating the social capital layer is imperative as it offers a multidimensional perspective, grounding business models' technical and operational facets in the socio-cultural realities of communities. By intertwining the hard metrics of microgrid operations with the soft metrics of the community's social fabric, our tool provides a more comprehensive, nuanced, and contextually relevant approach to business model selection for community microgrids.

Continuing, this paper is organised as follows: Section 3.2 establishes the groundwork for understanding the LEM concept and identifies its essential components. Section 3.3 examines the essential elements of BMs, including categorising potential BM archetypes. Section 3.4 presents the MCDA framework and its underlying principles. A case study is also presented to demonstrate the framework's usefulness and applicability as a decision-support tool. The paper concludes with Section 3.5, summarising our findings and proposing directions for future research.

3.2 Local Energy Market

This section provides an overview of the LEM concept by introducing terms such as market scope and Physical and Information and Communication Technology (ICT) layers. LEMs are observed to integrate two intertwined layers, the physical and the ICT layers [149], [150]. This section further investigates the characteristics found in these two layers to identify the intrinsic independence and dependencies. Subsequently, these layers are analysed to establish the foundations of the market mechanism.

3.2.1 Market Scope

The market scope defines the set of market actors and the products or services that can be exchanged in the market. Market actors are made up of market participants and the market operator [90]. The market operator balances different stakeholder interests while focusing on achieving market clearing and providing optimal tariff operation for customers [151]. Market operators and utilities may therefore have different objectives in grid-connected mode [150], as utilities are often more concentrated on technical aspects of the network such as reliability and power quality [22]. Following the definitions provided in [152], the market operator is the designed entity responsible for implementing market processes in line with the established market rules. Meanwhile, the market participants are the entities that participate within the market scope [152].

We further categorise the participants into additional classifications, which are presented as an overview in Table 3.1.

Table 3.1. Overview of (electricity) market participants.

Name	Type	Description
Market Operator	Organisation	Entity in charge of operating the market
Aggregator	Organisation	Entity which represents multiple consumers or owners of DERs and storage systems, facilitating the purchase or sale of electricity on their collective behalf
Grid Operator	Organisation	Operates the electricity grid and interacts with market
Consumer	Person/ organisation	Participates through energy consumption only
Prosumer	Person/ organisation	Participates through energy generation and consumption
Retailer	Organisation	Retailers serve as the commercial entities that provide a link between the wholesale energy market and the end consumers

As seen in Table 3.1, we differentiate between customers and prosumers. However, for this research purpose, both customers and prosumers are local members of the community who participate in the community microgrid activities. Consumers and prosumers can further be divided into individual households, businesses or institutions that produce, consume or store energy [22].

3.2.2 Physical Layer

The physical layer refers to the physical interconnections between market participants and the electrical system. Designing the physical configuration of a community microgrid involves taking into account various factors closely related to the integration of DER, point of common coupling (PCC), converter configurations, smart meter placement, and ESS [53].

Consequently, categorising the physical energy trading within LEMs is a complex task due to the wide range of potential structures.

Researchers have provided various definitions and categorisations based on specific cases. For example, Trivedi et al. [137] differentiates physical structures based on the locations of DERs and ESS and how these resources are interconnected to form a community microgrid. They outline seven distinct structures, considering the locations of converters, DERs, and ESS, whether central converters are integrated and if there is a PCC for possible island-mode operations [137]. In contrast, Lin and Wang [151] classify the physical structures of LEMs based on market structures, participant relationships, and analysis methods. The physical structure is categorised as centralised, where energy trading is realised through a common exchange point, or Peer-to-peer (P2P), where each participant is physically connected to each other [151].

Moreover, most studies do not distinguish between the physical and ICT layers and provide combined categorisations of different structures. For instance, the authors of Tushar et al. [149] presents three market categorisations for P2P energy-sharing markets, which expand upon the framework originally proposed by Tushar et al. [150]. Coordinated market – where both the trading process and the communication of information are centralised, and a central coordinator directly controls the energy export and import. Decentralised market – where the trading process and information communication are decentralised, providing participants full control of their decision-making. Community market – where the trading process is decentralised, and the communication between participants is centralised [149]. In each of these market structures, it is unclear how the communication or trading process is physically defined. Continuing, Neska and Kowalska-Pyzalska [44] distinguish between island and grid-connected modes for the physical structure. While this differentiation is clear from the physical perspective, the authors primarily concentrate on the ICT layer to delineate structural topologies associated with the energy markets [44]. This approach underscores the interplay between the physical and ICT layers, but it also raises questions about how to incorporate the physical characteristics more comprehensively into the structural classification. For the physical structure, the focus is on the ICT layer to provide structural topologies connected to the energy markets [44].

In summary, categorisation largely depends on the specific context and characteristics of the LEM under consideration in each reference. To provide a systematic approach, our analysis takes inspiration from the categorisation proposed by [151]. Based on this, we have introduced distinctions between decentralised and distributed structures. The specifics of these categories, as informed by our analysis, are presented in Figure 3.2 and detailed below:

- **Centralised:** Energy trading is realised through a common exchange point to which each participant is physically connected.
- **Decentralised:** Energy trading is realised through multiple common exchange points to which participants are physically connected. Each community has its own dedicated aggregation point, symbolising the multiple common exchange points.
- **Distributed:** Participants are physically connected to each other and can directly engage in energy trading with each other.

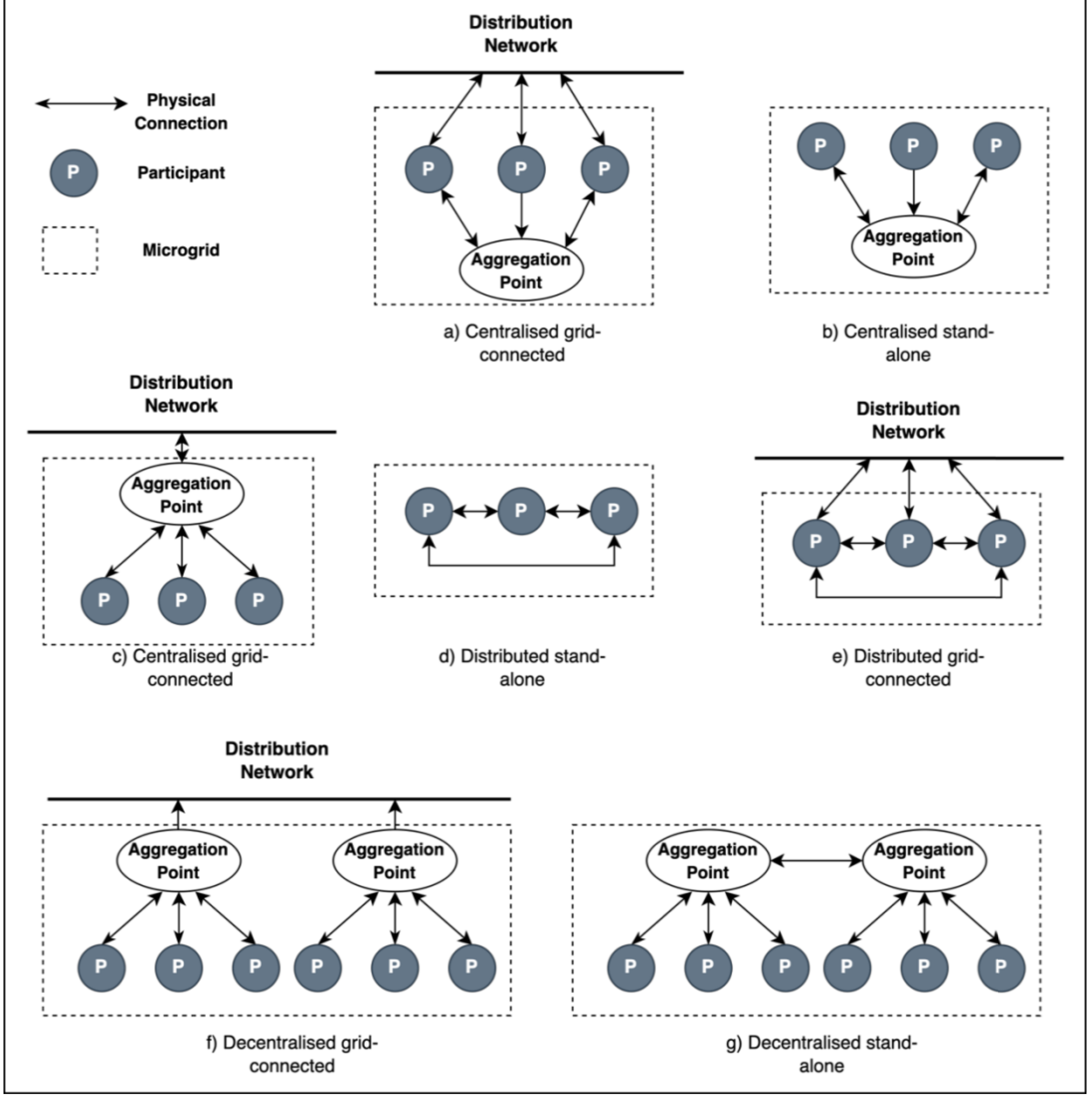


Figure 3.2. Schematic representation of the various configurations of the physical connections among participants and the physical network.

3.2.3 ICT Layer

At the core of community microgrids lies a sophisticated ICT system that acts as the central hub, connecting market participants to the LEM and hosts the primary platform for market operations [93]. By adhering to a well-defined market mechanism, the ICT system streamlines the functioning of the market [153]. Similarly, to the physical structure, researchers have identified different ICT structures through different categories. Generally, there are two distinct structures: Centralised and decentralised/distributed [154]. In centralised structures, each participant communicates only with the market operator or other central coordinating entity. Conversely, in decentralised or distributed structures, participants exchange information directly with each other or a specific subset of the community and may not require integration of a coordinating entity [152]. The authors in Trivedi et al. [137] offer a detailed overview of various subcategories of these structures. Under centralised structures, they identify two subcategories: C1, which refers to a single central DER with dispersed loads, and C2, defined as a central group of DERs with a single group of loads. The distributed structures are further divided into D1 – a group of distributed DERs with scattered loads, D2 – individual distributed DERs with scattered loads, and D3 – a group of distributed DERs with a group of loads. The decentralised structures are categorized into two types: DES, representing a single decentralised structure, and DEM, indicating multiple decentralised structures [152]. However, while the authors differentiate these categories based on the relationship between DERs and loads, the connection to the physical or ICT structure isn't explicitly stated. This ambiguity becomes more evident when comparing structures like C2 and D3, which, despite being categorised differently, seem to represent the same structure.

Furthermore, other classifications, such as the ones provided by Lin and J. Wang [151], where the ICT structures are divided into three categories:

- Centralised Structure with Local Market Operator (LMO): The LMO manages energy trading between participants.
- P2P Structure with Direct Negotiation and Transactions: Participants directly negotiate and trade energy without an intermediary.
- LMO-Facilitated P2P Structure: The LMO facilitates direct energy trading between participants [151].

In comparison, the authors of Guerrero et al. [92], focus on how the uncoordinated, coordinated and P2P approaches explain how the ICT structures comprise individual or multiple participants [92].

- Uncoordinated Structure: DER integration is not centrally planned, and each consumer operates their DER independently based on their sole benefit. Community engagement is minimal, as there is no direct collaboration or coordination between customers or aggregators [149]. Consumers are usually equipped with a Home Energy Management System (HEMS), which optimises their electricity consumption and production with the aim of minimising their electricity bill [92].

- Coordinated Structure: Central planning and operation of DER for the joint benefit of the consumers and the intermediary entity such as the aggregator [139]. This approach enables more efficient energy distribution and grid stability. Community engagement is higher as the operation focuses on cooperation and coordination, encouraging consumers to participate in energy-related activities [83].

- P2P Structure: Decentralised planning and operation of DER, with bilateral energy transactions between consumers [149]. Consumers take the role of buyer and seller as they are directly involved in energy trading and sharing within the microgrid. Community engagement is mainly focused on the DER owners but could be expanded to the broader community (consumers without DER) [100].

In line with the general structures and the classification in [137], [151], we consider four main divisions in the approaches to the ICT structure in community microgrids: Centralised, Distributed, Decentralised and Hybrid. The specifics of these categories, as informed by our analysis, are presented in Figure 3.3 and detailed below:

Centralised: The market operator or aggregator provides central control and coordination of the trading and communication process.

Distributed: Each participant has individual control over their trading and communication process without intermediate.

Decentralised: Multiple market operators or aggregators which provide central control and coordination for connected participants.

Hybrid: The trading and communication process is facilitated through the market operator or aggregator, allowing each participant to maintain individual control over the trading and communication activities.

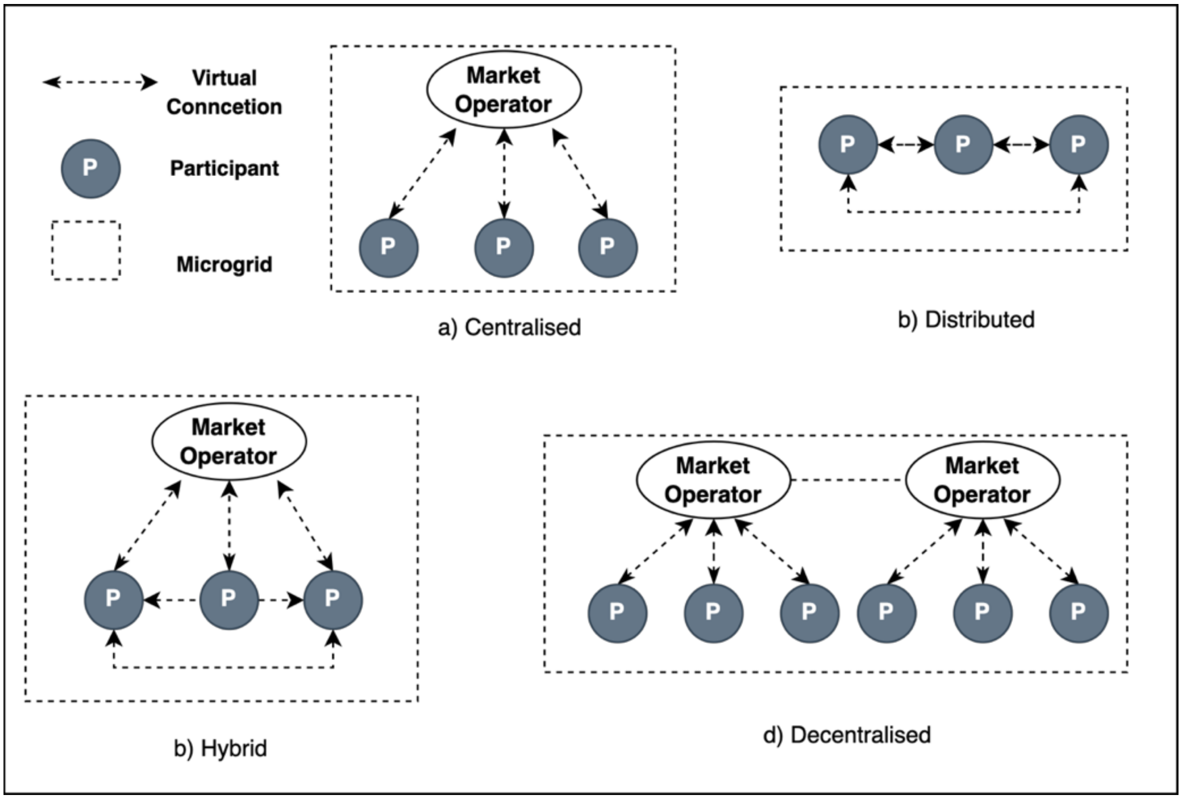


Figure 3.3. Different community microgrid configurations based on the virtual connection between the participants and the market operator.

3.2.4 Market Mechanism

This section introduces the market design mechanism, which plays a pivotal role in the functioning of any market, as it constitutes the set of rules that dictate the interaction and exchange of products between market participants [152]. To identify the possible set of rules defined by market models, we separate between price formation and mechanism, as seen in the following subsections.

Price Formation

The process of determining market prices is called price formation and operates within the market to set rules for communication and transactions [142]. This process involves reaching a consensus on electricity trades, from which the involved parties have no incentive to deviate [155]. The price formation does not only reflect the production costs but also means to influence consumer behaviour and preferences [112]. While price formation can be designed in various ways, we divide them into auction-based and system-determined [101].

Auction-based: These methods leverage an auction market for local demand and generation [43]. In this model, participants actively participate by submitting bids or offers for their energy demand or generation. The aggregation of these bids and offers is managed according to predefined rules to set the price strategy and allocate resources between single or double actions [142]. Single auctions are one-sided auctions where consumers submit their bid to the market operator for clearing, [90]. In comparison, double auctions involve both buyers and sellers to form the transactions. Participants can communicate by submitting quoted prices during the transaction cycle and the cost of participating is included before the auction is finished [143]. In both single and double auctions, the presence of a market operator or centralised platform is assumed to collect the bids and offers for the market clearing [156].

System-determined: The market operator determines the price settings based on pre-agreed frameworks. Uniform or fixed pricing models represent one approach to this structure and can be set to a certain limit or applied per unit to provide a predictable cost structure for participants [157]. However, there are a multitude of different approaches, often determined by the specific context of the research [90]. For example, the linkage between the main grid and/or the LEM often focuses on the export and import from the main grid due to the aggregated differential between the microgrid's total load and generation. Most studies assume that the corresponding prices are fixed [101] or do not specify their reasoning connected to the set prices [158]. Typically, the price for electricity export is assumed to be distinctly lower than the cost of the electricity import purchased from the main grid [90]. Alternatively, emerging studies introduce asset-sharing models, which adjust prices according to each prosumer contribution and usage, providing a more individualised and equitable energy pricing strategy within community markets [159]. For example, authors in [101], [108] consider bill-sharing where each participant pays for their individual electricity use. In [101], a virtual-net billing method is applied to distribute shared energy within a community of prosumers. The shared energy is split equally between net importers and the electricity bill, which is facilitated by a community manager based on meter readings. The electricity bill will include the collective benefit based on each participant's contribution (import/export) to the community [101]. In addition to these approaches, there are studies that employ a uniform pricing strategy for all participants, determined by the equilibrium of supply and demand. This method, as outlined in [108], ensures that all prosumers are charged the same rate per kWh for the energy consumed.

Trading Mechanism and Rules

The trading mechanism and rules refer to rules related to the information exchange and coordination between participants. The market mechanism is heavily dependent on the ICT system [151] and mainly three types of mechanisms can be distinguished: P2P, community-based and hybrid [160]. Each mechanism has distinct implications for the design of the microgrid, the level of community engagement and the overall effectiveness of the system [90], [160].

The P2P Mechanism is resailed through an online platform where participants trade energy directly without the intervention of a market operator or other intermediary [139]. Bilateral contracts are established between each participant and apply to both long-term and ad-hoc approaches [143].

Community-based Mechanism provides energy trading among participants through a market operator, aggregator, or other common intermediaries [46]. The market operator balances demand and supply based on the received information from participants [43]. This mechanism could also consist of multiple market operators or aggregators who manage distinct subgroups within the market. Each aggregator represents its members and interacts with other participants from the broader LEM. This multi-tiered mechanism allows for more nuanced control and communication within the LEM [161].

Hybrid M*echanism* can be described as a combination between the P2P and community-based mechanisms [44]. A market operator assists with the matching of participants (buyers and sellers) and combines the advantages of centralised coordination with the direct negotiation capabilities of the P2P mechanism [143], [160]. This is evident in community P2P energy-sharing models like the Brooklyn Microgrid [162], where prosumers communicate with the community manager. The community manager serves as a coordinator without directly influencing the prosumer's decision, thereby ensuring a greater degree of privacy and security as prosumers only need to share limited information [163].

While the complexity and level of cooperation among market mechanisms vary [141], we provide a high-level comparison in Figure 3.4. The P2P mechanism is identified as the most individualistic, as it allows participants to directly engage in energy based on individual preferences without the coordination of market operators. While the complexity of this mechanism can range from low to high depending on the number of participants and price formation [152], we summarise it to be of low complexity compared or the other methods. Conversely, the community-based mechanism can be viewed as more cooperative as participants are connected through a common intermediary and agree to exchange information to participate in the LEM [164]. However, this adds to the complexity as the coordination among multiple participants and potential multiple aggregators for distinct subgroups within the market [53]. Finally, the hybrid mechanism can be seen as a middle ground in blending individualistic and cooperative elements. It potentially offers the most flexibility, catering to the diverse preferences of participants with a level of coordination. Hence, the complexity is higher than the P2P mechanism.

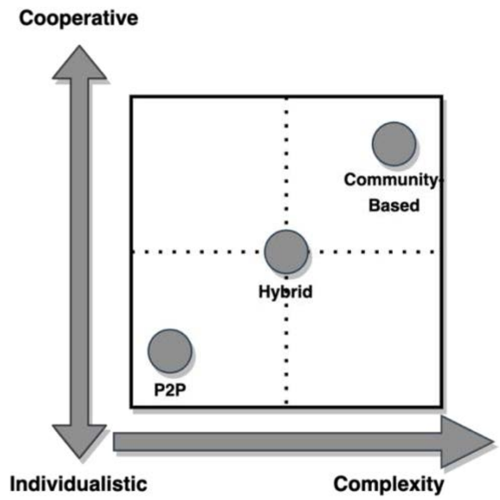


Figure 3.4. Different community microgrid configurations based on the virtual connection between the participants and the market operator.

3.2.5 Summary of LEM Characteristics

Based on the classification and categorisation found in previous literature and the established in previous sub-sections, a summary of the common characteristics found in the physical and ICT layers and the market model is provided in Table 3.2.

Table 3.2. Summary of common LEM characteristics with a focus on the physical layer, ITC layer, market mechanism and price formation.

Component		Option	Description
Physical	Grid connection	Off-grid On-grid	Standalone with no connection to the main grid Connected to the main grid
	Structure	Centralised Distributed Decentralised	Participants connected through common exchange point Participants are directly connected to each other Multiple common exchanges points
ICT	Structure	Centralised Distributed Decentralised Hybrid	Central control of trading and communication No central control or coordination Coordination between different control points Individual control with central coordination
Market Model	Market Mechanism	P2P Community-based Hybrid	No market operator, direct trade between participants Market operator facilitates energy trading Direct trade between participants with coordination of market operator
	Price Formation	Auction Based System determined	Single or double auction Predefined pricing

3.3 Business Models

The focus of this section is to explore the integration of business models into the decision-making process for the development and operation of community microgrids. To accomplish this, our analysis will centre around evaluating the ownership and governance structure, activities, revenue and pricing models, and value proposition associated with different BMs. In the following subsections, we will discuss each of these components before an overview of BM archetypes for community microgrids is presented.

3.3.1 Ownership

The ownership structure of community microgrids serves as a fundamental driver that determines the functioning and organisation of these systems [22]. As a result, understanding the ownership dynamics is essential in comprehending the variations in activities and operations across different BMs. The components in community microgrids, such as DERs, ESS, and the physical network can be owned by a single party or shared among multiple stakeholders [165]. The range of functions and components to be delivered in a community microgrid can therefore be through one single party or a collection of parties [3]. The design and architecture of microgrids are largely influenced by the internal stakeholder structure and ownership model, which can include distribution system operators (DSO), end consumers, independent power producers (IPP), or energy suppliers/retailers [58]. We further distinguish between four types of ownership structures possible for community microgrids: (i) Community Ownership, (ii) Utility Ownership (iii) Public-private Partnership and (iv) Third-Party Ownership.

i. *Community Ownership* refers to local members collectively owning and financing the microgrid project. This structure often highlights democratic decision-making processes and the sharing of benefits among members [52].

ii. *Utility Ownership* describes a model where a utility company owns and operates the microgrid [109]. This ownership structure provides professional management ad economies of scale, while downsides such as less local control for the community might be preferent [34].

iii. *Public-Private-Partnership is* also referred to as "mixed" ownership and involves collaboration between public entities and private companies [22]. This structure is generally discussed on the possibilities of leveraging the strengths of multiple stakeholders to develop and operate the microgrid [35].

iv. *Third-Party Ownership* refers to a separate entity owning the microgrid and providing energy services to the local community [166]. This model generally includes a contractual agreement between the owner and the customers of the local community [48].

3.3.2 Activities

As mentioned in the previous sub-section, the activities and operations depend largely on the ownership structure of the underlying business model. Hence, we separate the discussion below into each ownership structure.

Community Ownership: Decision-making is often democratic, with members having an equal say in the operations and policy [23]. Energy sharing is at the focus of this model, with community members pooling their resources to generate, distribute and manage their energy [44]. A community manager or other entity usually orchestrates the operations, facilitating coordination and collaboration among members [34]. They may engage with aggregators to optimise energy distribution and handle interaction with broader energy markets [167]. The mobilisation of resources and community engagement are key activities, create a sense of shared ownership and responsibility [168].

Utility Ownership: The utility company is responsible for all activities and operations connected to the construction, maintenance and operation of the microgrid [22]. The utility may work with independent aggregators to optimise energy generation and distribution [43]. They may also interact directly with the energy market, managing pricing and regulatory compliance. Decision-making is typically centralised, with limited direct community engagement in the operational decisions [34]. However, utilities may establish customer engagement initiatives to facilitate communication and promote customer satisfaction [24].

For example, some utilities might offer demand response programs, where customers are incentivised to reduce or shift their energy use during peak times [53].

Public-Private Partnership: Both public and private entities share responsibilities, often defined in the partnership agreement [24]. Generally, the private partner manages technical operations [169], with possible coordination with aggregators, while the public entity oversees regulatory compliance and community relationships. For example, the private partner might offer specific programs or services, such as efficiency upgrades or demand response programs [170]. The public entity may also have a role in decision-making processes, ensuring that operations align with community interests [24]. Community engagement can vary significantly, depending on the specific arrangements of the partnership agreement [169].

Third-Party Ownership: The third-party owner is responsible for most activities, with the potential involvement of aggregators for energy optimisation [153]. Depending on the implementation, they may also handle interactions with both local and external energy markets [43]. Decision-making lies primarily within the third-party owner [168], with community engagement limited to the service provision context [58]. However, some third-party owners may seek to actively engage the community, for example, through transparent communication or customer participation initiatives [48].

3.3.3 Revenue Models and Value Propositions

There are several options available for establishing revenue and pricing models for community microgrids, each catering to different business strategies and market conditions [45]. The choice of model can significantly impact the profitability, sustainability and attractiveness of the microgrid project to various stakeholders [58].

Utility Rate based – In this model, the utility company invests in the community microgrid and includes the costs in its regulated rate base [34]. The utility then recovers these costs from its members, who benefit from the increased reliability and resilience offered by the microgrid [49].

Power Purchase Agreements (PPAs): PPAs are contracts between participants of the microgrid (often buyers and sellers) [14]. The PPA specifies the amount of electricity to be sold, the price and delivery mechanism and other terms. This model provides a long-term and stable revenue stream and predictable electricity costs for the buyers.

Pay-As-You-Go (PAYG): This model enables consumers to pay for their energy consumption as it occurs, which is a common approach in today's electricity markets [58]. Unlike fixed plans, PAYG does not require long-term commitments, and aside from daily fixed charges, it allows consumers to adjust their spending in line with their actual usage [171].

Peer-to-Peer Trading: This is a more innovative model where members of the microgrid can trade electricity among themselves, often with the help of blockchain technology to manage transactions [157]. Prices in this model are set by the market - that is by the balance of supply and demand among the participants in the microgrid. It offers empowerment and independence for customers and can lead to more efficient use of resources.

3.3.4 Business Models as Archetypes

In synthesising the diverse range of BMs for community microgrids, we articulate a set of archetypes. Each archetype encapsulates distinct characteristics related to the BM and LEM components discussed in previous sections. They serve not only as analytical categories but also as tools to enhance the integration of BM and LEM components into the MCDA framework outlined in Section 3.4. This approach simplifies the complex dynamics between BM design and LEM components, enabling a clear comparison and aiding in the MCDA framework's application. The following archetypes, detailed in Table 3.3, serve as representative paradigms:

Community Ownership BM: A cooperative, by its inherent nature, is driven by the principle of collective ownership, decision-making and sharing of benefits [37]. This also translated into physical structure which can be centralised to provide a single common exchange point connecting the participants or decentralised where participants are connected through multiple exchange points [172]. Furthermore, to promote collective decision-making and equitable sharing of benefits, a centralised or hybrid ICT structure is often adopted [137].

This ensures a balance between local control and the need for coordinated management of resources and distribution of benefits [91]. The cooperative model is often characterised by system-determined pricing [90], given its focus on ensuring collaboration rather than profit maximisation [82]. The market mechanism therefore falls into community-based category, leveraging the collective strength of the members.

Utility Ownership BM: This BM typically exhibits a centralised physical structure, mirroring the traditional top-down electricity network where the utility is the sole producer and distributor of electricity. Centralised control allows of efficient management of grid operations, consistent service delivery, and the ability to effectively handle large volumes of energy [169]. Accordingly, the ICT structure also tends to be centralised to enable efficient coordination, control and communication [6]. Since utilities are often subject to regulations [91], the pricing is typically system-determined [34], guided by policy directives or regulatory frameworks [22]. While customers primarily engage in one-way transactions with the utility [53], traditional market mechanisms predominate [44].

Public-Private-Partnership BM: Due to the combination of both public and private sectors, its structure can vary greatly based on the unique partnership terms [36]. The physical structure may range from centralised to decentralised, depending on the scale of the project, the infrastructure available and the strategic goals of the partners [137]. The ICT structure might be centralised, benefiting from the operational expertise and efficiency of the private partner, but it could also be hybrid to allow for the public partner’s influence and oversight. The price formation can be system-determined or auction-based, reflecting a balance between the need for stability and predictability (typically favoured by the public partner) and the advantages of market dynamism and technical development (often advocated by the private partner). The market mechanism could be community-based or hybrid, blending centralised coordination and flexibility for direct negotiation, thus serving the interest of both partners and the community.

Third-Party Sponsored BM: Characterised by a centralised physical structure as the third party, as an expert service provider, assumes responsibility for the microgrid's ownership and operation. This centralisation allows for professional management, optimised performance and reliable service delivery [173]. The ICT structure could also be centralised for hierarchical coordination and control, or hybrid to allow some flexibility and individuality between customers. Price formation is typically system-determined, established under the service contract between the third-party owner and the community [76]. The community-based market mechanism applies as consumers buy energy services directly from the third-party owner [153].

P2P BM: This BM focuses on the individual energy trading of participants in community microgrids. While most studies focus on each participant generating, consuming and trading energy directly with others, participants may be full consumers as well. The physical structure can be centralised or distributed depending on specific project. To reflect the core idea of individual control over the trading and communication processes, fostering a sense of ownership and autonomy related to this BM, the ICT structure must be distributed or hybrid. Price formation in this BM is generally auction-based, reflecting the dynamic nature of energy trades in the LEM. This encourages competitiveness and innovation while allowing prices to adjust to real-time supply and demand conditions. However, both the P2P mechanism and hybrid mechanism can be applied to this BM depending on the specific project.

Table 3.3. Business model archetypes and their characteristics.

Business Model	Financing	ICT	Physical	Price Formation	Market Mechanism	FIT & Tariff	Cost & Distribution	Example
Utility Ownership	Funded by utility Ratepayer funds	Centralised Decentra-lised	Grid-connected Centralised Decentralised	Utility-based PPA	Distribution based on utility rules No LEM mechanism	Regulated FIT and tariff	Trough utility rates and customer bills	[109], [141], [174]
P2P Model	Community Grants or loans	Distributed Hybrid	Stand-alone Grid-connected Centralised Distributed	Auction based	P2P Mechanism Hybrid Mechanism	Localised FIT and dynamic P2P tariffs	Distributed based on P2P transactions and agreed-upon rates Shared costs for shared resources	[141], [149], [150], [160], [162]
Comm-unity Ownership	Community Grants or loans	Centralised Decentra-lised	Stand-alone Grid-connected Centralised Hybrid	System -determined	Community -based	Localised FIT and dynamic tariffs	Distributed based on agreed-upon rules Shared costs for shared resources	[49], [141], [175], [176], [177]
Public-Private-Partner-ship	Public-private funding PPA Grants and loans	Centralised Decentra-lised	Stand-alone Grid-connected Centralised Decentra-lised	System-determined Auction based	Community -based Hybrid Mechanism	Localised or market based FIT and tariffs	Distributed based on service-agreement or PPA	[42], [178], [179]
Third-Party Sponsored Model	Third-party PPA Leasing agreements	Centralised Decentralised	Grid-Connected Centralised Decentra-lised	System-determined	Based on PPA Community -based	Market-based FIT and tariffs	Distributed based on service-agreement or PPA	[48], [141], [173], [180]

3.4 Framework: Multi-Criteria Decision Making

Building on the conceptual foundation established in the sections above, our study introduces the distinctive MCDA framework tailored to help select the most suitable BM for community microgrids based on the community's social capital. This framework is organised from the foundational principles of MCDA [181]. MCDA is a structured approach that helps decision-makers evaluate and prioritise various alternatives when faced with competing objectives

[64]. It is particularly useful when decisions involve numerous stakeholders or impact various sectors, such as the environment, society, and economy [136].

At its core, MCDA is about breaking down complex decisions into more manageable parts [182]. This involves:

1. **Identifying Decision Criteria**: Determining the important factors for making the decision.
2. **Weighting the Criteria**: Assigning importance to each criterion to reflect its relative significance in the decision-making process.
3. **Scoring Alternatives**: Evaluating how well each alternative performs against the criteria.
4. **Aggregating Scores**: Combining the scores of each alternative across all criteria to provide an overall ranking or score.
5. **Analysing the Results**: Interpreting the aggregated scores to understand the trade-offs and implications of each alternative.

The overarching structure of the MCDA framework for this study is presented in Figure 3.5 below. It encapsulates the process from collecting unprocessed community knowledge via surveys to deriving processed and quantified community knowledge. At its core, the framework synthesises qualitative and quantitative data, represented by a cube with dimensions 'S', 'R', and 'C', signifying Structural, Relational, and Cognitive social capital. The MCDA framework is then detailed in a table that evaluates BMs against diverse criteria, concluding with a quantified knowledge output ready for practical application. The following sub-sections will delve into a detailed exposition of this process, culminating in a case study that demonstrates the practicality of the framework as a decision-support tool and provides insights into tailoring the MCDA framework for specific microgrid scenarios within community settings.

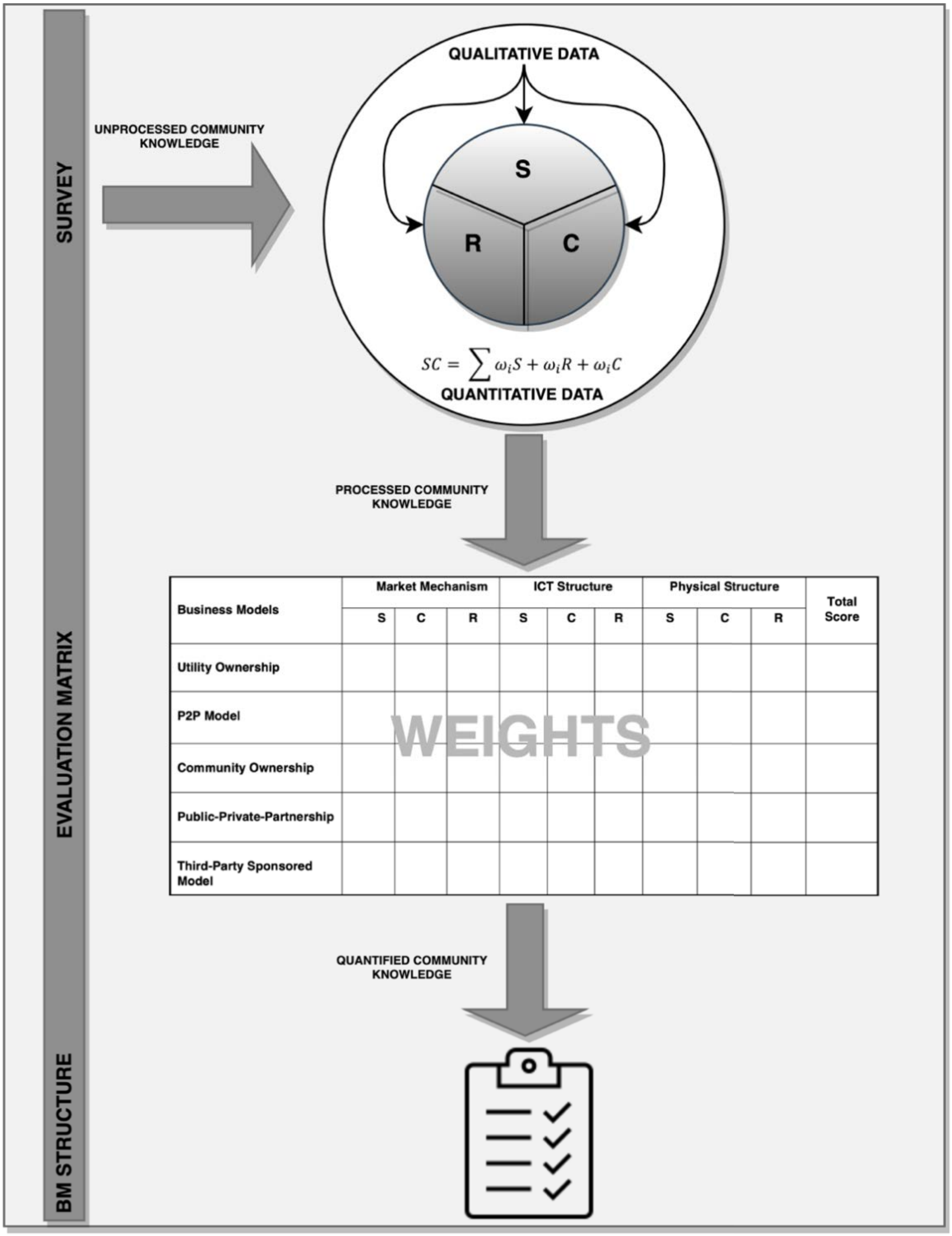


Figure 3.5. An overview of the MCDA framework.

3.4.1 Social Capital as a Foundation

As emphasised in Section 2 and 3, the success of community microgrids is deeply intertwined with the social dynamics of the communities they serve. These systems rely not only on the adoption by individual customers but also on the broader community's endorsement. Without the community's widespread approval, social capital—a resource as critical as any physical infrastructure—can be compromised, leading to potential fragmentation and weakening of communal ties. To mitigate this, we turn to the social capital framework developed in [148] which is instrumental in understanding and enhancing community engagement.

To ensure a comprehensive analysis, it is essential to revisit the three core dimensions of social capital as identified in [148]:

- Structural Social Capital: This encompasses the observable social structures such as networks, roles, rules, and precedents.
- Relational Social Capital: This dimension focuses on the personal relationships, trust, respect, and norms that emerge from the interactions among community members.
- Cognitive Social Capital: This pertains to the shared norms, values, attitudes, and beliefs that guide individuals' actions and interpretations.

Our framework, as visualised in Figure 3.5, starts by leveraging these dimensions to conduct thorough community surveys designed to gather unprocessed community knowledge. The tool from [148] is employed not only to collect this raw data but also to refine it through a systematic process that identifies key indicators and solicits responses through a Likert scale, facilitating both qualitative and quantitative analyses of social capital. The data harvested from these surveys provide both a qualitative and a quantitative perspective on the community's social capital. This dual perspective is crucial for a nuanced understanding that goes beyond numbers, capturing the essence of community interactions and shared values.

Following the collection of this data, the framework employs Equation (1) to process the information. Here, the numerical values assigned to survey responses are weighed (ω) to reflect the relative importance of each dimension of social capital within the specific community context. The weights are a critical component of the analysis as they determine the influence each dimension has on the overall social capital calculation, ensuring the index is tailored to the community's unique characteristics. The culmination of this process is the SCI—a composite metric that quantifies the social capital of the community. By summing the weighted scores from each dimension, the index provides a definitive, quantitative measure of the community's social resources. This index is not just a number; it is a critical determinant that feeds into the decision-making process, guiding the planning and implementation of community microgrids in a way that resonates with the community's social structure and collective goals.

$$SC = \Sigma \omega i\_S + \omega i\_R + \omega i\_C$$

(1)

3.4.2 Value Tree: Decision Criteria

Building upon the foundation of social capital established in the previous section, our MCDA framework progresses to a structured evaluation of BMs for community microgrids. The decision-making process is guided by a value tree, which is a hierarchical representation of the criteria that are critical to selecting the most appropriate BM for community microgrids. As shown in Figure 3.6, the value tree originates with the overarching goal to select a suitable business model. It then branches into primary criteria, which encompass ownership, activities, revenue/pricing, and value proposition—each representing a key aspect of BM and LEM components. These criteria are further broken down into more detailed sub-criteria, providing a granular approach to the analysis.

Through this value tree, our MCDA framework synthesises the various categorizations detailed earlier, culminating in a decision-making tool that is comprehensive, data-driven, and deeply rooted in the community context.

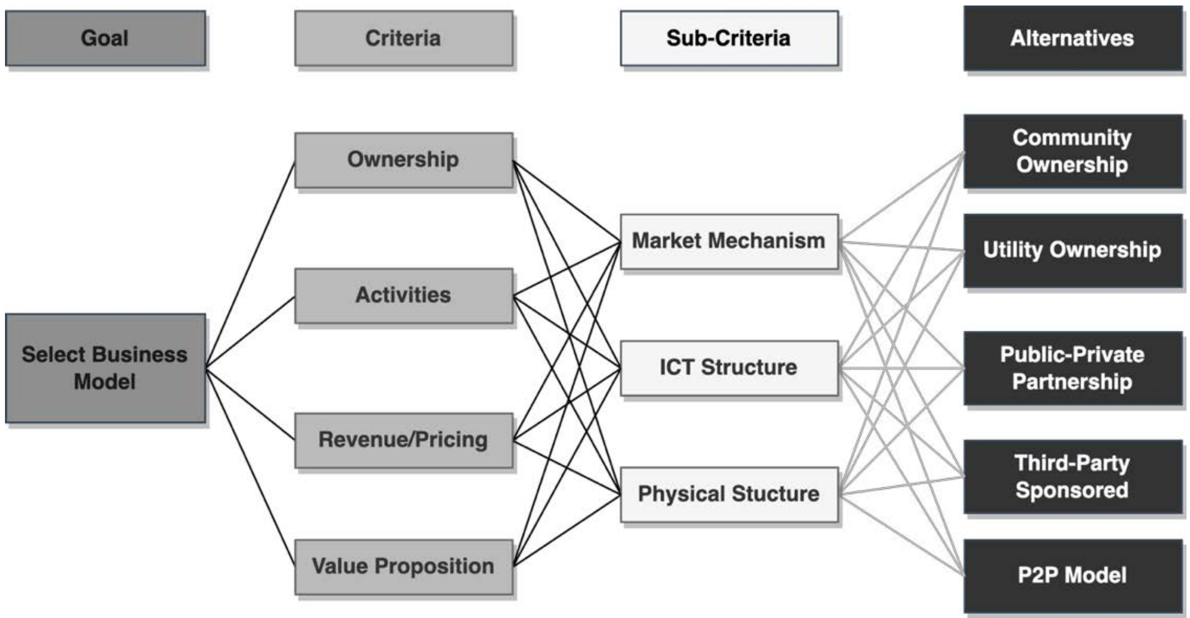


Figure 3.6. Value tree for selecting BMs for community microgrids, showing criteria, sub criteria and alternatives.

3.4.3 Scoring Alternatives: Quantifying Social Capital

Upon establishing the hierarchical structure of the value tree in our framework, the next vital step is to quantify the social capital that underlies each potential business model for community microgrids. This quantification is informed by the comprehensive survey data that has been collected and processed using the conceptual framework of social capital described in [148]. The survey responses, mapped against the criteria and sub-criteria outlined in the value tree, provide a rich fabric of insights into the community's social dynamics.

With Figure 5 serving as a guide, we translate the qualitative aspects of social capital into quantifiable measures through a decision matrix. This matrix evaluates each business model archetype against the community's structural, relational, and cognitive social capital, as delineated in the previous section.

The matrix operates with a scoring system that ranges from 0 to 5. Each score is a reflection of the social capital intensity required for the successful implementation of a BM under each sub-criterion:

Scoring System:

- **0**: No social capital required.
- **1**: Very little social capital required.
- **2**: Some social capital required.
- **3**: Moderate social capital required.
- **4**: High social capital required.
- **5**: Very high social capital required.

This scoring system is designed to be illustrative, offering a baseline for communities to adapt the values according to their unique social contexts and energy systems. Recognising that the social capital landscape can vary dramatically from one community to another, the flexibility of our tool allows for recalibration of scores to better reflect the specific nuances and dynamics of each community. By integrating the qualitative and quantitative data through this scoring system, we ensure that the selection of a business model is not only a reflection of technical and economic evaluations but also of the social capital that pervades the community. The subsequent section on normalisation and weighting further underscores this adaptability, providing a methodology for aligning the scores with the relative importance each community assigns to different sub-criteria. This ensures that the final evaluation is both reflective of and relevant to the community's unique social capital profile and BM aspiration.

3.4.4 Normalisation and Weighting

Weights are recommended to be applied for the individual community microgrid that is being assessed. Weighting can be applied with input from the community or field experts to determine the relative importance of each sub-criterion. Based on the weighting for each individual community, the total score obtained will change accordingly. Further, scores assigned to each sub-criterion are normalised on a 0-1 scale to facilitate comparison across different business models and communities, as inspired by the SCI in [148]. A score of '0' represents the minimum and '1' the maximum social capital requirement identified among the evaluated business models.

3.4.5 Final Evaluation

The BM with the highest cumulative normalised score is estimated to have the highest overall requirement for social capital from the community. This does not necessarily indicate the best or most viable BM but highlights which BM demands the most intensive community engagement and social capital formation. The final decision on selecting a BM should incorporate this analysis along with other strategic considerations, such as economic feasibility, technical viability, and alignment with long-term goals.

3.4.6 Case Study: Applying the Decision-Support Tool

The final part of this section applies the MCDA framework to a case study of a small rural community in Australia. This practical application will demonstrate the utility of the decision-support tool in a real-world context, aligning the community's social capital with potential business models. This community, situated in a mountainous region and located on a major highway between two tourist hotspots, thrives on the tourism that its natural capital attracts. Unique to this setting is that each of the less than 20 inhabitants' doubles as both a business owner and a residential member of the community, creating an intricate web of interests and interactions.

To begin our analysis, we applied the social capital framework as outlined in [148], by assigning equal weight (1/3) to each dimension. This profile was constructed through direct engagement with the community members, where surveys and interviews involving 75% of the inhabitants formed the basis for the SCI. Prior to commencing data collection, the university's research ethics committee granted approval, under the number ETH22-7777, ensuring compliance with human ethics protocols and data privacy protection. Presented in Figure 3.7, the scores reveal an overall SCI of 0.5, indicating a community with mid-range social cohesion. The relational score of 0.55 and cognitive score of 0.61 suggest moderate social interaction and a shared vision for community goals. However, the structural score of 0.35 points to a fragmented community structure, with less formal organisation and cooperative tradition.

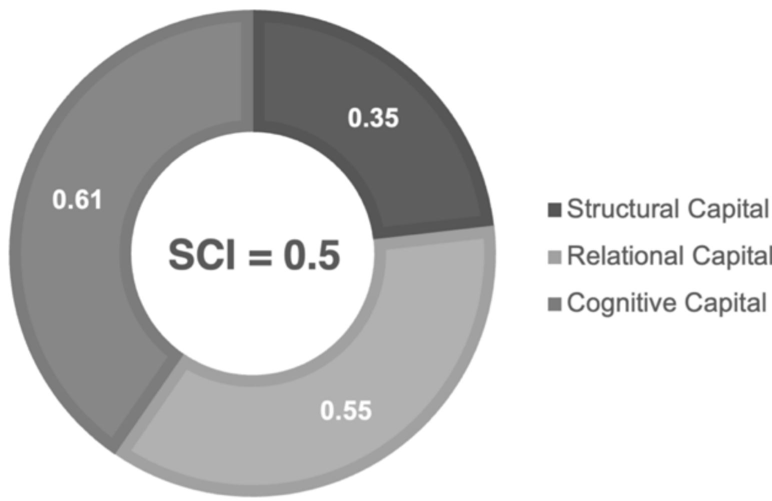


Figure 3.7. The overall SC Index and scores for all SC dimensions from the case study.

This quantitative assessment was further enriched by qualitative insights from the surveys and interviews, which depicted a community leaning towards individualism and self-reliance, particularly in the context of business operations and decision-making. This in-depth understanding of the community's social nuances allowed us to explore the suitability of different business models without imposing any additional weighting on the social capital dimensions or the MCDA framework criteria, maintaining the objective integrity of the framework for this demonstrative case.

With an understanding of the community's social fabric, we then consider the requirements for each potential business model. While [148] guides the assessment of the community's social capital, Table 3.4 lays out the anticipated social capital needs for various business models. This table serves as a general guide to evaluate how each business model might engage with the community's social capital to ensure successful implementation.

Table 3.4. Assessment of Social Capital requirements for chosen BMs.

Social Capital		Scale	Description
Community Ownership	Structural	High	Requires robust communal organisation, shared decision-making and collective resource management. Frequent interactions between members, strong communication links and active involvement in existing community-related activities/project are prevalent.
	Relational	High	Strong levels of trust, reciprocity and mutual understanding between all community members are essential. Strong unity and cooperation between members are also required.
	Cognitive	High	Shared norms and values of collaboration and mutual benefit are crucial, underpinning the concept of a cooperative. Common vision of energy sharing and pooling of resources.
Utility Ownership	Structural	Medium	Active participation from the community may not be necessary, but the capability of coordination between communities increases the feasibility of the project success.
	Relational	Medium	Trust in the utility to effectively manage power and generation and distribution is essential. Historical relationships and precedent can strongly influence the community's trust level. Though the model does not hinge on relationships among community members, unity can ease the process and outcome.
	Cognitive	Low-Medium	This model does not require community members to have technical expertise and thus does not require intensive cognitive commitment from the community. However, acceptance of centralised control and understanding of utility's role is needed.
Public-Private-Partnership	Structural	High	Requires the capacity to navigate and coordinate members through the complexity of multiple stakeholders.
	Relational	High	Strong unity and engagement with partner are needed. The community must trust both the public and private partners and believe in their commitment to community welfare.
	Cognitive	Medium	Shared commitment to the project and common vision for community infrastructure.
Third-Party Sponsored	Structural	Low-Medium	While the community delegates control to an external entity, reducing the need for strong infrastructural or organisational capabilities. Hence, moderate coordination capabilities needed.
	Relational	High	Trust in the third-party is critical, especially given the long-term nature of service contracts. Moderate reciprocity and trust within the community.
	Cognitive	Medium	Shared belief in the advantage of professional management and contract-based energy supply is necessary. Understanding the benefits and role of the third-party.
P2P Model	Structural	High	The community should have the capability to be involved in microgrid management and energy trading. Strong communication links and frequent interaction between members is needed to handle the complex processes of the P2P model.
	Relational	High	Direct energy trading among community members necessitates high levels of trust and mutual respect to overcome selfish or individualistic behaviour.
	Cognitive	High	Shared belief in individual autonomy, competition and innovation is crucial. Willingness to host DERs and common vision for energy sharing is required.

Next, we translate these social capital requirements into a detailed multicriteria evaluation matrix, as seen in Table 3.5. This matrix quantitatively rates each business model against the community's social capital dimensions derived from the data.

Table 3.5. An illustrative example of a multicriteria evaluation matrix for assessing BM archetypes in community microgrids.

Business Models	Market Mechanism			ICT Structure			Physical Structure			Total Score
	S	C	R	S	C	R	S	C	R	
Utility Ownership	2	1	2	2	1	1	1	1	2	**13**
P2P Model	5	4	5	5	5	4	5	4	5	**42**
Community Ownership	5	5	5	4	5	4	4	5	5	**41**
Public-Private-Partnership	3	3	4	3	3	3	3	3	3	**28**
Third-Party Sponsored Model	3	2	3	3	2	3	2	3	3	**22**

The matrix quantitatively appraises each business model archetype by scoring them against the community's social capital dimensions—Structural, Cognitive, and Relational—derived from the collected data. This process is informed by the sub-criteria established in our value tree, as illustrated in Figure 6 ensuring that the evaluation aligns with both the community's social dynamics and the specific characteristics of each business model. For this case study, the scores in the evaluation matrix are illustrative and have not been directly derived from case study data. Instead, each sub-criterion within the evaluation matrix has been assigned equal weight, with each dimension contributing 1/3 to the overall assessment. This equal weighting approach has been adopted to provide a balanced view of the social capital's influence on each business model; however, it may vary in other contexts where certain dimensions of social capital may have greater significance. Users are encouraged to customise these scores, considering their local knowledge, specific community dynamics, and the nuances of their energy systems. Consequently, it is important to acknowledge that the social capital landscape can vary significantly from one community to another. The flexibility inherent in our tool allows users to recalibrate the scoring to reflect their community's specific situation.

Lastly, we normalise the scores on a scale from 0 to 1, by performing a min-max normalisation for each business model's total score as seen in Figure 3.8. This process involves taking the score of each business model and applying Equation (2).

$$Normalised\ Score = \frac{Score - Score_{min}}{Scored_{max} - Score_{min}}$$

(2)

Where:

- **Score** is the total score of the business model.
- **Min Score** is the lowest total score across all BMs.
- **Max Score** is the highest total score across all BMs.

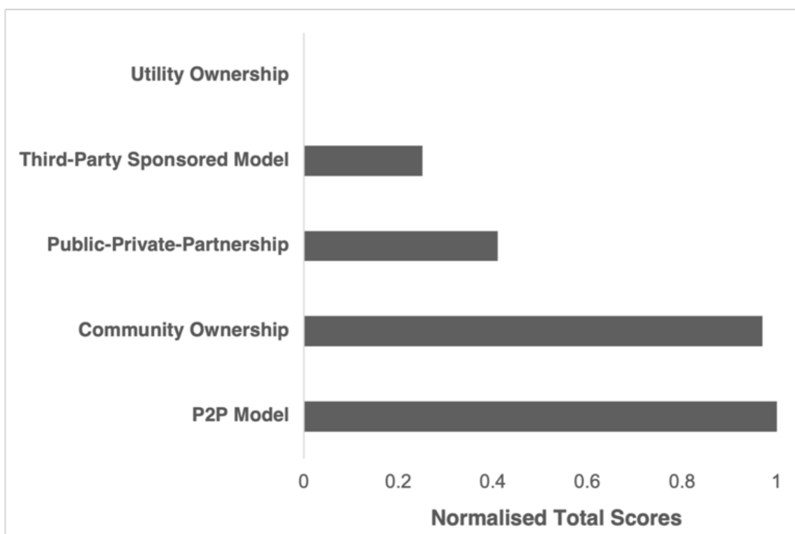


Figure 3.8. Normalised total score for the five business model archetypes in the case study community.

Matching the community's social capital scores against the normalised business model scores in Figure 8, Utility Ownership, Public-Private-Partnership, and Third-Party-Sponsored Model were identified as viable options. The Utility Ownership model could potentially resonate with the community's desire for organisational structure and professional management. Public-Private-Partnership might harness the modest yet present relational dynamics, inviting collaboration that could bolster the community's economic mainstay—tourism. The Third-Party-Sponsored Model seems appropriate for a community favouring individual business autonomy over communal ventures. Each option reflects a different facet of the community's social capital and presents distinct pathways to align the microgrid's operational model with the community's social and economic fabric.

3.5 Conclusion

This paper has focused on aligning the unique social fabric of communities with appropriate BMs for LEMs, to enhance the probability of successful microgrid development and operation. By ensuring that the selected business model is fully aligned with the community social capital, we believe that community microgrids can be developed and implemented more sustainably and efficiently. In this exploration, we have presented a novel MCDA framework meticulously designed to evaluate and integrate the socio-technical dimensions of community microgrids. Through the comprehensive case study applied within an Australian community, we have substantiated the framework applicability as a decision-support tool, demonstrating its capacity to harmonise the intricate interplay between community social attributes and the technical demands of microgrid systems.

Our exploration in this paper underscored the intricate interplay between the technological, economic, and social dimensions inherent in community microgrids. Each business model presented offers a unique combination of physical structure, ICT structure, and market mechanism. These attributes reflect the distinct operational characteristics, engagement strategies, and regulatory environments associated with each model, underscoring the complexity and diversity of the field. Crucially, these components are not static; they evolve over time, influenced by factors such as technological advancements, market dynamics, regulatory shifts, and changes in community needs and preferences. Consequently, a successful business model for a microgrid must be resilient and adaptable and capable of balancing multiple, often conflicting, objectives and constraints.

Lastly, future research directions may involve empirical application and the refinement of archetypes to assess the MCDA framework established in this study. This could provide a more nuanced understanding of microgrid development and operation within diverse contexts.

4 Evaluating the Interplay of Community Behaviour and Microgrid Design Through Optimisation Modelling in Local Energy Markets

Preamble

Paper Status

Under review in Renewable and Sustainable Energy Reviews

Overview

In the previous chapters, we laid the groundwork for understanding and integrating social dynamics into community microgrid design and operation. Chapter 2 introduced the theoretical foundation and provided a quantitative measure of the social fabric within communities. Chapter 3 utilised these insights to develop a decision framework for assessing and selecting feasible business models (BMs) for community microgrids.

Building on this, in Chapter 4, the goal is to propose an integrated methodology using social capital for embedding and assessing social factors in the operation of community microgrids. The focus of this chapter is to refine the selection process by applying Mixed-Integer Linear Programming (MILP) optimisation modelling to analyse and optimise the shortlisted BMs. This chapter further incorporates the social capital framework (Chapter 2) and introduces new Key performance Indicators (KPIs) to enhance our understanding of community behaviour and influence and impacts of microgrid operations.

When a shortlist of BMs is identified using the decision framework (Chapter 3), we further investigate the optimal business model and potential operations for a community's social capital. This investigation includes scenario testing to understand how different BM may influence and change social capital. By integrating social capital considerations directly into the optimisation model, we ensure that the model adapts to the social nuances and values of the community, promoting a more inclusive and sustainable microgrid operation.

Hence, this chapter highlights how various BMs influence microgrid operations and social outcomes and providing insights into creating sustainable and inclusive energy systems.

Abstract

This paper introduces an innovative method for integrating social dynamics into the design of community microgrids using Mixed-Integer Linear Programming (MILP). Traditional microgrid optimisations frequently overlook the intricate interactions between socio-economic factors and technical performance. Our proposed methodology addresses this gap by incorporating a Social Capital Index (SCI) to guide the selection of Business Model Archetypes (BMAs), ensuring that microgrid designs not only meet technical specifications but also resonate with community values and behaviours. We introduce and apply socially focused Key Performance Indicators (KPIs) to evaluate the impact of microgrid operations on community engagement, equity, and governance. The effectiveness of the proposed approach is demonstrated through an experimental case study with real-world data from Australia. The study reveals how various BMAs influence both the operational efficiency and social outcomes of community microgrids, providing valuable insights for developing more sustainable and inclusive energy systems. This research advances the understanding of the social implications of microgrid technologies, establishing a foundation for future research into energy solutions that are both technically and socially inclusive.

4.1 Introduction

The design and operation of community microgrids represent a vital nexus between technological innovation and social dynamics [30], intricately woven together through the mechanisms of market design and the regulatory frameworks that govern energy transactions and power flows [90]. The technological framework of a community microgrid includes key components such as Distributed Energy Resources (DERs) [69] like photovoltaic (PV) panels, energy storage systems (ESS) [159], a microgrid control centre [164], and connections to the main grid [6] (Figure 4.1). This setup enables the microgrid to manage energy flows efficiently, balancing supply and demand within the community [164]. In this framework, consumers and prosumers (members who both produce and consume energy) play distinct roles [183]. Prosumers generate excess energy, which can be shared or sold within the community, while consumers primarily draw energy from the grid or local sources [183].

Standalone DERs and ESS contribute to energy resilience and efficiency by providing localised generation and storage capabilities [184]. The microgrid operates through sophisticated communication and control systems that coordinate energy flows, manage grid connections, and ensure reliability [53]. The microgrid control centre oversees these operations, implementing strategies to optimise energy distribution and integrating with the broader grid as needed [6].

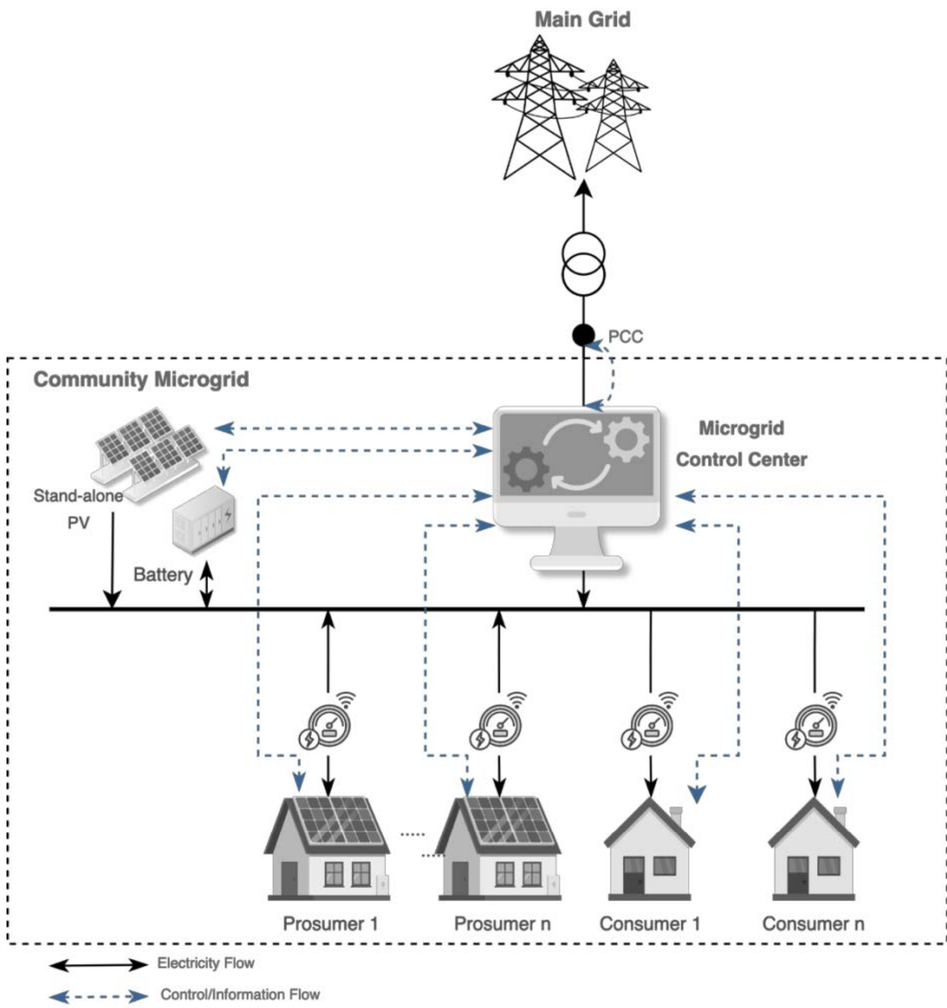


Figure 4.1. Example structure of a community microgrid.

At the core of this system lies the challenge of not only engineering a robust and efficient electrical infrastructure but also choosing a business model (BM) that harmonises with the behavioural patterns and preferences of the community it serves [8], [22]. This balance is crucial, as the rules laid out by market design profoundly impact community behaviour [46], influencing everything from energy consumption habits to the collective pursuit of sustainability goals [34]. Conversely, the collective actions and decisions of the community can shape the evolution of the microgrid's operational strategies and market rules, creating a dynamic feedback loop that continuously reshapes the landscape of energy production, distribution, and consumption [39]. For instance, the Brooklyn Microgrid in New York enabled local residents to trade solar energy within their community through a blockchain platform, enhancing energy resilience, promoting community engagement, and providing financial benefits [185]. Similarly, the Isle of Eigg microgrid in Scotland achieved energy autonomy by integrating renewable energy sources with community-driven initiatives [176], addressing technical challenges while fostering ownership and participation [186].

Navigating this complex interdependency requires a deep understanding of both microgrid systems' technical underpinnings and the community's social dimensions [33]. The challenge intensifies when attempting to encapsulate these social aspects within computer-based models, which are pivotal for planning, analysing, and optimising microgrid operations [28]. Traditional computational models excel at processing the quantitative data related to physical infrastructures and energy markets [40]. However, integrating the qualitative aspects of community behaviour and social dynamics into these models presents a unique set of challenges [28], [146]. Wolsink [39] proposed a comprehensive framework for incorporating social aspects, including community identity as 'identity factors', into smart grid and microgrid planning. Although Wolsink's study doesn't integrate these aspects into actual computer-based or quantitative methods, it provides an approach to identify key parameters that influence different community members, affecting microgrid planning, temporary islanding, and operation. Supporting this view, both Krumm et al. [28] and Dall-Orsolettaa [187] underscore the necessity for a more robust representation of social aspects within these models. Krumm advocates for a blend of various model types and calls for interdisciplinary research to enrich the modelling process. Dall-Orsolettaa et al. [187] highlights the critical importance of considering factors such as geographical resolution, time horizon and methodological approaches when incorporating social aspects. Additionally, Lazdins and

Mutule [188] provide a practical application of these principles, illustrating how variable factors can influence the effectiveness and sustainability of energy communities. Together, these studies highlight the importance of thoroughly integrating and examining social factors in computer-based models for community energy.

To address these challenges, researchers and practitioners increasingly turn to advanced modelling techniques that capture the multifaceted nature of community microgrids [80]. In the realm of optimisation, a body of work [145], [159], [173], including Suk et al. [79], Casalicchio et al. [108] others are pivotal. Suk et al. [79] pioneered a framework that integrated community multifaceted characteristics into the technical model, yet provided limitations on the documentation of these traits and their influence on techno-economic decisions. Casalicchio et al. [108], advanced this field with a linear optimisation model focusing on optimal dispatch and equitable benefit distribution through a Fairness Index. While this model advanced the technical optimisation of microgrids, it still provided limited insight into the broader social dynamics at play. This reflects a common challenge: technical models often prioritise efficiency and optimisation, potentially at the expense of understanding the social context. Similarly, Santos et al. [189], proposed a multi-objective optimisation framework for microgrid design that incorporates social analysis by including criteria such as equity, household benefits, community services, and productive activities. The framework was designed to align microgrid solutions with community needs and social context through multi-objective analysis. However, the assessment of social criteria remains vague, underscoring the ongoing challenge of integrating social dynamics into technical models and frameworks.

Complementing optimisation, game theory offers valuable insights into the strategic interactions between different stakeholders, including consumers, producers, and regulatory entities, highlighting how their decisions and strategies can influence the overall system dynamics [101], [190]. Gjorgievski et al. [101], which applies a virtual net-billing approach to distribute energy among a community's prosumers equitably. Here, a mathematical model assesses individual contributions to shared energy consumption, with cooperative game theory and a set of indicators providing a basis for evaluating fairness. This is further contextualised by comparing it to five other energy-sharing models in the literature [101]. Although the study acknowledges individual inputs, it does not sufficiently explore the complexities of social behaviour. Conversely, Moradi and Ghazizadeh [191] present a game-theory energy-sharing model within a residential microgrid that does consider individual social dynamics, particularly the propensity for neighbourly cooperation. However, its scope is confined to the parameters of willingness to cooperate and doesn't extend to a broader social behaviour analysis.

Agent-based modelling, with its ability to simulate the actions and interactions of individual agents based on a set of rules, emerges as a particularly promising tool for incorporating the social and behavioural dimensions into the analysis [192], [193]. Notably, Paredes et al. [194] utilised NetLogo model to examine how isolated microgrid systems interact with and impact community social dynamics. This model simulates daily routines and economic activities to assess the influence of varying microgrid configurations on these aspects. Nevertheless, the model simplifies complex social behaviours and is limited to an evaluation interval of only a few hours, thus impeding the ability to obtain detailed insights or make comprehensive comparisons across different scenarios.

To date, despite the considerable exploration of microgrid technologies and economic strategies, there has been a conspicuous absence of a holistic methodology that incorporates these with the social constructs of the communities they serve [28], [110]. The literature points to a predominant focus on the technical and economic optimisation of microgrids, with a tendency to marginalise the social parameters [78]. This has been noted by scholars who call attention to the scant integration of social objectives and community participation in microgrid design and planning [8], [34], [111].

The aim of this paper is to bridge this gap by developing an integrated method for incorporating and analysing social factors in the design and operation of community microgrids. While numerous studies have focused on methodologies and scenario comparisons, to the best of our knowledge, no integrated method exists where different BMs are tested based on the social capital of the community and how to integrate and analyse those parameters within a techno-economic optimisation model. Traditional optimisation efforts have focused largely on techno-economic aspects, often neglecting the critical influence of community dynamics. Our approach uniquely integrates social capital considerations directly into the design and employs a Mixed-Integer Linear Programming (MILP) model to analyse the optimal operation. Building on the groundwork laid by Eklund et al. [195], we utilise a set of Business Model Archetypes that are informed by a community's Social Capital Index (SCI) as established in [148]. This model seeks to refine the selection process further, conducting a more in-depth and quantitative analysis to determine the most suitable BM. This strategic choice acts as a cornerstone for our MILP model inputs. The methdology ensures that while the model retains its techno-economic core, it also adapts to the social nuances and values of the community, thus promoting a more inclusive and sustainable microgrid operation. However, this model does not seek to determine the intricacies of local energy market designs, such as clearing prices or bidding strategies, but rather to optimise the microgrid operation with a focus on the social dynamics at play. To evaluate the outcomes of our optimised model, we introduce an array of Key Performance Indicators (KPIs) tailored to assess the post-optimisation social behaviour of the community. These KPIs provide insights into how the microgrid's operation may affect social dynamics such as benefit distribution, financial transactions, and participatory governance.

In this effort, the main contributions are:

1. Incorporation of social capital into both the inputs of the optimisation model and the evaluation of its outcomes.
2. Development of socially focused KPIs with a social emphasis to measure the operation's impact on the community's social behaviour.
3. A demonstration of how different BMs influence the operation of the community grid and the social capital of the community.

Continuing, this paper is organised as follows: Section 4.2 details the methodology behind the development of the framework: optimisation model and post-analysis. Section 4.3 presents an experimental case study for comparison of different BM scenarios. Section 4.4 provides the results and discussion of the case study. The paper concludes with Section 4.5, summarising our findings and proposing directions for future research.

4.2 Methodology

This section outlines the methodology used to compare various BM scenarios within a community microgrid's framework, detailing the model's general characteristics and structure. As depicted in Figure 4.2, the method design incorporates the SCI developed by [148] to aid in selecting BMs, which subsequently influences the configuration of the Local Energy Market (LEM) as elucidated in reference [195]. The LEM and physical design aspects serve as direct input parameters for the optimisation model, which has been tailored to align with the community's social structure as determined by the SCI during the preliminary selection of the BMs. The optimisation aims to minimise the community's total electricity costs under the chosen business model. The outputs are processed to represent developed KPIs and control parameters. These outputs enable the analysis of social behaviours and their impact on social capital, offering a quantitative means to discern the most viable business model from those previously presented. This, in turn, refines the understanding of the community's SCI.

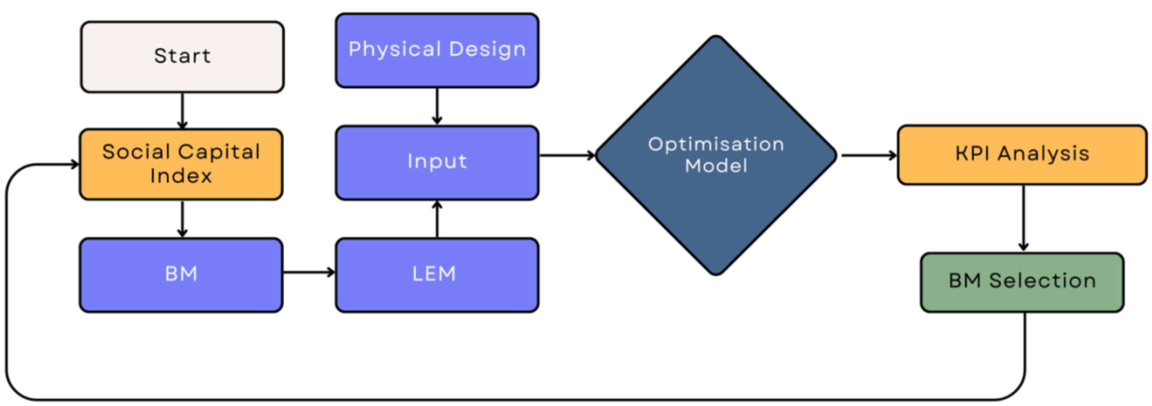


Figure 4.2. Model design framework introduced in this study.

4.2.1 BM Scenarios

We have adapted the assessment framework for social behaviour and the selection of BMs from previous studies [148] and [195]. Specifically, Eklund et al. [195] presents a Multi-Criteria Decision Analysis Framework for a systematic selection and evaluation of BMs tailored to community microgrids. This framework emphasises the importance of social capital in determining the viability of these BMs. It builds upon the conceptual structure and SCI originally developed in [148]. Additionally, the authors outline and systematically categorise various BM archetypes, assessing each archetype based on the requisite social capital scores. This assessment yields a range of BMs deemed suitable for a community, contingent on its initial SCI. Our study extends this framework, applying these BM archetypes to create distinct operational scenarios. We then quantitatively analyse how each BM may influence social capital levels and the behavioural changes within the community.

Three distinct BM scenarios within a community microgrid are chosen for comparison, as depicted in Figure 4.3:

- BM A: Third-Party Ownership Model, where there is no energy sharing or trading, and distributed energy resources (DERs) may be owned by either the members or the utility.
- BM B: Centralised Peer-to-Peer (P2P) Model, with system-determined energy trading amongst members.
- BM C: Community-Owned Model with bill-sharing, which adopts a cooperative approach to energy cost distribution among members.

These three BMs were selected for experimental purposes and to provide clear and coursed insights into their respective impacts on individual members and the community. Each BM illustrates different degrees of possible interaction, from individuality to collective and collaborative possibilities. Limiting the number of BMs allows for a more detailed comparison of each model's effects.

The community microgrid in these scenarios includes multiple members, each with individual ownership of rooftop photovoltaic (PV) systems and batteries. For this paper, only the electricity consumption of the households is considered in energy demand. Further, it is important to acknowledge that members are assumed to have the ability to buy and sell electricity in both the LEM and the wholesale market. However, this paper does not cover the communication protocols between the community manager and these markets. Detailed explanations and operational specifics of these models are provided in the following subsection 4.2.2, dedicated to articulating each model's varied structures and functional frameworks within the community microgrid setting.

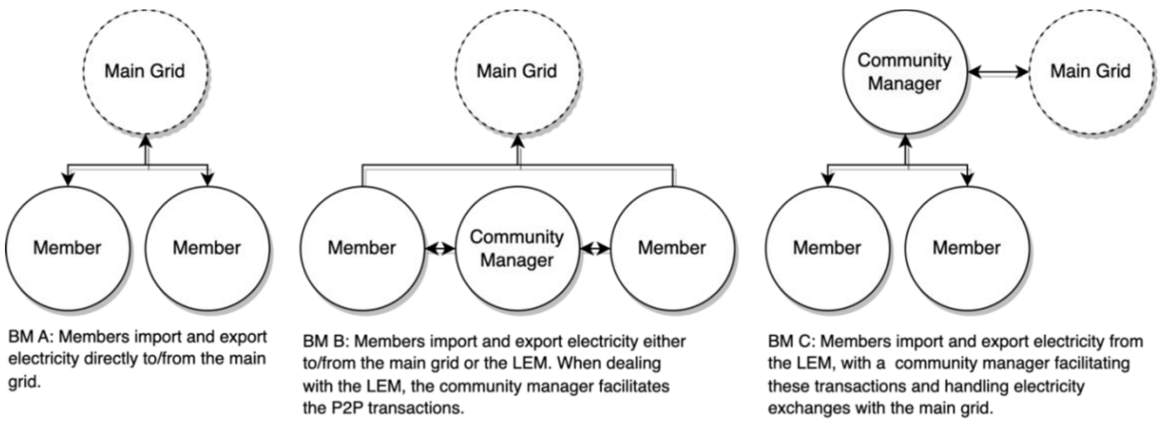


Figure 4.3. Overview of three BM scenarios considered for the CM.

4.2.2 General Model Formulation

The optimisation model employs a mixed-integer linear programming (MILP) approach with the objective of minimising total electricity cost. This can be evaluated at the scale of the whole community or an individual member level, contingent on the selected BMs. Our strategy involves a deterministic approach that relies on a projected estimate of solar energy production without considering potential uncertainties. To construct the optimisation model, we employed a bottom-up approach, leveraging the Python programming language for its extensive library ecosystem and its prominence in the scientific domain [196]. The model formulation was facilitated by using PuLP [197], an open-source linear programming library in Python. To solve these problems, we integrated the Gurobi optimiser [198], acclaimed for its capability to efficiently handle MILP challenges, which was essential for the intricate and expansive nature of microgrid optimisation tasks.

To support the understanding of the model formulation and the subsequent equations, we have detailed the specific decision variables, parameters, and constants for each BM scenario in Appendix A.

BMA A: Third Party Ownership Model

In this scenario, each member has no shared pool of energy or trading and only interacts with their individual system and the main grid. The members have already paid for their systems, and the operational cost of (A$/kWh) for using their PV and battery is not included in the objective function. Each member subscribes to the same time of use (ToU) electricity tariff plan—a variable rate subject to changes in demand, time of day, and other factors, as determined by the electricity retailer [199]. The goal of the BM A scenario is to minimise the cost of electricity for individual microgrid members through effective self-management of their energy systems. The objective function, provided in Equation (1), is expressed as the sum of costs for grid energy imports and revenues from energy exports:

$$\text{Minimise: } Z = \sum_{i=1}^{N} \sum_{t=1}^{T} (G_{i,t}^{import} \cdot C_t^{grid} - G_{i,t}^{export} \cdot FIT_t) \quad (1)$$

Where:

Z: Total cost of energy for the community

i: Index of community members set N

t: Time-step index of set T

$G_{i,t}^{export}$ and $G_{i,t}^{import}$: The total energy exported to and imported from the main grid by member *i* at time *t*

C_t^{grid}: Cost per unit purchased energy from the main grid at time *t*

FIT_t: Feed-In Tariff for energy exported back to the main grid at time *t*

The main constraints related to electricity generation and consumption are provided in Equations (2) and (3). Equation (2) ensures that the total electricity available (self-generated, imported and discharged from the battery) meets their demand at each time step *t*. While Equation (3) mandates that the electricity generated from member *i*'s PV system is either self-consumed, stored or exported.

$$PV_{i,t}^{self} - Bat_{i,t}^{discharge} + G_{i,t}^{import} = L_{i,t} \quad (2)$$

$$PV_{i,t}^{self} - Bat_{i,t}^{charge} + PV_{i,t}^{export} = PV_{i,t}^{gen} \quad (3)$$

Where:

$PV_{i,t}^{self}$: PV self-consumption by member *i* at time *t*

$Bat_{i,t}^{discharge}$: Power discharged from member *i*'s battery at time *t*

$Bat_{i,t}^{charge}$: Power charged by PV to the battery by member *i* at time *t*

$L_{i,t}$: Load of member *i* at time *t*

$PV_{i,t}^{export}$: PV power from member *i* for export to the main grid

$PV_{i,t}^{gen}$: Power produced from member *i*'s PV system at time *t*

Equation (4)-(5) addresses the constraints associated with the battery's charging and discharging processes, ensuring they do not exceed their capacities and adhere to the depth of discharge limits, as specified in Equations (6) and (7). To prevent simultaneous charging and discharging of the battery, we use binary variables and the Big-M method. The Big-M method is a mathematical approach used in linear programming problems to handle logical constraints effectively. It allows the model to enforce decisions, by introducing large constants (M) which limit the feasible region of the solution space [200]. Binary constraints for charging and discharging are presented in Equations (8) and (9), where the binary variable $Bat_{i,t}^{status}$ indicates the operational mode of the battery using the Big-M method. When the battery is not charging ($Bat_{i,t}^{status}$ = 0), Equations (8) ensures that the charge amount does not exceed 0 by setting the upper limit as $M \cdot 0$. Conversely, when the battery is discharging ($Bat_{i,t}^{status}$ = 1), Equation (9) caps the discharge amount at a maximum of *M*, which is functionally unrestricted due to the large value of *M*.

For the initial period ($t = 0$):

$$SOC_{i,0} = B_{i,o} + Bat_{i,t}^{charge} \cdot \eta^{charge} + Bat_{i,t}^{discharge} \cdot \eta^{discharge} \quad (4)$$

For subsequent periods ($t > 0$):

$$SOC_{i,t} = SOC_{i,t-1} + Bat_{i,t}^{charge} \cdot \eta^{charge} + Bat_{i,t}^{discharge} \cdot \eta^{discharge} \quad (5)$$

$$SOC_{,i,t} \leq \mathrm{B}_{i,t} \quad (6)$$

$$SOC_{,i,t} \geq \mathrm{B}_{i,t} \cdot DoD \quad (7)$$

$$Bat_{i,t}^{charge} \leq M \cdot (1 - Bat_{i,t}^{status}) \tag{8}$$

$$Bat_{i,t}^{discharge} \leq M \cdot Bat_{i,t}^{status} \tag{9}$$

Where:

$SOC_{i,t}$: State of charge of member i's battery at time *t*

$B_{i,t}$: Capacity of member i's battery at time *t*

η_{charge} and $\eta_{discharge}$: Efficiency of battery charging and discharging processes

DoD : Depth of Discharge limit for the battery

M : A large constant used to enforce constraints in the optimisation model

$Bat_{i,t}^{status}$: Binary variable to effectively act as an on/off switch for battery charging or discharging

BM B: Centralised Peer-to-Peer Model

Similar to BM A, community members own individual rooftop PV and batteries and subscribe to the same ToU tariff. BM B provides a market mechanism that facilitates energy transactions among members, with pricing determined by the individual cost A$/kWh per unit. A community manager is designated to orchestrate trades between members (LEM) and the main grid centrally. The model's objective is to minimise the total electricity cost for the community by efficiently managing production, consumption, storage, and trading activities. Equation (10) reports the objective function for the BM B model, which is identical to BM A's objective function. The rationale for not including the costs of energy trading between members directly in this equation is based on the principle of zero-sum trading within the community. In essence, when one member purchases energy from another member, there is a cost incurred by the buyer and an equivalent revenue gained by the seller. When aggregating the financial impact across the microgrid, these internal transactions neutralise each other, leading to a net effect of approximately zero on the community's collective energy expenditure. Therefore, the objective function focuses on the interactions with the main grid as the primary financial consideration.

$$\text{Minimise: } Z = \sum_{i=1}^{N} \sum_{t=1}^{T} (G_{i,t}^{import} \cdot C_t^{grid} - G_{i,t}^{export} \cdot FIT_t) \tag{10}$$

Further, Equation (11) builds upon the foundation set by Equation (2) in BM A by incorporating an additional trade term, where $P_{j,i,t}^{trade}$ is the energy purchased by member i from member *j* at time *t*. This term accounts for the energy traded between community members, ensuring that the load balance not only includes energy from self-generation, battery storage, and the main grid but also considers the energy received from or provided to other community members through P2P transactions. Additionally, the variable $Bat_{i,t}^{discharge,self}$, specifies that the power discharged from member *i*'s battery at time *t* is allocated for self-consumption as the battery can also be used for trading, clarifying its dual-purpose function. Similarly, Equation (12), while analogous to the Equation (11) in BM A, introduces a new variable, $PV_{i,t}^{trade}$, which represents the surplus PV energy available for trading within the community. After accounting for self-consumption and battery storage, this equation guarantees that any excess power produced by a member's PV system can now be allocated either for export to the main grid or P2P trading.

$$PV_{i,t}^{self} - Bat_{i,t}^{discharge,self} + G_{i,t}^{import} + \sum_{j}^{N} P_{trade,j,i,t} = L_{i,t} \tag{11}$$

$$PV_{i,t}^{self} - Bat_{i,t}^{charge} + PV_{i,t}^{export} + PV_{i,t}^{trade} = PV_{i,t}^{gen} \tag{12}$$

The battery storage constraints capturing the charging and discharging processes are equivalent to Equations (4)-(9) in BM A. However, a new constraint is introduced in BM B to account for the battery's capability to discharge for both self-consumption and trading. As depicted in Equation (13), the variable $Bat_{i,t}^{discharge,exp}$ represents the power discharged from member *i*'s battery for the purpose of P2P trading, distinguishing it from power used for self-consumption. This new constraint ensures the model accurately captures the dual functionality of the battery discharge in the context of energy trading.

$$Bat_{i,t}^{discharge} = Bat_{i,t}^{discharge,self} + Bat_{i,t}^{discharge,exp} \tag{13}$$

Trading is subject to certain restrictions based on generation and demand, as shown in Equation (14). The energy available for member *i* to trade at time *t* is limited to the surplus of their generated PV power after self-consumption and battery operations.

$P_{i,j,t}^{trade} \leq PV_{i,t}^{gen} - Bat_{i,t}^{discharge}$ (14)

To ensure that importing and exporting do not occur simultaneously, we apply the same methodology previously described for managing the charge and discharge cycles of the battery, as outlined in Equations (8) and (9) for BM A. The binary constraints that prohibit concurrent importing and exporting are delineated in Equations (15) and (16). Here, $\exp\_imp_{i,t}$ represents the binary variable that functions effectively as a switch to enable or disable importing or export energy.

$G_{i,t}^{import} \leq M \cdot (1 - \exp\_imp_{i,t})$ (15)

$G_{i,t}^{export} \leq M \cdot \exp\_imp_{i,t}$ (16)

BMA C: Community-Owned Model and Bill Sharing

For this scenario, similarly to BM A and BM B, community members own individual rooftop PV and batteries. The community microgrid optimises using locally produced energy from PV and batteries by prioritising intra-community distribution before exporting to the main grid. A community manager is tasked with oversight of this energy distribution, balancing imports from and exports to the main grid based on collective usage and production. Unlike BM A and BM B, members do not subscribe individually to a tariff from the retailer, as BM C incorporates a bill-sharing method. Hence, the community manager oversees this part and handles the net export and import with the main grid on behalf of the community members. The tariff structure of BM C is further explained in this subsection after Equation (20).

The objective of the model is to minimise the total cost of electricity for the community microgrid. The objective function, as shown in Equation (17), includes the costs incurred from main grid energy imports, costs for shared energy within the community, and revenues generated from energy exported to the main grid. Equations (18) and (19) delineate the interactions between the community microgrid and the main grid. These interactions are designed to accurately reflect the import of energy to satisfy demand, the export of surplus generation, and the management of the shared energy pool in the LEM.

Minimise: $Z = \sum_{t=1}^{T}(S_t \cdot C^{shared} + G_t^{import} \cdot C_t^{grid} - G_t^{export} \cdot FIT_t)$ (17)

$$\sum_{i=1}^{N} P_{i,t}^{net,export} = S_t + G_t^{export} \tag{18}$$

$$G_t^{import} = \sum_{i=1}^{N} P_{i,t}^{net,import} - S_t \tag{19}$$

Where:

S_t : The amount of energy shared among community members at time *t*.

C^{shared} : Cost per unit of shared energy.

G_t^{export} and G_t^{import}: The total energy exported to and imported from the main grid by the community at time *t*, respectively.

$P_{i,t}^{net,export}$ and $P_{i,t}^{net,import}$: Net energy exported to and imported from the microgrid by member *i* at time *t*

The optimisation is subject to several constraints that ensure the solutions are physically feasible and operationally viable. Similar to BM B, Equation (20) provides the energy balance for each member in every time period. The key difference in this scenario is the introduction of a new variable, $P_{i,t}^{net,import}$, which represents the net energy that each member imports from the community microgrid, as opposed to energy import from the main grid or P2P trading as seen in BM B. This variable shifts the focus from individual transactions to communal energy distribution, emphasising the collective management of energy resources within the microgrid.

$$PV_{i,t}^{self} - Bat_{i,t}^{discharge,self} + P_{i,t}^{net,import} = L_{i,t} \tag{20}$$

The battery storage constraints are the same as in BM B, with the change of variable $Bat_{i,t}^{discharge,exp}$ in Equation (14) to be exported to the community manager for either shared energy in the LEM or export to the main grid.

Post-optimisation, we reassess each member's electricity bill, streamlining the complexity of the initial optimisation model. Similar to BM A and BM C, where energy is purchased both from the main grid and within the microgrid, the pricing mechanism for electricity consumed by community members is influenced by the energy source at any given time. The cost of energy for members integrates various tariffs applicable to different energy sources. The aggregate cost per kWh for community members is derived by considering the amount of energy supplied by each source in proportion to their respective tariffs. While the per kWh rate is the same for all community members during a specific time period, the total monetary outlay for each member is contingent on their individual energy consumption patterns, as the rate is subject to hourly fluctuations. For BM C, the variable costs considered are based on the different tariff structures involved:

- **Microgrid Tariff**: This special rate applies when electricity is sourced from the microgrid, also described as C^{shared}.
- **TOU**: This variable rate changes based on the time of day charged by the electricity supplier, C_t^{grid}.
- **Mixed**: Mixed tariff based on the combination of the Microgrid tariff and the TOU, C_t^{mixed}.

To calculate the cost per kWh for the mixed tariff structure, we employ a weighted average method, Equation (21). It takes into account the proportionate contribution of each electricity source to the total net electricity imports for the microgrid, as well as the respective cost associated with each source.

$$C_t^{mixed} = \frac{C^{shared} \cdot S_t + C_t^{grid} \cdot G_t^{import}}{S_t + G_t^{import}} \tag{21}$$

For a comprehensive understanding of the bill-sharing mechanism within the BM C, adjustments are made for the energy pricing based on consumption or generation by the community members. The pricing strategy for shared energy consumption within the microgrid is established to be greater than the cost per kWh of individual member production, considering the disparity in the A$/kWh for battery and PV. These rates are computed based on the capital expenditure and planning period of each member's DERs. The selected tariff is, however, set below the cost of importing electricity from the main grid [201]. These parameters may be adjusted to address specific scenarios and to reflect the BM's decisions based on member agreements.

To distribute the proceeds from exporting electricity to the main grid, a proportional reimbursement model is employed for BM C. This approach, detailed in Equation (22), accounts for each member's contribution, which is weighted and normalised. Specifically, it considers the member's export contribution (λ_i^{exp}), self-consumption contribution (λ_i^{self}), and the contribution from the reversed import ratio (λ_i^{import}). This expresses each member's weighted contribution as the sum of these three factors divided by the total number of members (N). After this initial calculation, Equation (23) is used to determine each member's individual reimbursement (R_i). This is done by taking the member's weighted contributions, dividing by the sum of all members' weighted contributions, and then multiplying by the total revenue (C^{rev}).

$$\gamma_i = \frac{\lambda_i^{exp} + \lambda_i^{self} + \lambda_i^{imp}}{N} \tag{22}$$

$$R_i = \frac{\gamma_i}{\Sigma \gamma_i} \cdot C^{rev} \tag{23}$$

4.2.3 Key Performance Indicators (KPIs)

Understanding the importance of social capital in the successful operation and adoption of the community microgrid is critical [148]. To address this, we provide a systematic approach to assess the optimal BM choices based on their influence on social capital. We have identified seven KPIs designed to measure the impact of different BMs on community microgrid behaviour and performance. Table 4.1 presents a summary of these KPIs, and a detailed explanation is provided below.

Table 4.1. Overview of KPIs.

KPI	Description
KPI 1: Total Cost Savings	The total reduction in the electricity bills for the entire community
KPI 2: Collective Self-Sufficiency	The ratio of self-consumption, shared energy or traded energy of all members to the total energy demand in the community microgrid.
KPI 3: Individual Cost Savings	The total reduction of each member's individual electricity bill

KPI 4: Net Importers and Exporters	The ratio of energy imported vs exported by each member
KPI 5: Self-Consumption vs Sharing	The ratio of self-consumption vs sharing (net exports or trading)
KPI 6: Self-Sufficiency	The ratio of self-consumption vs energy consumption per member
KPI 7: Quality of Sharing	The factor evaluating both the quantity of shared/traded energy and its alignment with peak demand periods.

KPI 1 - Total Cost Savings: By comparing the total costs before and after implementing a BM, we can assess the total cost savings of the community. This is expressed by Equation (24), where $C^{bill,old}$ represents the community's electricity bill from the previous year, $C^{bill,new}$ is the current year's bill, and C^{invest} is the annual investment in DERs.

$$C^{savings} = \frac{C^{bill,old} - \left(C^{bill,new} + C^{invest}\right)}{C^{bill,old}} \tag{24}$$

KPI 2 - Collective self-sufficiency (CSS): The measure of the community's reliance on its own energy generation and sharing efforts compared to its total energy demand over the specified time period. Expressed in Equation (25), it is calculated as the ratio of total self-consumption of PV-generated energy ($PV_{i,t}^{self}$) and self-consumed energy from the battery discharge ($Bat_{i,t}^{discharge,self}$) by all community members, combined with the total energy shared or traded ($S_{i,t}$) within the community, to the total energy demand (L_t^{total}) of the community.

$$CSS = \frac{\sum_{t=1}^{T}(\sum_{i=1}^{N} PV_{i,t}^{self} + Bat_{i,t}^{discharge,self} + S_{i,t})}{L_t^{total}} \tag{25}$$

KPI 3 - Individual Cost Savings: The total reduction in each member's electricity bill provides insights on the economic distribution among members post-BM implementation. By comparing the individual costs before and after implementing a BM, we can assess the individual cost savings for each member. Similar to Equation (24) but calculated for each member *i* and is expressed in Equation (26).

$$C_i^{savings} = \frac{C_i^{bill,old} - \left(C_i^{bill,new} + C_i^{invest}\right)}{C_i^{bill,old}} \tag{26}$$

KPI 4 - Net Importers and Exporters: This KPI measures the ratio of total energy imported to total energy exported by each member, offering insights into whether members are predominantly consumers or producers and how these roles evolve with different BMs. A ratio greater than 1 indicates a net importer (consumer), while a ratio less than 1 indicates a net exporter (producer). The ratio is calculated using Equation (27), where E_i^{imp} and E_i^{exp}represent the total energy import and export by member *i,* respectively.

$$NET = \frac{E_i^{imp}}{E_i^{exp}} \tag{27}$$

KPI 5 - Self-consumption vs Sharing (SCS): Analysing the ratio of self-consumption to sharing (net exports) for each member might give insight into how different BMs affect behaviour. For instance, members with higher ratios of self-consumption might be less willing to invest in sharing infrastructure. Tracking how these ratios change based on different BMs can give insight into behavioural changes. The ratio is calculated using Equation (28), where E_i^{self} represents the total energy self-consumed by member i and E_i^{exp} represents the total energy exporter by member i.

$$SCS = \frac{E_i^{self}}{E_i^{export}} \tag{28}$$

KPI – 6 - Self-sufficiency (SS): The ratio of individual self-consumption compared to energy demand (L_i^{total}) for each member over the time period, expressed in Equation (29). Higher self-sufficiency could indicate less dependence on the main grid and other community members.

$$SS = \frac{E_i^{self}}{L_i^{total}} \tag{29}$$

KPI 7 - Quality of Sharing (QoS): The quality of shared energy, which accounts for both the quantity of energy shared and its alignment with peak demand periods. A Quality of Sharing (QoS) factor is developed and consists of two main components: Timing Relevance Score (TRS) and Quantity Score (QS) to holistically assess each member's contribution to the energy in the local energy market. TRS reflects the value of the timing of energy sharing, and QS is the total shared energy by a member over all considered time periods. QoS is defined in Equations (30)-(32):

$$TRS_i = S_{i,t} * (\frac{L_t^{total}}{\max(L_t^{total})})^\alpha \quad (30)$$

$$QS_i = \sum_{t=1}^{T} S_{i,t} \quad (31)$$

$$QoS_i = \sum_{t=1}^{T} (TRS_{i,t} * \beta * QS_{i,t}) \quad (32)$$

$$Normalised\_QoS_i = \frac{QoS_i}{\max(QoS)} \quad (33)$$

Where:

max (L_t^{total}): Highest load observed across all time periods

α : Parameter that adjust the weight of timing relevance, with values ranging from 0 to 1

QoS_i: Overall QoS for each member *i*

β : Weight factor for the QS relative to the TRS, with values ranging from 0 to 1

Normalised_QoS i: Standardised QoS score (0-1) for each member to be used across different scenarios

Max(QoS): Highest QoS score among all members.

To link the KPIs to the evaluation of social capital post-BM implementation, we utilise the conceptual framework liking social capital to the impact on the microgrid design developed by Eklund et al. [148]. To understand how the different BMs might directly affect social capital in the community, we can look at the expected outcomes represented by the KPIs as indicators of changes in social capital. Each KPI, reflecting a specific aspect of the microgrid's performance, can have a direct impact on the components of social capital (cognitive, relational, and structural), as summarised in Table 4.2.

Table 4.2 Assessment of KPIs and their direct impact on different SC dimensions post-BM implementation.

KPI	Impacts on Social Capital	SC Dimension	Expected Outcome
KPI 1: Total Cost Savings	Validates the efficacy of the microgrid, potentially increasing trust in the system and willingness to participate.	Structural	Enhanced governance and institutional trust
KPI 2: Collective Self-Sufficiency	Reflects the community's collective ability to sustain its energy needs, which could promote a shared sense of achievement.	Structural & Cognitive	Stronger community identity and collaboration towards shared goals
KPI 3: Individual Cost Savings	Direct financial benefits strengthen belief in the system's fairness and effectiveness.	Cognitive & Relational	Greater engagement and cooperation within the community
KPI 4:Net Importers and Exporters	A balanced ratio could reflect the community's energy independence and interconnectedness.	Cognitive & Relational	Improved local resource management and self-reliance
KPI 5: Self-Consumption vs Sharing	High sharing ratio may encourage community interaction and reciprocity.	Relational	Strengthened community bonds and trust
KP1 6: Self-Sufficiency	High self-sufficiency can lead to a greater collective understanding of sustainable practices and the benefits of energy independence.	Structural & Cognitive	Reinforced local governance and collective competency
KPI 7: Quality of Sharing	Positive sharing experiences can foster a supportive community atmosphere and trust.	Relational	Increased trust and quality of interpersonal relationships

4.3 Case Study

We conducted an experimental case study for a small hypothetical community of residential households to perform a comparative analysis of the three previously introduced BM scenarios. The focus was on evaluating their dynamics, economic viability, and operational feasibility for a community microgrid. Load profiles were derived from the open-access dataset from Ausgrid [202], while PV generation profiles were generated through the NASA Merra-2 meteorological database [203] to reflect conditions specific to Sydney, Australia. Although the load data from Ausgrid's Solar Home Electricity Data included PV capacity and generation data, we opted not to use this data directly due to significant advancements in PV technology and cost reductions since the data was collected. Instead, we scaled the PV sizes proportionally to today's typical sizes and costs to ensure the PV capacity aligns with current household energy consumption patterns and market conditions. Figure 4.4 illustrates the annual load and PV generation for this simulated community. To ensure a controlled comparison, simulated load profiles, PV generation data, battery capacities, and cost parameters are uniformly applied across all scenarios. Detailed techno-economic inputs, central to the optimisation model, are provided in Tables 4.3 and 4.4.

Our economic evaluation starts with the simulated costs of energy production from PV installations under ideal conditions, such as perfect alignment for solar exposure and the absence of shading. It is important to note that our model design is inherently flexible, allowing for modifications to reflect non-ideal conditions and additional physical constraints, such as limited roof space and shading. This adjustability not only extends the model's application but also ensures that the results can be calibrated to reflect real-world scenarios more closely, thus providing a more dynamic and realistic output. In the initial modelling phase, sensitivity analysis was performed on key input parameters such as tariffs, PV sizes, and battery capacities. This analysis tests the model's responses to changes in input variables, further validating the robustness and reliability of our results. Additionally, the optimisation model provides a time horizon of 1 year with 1-hour time steps to ensure comprehensive temporal analysis. This high-resolution modelling captures the nuanced interplay between the community members for a minimum time period to enable possible comparison of different BM scenarios.

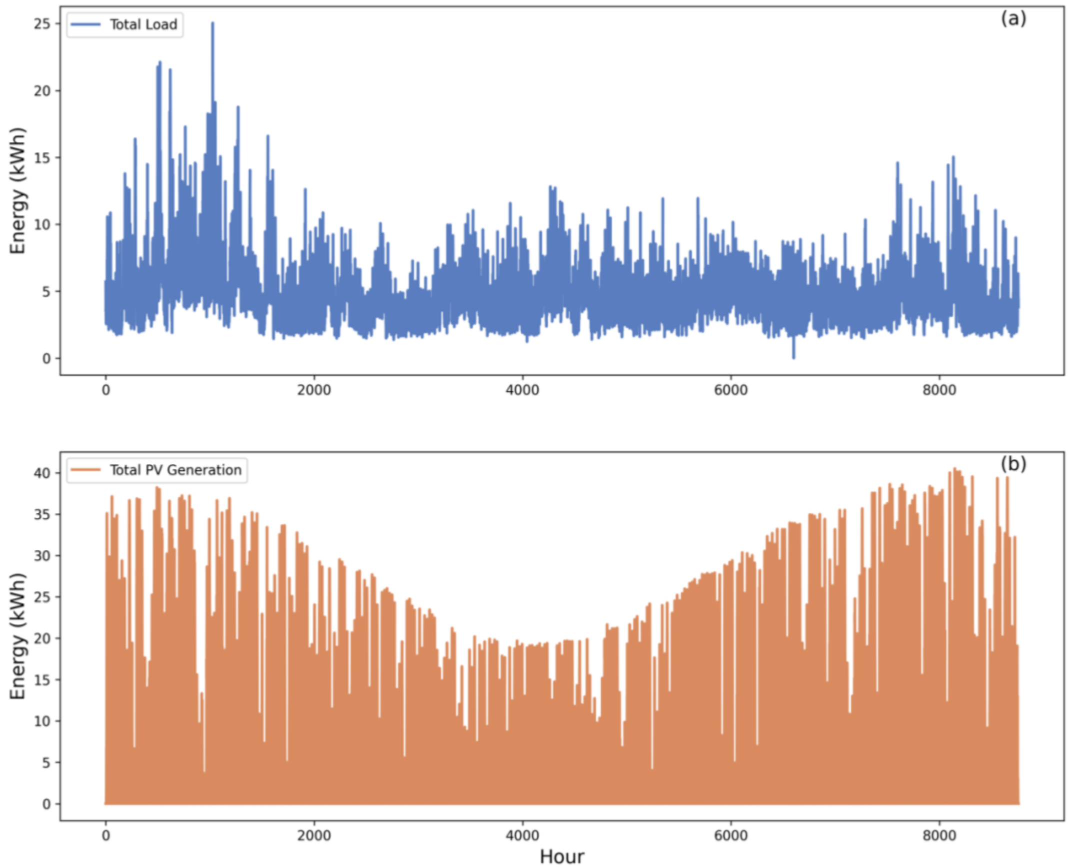


Figure 4.4. Total load (a) and total PV generation (b) of the community over one year (January to December, hourly resolution).

Our focus on energy is strictly confined to electricity, with an economic model that simplifies to only usage-related costs, deliberately excluding fixed supply charges. In the simulated environment without a microgrid, we calculate the annual electricity costs for the community to be A$10,120/year, as demonstrated in Table 4.3. The costs associated with the PV and batteries are provided in Table 4:4, where the CAPEX includes possible rebates. Table 4.5 lists the specific capacities for each DER installation and each member's annual investment cost. Moreover, the efficiency of the PV systems is assumed to be 20%, while for the batteries, a 95% efficiency for charging and a 90% for discharging is chosen. The planning period time is chosen to be 20 years for both the PV system and battery storage to provide scenarios where a community microgrid will be financially feasible [173].

Table 4.3. The annual electricity load and electricity bill for each member with no microgrid involved.

	Member 1	Member 2	Member 3	Member 4	Member 5	Member 6
Load (kWh/year)	5320	4440	9620	7130	6920	7440
Electricity bill (A$/year)	1330	1100	2320	1780	1730	1860

Table 4.4. The CAPEX and planning period associated with the PV and battery.

	PV system	Battery	Reference
CAPEX (A$/kW Capacity for PV, A$/kWh Capacity for Battery)	900	1300	[204]
Planning period (years)	20	20	[173]

Table 4.5. PV and battery installation capacity and annual investment cost for each member of the community microgrid for all three scenarios, BM A-C.

	Member 1	Member 2	Member 3	Member 4	Member 5	Member 6
PV (kWp)	5	5	6.6	6.6	6.6	6.6
Battery (kWh)	9.6	0	13.5	9.6	0	0
CAPEX (A$/year)	849	225	1176	921	297	297

In this case study, all scenarios utilise a consistent ToU pricing strategy, with rates set at A$0.13/kWh for the off-peak period, A$0.21/kWh for the shoulder period, and A$0.53/kWh for the peak period [205]. Additionally, Business Models B and C implement a flat rate of A$0.05/kWh for energy that is traded or shared within the community. The cost of shared energy within the community can be significantly lower than the retail electricity rates, as it bypasses the grid and reduces transmission losses and grid fees [49]. This avoidance leads to a reduction in transmission losses and grid fees. The pricing for shared energy could be determined by the operational expenses associated with the production and distribution of this energy, along with a profit margin that contributes to the maintenance and further development of the community microgrid. The proposed pricing framework promotes the economic advantages and the possibility of broader implementation of community microgrids in a theoretical environment.

4.4 Result and Discussion

In this section, we provide a comprehensive summary of the outcomes derived from the optimisation model across all three scenarios. Subsequently, we delve into a member-specific in-depth presentation and analysis of the results for each scenario. To culminate, we offer a comparative discussion of the scenarios connected to social capital to encapsulate the insights gathered from the discussions.

4.4.1 Overview of KPI Results Across all Three Scenarios

The KPIs resulting from the optimisation showcase a comprehensive view of the microgrid's operational efficiency and member participation across three scenarios: BM A, BM B, and BM C, as seen in Table 4.6. KPI 1 and KPI 2 reflect total cost savings and community self-sufficiency, respectively, providing an overarching measure of economic and environmental impacts. Individual member analysis, indicated through KPIs 3 to 7, presents granular insights into cost savings per member, import/export ratio, self-consumption vs. trading/sharing ratio, self-sufficiency, and the quality of sharing.

The results suggest a diversified performance, with members experiencing varying degrees of improvement or decline in each scenario. For instance, in scenario BM A, we observe moderate values in total cost savings and community self-sufficiency, with individual KPIs fluctuating across members. Scenario BM B shows enhanced overall cost savings and self-sufficiency but with significant disparities among members in import/export ratios and sharing quality. Scenario BM C reveals a balanced approach with notable improvements in self-sufficiency and energy-sharing quality. For example, Figure 4.5 illustrates the disparity between member-specific KPIs across all scenarios, highlighting the individual contributions to the microgrid's collective goals. Meanwhile, Figure 4.6 shows how the same KPI results are distributed across all scenarios through a boxplot.

Table 4.6. KPI results after optimisation (*KPI 1* total cost savings, *KPI 2 community self-sufficiency, KPI 3 total cost savings per member, KPI 4 import/export ratio per member, KPI 5 self-consumption vs trading/sharing ratio per member, KPI 6 self-sufficiency per member and KPI 7 quality of sharing/trading per member).*

BM	KPI 1	KPI 2
A	0.55	0.53
B	0.65	0.6
C	0.62	0.6

BM	Member	KIP 3	KIP 4	KPI5	KPI 6	KPI 7
A	Member 1	0.47	0.3	-	0.81	-
	Member 2	0.79	0.44		0.36	
	Member 3	0.4	0.78		0.57	
	Member 4	0.55	0.4		0.70	
	Member 5	0.7	0.55		0.37	
	Member 6	0.52	0.62		0.33	
B	Member 1	0.31	0.68	0.72	0.49	0.78
	Member 2	0.98	0.33	0.26	0.37	0.10
	Member 3	0.36	1.1	1.19	0.49	1.00
	Member 4	0.45	0.6	0.67	0.50	0.72
	Member 5	0.94	0.4	0.33	0.37	0.10
	Member 6	0.99	0.34	0.32	0.34	0.09
C	Member 1	0.37	0.44	0.76	0.63	0.63
	Member 2	1.1	0.44	0.26	0.37	0.13
	Member 3	0.36	0.81	0.96	0.54	1.00
	Member 4	0.47	0.47	0.72	0.61	0.53
	Member 5	0.87	0.55	0.32	0.37	0.12
	Member 6	0.82	0.62	0.31	0.33	0.09

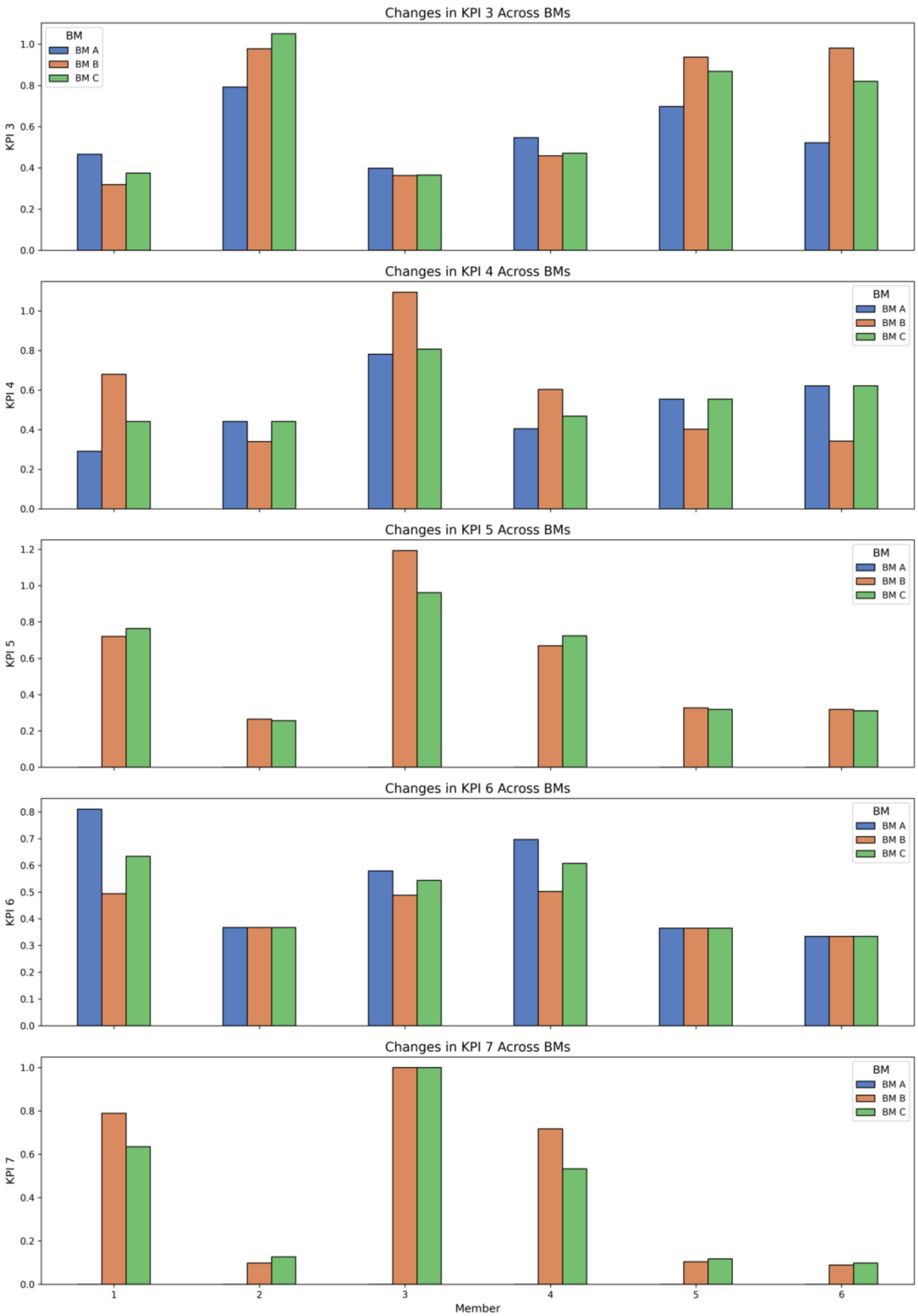

Changes in KPI 3 Across BMs
KPI 3
BM
BM A
BM B
BM C
Changes in KPI 4 Across BMs
KPI 4
BM
BM A
BM B
BM C
Changes in KPI 5 Across BMs
KPI 5
BM
BM A
BM B
BM C
Changes in KPI 6 Across BMs
KPI 6
BM
BM A
BM B
BM C
Changes in KPI 7 Across BMs
KPI 7
BM
BM A
BM B
BM C
1
2
3
4
5
6
Member

Figure 4.5. Comparison of member specific KPIs (*KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing)* between scenario BM A, BM B and BM *C.*

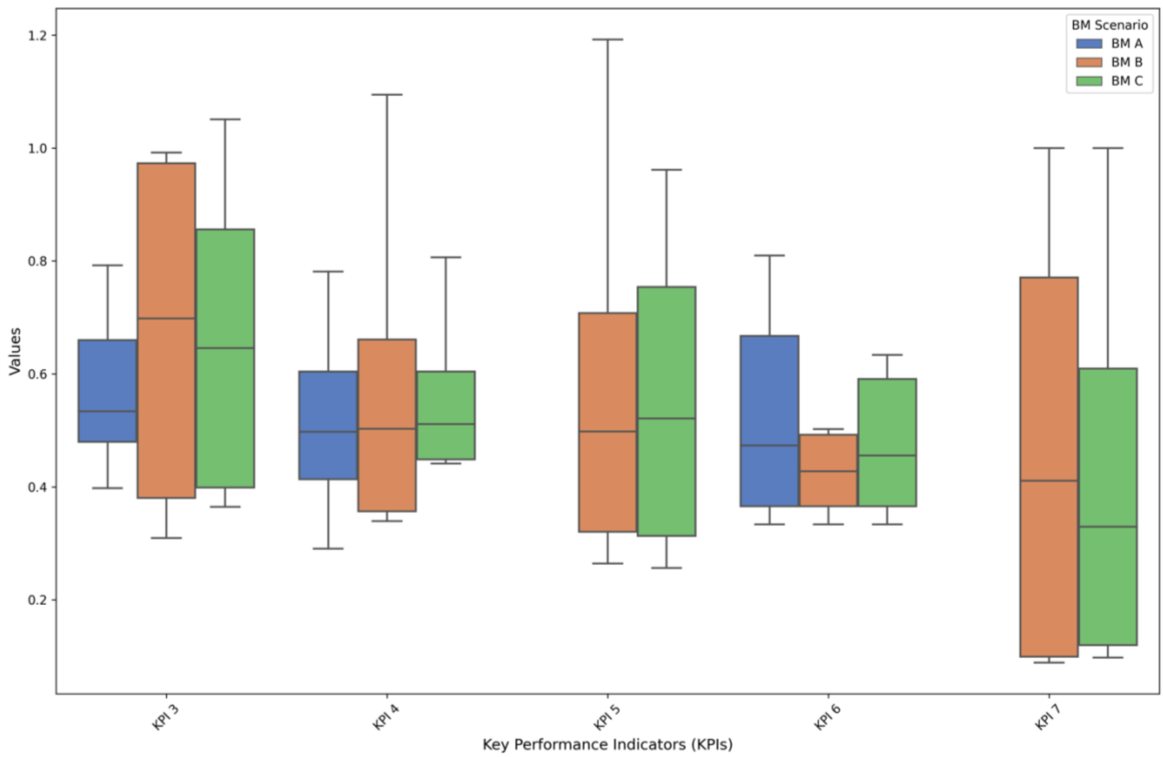


Figure 4.6. Comparison of member specific KPIs (*KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing)* between scenario BM A, BM B and BM *C.*

Further, the results from KPI 7 underscore the temporal distribution of energy exports, which is instrumental in gauging the effectiveness of energy sharing and time-of-use efficiency. To elucidate the insights derived from KPI 7, we employ BM C as an illustrative scenario to demonstrate the temporal distribution of energy exports. While BM C is utilised here, it is important to note that any scenario could serve this purpose to provide a tangible representation of KPI 7 findings. The heatmap in Figure 4.7 visualises the aggregated energy exports by each member across specified time blocks of the day: Morning (06-12), Afternoon (12-18), Evening (18-24) and Night (0-6) for the given time horizon. This graphical representation facilitates a clearer understanding of the dynamics captured by KPI 7, shedding light on the efficacy of energy sharing and time-of-use efficiency within our broader research context. Additionally, it's clear from Figure 4.7 that member 3 contributes the most during the evening and often during peak periods. Similarly, the more uniform energy export levels from member 2 across all time blocks may reflect a consistently managed energy output, contributing to the microgrid's stability.

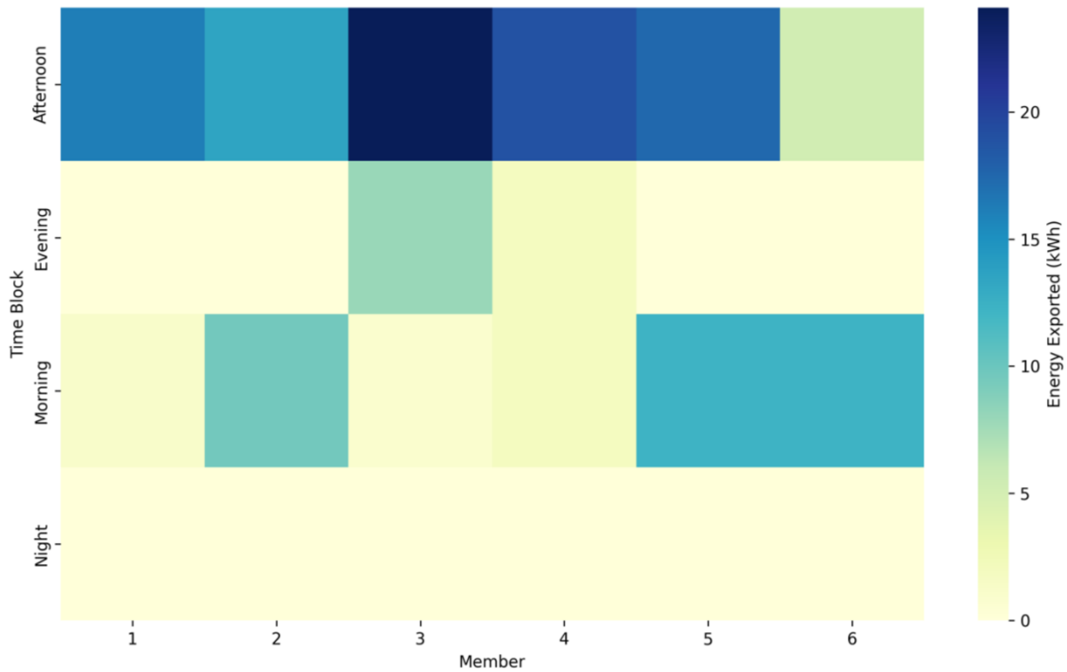


Figure 4.7. Energy export by member across time blocks for BM C.

Overall, the KPI results post-optimisation reveal the intricacies of balancing individual member behaviour with the communal goals of cost-saving and sustainability in a microgrid context. The following subsections will delve into the specifics of each scenario, providing a detailed narrative of the operational dynamics within the microgrid community.

4.4.2 Scenario BM A

In this scenario, members are dependent on the main grid and individual PV systems, indicating a scenario where self-generation is a priority but within the limits of individual capacity. While battery usage is present, it does not significantly offset grid dependence, as seen in Figure 4.8.

- KPI 1 and KPI 3 show a high variation in total cost savings per member. This indicates a substantial inequality in financial benefits, which can affect social capital negatively by creating a divide between 'haves' and 'have-nots' within the community. A large disparity in savings could lead to resentment or a sense of unfairness.
- KPI 4 suggests some members are net consumers (importers) rather than net producers (exporters) of energy. Without the opportunity to share or trade energy, members with less capacity to produce their own energy (due to financial, spatial, or other constraints) may feel marginalised.
- KPI 6's self-sufficiency and KPI 2's community self-sufficiency indicate how independent each member and the community as a whole are from external energy sources. Higher numbers are generally positive for social capital as they foster a sense of autonomy and resilience. However, if only a few members achieve high self-sufficiency, it can undermine community cohesion.
- KPI 5 and KPI 7, the self-consumption vs trading/sharing ratio and the quality of sharing, are not applicable here since there is no sharing or trading mechanism in place in BM A.

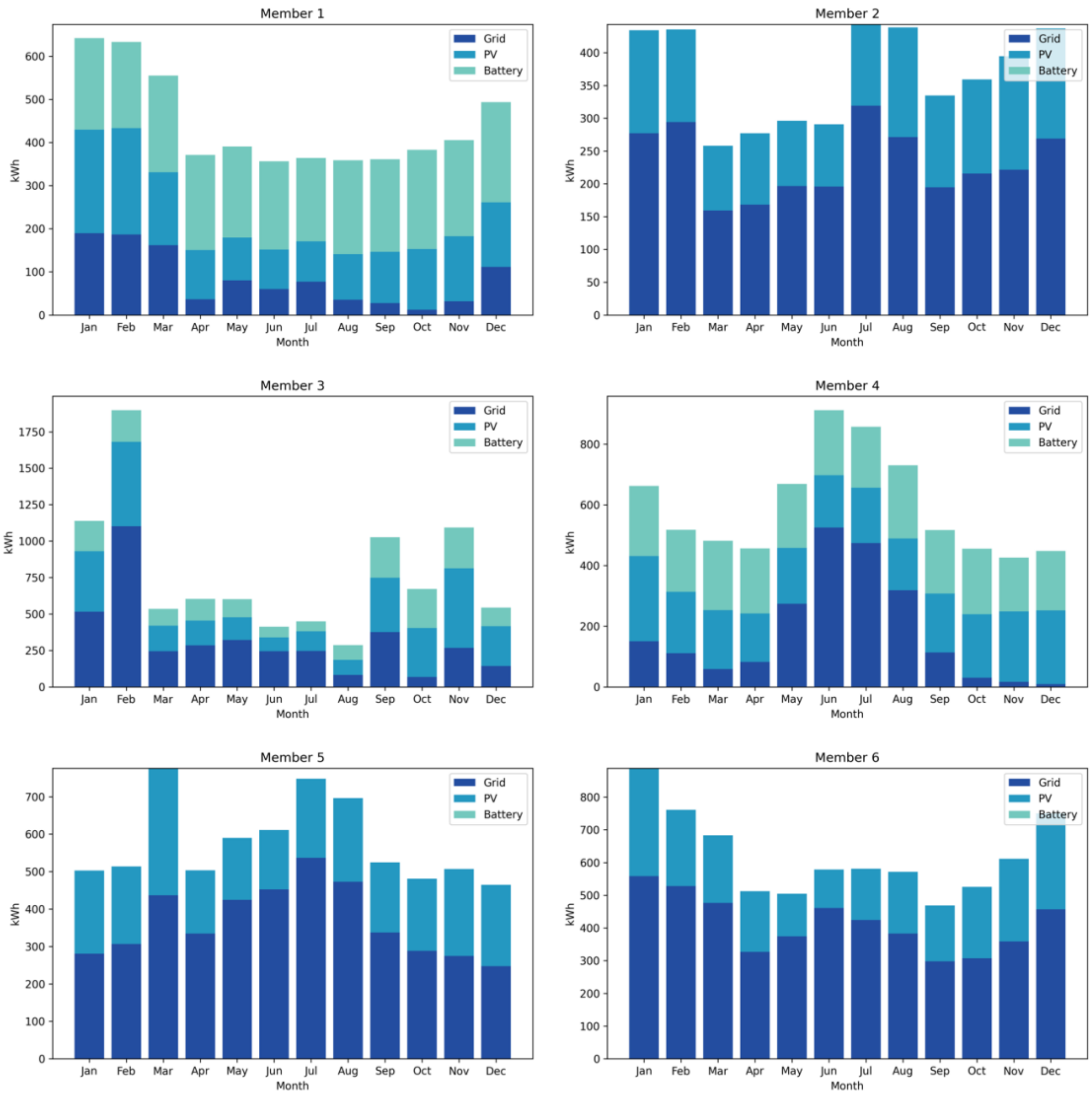


Figure 4.8. Breakdown of how each member's energy demand is satisfied during BM A.

4.4.3 Scenario BM B

With the introduction of P2P transactions in BM B, a new layer of complexity is added to the members' energy profiles. Figure 4.9 shows varied levels of P2P engagement, suggesting differences in production surplus and consumption patterns. A notable pattern is that the grid energy consumption for most members is lower in BM B than in BM A during months when P2P is most active. This implies that P2P trading could be a buffer that enhances energy autonomy and lowers grid reliance. There is also a noticeable balance in the roles of producers and consumers among members, with some consistently supplying P2P energy while others consume it, pointing towards an underlying structure in the energy trading market.

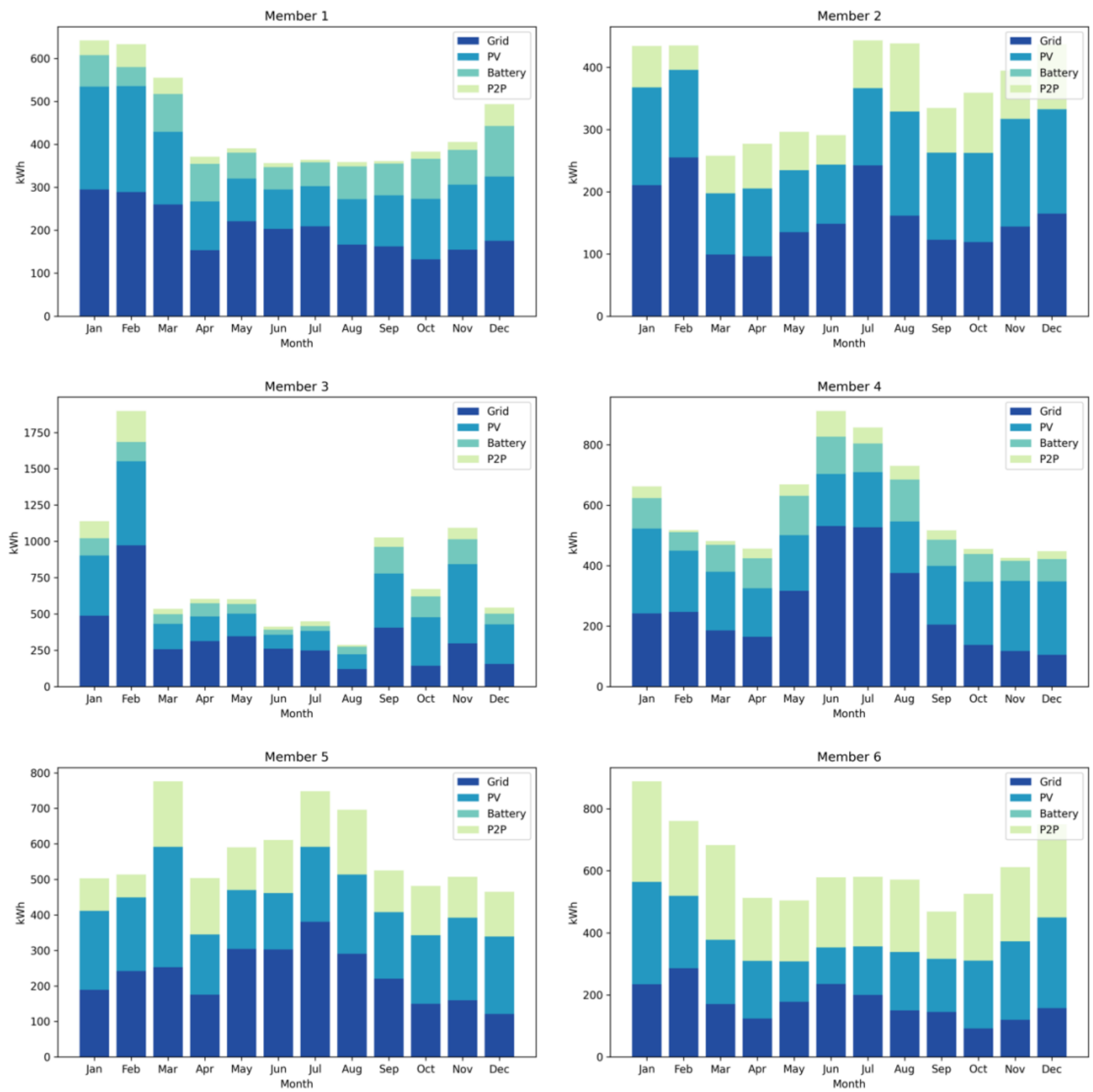


Figure 4.9. Breakdown of how each member's energy demand is satisfied during BM B.

- KPI 1 and KPI 3 indicate a levelling effect on savings per member compared to BM A, suggesting that the P2P model provides a more equitable financial benefit. This can enhance social capital by reducing financial disparities and fostering a sense of fairness.

- KPI 4's import/export ratios are more balanced, reflecting a system that encourages energy sharing, which can improve community ties and reciprocal relationships, enhancing social capital.
- KPI 4, which is notably higher for some members, shows a good balance between self-consumption and energy sharing. This balance is key in strengthening community bonds as it suggests active participation in the energy ecosystem.
- KPI 6 and KPI 2 show that while self-sufficiency is varied, the community as a whole benefits from shared resources, which may promote a stronger sense of community and collective responsibility.

4.4.4 Scenario BM C

The overall difference in the BM C scenario lies in the introduction of shared energy among community members and the bill-sharing mechanism, which provides additional flexibility and cost efficiency to the community. As seen in Figure 4.10, while the dependence on the main grid remains, the shared energy seems to be smoothing out consumption peaks, likely leading to a more stable and predictable grid demand profile. An in-depth pattern to explore is the relationship between the individual PV contributions and the amount of shared energy utilised by each member. There is a suggestion that members with higher PV generation do not equally rely on shared energy, which could be indicative of a possible cap to shared energy allocation or the presence of incentives to encourage self-consumption before drawing from communal resources. Member 3 stands out again, suggesting that their significant contribution to the shared pool could be underutilised, which may raise questions about the equity of the bill-sharing mechanism.

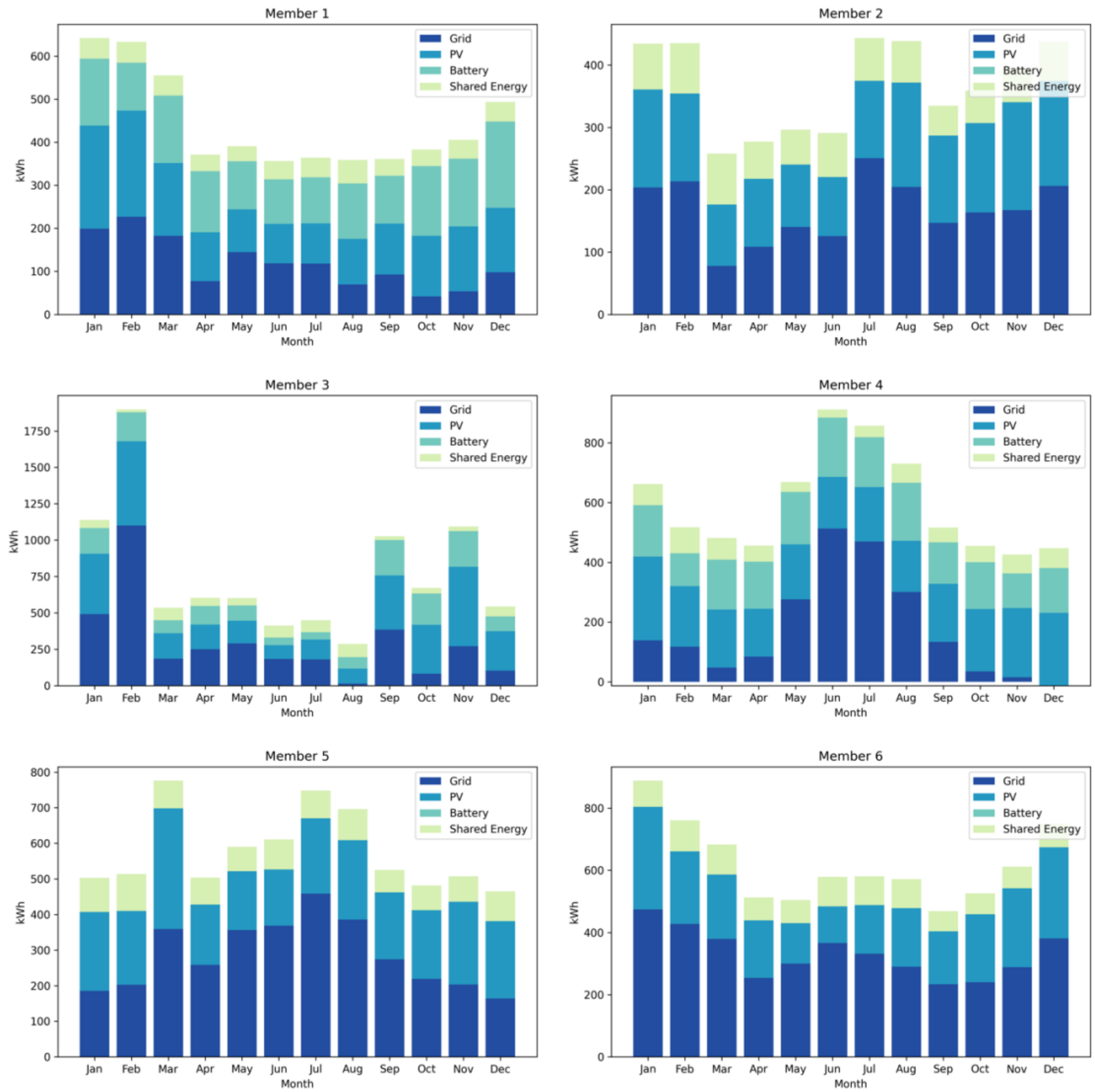


Figure 4.10. Breakdown of how each member's energy demand is satisfied during BM C.

- KPI 1 reveals the second-highest total cost savings across BM scenarios, suggesting that communal ownership is a beneficial model financially. This can positively influence social capital by ensuring that all community members benefit equally from the energy system, which can lead to stronger community ties and a higher sense of belonging.
- KPI 3 shows less variation in cost savings per member than in BM A but more than in BM B, indicating that while there is some degree of financial equity, it's not as pronounced as in BM B.

- KPIs 2 and 4-7 generally suggest that this model promotes both individual and collective self-sufficiency, which can lead to enhanced social capital. The act of bill-sharing can cultivate trust and interdependence among community members, which are central aspects of social capital.

4.4.5 Implications on Social Capital

When discussing the impact of the different BMs on social capital within the community, it is essential to explore how each KPI influences the various dimensions of social capital—structural, cognitive, and relational. This discussion will incorporate the expected outcomes derived from the performance of each KPI under the different BMs.

KPI 1: Total Cost Savings - Structural Dimension

BM B, showing the highest total cost savings, validates the efficacy of the P2P model. This outcome likely enhances governance and institutional trust as members see tangible financial benefits from their cooperative efforts. Such validation can be expected to increase members' trust in the system and willingness to participate. In contrast, the lower cost savings in BM A might not contribute as significantly to building institutional trust.

KPI 2: Collective Self-Sufficiency- Structural and Cognitive Dimensions

The self-sufficiency seen in BM C and BM B illustrates the community's ability to meet its energy needs, which likely bolsters a shared sense of identity and collaboration toward shared sustainability goals. BM A, with the least self-sufficiency, may contribute the least to this aspect of social capital.

KPI 3: Individual Cost Savings - Cognitive and Relational Dimensions

Individual cost savings, especially prominent in BM B and BM C, can strengthen members' belief in the fairness and effectiveness of the microgrid, potentially increasing community engagement and cooperation. However, both BM B and BM C present variability in individual cost savings, which might lead to differential perceptions of system fairness. BM A could risk lower relational engagement due to its limited individual financial benefits.

KPI 4: Import/Export Ratio - Cognitive and Relational Dimensions

A balanced import/export ratio, indicative of energy interdependence as seen in BM C, can improve local resource management and self-reliance. BM B, with a higher ratio, suggests active energy trading and inter-member reliance, which may also foster relational ties. However, the lower ratio in BM A indicates a potential undercurrent of dependence on external sources, which could undermine local relational ties.

KPI 5: Self-Consumption vs. Sharing - Relational Dimension

BM B's high self-consumption ratio, combined with quality sharing (KPI 7), suggests a model that supports strengthened community bonds through reciprocal energy sharing. The moderate but more cohesive sharing in BM C indicates some level of interaction and reciprocity but possibly not as strong as in BM B. The lack of a sharing component in BM A means it contributes the least to relational social capital in this context.

KPI 6: Self-Sufficiency - Structural and Cognitive Dimensions

BM A's self-sufficiency aligns with a deeper collective understanding of sustainable practices, likely reinforcing local governance and a sense of collective competency. However, the variability in self-sufficiency for BM A may reflect different levels of commitment to or realisation of energy independence, with implications for shared cognitive understanding. In contrast, while BM B and BM C may exhibit lower individual self-sufficiency, they tend to have more cohesion across members. This cohesion likely arises from higher collective self-sufficiency in these scenarios compared to BM A. However, lower self-sufficiency may limit the development of a collective understanding of sustainability within the community.

KPI 7: Quality of Sharing - Relational Dimension

The high quality of sharing seen in BM B can foster a supportive community atmosphere, likely increasing the trust and quality of interpersonal relationships. In BM C, the quality of sharing may vary, indicating that while some members experience supportive interactions, others may not, which could affect overall community cohesion.

In conclusion, BM B consistently supports social capital across all dimensions, reflecting its cooperative and participatory nature. BM C shows mixed results, suggesting that while the bill-sharing mechanism creates interconnectivity, it might not uniformly benefit all members, possibly leading to social stratification within the community. BM A, with its external reliance, might create a less cohesive community with weaker social bonds. Behaviour analysis across these business models reveals that members under BM C are likely to engage in cooperative behaviour spurred by the shared benefits and equitable distribution of costs. Conversely, in BM B, members may adopt strategic behaviour aimed at maximising personal gains from the P2P market, potentially cultivating a competitive environment. Members within BM A appear to be the least engaged in community energy dynamics, attributed to the lack of a direct stake in energy sharing and management. Ultimately, the social capital within the community is profoundly influenced by the chosen BM, with BM B fostering the most robust social capital across all dimensions, BM C creating a similar but more variable social landscape, and BM A presenting potential challenges to building strong social capital. This analysis underscores the critical role that business models play in not only economic outcomes but also in shaping the social fabric of community-based microgrid projects.

4.5 Conclusion

This study highlights the nuanced interplay between business models and social capital in community microgrids. It demonstrates that while certain business models, particularly those emphasising interactive mechanisms, can significantly enhance social capital and align with community sustainability goals, the relationship between individual and collective interests is complex.

The analytical framework developed in this study extends beyond traditional quantitative approaches, incorporating KPIs that shed light on the qualitative dimensions of community energy initiatives. Such an approach enables a holistic evaluation of business models, ensuring they not only meet technical and financial criteria but also harmonise with the social structures they operate within. By comparing three distinct business model scenarios (BMA, BMB, and BMC), we demonstrate the robustness of our model. This approach helps identify how different operational conditions may affect outcomes, thereby verifying the model's consistency and reliability across various settings. Through this lens, the research identifies a paradigm shift from individualistic strategies to collective energy practices, highlighting the dual nature of shared energy benefits as both unifying and potentially disincentivising for personal investments in self-generation.

Applying this approach can provide a more accurate representation of microgrid design and operation tailored to the specific community, increasing the likelihood of long-term successful operation and positive financial outcomes. Moreover, by integrating social capital into the optimisation process, our methodology improves the modelling of local energy markets by ensuring that technical solutions are aligned with community-driven goals. This allows for a more adaptive and resilient microgrid configuration that optimises not just economic efficiency but also social outcomes. The use of our socially focused KPIs introduces a multi-dimensional aspect to the optimisation process, providing a richer set of metrics to assess both technical and social performance.

Lastly, the next step in line with this research would be to evaluate the long-term effect of social capital on community microgrid performance and sustainability, alongside incorporating the technical aspects of power grid design, which were beyond the scope of this paper. Further refinement could be achieved by integrating real-time data, such as dynamic pricing and demand-response mechanisms, to enable more adaptive and responsive decision-making in fluctuating market conditions. Additionally, future work could include real-world case studies and conduct empirical studies to validate and apply these findings in practical settings.

5 Fairness Analysis of Electricity Tariffs and Business Models in Community Microgrids

Preamble

Overview

In Chapter 5, we build on Chapter 4 by expanding the analysis to include a wider array of tariff structures and incorporating energy justice theory to focus on fairness. It utilises the Key Performance Indicators (KPIs) from the previous chapter to evaluate the equitable distribution of energy costs and benefits, linking these metrics directly to concepts of fairness. We introduce three tariff structures—Single Rate, Time-of-Use (ToU), and Dynamic Tariff—and evaluate them under the same three business models (BMs) used in Chapter 4: Third-Party Ownership, Centralised Peer-to-Peer (P2P), and Community-Owned models. Using the integrated method developed in Chapter 4, we assess how these combinations influence social capital and fairness within a community.

Through scenario testing, we find that ToU tariffs generally promote more dynamic and equitable energy use patterns compared to Single Rate and Dynamic Tariffs. The findings suggest that different BMs and tariffs have varying impacts on community engagement, cost savings, and the quality of energy sharing.

By examining how different tariffs impact various business models, this research provides a nuanced discussion on the role of social capital and fairness in community microgrids. It highlights the importance of understanding the outcome of different business model and tariff combinations in fostering community satisfaction and trust.

5.1 Introduction

Fairness in energy distribution is a critical aspect of sustainable and socially acceptable energy systems [206], [207], particularly within the context of community microgrids [168]. Community microgrids are localised energy systems operating autonomously or in conjunction with the main grid [148]. These systems offer unique opportunities for decentralised energy management but also present challenges in ensuring the fair distribution of energy resources and costs among community members [108]. Community microgrids operate under various business models [49], which shape their operational characteristics and social dynamics [195]. These models can range from centralised utility-owned systems to decentralised peer-to-peer (P2P) networks and community-owned cooperatives [58]. Each business model impacts how energy is generated, consumed, and shared, influencing social behaviour and the perceived fairness of energy distribution [208], [209]. Different tariff structures, such as Single Rate, Time-of-Use (ToU), and dynamic tariffs, may affect these outcomes [210], even within the same business model, leading to varying implications for fairness.

The concept of fairness in energy tariffs is multifaceted and subject to diverse interpretations. Jenkins et al. [211] emphasise distributive justice, which focuses on the equitable distribution of costs and benefits, ensuring that no community member is unduly burdened or unfairly advantaged. Simshauser [212] highlights that poorly designed tariffs can exacerbate social inequities, potentially leading to energy poverty among vulnerable members. These perspectives underscore the importance of integrating fairness into the design and evaluation of energy tariffs [213]. Different studies have used various terms, metrics, and indicators to assess fairness, resulting in a lack of cohesion in the literature [201]. Considering these varied definitions and interpretations, the variability in costs among community members is often used to assess fairness [214]. This variability can be measured using statistical metrics such as mean, standard deviation, minimum, and maximum costs per kWh [215]. The proportionality of cost to consumption is another fairness metric used by researchers. Neuteleers et al. [216] demonstrated that transparent and proportional tariff structures significantly enhance community satisfaction. When costs align closely with individual consumption levels, members who use more energy pay more, and those who use less pay less [216]. This alignment ensures that tariff structures are perceived as fair and encourages acceptance among community members. Further, Moret and Pinson [168] used Quality of Service (QoS) and Quality of Experience (QoE) metrics in their study, where they simulated a number of test cases for an energy collective. These metrics, derived from typical principles in the analysis of communication networks and distributed systems, are applied to assess community fairness. QoS evaluates the reliability and quality of energy supply, ensuring consistent and dependable service, while QoE measures overall satisfaction with the energy service, considering factors such as ease of use, customer support, and perceived value. Min-Max fairness (MiM) is also employed to minimise the maximum disparity in costs or benefits among members, promoting equity by reducing the gap between the highest and lowest costs or benefits [168]. Covington et al. [208] proposed a method for evaluating the fairness of electricity tariffs by considering income levels. They introduced three metrics—Savings Compared to Baseline, Percentage of Income spent on Utilities, and Change in Percentage of Income spent on Utilities—to assess the relative financial burden of different pricing plans on households. Their study found significant disparities in energy affordability, particularly under time-variable pricing plans, highlighting the need for location-specific solutions to ensure equitable energy policies.

Nonetheless, fairness perception is inherently subjective [217] and varies widely among community members based on their unique circumstances and consumption patterns [41]. For instance, a study by Walker and Day [218] found that perceptions of energy justice varied significantly across different communities in the UK. Some communities prioritised affordability and access, while others emphasised environmental sustainability and local job creation. This subjectivity highlights the importance of engaging with diverse community perspectives to understand their specific notions of fairness [218]. Additionally, members within the same community may perceive fairness differently. For instance, a high-consumption member might favour a proportional cost structure, while a low-consumption member might prioritise equitable access to shared benefits [219], [220]. Community norms and values also play a significant role in shaping perceptions of fairness, with some communities prioritising collective well-being and others emphasising individual responsibility [37]. Hence, understanding the social capital of a community is beneficial for assessing and analysing fairness in community microgrids [24], [217]. Social capital refers to the networks, norms, and trust facilitating coordination and cooperation for mutual benefit [63]. High levels of social capital can enhance the acceptance of tariff structures perceived as fair and support collective action to address perceived inequities [221], [222]. Considering social capital allows policymakers to design and implement equitable, widely accepted tariffs and support community cohesion [148].

Despite the existing research presented and summarised in Table 5.1, a comprehensive analysis and discussion of how different tariffs impact fairness under various business models for community microgrids remains lacking. Many studies rely on subjective or non-comprehensive measures and indicators, leading to inconsistent conclusions. This chapter addresses this gap by adopting a social capital lens to discuss fairness, moving away from fixed and finite definitions. We will consider three business model cases and three tariff structures, each forming scenarios for one community microgrid setup, to provide a nuanced and holistic understanding of fairness in community microgrids. Building on the methodology developed in Chapter 4, which used a Mixed-Integer Linear Programming (MILP) model to optimise microgrid design focusing on social dynamics [8], this study introduces two additional tariff structures: Single-Rate and Dynamic Tariff. The analysis shifts to examine how different tariffs operate under the given business models. While social capital Key Performance Indicators (KPIs) from our previous study are adopted, they will be utilised to facilitate a discussion on fairness. This approach allows us to investigate how different tariffs affect social behaviour within various business model archetypes in community microgrids. By exploring these impacts, the chapter contributes to the literature by providing a comprehensive analysis of tariff structures' influence on the social fabric of energy communities, thereby guiding the development of more inclusive and equitable energy policies.

The chapter is organised as follows: Section 5.2 introduces the theoretical context of this chapter. Section 5.3 provides the research design, detailing the structure of case studies and scenarios and the analytical framework. Section 5.4 presents the results which explore the variability and performance outcomes of different KPIs. Section 5.5 discusses and analyses fairness implications for each BM and tariff scenario. Finally, Section 5.6 concludes with a summary of the findings.

Table 5.1**.** Summary of fairness definitions and examples in previous literature.

Ref.	**Topic**	**Example**	**Definition**
Ansarin et al. [199]	Review of equity in residential electricity tariffs with DERs	Equal customers paying the same price for the same product.	Subsidisation of a product by some consumers for other similar consumers (cross-subsidisation).
Menghawani et al. [223]	Exploring fairness in electricity pricing by incorporating affordability	Equality scenario: Everyone pays the same price for electricity (a weighted average based on consumption and the baseline LCOE). Equity scenario: Prices in a location are adjusted based on the local population's affordability, using the poverty rate as a proxy.	A cross-subsidy approach to understand equality and equity in pricing, where part of the population subsidises the rest by paying higher prices.
Kim et al. [224]	Lessons for emerging economies to avoid draining energy resources	Assesses the fairness of electricity consumption by comparing the electricity usage and costs of businesses versus households, as well as with other countries.	Impartial representation of individuals and groups in institutional and cultural processes without degrading their identity or discriminating against them. Fair distribution of benefits and burdens associated with primary goods, rights, and responsibilities across society. Decision-making through fair and impartial procedures.
Aurangzeb et al. [171]	Fair pricing mechanism in smart grids for low energy consumption users	The fair pricing scheme charges high-energy consumers more during peak hours to minimise costs for low-energy consumers. Penalty costs are applied for high-energy usage during peak hours, while off-peak rates are similar for all consumers.	No specific definition provided. Uses consumption/price ratio to evaluate fairness.
Jing et al. [225]	Fair P2P energy trading between residential and commercial prosumers	Fairness is achieved by ensuring profit is allocated equitably between residential and commercial prosumers using a Nash-type game model.	Profit allocation fairness: Ensures individual rationality and equality, with each prosumer aiming to maximize their own profit, ultimately reaching an equilibrium.
Gjorgievski et al. [101]	Fair energy sharing method for collective self-consumption using game-theory	Fairness definitions are used to calculate three numerical indicators: maximum excess, fairness index (F), and Jain's index (J). These metrics assess dissatisfaction, solution proximity to a benchmark,	Meritocratic individual rationality: Ensures a non-negative payoff based on individual contribution. Minimized inequality: Reduces differences in payoffs among community members. Coalition stability: Ensures members

		and solution similarity to a benchmark, respectively.	are better off within the community and that separation would not improve their payoff.
Oh [226]	Fair operation of energy storage for smart communities	Fairness is considered in terms of cost and resource distribution in an optimization model. Cost fairness aligns rewards with invested costs (similar to ROI), and resource fairness aligns VESS usage with allocated VESS capacity.	Fairness is defined as proportional allocation of costs and resources based on individual contributions, with a fairness index used for VESS operation to maximize social welfare while maintaining fairness constraints.

5.2 Theoretical Context

5.2.1 Energy Fairness

Fairness in relation to community energy and microgrids is commonly used interchangeably with the term's energy justice or energy equity [227]. It is often referred to as a multifaceted concept that addresses the equitable distribution of energy resources [211], fair decision-making processes and the acknowledgement of everyone's right to energy access [206]. However, as previously mentioned, fairness encompasses a range of definitions, highlighting different aspects of equity and justice in energy systems [228], [229]. Key definitions include distributive justice, procedural justice, recognition justice and restorative justice [211]. Distributive justice concerns allocating resources and responsibilities, aiming for equity among all members. Procedural justice focuses on the fairness of the processes and decision-making mechanisms that lead to tariff structures, including transparency and inclusiveness [230]. Recognition justice seeks to respect and acknowledge all community members' diverse needs and contributions, ensuring everyone's voice is heard [66]. Lastly, restorative justice focuses on addressing past injustice and rectifying the harm and preventing future injustice [206].

Continuing several frameworks have been developed to conceptualise energy fairness and to help provide a structured approach to understanding and addressing key issues. One of the most dominant energy justice frameworks proposed by researchers such as McCauley et al. [66] and Jenkins et al. [211] outlines three core dimensions of energy justice: distributional, procedural, and recognition justice. It provides a comprehensive approach to identifying and addressing injustice in energy systems, focusing on the need for equitable distribution of resources, inclusive decision making and recognition of diverse community values and needs. In comparison, Sovacool and Dworkin [231] developed a framework focusing on availability, affordability and acceptability. Similarly to McCauley et al. [66] and Jenkins et al. [211], it emphasises the need to ensure that energy resources are available to all, affordable for all income levels and acceptable regarding social and environmental impacts [231].

5.2.2 Social Capital and Fairness

Social capital can provide a lens through which the fairness of different energy tariffs and business models can be evaluated. This involves analysing the initial social capital within a community and how it responds to different scenarios [195]. For example, previous research by Hou et al. [232] has identified that higher social capital leads to a high sense of social fairness. Their study explored how social capital impacts the perception and outcome of fairness, influencing farmers' political participation in rural China. The findings suggest that efforts should focus on building and reinforcing social trust and networks to create environments where both processes and outcomes are perceived as fair [232].

Implementing different tariffs and business models can influence social capital by altering trust levels, community participation, social networks and governance practices [195]. For instance, a study by Bauwens et al. [37] on community renewable energy projects demonstrated that transparent and inclusive decision-making processes, which are facilitated by high social capital, led to higher perceived fairness and greater community acceptance. Institutional structures, as integral components of social capital, play a critical role in these dynamics [62]. Internal elements like leadership and voting mechanism [106], alongside with external frameworks such as regulations [33] and ownership laws [91], influence how decisions are made and perceived, shaping trust and cooperation within the community [24].

5.3 Research Approach

We adopt the optimisation model outlined in Chapter 4 [1], which applies a mixed-integer linear programming (MILP) approach to minimise the total electricity cost across various business models for community microgrids. For clarity, Figure 5.1 provides an overview of the cases and repeats Figure 4.2 in Chapter 4. The methodology and detailed equations are comprehensively presented in Chapter 4, Section 2. In this chapter, we use the same case study data as in Chapter 4, with the addition of new scenarios and modifications further explained in subsections 5.3.1 and 5.3.2.

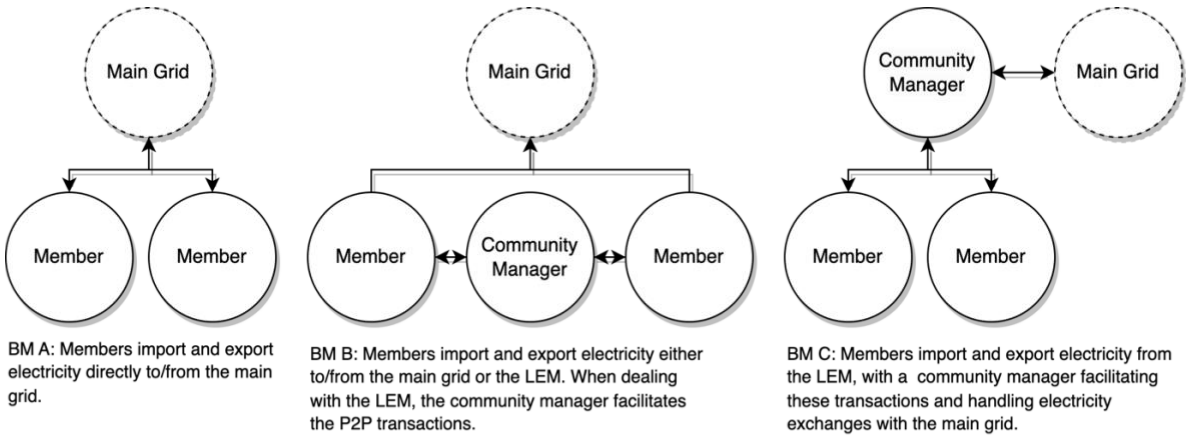


Figure 5.1. Repeated Figure from Chapter 4 showing BM archetypes from Eklund et al. [233].

5.3.1 New Scenarios

Electricity tariffs are designed to meet various goals, such as managing the energy load on the grid, encouraging energy conservation, and allowing utilities to recover costs while providing reliable service [213]. This chapter focuses on three different tariffs—Single Rate, ToU and dynamic—each addresses these goals differently. Previously, Chapter 5 analysed the impact of ToU tariffs under three different BMs. This chapter expands the analysis by introducing two additional tariff scenarios, Single Rate and Dynamic tariffs, to be tested under the same three BM cases. Thus, we will evaluate the performance of Single Rate, ToU, and Dynamic tariffs across all three BM cases, providing a comprehensive understanding of their implications. An overview of the three tariffs is provided below:

Single Rate Tariff

Single Rate tariffs are the simplest form of electricity pricing, where consumers pay a constant rate for electricity regardless of the time of day or the consumption volume [219]. This approach offers predictability and ease of understanding for consumers. However, it does not incentivise energy saving or shifting consumption to off-peak times, which can lead to higher peak demands and increased need for capacity [220].

ToU Tariff

ToU tariffs charge different rates for electricity based on the time of day, typically dividing the day into peak, off-peak, and shoulder periods. The aim is to encourage consumers to reduce consumption during peak periods when the grid is most strained, and electricity is more expensive to produce. For this study, the ToU tariff was calculated based on the definition provided by Ausgrid [205], which identifies peak hours as 2 pm to 8 pm on weekdays. Off-peak hours are from 10 pm to 7 am daily, and shoulder periods cover all other times. The Single Rate tariff was set to be slightly higher than the average of the ToU tariff [205].

Dynamic Tariff

Dyamic tariffs, including real-time pricing, offer a more granular approach to energy pricing by allowing rates to fluctuate based on real-time supply and demand conditions [234]. These rates can change hourly or even more frequently, providing strong incentives for consumers to adjust their usage in response to price signals [235]. The dynamic pricing tariff data for this study was sourced from the aggregated wholesale market price and demand data collected by the Australian Energy Market Operator (AEMO) for each month over a year [236]. Since the dynamic price reflects variations in wholesale market prices but are set by retailers, we add the additional fixed cost factors provided by the Australian Energy Regulator (AER) [237]:

- **Network costs:** cover the efficient costs of building and operating electricity networks and provide a commercial return to the network's financiers.
- **Environmental costs:** include payments to fund renewable energy targets, feed-in tariffs for solar PV installations and state government-operated energy efficiency schemes.
- **Retail costs and margin:** includes in the costs of servicing customers are managing billing systems and debt, handling customer inquiries, and complying with regulatory

obligations. Customer acquisition and retention costs relate to marketing and other activities aimed at gaining or retaining customers.

Due to the confidential nature of some of these cost factors, we utilised data collected by the Australian Competition and Consumer Commission (ACCC) [238], which provides breakdowns of these cost factors, presented as averages for different customer types and states [238] (see Table 5.2).

Table 5.2. Breakdown of the fixed charges in the Dynamic tariff.

Network costs	Environmental costs	Retailer costs and margin
0.13/kWh	$0.025/kWh	$0.035/kWh

To provide a comparison of the tariffs, Table 5:3 presents the minimum and maximum prices for Single Rate, Time-of-Use (ToU), and Dynamic tariffs. Figure 5.2 further illustrates the variability and differences in A$/kWh across these tariffs.

Table 5.3. Min and max cost for all tariffs (*Single Rate, ToU and Dynamic tariffs*).

Electricity Price	Single Rate	ToU	Dynamic
Min	$0.35/kWh	$0.13/kWh	$0.17/kWh
Max	$0.35/kWh	$0.53/kWh	$14.89/kWh

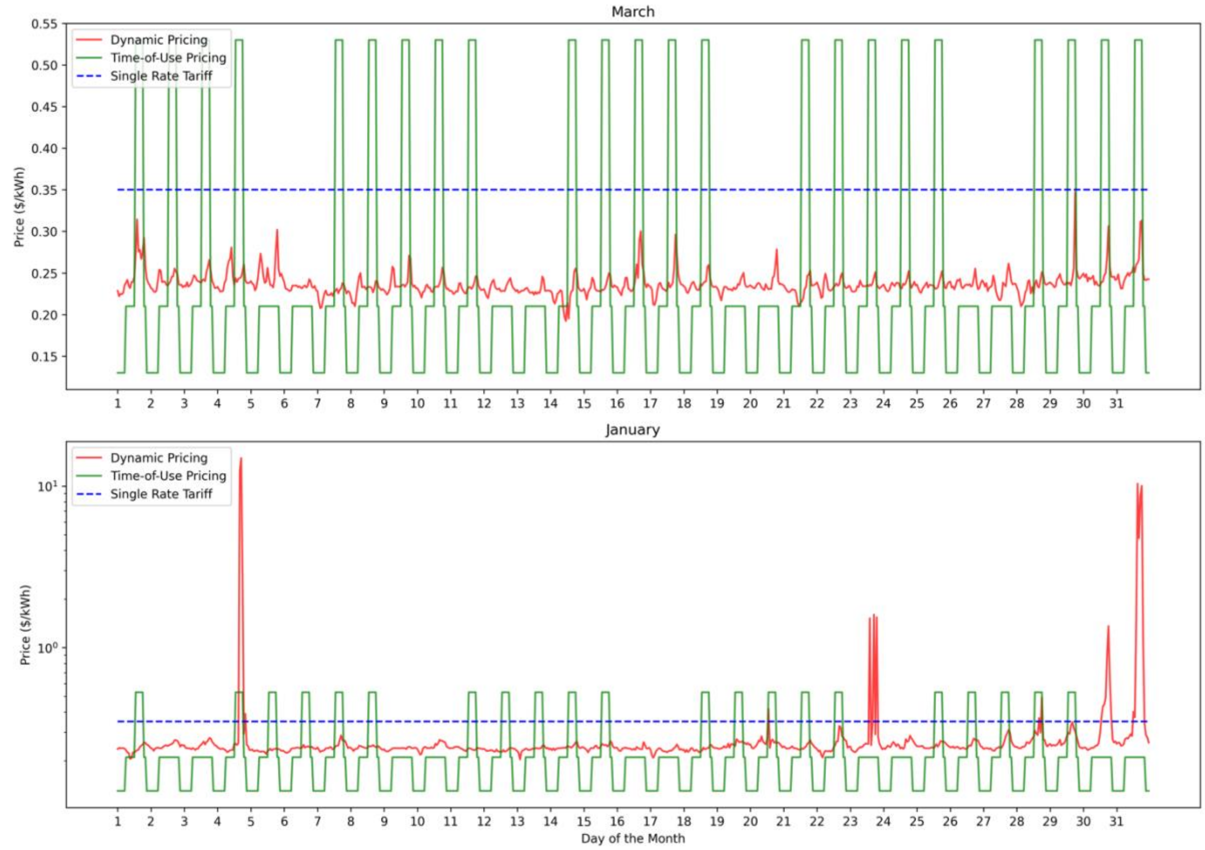


Figure 5.2. Comparison of Electricity Pricing Tariffs in March and January. The second subplot uses a logarithmic scale of the y-axis to provide clearer view of price variations.

5.3.2 Fairness and Social Capital KPIs

Instead of utilising metrics such as the Gini coefficient and Jain's fairness index, we recognise that fairness is subjective and highly influenced by the community's social capital [217]. Therefore, in this chapter, we expand on the social capital KPIs developed in Chapter 4 [233] to directly link them to fairness discussion and assessment, as shown in Table 5.4. Consequently, we will assess and discuss fairness based on the distribution of results across members rather than the absolute values of each KPI, facilitating a more straightforward discussion and evaluation of fairness.

Table 5.4. An overview of the Social Capital KPIs and how they link to fairness.

KPI	Impacts on Social Capital	SC Dimension	Expected Outcome	Link to Fairness
KPI 1: Total Cost Savings	Validates the efficacy of the microgrid, potentially increasing trust in the system and willingness to participate.	Structural	Enhanced governance and institutional trust	Increased trust leads to greater acceptance of tariffs and business models, seen as
KPI 2: Collective Self-Sufficiency	Reflects the community's collective ability to sustain its energy needs, which could promote a shared sense of achievement.	Structural & Cognitive	Stronger community identity and collaboration towards shared goals	Collective success fosters a sense of shared benefits, enhancing perceived fairness.
KPI 3: Individual Cost Savings	Direct financial benefits strengthen belief in the system's fairness and effectiveness.	Cognitive & Relational	Greater engagement and cooperation within the community	Fairness is assessed based on the distribution of the savings and significant disparities in individual savings may indicate inequalities.
KPI 4: Net Importers and Exporters	A balanced ratio could reflect the community's energy independence and interconnectedness.	Cognitive & Relational	Improved local resource management and self-reliance	A balanced and equitable distribution of import/export roles among community members indicates fairness. A skewed distribution may suggest disproportionate benefits or contributions, raising fairness concerns.
KPI 5: Self-Consumption vs Sharing	High sharing ratio may encourage community interaction and reciprocity.	Relational	Strengthened community bonds and trust	This KPI assesses the distribution of self-consumption and sharing practices among community members. Fairness is indicated by a balanced distribution. Imbalances may highlight potential inequities.
KP1 6: Self-Sufficiency	High self-sufficiency can lead to a greater collective understanding of sustainable practices and the benefits of energy independence.	Structural & Cognitive	Reinforced local governance and collective competency	Fairness through equitable participation and benefits; disparities reveal fairness concerns. Disparities in participation or benefits may reveal fairness concerns.
KPI 7: Quality of Sharing	Positive sharing experiences can foster a supportive community atmosphere and trust.	Relational	Increased trust and quality of interpersonal relationships	High quality of sharing suggests fair and supportive interactions; poor quality may indicate unequal benefits or participation.

5.4 Results and Discussion

The results of the community-specific KPIs are presented in Figure 5.3. For KPI 1, BMB consistently shows higher total cost savings across all tariff structures, particularly under the ToU tariff. In contrast, KPI 2 show less variability across BMs and tariffs, with BM B and BM C showing similar results.

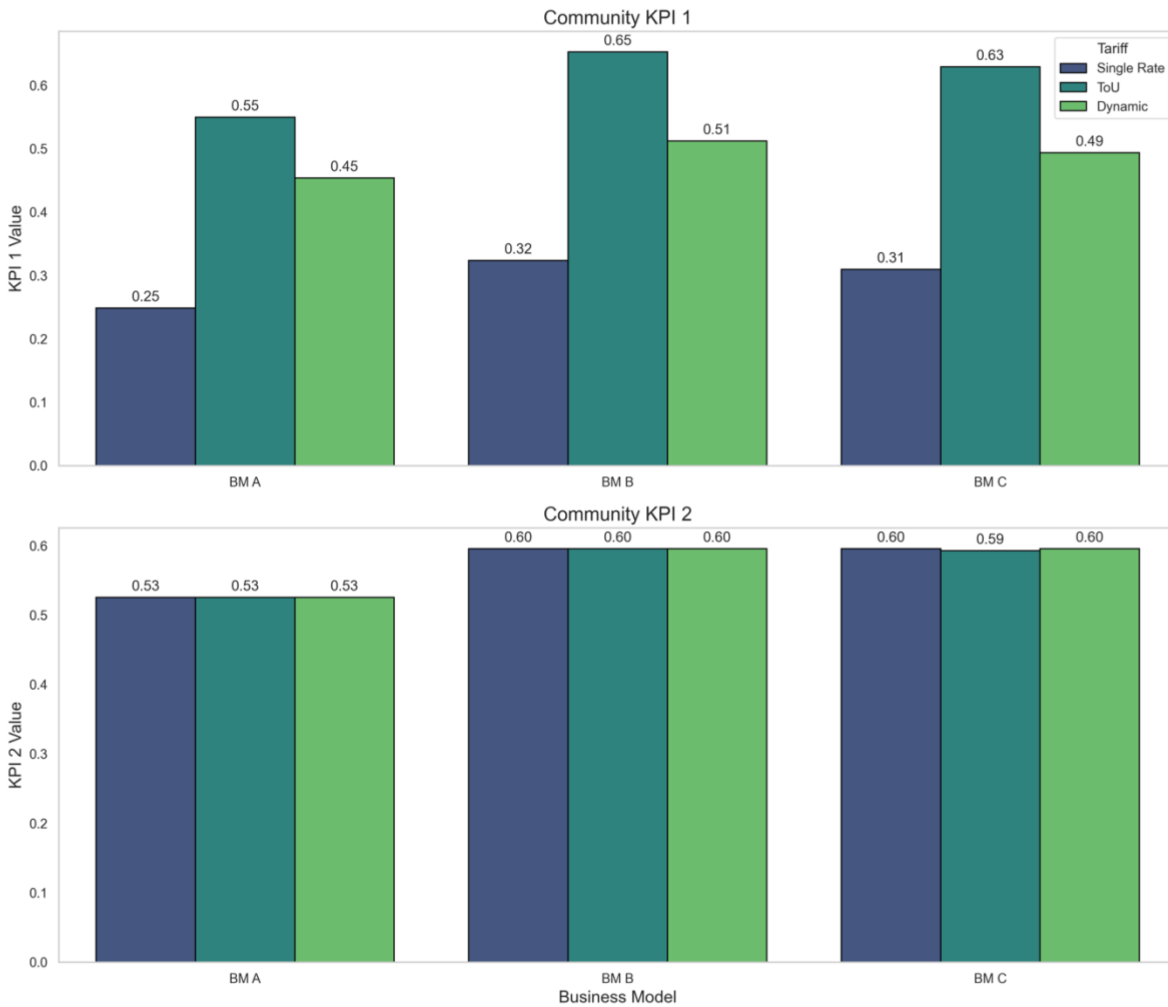


Figure 5.3. Comparison of KPI 1 and KPI 2 results across BMs and tariffs.

Figure 5.4 illustrates the scatter plots for each member-specific KPI, highlighting how each member responds under Singe rate, ToU, and Dynamic tariffs. The visual representation allows a clear comparison of these tariffs' impacts on energy efficiency, economic benefits, and overall member engagement in the microgrid. The varied performance across members within the same BM and tariff suggests disparities in how different members benefit from the microgrid's configurations. For instance, members with higher PV capacity may gain more in BM B and C through trading or sharing, potentially leading to perceptions of inequity. The BMs' design, particularly in BM C, attempts to address these disparities by pooling resources, which may help even out the benefits and burdens across the community, thus enhancing perceptions of fairness. Notably, the results reveal significant variations in KPI outcomes across members, suggesting that tariff structuring influences member behaviour and operational efficiency within the microgrid. Similarly, more granular insights of these results are provided in Table 5.4-5.6.

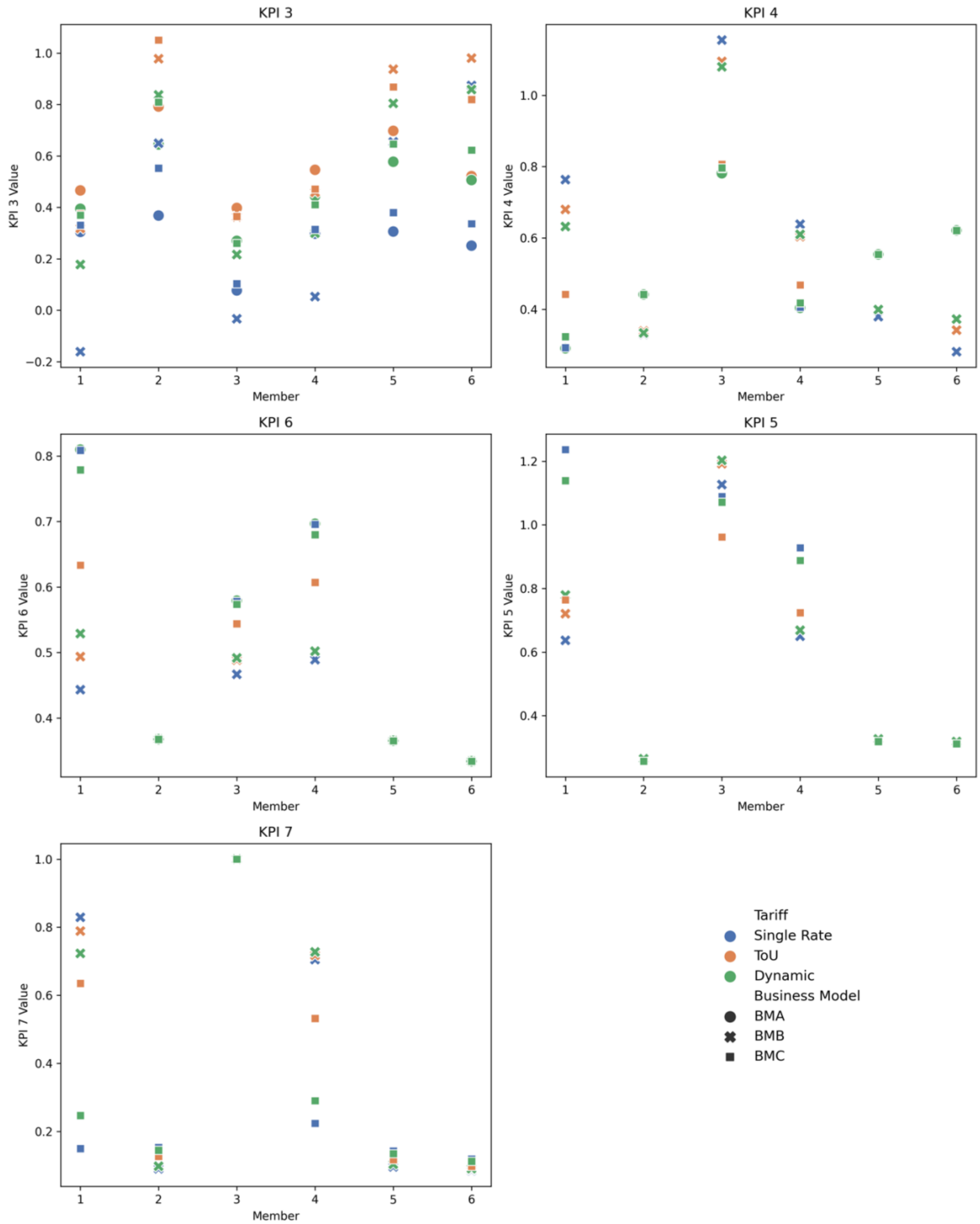


Figure 5.4. Scatter plots showcasing the distribution of member-specific KPIs across different BMs and tariff structures. Each subplot represents a separate KPI, illustrating variations and trends among community microgrid members under Single rate, ToU, and Dynamic tariff conditions.

To further extend our analysis of the numerical results, we look at the coefficient of variation (CV) between each BM and tariff scenario and how the member-specific KPIs are affected. Figure 5.5 highlights several key findings. KPI 4 consistently shows low and similar CV values across all business models and tariffs, indicating high consistency and stability. In contrast, KPI 3 displays significant variability in BM B under the Single Rate tariff, suggesting sensitivity to this tariff structure. KPI 7 demonstrates the highest variability in BMC, particularly under the Signel Rate tariff, while ToU consistently shows the least variability across all business models. Overall, BMA exhibits the least variability across different KPIs and tariffs, indicating a more stable performance profile. Conversely, BMB shows the highest variability, especially with the Single Rate tariff, suggesting areas for further investigation and improvement.

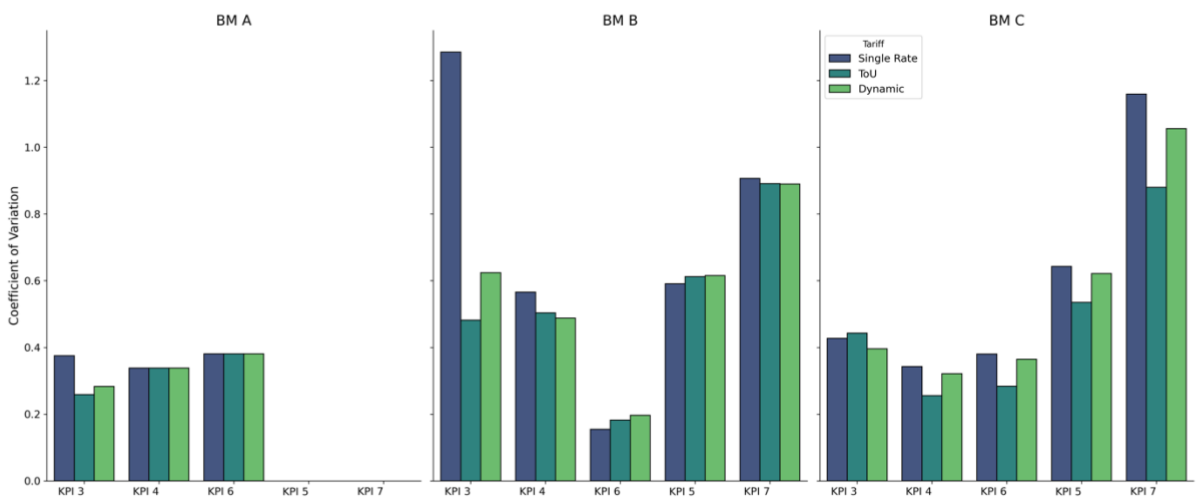


Figure 5.5. Coefficient of Variation for member-specific KPIs by BM and Tariff

Table 5.5. KPI results for BM A after optimisation (*KPI 1 total cost savings, KPI 2 community self-sufficiency KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing and trading*)

Tariff	**KPI 1**	**KPI 2**
Single Rate	0.25	0.53
ToU	0.55	0.53
Dynamic	0.45	0.53

Member	**KPI 3**	**KPI 4**	**KPI5**	**KPI 6**	**KPI 7**
Member 1	0.30	0.29		0.81	
Member 2	0.37	0.44		0.37	
Member 3	0.08	0.79	-	0.58	-
Member 4	0.30	0.41		0.70	
Member 5	0.31	0.55		0.37	
Member 6	0.25	0.62		0.33	
Member 1	0.47	0.29		0.81	
Member 2	0.79	0.44		0.37	
Member 3	0.40	0.78	-	0.58	-
Member 4	0.55	0.40		0.70	
Member 5	0.70	0.55		0.37	
Member 6	0.52	0.62		0.33	
Member 1	0.39	0.29		0.81	
Member 2	0.64	0.44		0.37	
Member 3	0.27	0.78	-	0.58	-
Member 4	0.44	0.40		0.70	
Member 5	0.58	0.55		0.37	
Member 6	0.51	0.62		0.33	

Table 5.6. KPI results for BM B after optimisation (*KPI 1 total cost savings, KPI 2 community self-sufficiency KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing and trading*)

Tariff	**KPI 1**	**KPI 2**
Single Rate	0.32	0.6
ToU	0.65	0.6
Dynamic	0.51	0.6

Member	**KPI 3**	**KPI 4**	**KPI5**	**KPI 6**	**KPI 7**
Member 1	-0.16	0.76	0.64	0.44	0.83
Member 2	0.65	0.33	0.26	0.37	0.09
Member 3	-0.03	1.15	1.13	0.47	1.00
Member 4	0.05	0.64	0.65	0.49	0.70
Member 5	0.65	0.38	0.33	0.37	0.10
Member 6	0.87	0.28	0.32	0.33	0.08
Member 1	0.32	0.68	0.72	0.49	0.79
Member 2	0.98	0.34	0.26	0.37	0.10
Member 3	0.36	1.09	1.19	0.49	1.00
Member 4	0.46	0.60	0.67	0.50	0.72
Member 5	0.94	0.40	0.33	0.37	0.10
Member 6	0.98	0.34	0.32	0.33	0.09
Member 1	0.18	0.63	0.78	0.53	0.72
Member 2	0.84	0.33	0.26	0.37	0.10
Member 3	0.22	1.08	1.20	0.49	1.00
Member 4	0.30	0.61	0.67	0.50	0.73
Member 5	0.80	0.40	0.33	0.37	0.10
Member 6	0.86	0.37	0.32	0.33	0.09

Table 5.7. KPI results for BM C after optimisation (*KPI 1 total cost savings, KPI 2 community self-sufficiency KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing and trading*)

Tariff	KPI 1	KPI 2
Single Rate	0.31	0.6
ToU	0.65	0.6
Dynamic	0.49	0.6

Member	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7
Member 1	0.33	0.29	1.24	0.81	0.15
Member 2	0.55	0.44	0.26	0.37	0.15
Member 3	0.10	0.79	1.09	0.58	1.00
Member 4	0.31	0.41	0.93	0.70	0.22
Member 5	0.38	0.55	0.32	0.37	0.14
Member 6	0.34	0.62	0.31	0.33	0.12
Member 1	0.37	0.44	0.76	0.63	0.63
Member 2	1.05	0.44	0.26	0.37	0.13
Member 3	0.36	0.81	0.96	0.54	1.00
Member 4	0.47	0.47	0.72	0.61	0.53
Member 5	0.87	0.55	0.32	0.37	0.12
Member 6	0.82	0.62	0.31	0.33	0.10
Member 1	0.37	0.32	1.14	0.78	0.25
Member 2	0.81	0.44	0.26	0.37	0.14
Member 3	0.26	0.80	1.07	0.57	1.00
Member 4	0.41	0.42	0.89	0.68	0.29
Member 5	0.65	0.55	0.32	0.37	0.13
Member 6	0.62	0.62	0.31	0.33	0.11

To further understand the relationship between the individual KPI results, we look at the correlations and trade-offs between KPIs. As seen in Figure 5.6, significant insights emerge, particularly regarding the interplay between economic benefits and community energy dynamics. A notable finding is the strong negative correlation between KPI 3 (Total Cost Savings per Member) and both KPI 5 (Self-Consumption vs Trading/Sharing Ratio) and KPI 7 (Quality of Sharing and Trading). Specifically, a correlation of -0.72 between KPI 3 and KPI 5 suggests that increased self-consumption and trading/sharing ratios, while promoting energy independence, are achieved at the expense of economic efficiency. Furthermore, the correlation of -0.76 with KPI 7 indicates more efficient energy-sharing systems.

Conversely, KPI 4 (Import/Export Ratio per Member) shows a strong positive correlation of 0.82 with KPI 7, highlighting that members with higher import/export ratios contribute significantly to a higher quality in the trading system. Another strong positive correlation is observed between KPI 5 and KPI 6 (Self-Sufficiency), with a coefficient of 0.83. This correlation confirms that higher self-consumption directly correlates with greater self-sufficiency, indicating that members who consume much of the energy they produce are less reliant on external energy supplies. Additionally, the positive correlation of 0.75 between KPI 6 and KPI 7 suggests that members who achieve higher self-sufficiency also positively impact the quality of sharing and trading within the community.

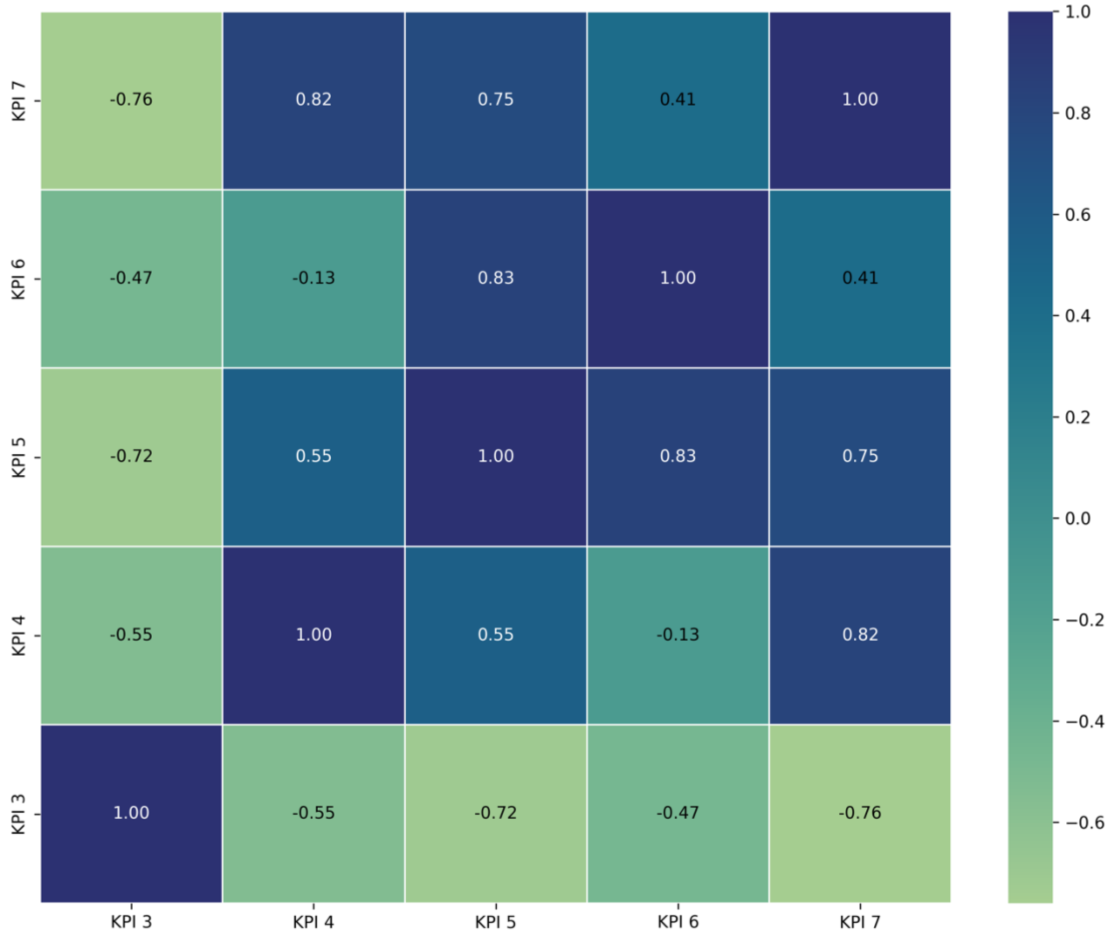


Figure 5.6. Visual and numerical representation of the correlation coefficients between member-specific KPI pairs for all three BMs and tariff structures.

We continue our analysis by investigating how each member's energy demand is satisfied under each BM and tariff structure. As seen in Figure 5.7, the changes are very small when comparing across tariff scenarios, while the changes are much larger across BM cases.

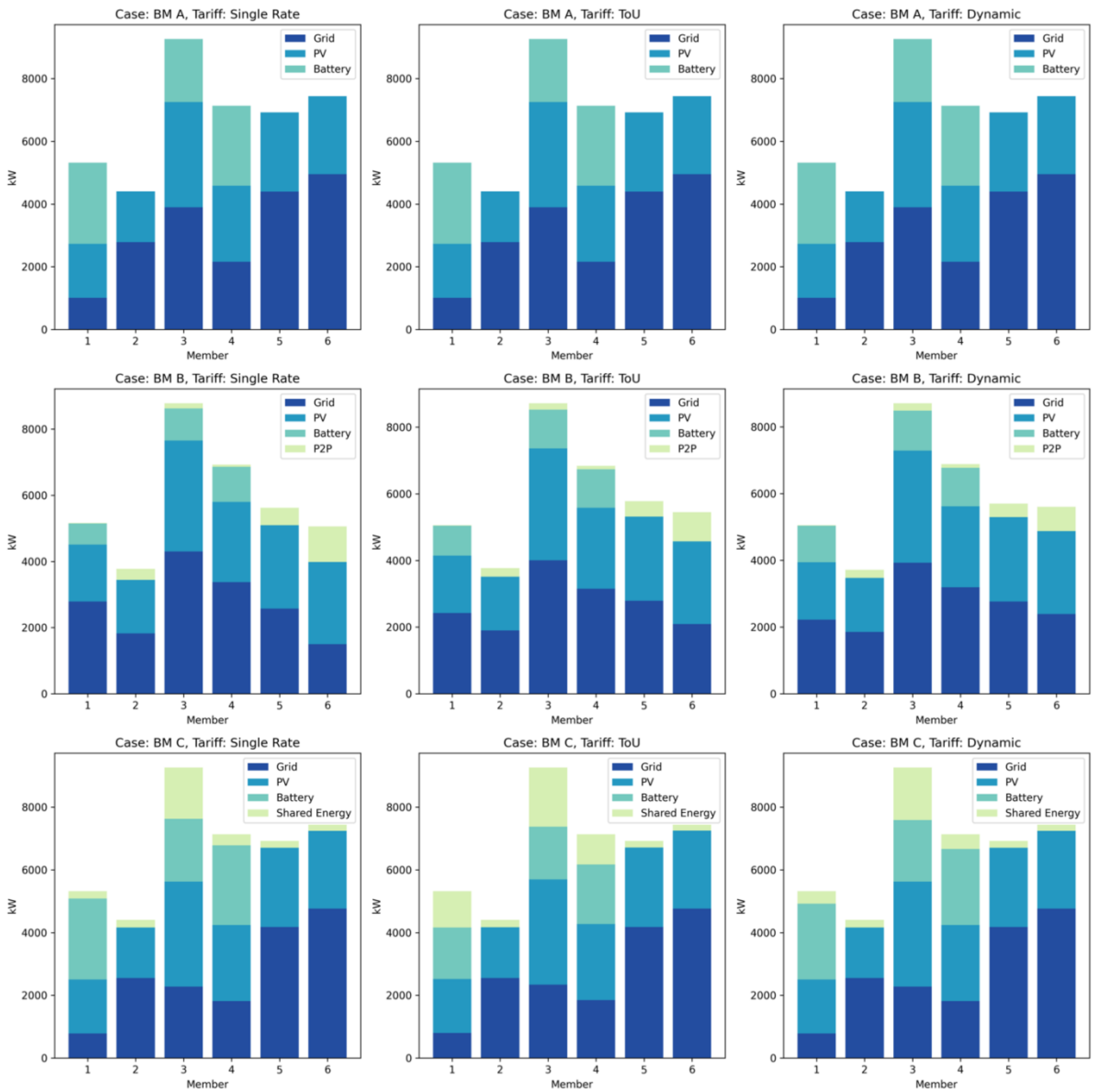


Figure 5.7. Breakdown of how each member's energy demand is satisfied for all cases and scenarios.

Observing the energy consumption figures for BM A, members primarily rely on the grid, particularly during months with lower PV output. This reliance indicates limited flexibility and individualistic energy management, reflected in lower scores for KPI 6 related to self-sufficiency. In BM B, the introduction of P2P energy trading visibly alters consumption patterns, reducing grid reliance as members buy and sell energy among themselves. This is evident from the increased use of P2P in the figures for BM B, especially during peak months. This model scored higher on KPIs concerning community self-sufficiency (KPI 2) and import/export ratios (KPI 4), highlighting a shift towards more interdependent energy practices. The figures for BM C indicate a balanced use of shared, battery, and PV sources, suggesting a collective approach to energy management. This model generally shows improved scores on KPIs for sharing quality (KPI 7) and total cost savings (KPI 3), suggesting effective communal resource utilisation and cost-efficiency.

5.5 Discussion: Impact on Social Capital and Fairness

To further analyse and discuss the distribution of benefits and the influence of tariff structures, we delve into the patterns observed in the results and their relationship to fairness and social capital. The Single Rate Tariff shows consistent energy sourcing patterns with minimal fluctuation, as depicted in Figure 5.7. This suggests a passive response to a uniform cost structure, leading to minimal strategic engagement from the members. Despite this, there is significant variability in cost savings and quality of sharing/trading, as seen in Figure 5.4. The high coefficient of variation (CV) for Single Rate tariffs across KPIs, shown in Figure 5.5, reflects this inconsistency. While a uniform cost structure might initially seem fair, the resulting passive engagement and unequal benefits distribution suggest otherwise. Members with higher energy needs or better resources might benefit more, leading to perceived unfairness.

The ToU tariff encourages more dynamic utilisation of energy sources, particularly battery storage during peak hours, indicating active engagement by members to avoid higher costs. This behaviour aligns with higher values seen in KPI 3 (Individual Cost Savings) under ToU conditions, as shown in Figure 5.4. Consistent performance across business models, indicated by lower CV values in Figure 5.5, suggests more predictable benefits. The active engagement facilitated by ToU tariffs promotes equitable distribution of benefits. Members feel empowered to manage their energy consumption, leading to higher perceived fairness. The uniformity in energy source distribution further supports fair resource allocation, as shown in Figure 5.5. In contrast, the Dynamic Tariff shows consistency in import/export behaviour and individual self-sufficiency (KPI 4 and KPI 6), as illustrated in Figures 5.4 and 5.5. However, high variability in cost savings (KPI 3), self-consumption vs trading/sharing (KPI

5), and quality of sharing/trading (KPI 7) indicate diverse outcomes. Dynamic tariffs offer opportunities for strategic behaviour, but the actual benefits vary significantly depending on the business model and member strategies. While the potential for high benefits exists, the uneven distribution of outcomes under Dynamic tariffs might lead to perceptions of unfairness. Members with better knowledge or resources might capitalise more on the tariff structure, creating disparities.

Trade-offs and social capital dynamics are highlighted by the negative correlation between cost savings (KPI 3) and both high-quality sharing (KPI 7) and high self-consumption (KPI 5), as seen in Figure 5.6. This suggests a trade-off where engaging more actively in community energy systems might reduce individual cost savings. This trade-off could influence how members perceive the benefits and costs of community energy activities. Fairness perceptions might be impacted as members need to balance individual savings with community engagement. Policies promoting both individual benefits and community activities are essential to maintain fairness. However, enhanced community trading dynamics are reflected in the positive correlations between import/export ratios (KPI 4), self-sufficiency (KPI 6), and quality of sharing (KPI 7), also shown in Figure 5.6. These correlations suggest a robust community trading system. Active participants benefit from and contribute to community energy resilience and sustainability. These positive correlations indicate fairness through mutual benefits and active participation. Community cohesion and trust are enhanced, reflecting the relational and cognitive dimensions of social capital.

Continuing, it is important to highlight that while a uniform distribution might suggest a fairer allocation of resources, it is important to recognise that this may also depend on the initial social capital in the community. High social capital can help manage and distribute benefits more effectively, enhancing perceived fairness. In communities with high social capital, characterised by strong networks, trust and active participation, the perception of fairness is likely to be more positive. These communities can better manage and distribute the benefits of different tariffs and business models. For example, the cohesive distribution of benefits, mostly seen in the ToU tariff scenario, would be more readily perceived as fair by communities with high social capital, as trust and cooperation facilitate collective understanding and higher acceptance of the different outcomes. Conversely, the same outcomes might be perceived differently in communities with low initial social capital. Lack of trust and weaker social networks can lead to scepticism and perceived unfairness, even if the distribution of benefits is objectively equitable. For example, the variability in cost savings under the Dynamic tariff could exacerbate existing distrust and lead to perceived inequities, especially if some members feel disproportionately disadvantaged.

Similarly, the outcomes from different tariffs and business models can also affect the existing social capital and fairness perceptions. Fair and equitable distributions foster trust, cooperation, and stronger community bonds, feeding back into higher social capital. In particular, the consistent performance of the benefit distribution under the ToU tariff can enhance trust and cooperation within the community and, thereby, increase social capital and fairness. However, perceived unfairness and unequal benefit distribution can erode social capital. Members who feel disadvantaged may disengage, reducing overall community participation and weakening social networks. This type of negative feedback loop can make it more challenging for the community to achieve fairness in future energy initiatives. Conversely, exclusionary or rigid governance systems may exacerbate perceptions of fairness, even in communities with initially high social capital. For example, while a community with strong trust and networks might navigate challenges effectively, misaligned or overly restrictive policies can still undermine perceptions of fairness and trust [33].

Table 5.8 consolidates the key findings of this study by summarising the performance of the KPI results across all business models and tariff scenarios. This table provides a comprehensive overview of how these combinations may impact fairness and the operational outcomes within community microgrids. Hence, reflecting the detailed analysis and discussion presented above. Each cell in the table categorises the outcomes as very positive (++), positive (+), or negative (-), offering a straightforward assessment of the impacts of various scenarios. Very positive outcomes reflect scenarios where the combination of BMs and tariffs effectively promotes equitable distribution of benefits, enhances community cooperation, and fosters trust. Positive outcomes generally indicate favourable results with some areas for improvement, while negative outcomes suggest potential issues with uneven benefit distribution or lower levels of member engagement and trust.

Table 5.8. Summary of KPI results across BMs (*BM A, BM B and BM C*) and tariff scenarios (*Single rate, ToU and Dynamic*). Each cell indicates the outcome as very positive (++), positive (+) or negative (-) based on the results and their link to fairness.

KPI	BM A			BM B			BM C		
	Single Rate	ToU	Dynamic	Single Rate	ToU	Dynamic	Single Rate	ToU	Dynamic
KPI 1: Total Cost Savings	-	+	+	-	++	+	-	++	+
KPI 2: Collective Self-Sufficiency	+	+	+	++	++	++	++	++	++
KPI 3: Total Cost Savings per Member	-	+	+	-	++	+	-	++	+
KPI 4: Import/Export Ratio per Member	++	++	++	+	+	+	++	+	++
KPI 5: Self-Consumption vs Trading				-	+	+	++	-	+
KPI 6: Self-Sufficiency	-	+	0	+	+	+	++	+	++
KPI 7: Quality of Sharing and Trading				++	++	++	-	+	-

5.6 Conclusion

The detailed analysis linking observed patterns and results to fairness and social capital offers a comprehensive view of how different business models and tariff structures impact community microgrids. By promoting equitable distribution of benefits and efficient energy use, ToU tariffs and BM B model seem to enhance trust and cooperation, essential for community energy systems' long-term success and sustainability. Integrating social capital considerations into the design and assessment of community microgrids enables diverse perspectives to be accounted for, leading to outcomes perceived as fairer and more acceptable. The critical role of tariff design in achieving fair and efficient energy distribution is evident, with ToU tariffs emerging as the better choice for sustainable community energy systems. Policymakers and researchers must recognise the complex interplay between social capital and fairness to develop more equitable, sustainable, and effective energy solutions.

6 Community Capacity Building for Microgrid Projects: An Australian Case Study

Preamble

Paper Status
Under review in Energy Research and Social Science

Ethics approval
ETH22-7777 from the University of Technology Sydney

Overview
Chapter 5 builds on the last level of the CMD framework, connecting the insights from previous chapters on social capital (Chapter 2), business models (Chapter 3), and optimisation (Chapter 4 and Chapter 5). The goal of this chapter is to develop a comprehensive capacity-building strategy for community microgrid projects. We connect the theoretical frameworks and practical applications discussed earlier, focusing on enhancing community engagement and participation through targeted capacity-building initiatives.

We extend the work presented in Eklund et al. [239] by offering an initial analysis of the role of community engagement and capacity building in a community microgrid case study. The methodology includes a thorough capacity assessment, the development of a tailored capacity-building strategy, and iterative implementation with ongoing monitoring and evaluation.

In the assessment phase, we use the Social Capital Index (SCI) from Chapter 2 to evaluate the community's existing capacities, identifying both strengths and gaps. This assessment involves surveys and in-depth interviews to gather insights into the community’s energy usage patterns, willingness to invest in renewable energy, and attitudes towards collective resource management. The findings from this assessment inform the development of a capacity-building strategy that addresses the community's specific needs.

Based on the assessment results, we formulate a tailored strategy to address identified capacity gaps. This strategy includes individual training sessions on energy consumption, smart meter usage, solar production potential, and battery storage. By focusing on personalised interactions rather than group sessions, the strategy caters to the community’s preference for individual engagement, thus enhancing the effectiveness of the training.

The implementation phase involves executing the capacity-building plan through hands-on training and educational sessions. The final phase, continuous monitoring and evaluation, provides a feedback loop to the social capital framework discussed in Chapter 2. This phase assesses technical performance, gathers community feedback, and reevaluates social capital. By monitoring the microgrid’s operations, identifying areas for improvement, and evaluating community engagement, this phase ensures that the strategy remains responsive to the evolving social dynamics of the community.

This research offers valuable insights and practical strategies for implementing microgrids in diverse social contexts, advocating for inclusive and community-focused energy solutions.

Abstract

This paper thoroughly examines the prerequisites for community capacity building in the context of community microgrid implementation. It discusses a multi-faceted assessment approach that includes personalised interactions tailored to community capacity and knowledge enhancement preferences. The approach emphasises the importance of understanding community dynamics, collecting in-depth feedback, and addressing identified capacity gaps through targeted educational sessions. By integrating a case study, the paper investigates the tailored application of this framework in a community characterised by social fragmentation. Despite encountering challenges such as concerns over financial viability and system integration, the study illustrates the effectiveness of individualised support and detailed discussions on energy systems. The paper outlines the short- and long-term monitoring plans for these capacity-building measures, highlighting the need for adaptive and community-focused strategies. The insights gained underline the necessity of crafting bespoke microgrid policies that consider local social dynamics and advocate for a sustainable and inclusive energy future.

6.1 Introduction

The global energy landscape is evolving at a rapid pace, with renewable energy sources gaining increasing importance in mitigating climate change [240]. Community microgrids have emerged as a promising option for energy distribution and management, presenting an alternative to the traditional centralised power grid [1]. These microgrids are small energy networks designed to offer reliable, sustainable, and resilient energy supply to specific communities. Capable of operating independently or in parallel with the main grid, they can serve a wide range of geographical areas, load types, and community sizes [22]. Community microgrids can significantly reduce the carbon footprint of energy consumption and allow communities to produce and manage their electricity, offering a chance for economic development and resilience [3]. Hence, community microgrids are not merely technical infrastructures; they represent a radical shift towards community empowerment in energy production and management [137].

The deployment and sustainable operation of community microgrids encompass complex technical, financial, and social challenges [33]. The technical challenges involve the integration of various renewable energy sources and maintaining grid stability [241], while financial challenges include securing initial investment and managing ongoing operational costs [58]. Beyond these, social challenges are often the most intricate [242]. These involve aligning the microgrid's design and operation with the unique cultural, social, and economic contexts of the community [74]. Ensuring community buy-in and participation is crucial, as these elements foster a sense of ownership and responsibility essential for the long-term success of the projects [106].

Amid these challenges, community capacity building emerges as a critical strategy [243]. It aims to empower community members with the skills and knowledge necessary to take ownership of the microgrid projects [244]. This goes beyond simply understanding the technical aspects of the systems; it includes appreciating the social, economic, and environmental benefits and recognising the potential for community transformation [131]. Effective capacity building also involves creating educational programs, workshops, and participatory planning sessions that engage various community stakeholders [245]. For example, collaboration with stakeholders and project partners, each offering unique field expertise, is integral to this process [36]. Depending on the business model involved, the ownership and stakeholder configuration may differ, guiding the project to maintain alignment with community needs and objectives [246].

Significant research has been conducted on the elements necessary for the success of community microgrid projects. For instance, Chmutina and Goodier [247] have highlighted the importance of both technical and organisational knowledge as key components of community capacity. Additionally, studies like those conducted by Broska [24] have demonstrated that successful community energy projects often leverage and build upon existing levels of social capital, enhancing it through continued engagement and education initiatives. For example, the study on the successful community energy project on Samsø Island [102] highlights the importance of entrepreneurial individuals who were part of a strong network on the island and could build new relationships outside it. The island's community is known for having many formal and informal local networks that promote community spirit and inclusiveness. This leads to a commitment to social relations that supports the island's search for new opportunities. The study also emphasises the importance of strong relations between local organisations and the community as an essential background condition [102].

While studies have examined social factors in community microgrids, the majority have focused on the successful parameters in cooperative communities [37], [75], [115]. Few studies have explored conflictual relationships in physical community microgrid projects and how they affect governance arrangements and social and environmental outcomes [33]. This highlights a gap in the literature emphasising the need for further research into the challenges associated with implementing community microgrids in fragmented communities where social divisions may complicate the process [248]. In fragmented communities, social divisions can create significant obstacles for community microgrid projects [249]. These challenges can range from a lack of trust and cooperation [105] to disputes over the distribution of benefits and the technical feasibility of the project [250]. These issues may impede the development and adoption of community microgrids [56], leading to a loss of opportunities for energy resilience and economic development in these communities.

This paper aims to examine and develop a community capacity-building approach that is tailored to the specific needs and social dynamics of communities implementing microgrids. By doing so, it seeks to bridge the identified gap by focusing on communities that are not inherently cooperative. Consequently, we conduct a case study of a community microgrid project in a fragmented community to further contribute to the existing literature and develop more inclusive strategies and frameworks for community microgrids. Through this approach, the paper contributes to the existing literature by offering insights and practical strategies that facilitate the successful implementation of community microgrids in a wider array of social contexts.

The paper is guided by the following research questions:

1. How can personalised interactions and targeted educational sessions enhance community capacity and knowledge about microgrid systems?
2. What are the challenges and effectiveness of community-specific strategies in addressing social fragmentation and enhancing system integration?
3. What are the necessary short- and long-term monitoring plans for capacity-building measures in microgrid implementation to ensure sustainability and inclusivity?

This paper is organised as follows: Section 6.2 presents previous research on community capacity and engagement strategies and theories. Section 6.3 describes the methodology and explains the approach to community capacity building developed in this paper. Section 6.4 presents the case study together with results and discussion. The paper concludes with Section 6.5, summarising our findings and proposing directions for future research.

6.2 Understanding Capacity Building

Capacity building is a multifaceted process crucial for fostering sustainable development within communities [245]. Enemark and Williamson [251] define capacity building as the process of strengthening the abilities of individuals, organisations, and communities to effectively address their needs and pursue their goals. This includes enhancing skills, knowledge, resources, and social capital to enable communities to respond to challenges and seize opportunities [252]. Historically, the concept of capacity building has evolved from a primary focus on infrastructure development to include social, economic, and environmental dimensions, reflecting a holistic approach to sustainable development [67]. Within the context of community microgrids, capacity building becomes essential for empowering local stakeholders to actively participate in energy decision-making and management processes.

6.2.1 Theoretical Foundations of Capacity Building

Social Capital Theory, integral to community capacity building, posits that social networks have value. Social capital refers to the collective value of all social networks and the inclinations that arise from these networks to do things for each other [120]. According to Woolcock and Narayan [62], social capital facilitates coordination and cooperation for mutual benefit, enhancing the effectiveness of society by reducing costs of working together. In the context of community microgrids, social capital is critical as it underpins the collaborative efforts needed to plan, implement, and sustain these systems. Putnam's [253] seminal work on social capital highlights the importance of trust, reciprocity, and networks in facilitating collective action and resource mobilisation within communities.

Empowerment theory and community participation frameworks also play crucial roles in capacity building [130], [243]. These theories emphasise the importance of involving community members in decision-making processes, ensuring that projects are not only done "for" the community but "with" the community, thus fostering a sense of ownership and responsibility [254].

Further, effective capacity building requires an accurate assessment of the existing capacities within the community. Tools such as the Social Capital Index can provide valuable insights into the social structures and potential collaboration levels within a community [148]. Such tools help in identifying capacity gaps and designing appropriate interventions. Based on the findings from the capacity assessment phase, tailored strategies are developed to address the identified needs. As noted by Becker et al. [255], capacity-building strategies must consider both the technical and socio-economic aspects of community microgrids, ensuring that the initiatives are sustainable and context-specific.

6.2.2 Community Engagment and Development in Microgrids

Effective community microgrid projects require a high level of participation and engagement from community members at all project stages [51]. Community members' contribution is essential for achieving the project's objectives, ensuring the project aligns with their needs and values, and ultimately, ensuring the project's long-term success [82]. A key factor in achieving success is the ability of community members to act collectively towards a shared purpose, which helps to build a sense of ownership and commitment to the project [24]. To address these social dimensions, it is essential to engage citizens through community training and capacity building, thereby facilitating the transition towards a more decentralised energy system [256]. By actively involving community members in each phase of the project, community microgrids can effectively address the specific energy needs and requirements of the community while promoting energy self-sufficiency, reducing carbon emissions, and creating a more sustainable energy future. Furthermore, community involvement in these projects can build trust, foster collaboration, and encourage ownership and accountability, leading to stronger, more resilient communities [41].

However, achieving success in community microgrid projects is context-dependent and may face unique challenges in different communities [102]. For example, the use of common pool resources such as energy can provide opportunities for cooperation and collective action among community members [56], but it can also lead to free-rider behaviour and barriers to participation and fair benefit distribution [85]. Additionally, the motivations of community members to participate in the project, as well as their physical limitations, can also affect the project's success [56]. Therefore, it is crucial to take a community-specific approach that considers the unique challenges and motivations of community members to ensure the success of community microgrid projects [58].

To further understand the social success parameters of community microgrids, this paper draws inspiration from the recommendation to examine the social capital present in the community, as suggested by previous research [148]. This involves considering:

- Structural Social Capital: This encompasses the observable social structures such as networks, roles, rules, and precedents.
- Relational Social Capital: This dimension focuses on the personal relationships, trust, respect, and norms that emerge from the interactions among community members.
- Cognitive Social Capital: This pertains to the shared norms, values, attitudes, and beliefs that guide individuals' actions and interpretations.

6.3 Methodology

The approach to community capacity building is an iterative process emphasising continual learning and improvement. It comprises four interconnected phases (Figure 6.1): Capacity Assessment, Capacity Development Strategy, Implementation, and Monitoring and

Evaluation. Each phase feeds into the next, creating an iterative approach that is responsive to the community's needs and the evolving demands of the project.

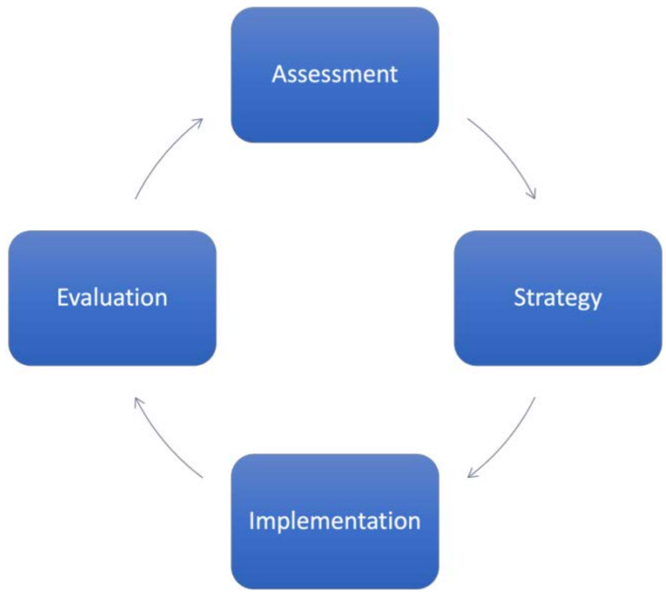


Figure 6.1. The conceptual framework of the iterative community capacity-building approach.

6.3.1 Capacity Assessment

In the initial phase of our method, we apply the framework and Social Capital Index (SCI) tool delineated in reference [148], built on the principles of social capital theory. This framework offers a structured approach to examine community traits vital for adopting microgrids. It's divided into four distinct elements: social capital, community capability, community classification, and the anticipated impact of microgrid integration. The tool, underpinned by an SCT-based metric, enables the evaluation and interpretation of unique social dimensions within communities. This aids in the categorisation and comparison of varying community types. Employing this framework, we conduct a thorough assessment of the community's capacity needs, identifying the necessary skills, knowledge, resources, and competencies the community must possess for successful project implementation. Additionally, we assess the community's existing capacity, determining the strengths to leverage and the areas that need bolstering. By contrasting the community's needs with their current capabilities, we pinpoint capacity shortfalls. These identified gaps guide our focus for the subsequent capacity-building efforts. Furthermore, the use of this framework allows us to delve into the SCI score of the community and acquire deeper insights into the social structure.

As a first step, an initial survey was conducted to gather information about the community's views and motivations regarding the implementation of a microgrid. The purpose of the survey was to collect data on each community member’s current energy status quo and their vision for a possible microgrid. The survey also aimed to assess the community's willingness to invest financially in purchasing and selling local renewable energy. It included questions designed to inform the community about microgrids and gather input on how they would like to use and generate electricity. Additionally, the survey collected information on electricity usage patterns, interest in hosting renewable energy sources, and views on the current electricity quality and stability. Other aspects covered by the survey included community members' willingness to pay more for greater reliability, interest in being active in a community microgrid, and engagement in the development process.

The primary focus and the second step of the assessment involved conducting in-depth interviews to explore the community’s social factors in greater detail, with the aim of understanding the feasibility of a community microgrid. The interviews were designed to investigate the community's social structure, which included examining factors such as trust, identity, norms, attitudes, and willingness to collaborate. To facilitate the interview process, a framework was developed to ensure consistency and comparability across interviews. This framework consists of various indicators to identify successful social factors in the community. Further details about the framework and its associated indicators are presented in Appendix B, developed based on the methodologies outlined in [148]. It is important to clarify that the survey conducted as part of the first step is not included in Appendix B, as the appendix focuses solely on the framework and indicators designed for the interview process.

6.3.2 Capacity Development Strategy

Based on the findings from the Capacity Assessment, we formulate a Capacity Development Strategy. This strategy is tailored to the identified capacity needs and gaps, outlining a detailed plan for enhancing the community's abilities and resources. Additionally, this stage involves selecting preliminary business models and outlining potential designs for the microgrid to ensure the developmental initiatives are sustainable and tailored to the community's unique context and energy requirements.

6.3.3 Implementation

In the Implementation phase, the Capacity Development Strategy is implemented. Here, we execute the outlined plan, focusing on closing the capacity gaps identified during the assessment phase. This is a hands-on phase where stakeholders actively engage with the community to build the required capacity.

6.3.4 Monitoring and Evaluation

This final phase involves tracking the progress of our capacity-building initiatives and evaluating their effectiveness. We gather feedback and assess outcomes, which provide crucial insights into what is working and what might require adjustments. This phase is pivotal in acknowledging that as social capital within the community evolves, our business models and market mechanisms may also need to be re-evaluated and adapted to align with these shifts. Thus, it ensures that our capacity-building efforts are responsive to the community's changing landscape and supports a sustainable progression of social capital development.

6.3.5 Process Overview and Timeline

To provide an overview of the research process, we present a simplified timeline of the phases of this capacity-building framework in Table 6.1. While this methodology section outlines the process at a conceptual level, detailed activities and outcomes are elaborated in Section 6.4 as part of the case study. Although work on all phases was initiated as part of the case study, the *Monitoring & Evaluation* phase was not fully completed at the time of writing due to its long-term nature. However, this phase remains an integral part of the framework and has been included to present a comprehensive representation of the research process. Future applications of this framework, including ongoing work in the case study, will address the evaluation activities to ensure the framework's iterative goals are achieved.

Table 6.1. Overview of the capacity-building framework phases, including approximate timelines and completion status in the case study

Phase	Timeline	Status
Capacity Assessment	Month 1-3	Completed
Development Strategy	Month 4-5	Completed
Implementation	Month 6-12	Completed
Monitoring & Evaluation	Post Implementation	Not Completed

6.4 Community Microgrid Case Study

The case study was carried out in a remote community with less than 20 inhabitants, located in a mountainous region of Australia, which serves as a popular tourist destination due to its location on a major highway between two popular destinations. Tourism in the area is generated by passers-by as well as by nearby attractions with a focus on the community’s natural capital. residential member of the community. This community is, therefore, especially interesting as each participant in this study is both a business owner and a residential member of the community.

In the past decade, except for a couple of years, there have been occasions when the System Average Interruption Duration Index (SAIDI) limits were exceeded. During one incident, the town experienced a power outage that lasted for more than two days due to suspected lightning, while another outage lasted over two days due to wires being down. The community also suffers from poor internet connectivity, and in the event of a power outage, all telecommunications services become unavailable after approximately four hours. The limited backup battery storage of the telecommunication tower, which relies on the town's power supply, is the primary cause of this issue. To ensure the town can withstand such extended outages, the solution must have significant capacity. Additionally, the town experiences severe weather conditions in winter and high fire danger in summer.

6.4.1 Capacity Needs Assessment

To ensure that the interviews were as informative as possible, the insights gathered from the survey were used to inform the interview questions. The interviews were structured as individual 30-minute in-person sessions for each community member, allowing for personalised attention and deeper exploration of their views and opinions. Prior to collecting data, the university's research ethics committee approved the human ethics protocols and data privacy protection measures under approval number ETH22-7777. For both the survey and interviews, 6 out of 8 community members participated, representing approximately 20 people from their households. The results from the community capacity assessment are summarised in Figure 6.2 and presented and discussed below.

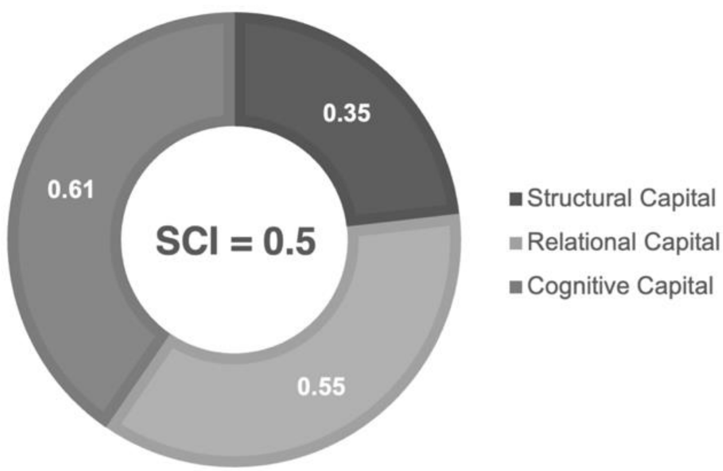


Figure 6.2. The overall SC Index and scores for all SC dimensions from the case study.

Presented in Figure 6.2, the scores reveal an overall SCI of 0.5, indicating a community with mid-range social cohesion. The relational score of 0.55 and cognitive score of 0.61 suggest moderate social interaction and a shared vision for community goals. However, the structural score of 0.35 points to a fragmented community structure, with less formal organisation and cooperative tradition.

Community Structure

Community members show a willingness to help each other in tourism-related business activities, underlining a sense of professional collaboration. Collaborative efforts tend to be more pronounced in this area, indicating a focus on shared business interests. Community members also share varying opinions on knowledge and information sharing with each other. However, the majority seem to state that important information and communication tend to occur after significant events have taken place.

Continuing, the geographical structure of the community may impact the cohesiveness and possibility of cooperation. As seen in Figure 6.3, this community has a scattered structure and long distances between some of its community members. Interactions between community members are therefore separated to mostly be one-to-one communication when needed. This further seems to cause fewer physical meetings and communication between the community.

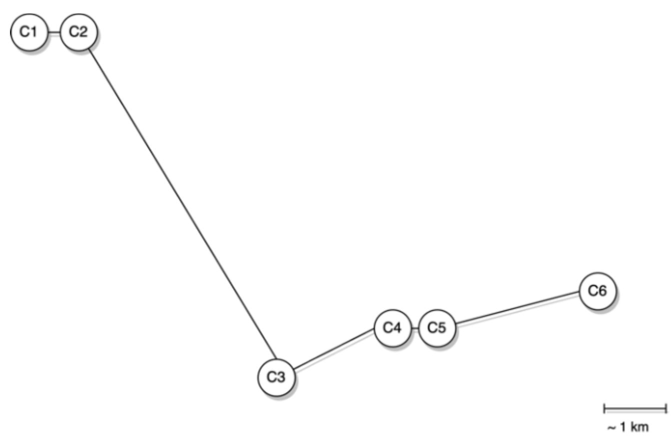


Figure 6.3. The representation shows the geographical distance between participants in the community, with C1 to C6 representing community member 1 through community member 6**.**

Community Identity

Managing shared power resources is complex, and some community members may need to be convinced of the benefits of a microgrid solution. For example, all respondents agree that resilience against power outages is important, but only half are willing to pay more for greater reliability. None of the respondents believes that they will become more independent from the main grid through a microgrid solution, but all agree that they would want to host renewable energy sources. Despite this interest, opinions are divided on the financial commitment to local renewable energy initiatives in the long term, reflecting concerns over the community's capacity to manage such a system and issues related to maintenance, resource distribution, and collaborative efforts beyond business interactions, all of which are significant hurdles to the success of the project.

The prevailing attitude among community members is one of self-preservation, with a focus on individual businesses rather than the community as a whole. There is a common observation that cooperative initiatives generally emerge when there is potential for individual business growth. However, this observation doesn't conclusively signify a deficiency in community togetherness or merely the prevalence of entrepreneurial tendencies. It could be a combination of both or other factors not explicitly addressed, highlighting the complexity of community dynamics.

Lastly, the community's primary identity is rooted in the hospitality and tourism industry. While the community may lean more towards self-reliance, adaptability is also a notable characteristic. It is crucial to address these dynamics and ensure that monetised solutions are in place while maintaining fairness in how electricity is used during outages.

Community Relations

We further identify that the willingness to participate in a possible community microgrid is highly dependent on the norms and relationships in the community as previously identified in studies such as [105], [257]. When it comes to attitudes connected to collective resources, the majority of the community does not believe in sharing resources without some sort of monetised solution. There is a great belief in the community that others would benefit more from sharing resources than themselves. The uncertainty of others can be related to the trust in the community, Trust dynamics within the community are intricate, reflecting a diversity of perspectives and preferences. Some individuals place their trust in specific business owners, recognising their expertise or reliability in certain areas. On the other hand, there are community members who extend their trust to non-business owners, valuing their contributions and involvement in community affairs. This division in trust highlights the nuanced nature of interpersonal relationships within the community.

However, despite these divisions, a noteworthy finding is the strong level of trust the community has in the network and service provider. Community members view the network and service provider as a trustworthy entity with the necessary knowledge and capabilities to lead the microgrid project. That being said, it is s important to consider that the interviews were conducted in partnership with the network and service provider, which might have influenced positive responses. This potential bias should be considered in our evaluation.

Knowledge and Technical Skills

The assessment of the community's technical knowledge regarding their energy system reveals a varied understanding among members. While a solid grasp of energy consumption and tariffs is prevalent, technical knowledge relating to the microgrid, smart meters, and the working of solar panels and batteries is less established. The in-depth nature of these queries suggests a significant but bridgeable gap in the community's understanding.

Several members of the community demonstrated an advanced awareness of renewable energy options, having previously considered the installation of PV panels and batteries. Interestingly, these members decided against the installation on the advice of installation companies who cited the geographical location of the community as potentially limiting the effectiveness of these renewable energy sources. This shared experience highlights the local understanding of renewable energy options and presents an opportunity to provide clarity about the potential of microgrids in such geographical contexts.

The community's concerns primarily revolved around:

- **Backup Systems:** Community members were uncertain about how the new installations would affect their existing backup systems, such as diesel generators.
- **Grid Connection:** There were questions about whether the adoption of a microgrid would sever their connection to the main grid.
- **Interdependency:** Community members were concerned about how their resilience might be affected by other members' installations if they were connected to the microgrid.

- **Geographical Implications:** Given the geographical location of the community and its lower sun exposure, community members questioned the efficiency of PV installations in their region.
- **Installation Limitations:** Members also asked why PV panels couldn't be installed on different parts of the roof, indicating a lack of understanding about optimal installation sites for maximum solar efficiency.
- **Overall Operation:** There was a pervasive need for clarification on how all components of the microgrid would work together to generate, store, and distribute power.

Many community members, being business owners, conveyed that their energy consumption patterns were non-negotiable due to the specific requirements of their businesses. For example, heating cabinets, cooking, and maintaining safety systems are energy-intensive tasks that cannot be compromised or significantly adjusted for energy conservation. This sentiment highlights a significant challenge to achieving flexibility in energy consumption patterns and emphasises the need for strategies that can provide renewable energy solutions without disrupting business operations.

In summary, while there is a robust foundational understanding of energy matters within the community, there exist targeted areas for development. The community's pre-existing interest in renewable energy, their engagement with technical questions, and the identification of specific concerns represent promising starting points for capacity development initiatives. Leveraging these points while addressing the identified concerns will be crucial in our capacity development strategy, aiming to enable the community to operate and manage their microgrid system effectively.

Summary and Key Insights

Our comprehensive capacity assessment of the community has yielded several critical insights that will inform the strategic direction of subsequent project activities. Here we summarise the most significant findings:

1. **Unique Community Structure:** A distinctive characteristic of the community is its decision-making process, which often operates with an emphasis on individual input. This reflects a potential area for enhancement through broader consultation, ensuring that the perspectives of all affected parties are adequately represented. Such insights underline the potential to foster a more inclusive and open decision-making framework as the project progresses.

2. **Limited Interaction and Knowledge Sharing:** There seems to be minimal mechanisms for interaction and knowledge sharing within the community. Such a limitation can inhibit trust-building and the development of a shared understanding—both fundamental for the successful realisation of a community-centric project such as a microgrid.

3. **Potential for Increased Connectedness and Coordination Capability:** The capacity assessment highlighted potential areas for enhancement in the community's ability to coordinate and act collectively. Enhancing these capabilities can help facilitate more effective decision-making and collective action, which are key components for the successful implementation and operation of a microgrid.

4. **Varied Technical Knowledge and Interest in Renewable Energy:** On a more encouraging note, the community demonstrated a sound baseline understanding of energy-related matters, alongside a marked interest in renewable energy. Despite this, targeted areas for further development were identified, mainly concerning technical knowledge related to microgrid operation, smart meters, and solar panels.

5. **Specific Concerns and Queries:** The community raised specific concerns and queries about the microgrid project, including the impact on existing backup systems, the potential influence of other members' installations on individual resilience, and geographical constraints on solar panel efficiency. These concerns reflect engagement and a readiness to learn more about the project.

6. **Energy Consumption Patterns:** The community, primarily made up of business owners, conveyed non-flexible energy consumption patterns due to their business

requirements. This insight points to the need for renewable energy solutions that don't disrupt their operations.

Elaborating on our key insights, we have summarised the results of the community capacity assessment in Table 6.2. This table offers a comprehensive view of the community's existing capacities, outstanding needs, and areas displaying capacity gaps.

Table 6.2. Assessment of community capacity needs, existing capacities, and capacity gaps for microgrid operation and management.

Aspects	Existing Capacity	Capacity Gaps
Social Structures for Microgrid Management		
Collective Decision-Making for Microgrid Operation	Decisions are typically made on an individual basis	Cooperative decision-making structures for microgrid management
Communication & Trust for Shared Microgrid Responsibility	Limited cooperation among community members	A common platform for communication and trust-building related to microgrid responsibilities
Integration of Microgrid Project with Community Identity	Positive attitude towards renewables, but no specific connection with microgrid concept	Formulating the microgrid project as part of community identity and aspirations
Technical Knowledge & Skills for Microgrid Operation		
Understanding of Microgrid Components, Operations and Maintenance	Basic knowledge about microgrids, PV, battery systems, but not about their integration and operation	In-depth understanding of microgrid components, operations, maintenance, and troubleshooting
Knowledge of Energy Consumption Patterns & Tariffs in Context of a Microgrid	Good understanding of personal consumption, tariffs but not in relation to a microgrid	Understanding of how energy consumption patterns and tariffs would change in a microgrid context
Confidence in Installing and Operating Renewable Energy Components within a Microgrid	Some members have interest in renewables but were previously advised against installation	High confidence in viability, installation, and operation of renewable energy components within a microgrid
Ability to adapt to Microgrid-Driven Changes in Energy Consumption	Limited understanding of flexibility due to business demands	Understanding and readiness to adapt to potential changes in energy consumption in a microgrid setting

6.4.2 Capacity Building Strategy

The strategy outlined in this section is rooted in the insights obtained from Table 6.2, which represent the cornerstone of our strategic approach. The primary objective is to enhance the community's capacity to manage and operate the microgrid system effectively. The strategy targets four key areas: inclusive decision-making, communication and knowledge sharing, community connectedness and coordination, and the bridging of specific technical knowledge gaps.

The capacity assessment revealed a community preference for personalised, one-on-one interactions over group sessions. Consequently, the strategy was designed to prioritise individualised education and training, targeting areas such as energy consumption, smart meter usage, photovoltaic production potential, and battery storage. This tailor-made approach intends to equip community members with an in-depth understanding of the microgrid system, empowering them to make informed decisions about their energy usage and actively participate in the project.

We observed the community's diversified characteristics and the individualistic approach towards resource sharing, management, or operation of the microgrid. While these features present unique considerations for capacity building and collaboration, they directed us to focus on individual capacity needs. With respect to community members' time limitations, the initial plan was revised to optimise the efficiency of our capacity-building efforts. Instead of conducting multiple workshops and sessions spread over different dates, we streamlined the process by integrating multiple sessions into a single day. This approach enables different stakeholders to participate concurrently, facilitating targeted training and engagement while respecting their scheduling challenges.

Through the capacity-building efforts, we seek to enhance social cohesion within the community and tap into the individual willingness of community members to participate, fostering a more inclusive environment. We will therefore address the specific technical knowledge gaps and provide the necessary skills and resources with a focus on the potential individual systems hosted by the community members. By adopting this approach, we aim to build capacity within the community as a whole while addressing the specific needs of each member. We recognised that direct communication and engagement during these sessions, as well as thorough preparation and analysis of individual customer requirements, would enhance time efficiency and effectiveness. By doing so, we aim to address concerns, leverage existing interests and engagement, and ensure the long-term sustainability and success of the microgrid project.

Now, expanding upon this, the evaluation and selection of the initial microgrid design and business model were critical steps. Recognising the necessity for individualised solutions, we opted for a utility-owned business model for the trial phase. Here, the utility will own the microgrid, allowing community members to experience the system without upfront investment. After the trial, there is the option for individuals to purchase their installations, fostering a sense of ownership and investment in the community's energy future.

This approach precludes energy trading or sharing between members during the trial period, instead focusing on individual rooftop solar installations and battery systems. This simplifies the operation and eases the community into the new energy framework without the complexities of managing shared energy resources. Post-trial, the community can evaluate the efficacy of the microgrid and make informed decisions regarding energy sharing and trading, as well as the potential for a more cooperative business model.

In summary, our capacity-building strategy builds upon the insights from our capacity assessment and tailors the approach to meet the unique needs and constraints of the community. The upcoming section will delve into the specific activities conducted during the implementation of this strategy.

6.4.3 Implementation

In this section, we provide a summary of our capacity-building activities and the outcomes. These sessions were held on-site at each community member's business location during the second PV and battery installation assessment, limiting their need for travel and ensuring their convenience. For a comprehensive overview of these activities, please see Table 6.3.

The subsections that follow offer a more detailed description of each activity, along with the associated outcomes.

Integral to this process is the collaboration with project partners, each offering unique field expertise. The grid operator guides the project, maintaining alignment with objectives and community needs. Industry partners supply advanced monitoring equipment, enriching the community's understanding of the microgrid's operation. The academic partner conducts rigorous research to help community members comprehend the potential benefits and implications of the microgrid system. Lastly, the industry partner's expertise in installation and system assessment enhances the community's hands-on knowledge. Their combined expertise significantly influences the success of the community capacity-building strategy.

Through this collaborative approach, the stakeholders are leveraging their strengths to deliver the best outcome for the community. This report will further elaborate on our approach to community capacity-building, the vital contributions of our partners, and the importance of this capacity-building phase to the project's overall success. Our efforts aim to build on the previous engagement strategy, draw from the insights of the customer trial, and progress with a project that is responsive, sustainable, and community-driven.

Table 6.3. Summary of completed capacity-building activities over a one-year period.

Date	Activity	Purpose	Groups
Nov 2022	Community Interviews	Capacity Assessment, trust building and providing information and gathering feedback	Network and Service Provider & Academic Partner
March 2023	Rooftop PV and Battery Training	Educating the community on smart meters, PV panels, battery system and how they can use digital systems to stay informed.	Network and Service Provider, Industry Partners and Academic Partner
March 2023	Installation Assessment and Training	On-site assessment was conducted to gauge the location's suitability and involve community members in the process	Network and Service Provider, Industry Partner and Academic Partner
March 2023	Provision of Individual	Information and explanation of new installations for community members.	Network and Service Provider, Industry

	Load Patterns/Training	Providing insights into possible solutions and how the installations will affect their current energy behavior.	Partner and Academic Partner
Ongoing	Project Updates	Keep the community updated and gather feedback	Network and Service Provider

Installation, Assessment and Education

This activity entailed conducting individual on-site assessments to examine potential installation sites for the solar and battery systems of each community member. The assessments were carried out to thoroughly evaluate the suitability of the sites for installing solar and battery systems. The installation project partner, led the process, with additional support from Network and Service Provider, to ensure an accurate and thorough evaluation. This session served a dual purpose: firstly, to gauge the feasibility of the potential installation locations considering existing infrastructures and natural conditions, and secondly, to bolster the community members' technical understanding of the system's installation and operation. The assessment also placed significant importance on community input and considerations, ensuring their active participation throughout the process.

Key outcomes of this session included:

1. **System Integration Clarification:** One of the crucial objectives of this session was to enhance community members' understanding of how the new solar and battery systems would integrate with their existing power systems, particularly with their backup diesel generators. This initiative was crucial to dispelling previous concerns about potential disruptions to their backup power systems. The walkthrough helped to visually illustrate how the new and existing systems would coexist and work together.
2. **Resilience and Power Outage Management:** The session provided valuable insights into the new systems' performance during power outages. It reinforced the fact that the proposed solar and battery systems would not only seamlessly integrate with existing setups but also add a layer of resilience to their power supplies. This information went a long way towards building community confidence in the practicality and reliability of the microgrid project.

3. **Site Feasibility Discussion:** Involving community members in the site assessment process allowed them to see first-hand the considerations taken into account when choosing an installation site. These included discussions about geographical barriers, impact on natural resources, and existing infrastructure. Engaging the community in this manner helped underline the importance of site selection in ensuring efficient system operation.

4. **Addressing Direct Concerns:** The walkthrough offered an excellent opportunity for community members to raise and address specific concerns about the installations. This included questions about the potential impact on the natural environment of the installation sites and assurances that the community's preferences would be respected.

5. **Promoting Engagement and Flexibility:** Throughout the process, community members demonstrated active engagement and flexibility regarding potential installation locations. Their willingness to understand and accommodate the technical requirements of the installation process underscores their commitment to the project.

Presentation of Technology: Physical Structure and ICT

An individual session was organised to introduce the smart solar storage solution manufactured and distributed by the industry partner. This session served as a gathering for key project stakeholders, who were physically present on-site with the customers. The industry partners actively participated in the session through a digital format, ensuring their presence and contribution. The main goal of this session was to provide community members with a comprehensive understanding of the technical system, with a specific focus on the functionality of their digital solution, which includes an app and a web interface. This digital solution offers an efficient way for community members to monitor the real-time performance of their individual rooftop PV and battery systems.

The industry partners led the presentation, providing detailed explanations of the features and capabilities of their digital solution. Following the presentation, a question-and-answer session allowed customers to ask specific questions about their own systems. This experience was further enhanced by providing a live demo of the app for tracking the operation of the rooftop PV and battery system, showcasing how smart meters can be utilised to gain insights into the system's operation, energy usage, and production.

Key outcomes of this session included:

1. **Enhanced Awareness:** The session significantly increased the community members' awareness of the rooftop PV and battery system and its capabilities. They gained a deeper understanding of how the system works, its benefits, and its potential impact on their energy consumption.
2. **Empowered Customers**: Through the session, community members were empowered to take more control over their energy usage. They learned how to leverage the rooftop PV and battery system's digital solution, including the app and web interface, to monitor and optimise their individual solar and battery systems. The community members gave positive feedback about the digital solution provided by the industry partner. The real-time behaviour monitoring of their individual systems via the app and web interface was particularly appreciated, enhancing their understanding of the system's operations.
3. **Increased Transparency**: The session helped increase transparency on how their monitoring systems, specifically smart meters, operate. It also showed how these tools can be used to generate individual value for each customer by providing insights into energy usage and production.
4. **Customisation Options:** Community members discovered the customisation options available with the rooftop PV and battery system. The session also helped increase transparency on how their monitoring systems, specifically smart meters, operate. It also showed how these tools can be used to generate individual value for each customer by providing insights into energy usage and production.

Provision of Individual Load Patterns, Inofrmation and Explanation of New Installations

Similarly, to the two previous capacity-building activities, this activity, provided individual training, information, and engagement with community members. The primary objective was to provide personalised information to community members about their energy usage patterns and the potential functionality of the new solar and battery systems.

The session kicked off with an analysis of each member's historical load data. We used this data to simulate case scenarios showing how the new systems would perform given each member's unique energy consumption patterns. We also shared comprehensive information about the rooftop PV and battery system, including its integration with existing energy infrastructure, potential solar production, and battery storage capabilities. The dialogue evolved around these simulations and the proposed system, leading to meaningful interactions with the community members.

Moreover, by adopting a more interactive and discursive format, the project facilitated a meaningful dialogue that allowed community members to actively participate, ask questions, and explore the potential advantages and challenges associated with the proposed installations.

Key outcomes of this session included:

1. **Addressing Feasibility Concerns:** Despite providing personalized calculations and explanations to address the financial concerns raised by community members, it was evident that some individuals still held reservations about the financial viability of the proposed solar and battery installations. Their concerns primarily centered around potential insufficient returns and the possibility of having to remove the installations after the trial period. The project partners acknowledge these concerns and will take them into consideration during the system design phase to ensure the financial feasibility and viability of the system.
2. **Understanding Tariff Structures:** An important part of the dialogue revolved around tariff structures. For customers on a flat tariff, we addressed their specific limitations and possibilities, particularly relating to the settings for battery charge/discharge. This discussion helped customers understand how tariff structures could impact their use of the new systems and how to optimize their settings for maximum benefits.

3. **Increasing Community Engagement:** The personalised nature of the updates and discussions spurred greater engagement from community members. We observed a positive shift in attitudes, with previously hesitant members showing an increased interest in the microgrid project. This was a crucial outcome, as active engagement from all community members is vital for the project's successful implementation and ongoing operation.

6.4.4 Monitoring and Evaluating

The final step in our community capacity-building approach involves the monitoring and evaluation of capacity-building activities. The effectiveness of these initiatives, both in the short term and long term, is a vital consideration in meeting the community's capacity needs. In the short term, as outlined in the previous sections, we assess the immediate outcomes and feedback from each capacity-building activity. Additionally, ongoing customer trial phone calls have proven instrumental in gathering real-time feedback. This approach allows us to swiftly identify successes and areas that need further attention or adjustment, providing invaluable data for immediate iterative improvements.

Regarding the concerns raised by some community members regarding the financial viability of the system, please note that these concerns have been duly addressed during the session. The project partners have carefully considered and made appropriate adjustments during the system design phase to ensure the financial feasibility of the proposed solution. Furthermore, the presentation included results demonstrating the potential performance of a customer's system under a dynamic tariff, specifically taking into account any concerns related to flat tariff structures.

Moreover, the settings for battery charge and discharge have been adjusted to reflect these considerations. The project partners remain fully committed to ensuring that the new solution does not impose any financial burden during the customer trial. They have actively worked to address the concerns raised by the community members, ensuring that the system is not only financially viable but also beneficial for all participants. These concerted efforts aim to provide an optimised solution that meets the community's energy needs while maximising financial benefits and minimising any potential financial concerns.

Long Term Feedback Loop

Looking to the long term, we aim to extend our monitoring and evaluation measures to capture the sustainability of the capacity-building efforts. There are two primary strategies we have outlined for this extended evaluation:

1. **Analysis of PV and Battery Operation Data:** After the completion of the PV and battery installations, we will conduct individual sessions reviewing the actual operational data of each customer's system. These reviews planned for a few months post-installation, will allow us to assess how each system has performed over an extended period and provide insights into any issues or areas for optimisation.

2. **Follow-up Community Surveys:** To gauge the enduring impact of our capacity-building activities, we plan to conduct another survey to assess the community's knowledge and willingness to continue participating in the project. This survey will take into account factors such as the time and financial commitments community members are willing to make now that they have increased knowledge and trust in the project. Comparing these results with the baseline data from the initial assessment will provide insights into the long-term effectiveness of our capacity-building efforts.

3. **Capacity Reassessment:** It is crucial to periodically reassess the community's social capital post-implementation to determine whether the project design and business model remain effective. Fluctuations in social capital may necessitate alternative strategies and modifications. A repeated capacity assessment can be employed to re-evaluate the social capital index and formulate a revised capacity-development strategy. This reassessment could become a recurring process, such as an annual review, to adapt proactively to the evolving social dynamics within the community.

In addition to these strategies, the project will continue to maintain open lines of communication with the community, primarily through regular phone calls. This method of contact not only serves to update the community on the progress of the project but also provides an additional channel for gathering feedback. By maintaining this continuous dialogue, the project can ensure the community remains informed, involved, and confident in the project's progression.

By implementing these next steps based on the findings and outcomes of the capacity-building activities and assessments, it aim to sustain the momentum of the project, address any operational challenges, and ensure the long-term success and effectiveness of our capacity-building efforts within the community.

6.5 Discussion and Policy Implications

The perception of the community towards the microgrid project can vary depending on the questions we ask and the approach we take, as demonstrated by the case study. Initially, the information about the community seemed promising. The community had positive attitudes towards renewable energy and community microgrid solutions. They also expressed a need for resilience and showed a willingness to host distributed energy resources and participate in the project. However, when the survey and interviews were conducted, multiple barriers to the project became apparent. The community's structure and dynamics posed challenges to the project's success, and some community members were not showing up to local community information sessions. Additionally, some members were interested in the outcome but generally lacked the time to commit to the project.

Further, an interesting finding from the case study was that, in the survey, resilience against outages was identified as the community's number one priority. However, the results also indicated that the community was not willing to pay more for this to happen. On the other hand, the interviews identified that the community might be more positive towards a community microgrid if it removed the dependency on having individual backup diesel generators to protect each business during possible outages. Questions regarding the investment and time needed for these separate backup generators showed that willingness to pay more for resilience was already there. However, a lack of knowledge about the community microgrid restrained the answers due to not fully understanding the possibilities of such as system.

When it comes to community engagement, we also identified technical and physical barriers to possible participation. Given the limited internet connectivity in the town, online webinars were not a viable option for engaging with the community. Therefore, the most effective approach was identified to be in-person meetings with the residents, supplemented with occasional phone calls and email updates to keep them informed. The community also showed a lack of time to participate or engage in a possible microgrid which also affects the ability to participate. Hence, compared to microgrid projects initiated by the community itself or a cooperative community, a project similar to this one might have to find alternative ways to community engagement and participation.

Based on the community capacity assessment, capacity-building activities and outcomes, several recommendations for the design of microgrid policies and processes emerge:

- **Individual Autonomy and Control:** Reflecting the community's preference for individualism, microgrid designs should prioritise individual autonomy and control. Policies should ensure that each household or business has a degree of control over their energy consumption and generation. This could include individual metering and billing, and control over energy storage and consumption patterns.
- **Transparency and Fairness:** Policies must instill fairness and transparency, particularly regarding the distribution of power and cost allocation, especially during outages. These could include clear rules for power sharing during times of scarcity and transparent, usage-based billing mechanisms.
- **Inclusive Decision-Making:** To address concerns about influence in decision-making, policies need to incorporate mechanisms for inclusive and participatory decision-making. This might involve community meetings, consultations, or democratic voting processes on key microgrid decisions.
- **Maintenance and Resource Allocation:** Clear policies and processes need to be outlined for the maintenance and allocation of shared resources. This could include forming partnerships with service providers, establishing community-based maintenance teams, or incorporating maintenance costs into billing mechanisms.

- **Education and Engagement:** Given the technical nature of microgrids, ongoing education and engagement activities should be incorporated into the microgrid's operation. This might include regular information sessions, user-friendly guides and manuals, and open channels for questions and feedback.
- **Flexibility and Scalability:** The microgrid design should be flexible and scalable to accommodate changing community needs, including property sales or the addition of new properties. This could involve modular or scalable design elements and flexible contractual arrangements.
- **Effective Communication Channels:** As indicated by the community's preference for phone calls and in-person visits, the importance of establishing and maintaining effective communication channels cannot be overstated. Regular updates, open dialogue, and easily accessible contact points should be integral components of the microgrid's operational procedures.

6.6 Conclusion

Our investigative approach has delineated pivotal understandings concerning the integration of social structure considerations, technical acumen, and the requisite community capabilities for community microgrids. Engagement on both individual and communal levels has been a cornerstone in delineating the distinctive dynamics critical to the advancement of microgrid projects. The case study of the microgrid project in Australia serves as a referential model, with the gleaned insights offering substantial implications for a wider application.

The tailored interventions, including bespoke presentations, local assessments, and comprehensive dialogues regarding specific energy consumption patterns and technological upgrades, have proven effective in addressing initial community reservations. This has resulted in a paradigm shift towards increased engagement and a refined understanding of the microgrid infrastructure. This case study highlights the necessity for an enduring commitment to capacity building as an iterative process, where short-term gains must be fortified by continuous long-term oversight and reassessment. The ongoing endeavours to enrich community understanding through the analysis of photovoltaic and battery operation data, supplemented by successive community surveys, are reflective of this commitment.

From this analysis, several generalisable conclusions can be drawn:

1. The design phase of microgrid projects should be underpinned by a viable strategy for community engagement, ensuring that the local context and potential for participation are central to the developmental process.

2. The successful implementation of a microgrid necessitates an in-depth appreciation of the prevalent attitudes within the community concerning resource sharing and interpersonal trust, which are critical to collaborative success.

3. Effective capacity-building initiatives ought to prioritise individualised engagement, catering specifically to those who may exhibit reluctance towards group involvement.

4. Recognising the nuanced nature of microgrid implementation outcomes is imperative, as they may only sometimes engender positive community developments, potentially exacerbating existing divisions.

The principles of individual autonomy, transparency, inclusiveness, maintenance, resource allocation, and communication underscore our policy and process formulation recommendations in microgrid design. These principles are integral to fostering a robust and adaptable microgrid project. When these considerations are embedded in microgrid projects' design and implementation phases, they enhance the probability of achieving a successful and sustainable energy solution, as demonstrated in the case study, with potential replication across diverse community settings.

7 Sandboxing Tool for Policy Analysis

Preamble

Overview

In Chapter 7, we translate the theoretical insights from previous chapters into practical tools for policy discussions and decision-making in community microgrids. By synthesising the Social Capital Index (SCI) from Chapter 2 and the Multi-Criteria Decision Analysis (MCDA) framework from Chapter 3, a comprehensive dashboard is introduced to serve as an interactive online platform for communities and stakeholders.

The dashboard systematically evaluates and utilises social capital within communities, starting with determining the SCI through a survey tool that captures structural, cognitive, and relational dimensions. Using the SCI, the dashboard employes the MCDA framework to shortlist feasible business models (BMs) suited to the community's social fabric. This ensured alignment with the community's capacity for engagement and benefit from the microgrid system.

Additionally, the platform provides interactive elements allowing users to adjust weights and parameters, enabling stakeholders to explore various scenarios and understand the impact on BM feasibility. This customisation helps align the models with community expectations and sustainability goals. Further development is planned to enhance the platform's capabilities and usability, ensuring it remains a valuable tool for fostering sustainable and inclusive energy solutions.

7.1 Introduction

The deployment and effectiveness of these community microgrids are heavily influenced by the regulatory and policy environments in which they operate [14], [91], [247]. Policy development for community microgrids involves creating guidelines [32], regulations [184], and incentives that support the integration of renewable energy sources at the community level [258], ensure equitable distribution of energy benefits, and foster community participation in energy governance [38].

Energy regulations vary significantly across countries, reflecting the unique contexts of their electricity systems [14]. In many cases, microgrids are governed under frameworks originally designed for distributed energy resources, which can impose both technical and procedural requirements [237]. For example, interconnection policies in the United States differ by state and often outline detailed criteria for integrating microgrids with the main grid [259], while in Singapore, regulations focus on capacity thresholds and market participation [260]. In Australia, regulatory complexity arises from the interplay between federal and state jurisdictions. Nationally, the National Electricity Law and National Electricity Rules establish foundational requirements such as licensing and registration for microgrids [261]. Remote systems like stand-alone power systems (SAPS) may benefit from tailored provisions, whereas grid-connected microgrids must navigate additional obligations, including registration with the Australian Energy Market Operator (AEMO). State-level rules, such as Victoria's Electricity Industry Act 2000 and related licensing schemes, impose further conditions shaped by the scale and scope of individual projects [262].

These regulatory frameworks also influence decisions around asset ownership and operational models [106]. Microgrid projects must clearly allocate ownership of components like rooftop solar panels, often owned by individual prosumers, versus shared infrastructure such as energy storage or distribution networks, which may fall under the management of a distribution network service provider (DNSP) [263]. Financial arrangements, including tariffs and pricing structures, further depend on early coordination with energy retailers and DNSPs to meet compliance requirements and establish a sustainable economic model [237].

Current energy policies often fall short of addressing the unique needs and potential of community-based energy solutions [106]. Traditional energy regulations are typically designed for large-scale, centralised systems and may not account for community microgrids' decentralised, participatory nature [22]. As such, there is a crucial need for policies that are specifically tailored to promote the development, implementation, and sustainability of community microgrids [256]. These policies must consider local energy needs, community social dynamics, technical capabilities, and economic frameworks to be effective [264].

The previous chapters in this thesis has developed a comprehensive multi-level framework that integrates technical, social, and economic factors influencing community microgrids [148], [195]. While the preceding chapters have explored these elements through detailed academic analysis, this chapter aims to translate these insights into practical policy-making discussions. This involves examining how policies can be structured to support the unique aspects of community microgrids, such as community ownership, collaborative energy management, and local energy market (LEM) integration.

This chapter introduces an online platform designed as an interactive dashboard and sandboxing tool to facilitate translating theoretical research into practical insights. This tool enables policymakers, stakeholders, and communities to gain insight and evaluate the implications and possibilities of their communities' specific social structures. By incorporating the multi-level framework from the thesis, the dashboard enables in-depth discussions of how different policies might impact community microgrid projects in diverse contexts.

This chapter is structured as follows: Section 7.2 summarises key findings on policy implications from previous chapters of this thesis. Section 7.3 presents the platform and its features for an easy understanding of its functionality. In Section 7.4, a discussion on how the dashboard can be used as a sandboxing tool to facilitate policy discussions is provided. Section 7.5 provides the conclusions of this chapter.

7.2 Analysis of Research Findings for Policy Development

In the context of community microgrid implementation, incorporating insights about a community's social fabric into policy discussions is crucial for fostering effective and equitable decision-making. As explored in previous chapters of the thesis, understanding the social dimensions—such as community engagement, equity, and autonomy—is vital for crafting policies that not only achieve technical and financial objectives but also resonate with community values and needs. The complex interplay between technical requirements and social considerations has been a recurring theme. Regulatory frameworks, such as those governing licensing, asset ownership, and operational models, can either support or constrain the implementation of business models that align with community priorities. In Australia, for instance, the intersection of federal and state regulations creates a layered compliance landscape that can impact the viability of decentralised ownership structures or participatory governance models. While such requirements may introduce challenges, they also present opportunities to innovate within policy boundaries.

At the same time, successful microgrid initiatives can influence policy evolution. Demonstrating the benefits of community-oriented approaches, such as increased resilience or equitable energy access, can prompt updates to regulatory frameworks, fostering greater flexibility and inclusivity. This holistic approach ensures that policies do not merely impose solutions but facilitate them in a way that communities feel ownership and agency in the microgrid projects.

Financial strategies, such as the provision of subsidies or innovative financing models like public-private partnerships, must be designed with a clear understanding of the local socio-economic landscape to ensure that they are accessible and fair. This not only enhances the feasibility of microgrids but also helps in garnering broad community support. Moreover, the role of utilities in microgrid development, as highlighted in earlier discussions, illustrates the need for policies that balance professional expertise and infrastructure with community aspirations and sustainability goals. Such policies must pave the way for utilities to support community projects without overshadowing local governance and decision-making processes. Similarly, the need for resilience and emergency preparedness in microgrid planning underscores the importance of considering community-specific vulnerabilities and capacities. Policies crafted with a deep understanding of these aspects can provide more than just energy security; they can enhance community resilience against broader socio-economic shocks.

By integrating these insights from previous discussions, it becomes apparent that successful policy-making in the realm of community microgrids is not just about addressing the present needs but also about anticipating future challenges and opportunities. This approach not only enriches the policy framework but also ensures that microgrid projects are sustainable, inclusive, and aligned with the community's long-term aspirations. The next section will explore the design and functionality of the platform, which plays a crucial role in synthesising and presenting these social insights effectively to stakeholders, thereby supporting enhanced policy discussion and decision-making.

7.3 Platform Design and Functionality

The design and functionality of the Grid4Us platform [265] are central to facilitating a data-driven approach to the planning and implementation of community microgrids. The platform is designed to systematically evaluate and utilise the social capital of communities to optimise the selection of business models for microgrid implementation. Built in Python and available as a web-accessible dashboard, Grid4Us allows users to access and interact with it directly through the web. This section describes the high-level design and functionality.

7.1.1 Core Functionalities

The core functionalities are described below, with the accompanying flowchart in Figure 7.1.

Identification of Social Capital and SCI

The first step in the dashboard's operation involves determining the SCI of a community. This is achieved through the SCI tool that collects and analyses responses to survey questions designed to capture various dimensions of social capital—structural, cognitive, and relational. The SCI is a crucial metric, represented on a scale from 0 to 1, that provides a quantitative basis for subsequent decisions in the microgrid development process.

Generation of Feasible Business Models

Utilising the SCI, the dashboard engages a MCDA framework to shortlist feasible business models (BMs) best suited to the community's social fabric. This step ensures the selected models align with the community’s capacity to engage with and benefit from a microgrid system. The MCDA framework considers multiple factors, including the community’s preference for autonomy, engagement in decision-making, and equity in energy access and costs.

Interactive Decision-Making

To accommodate diverse community goals and needs, the dashboard incorporates interactive elements that allow users to adjust weights and parameters within the decision-making process. This functionality enables stakeholders to explore various scenarios and understand how different settings might impact the feasibility of each business model. By adjusting these parameters, users can align the business models more closely with the community's expectations and sustainability objectives.

The dashboard design integrates considerations of fairness directly into its operational logic. Instead of relying on subjective assessments, fairness is systematically embedded in the decision-making process through the objective metrics of the SCI. This approach ensures that the chosen business models are not only technically feasible and economically viable but also socially equitable, enhancing the likelihood of long-term success and acceptance of the microgrid within the community.

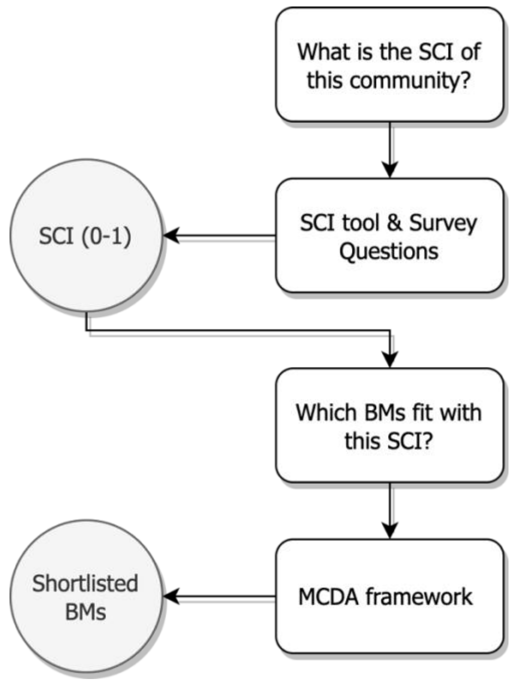


Figure 7.1. Flowchart showing the high-level design of the dashboard.

7.1.2 Dashboard Interface

The first page of the dashboard serves as an introduction (Figure 7.2), welcoming users and providing a brief overview of the tool's purpose and primary functions. This page is many for first-time users to understand the scope and capabilities of the dashboard.

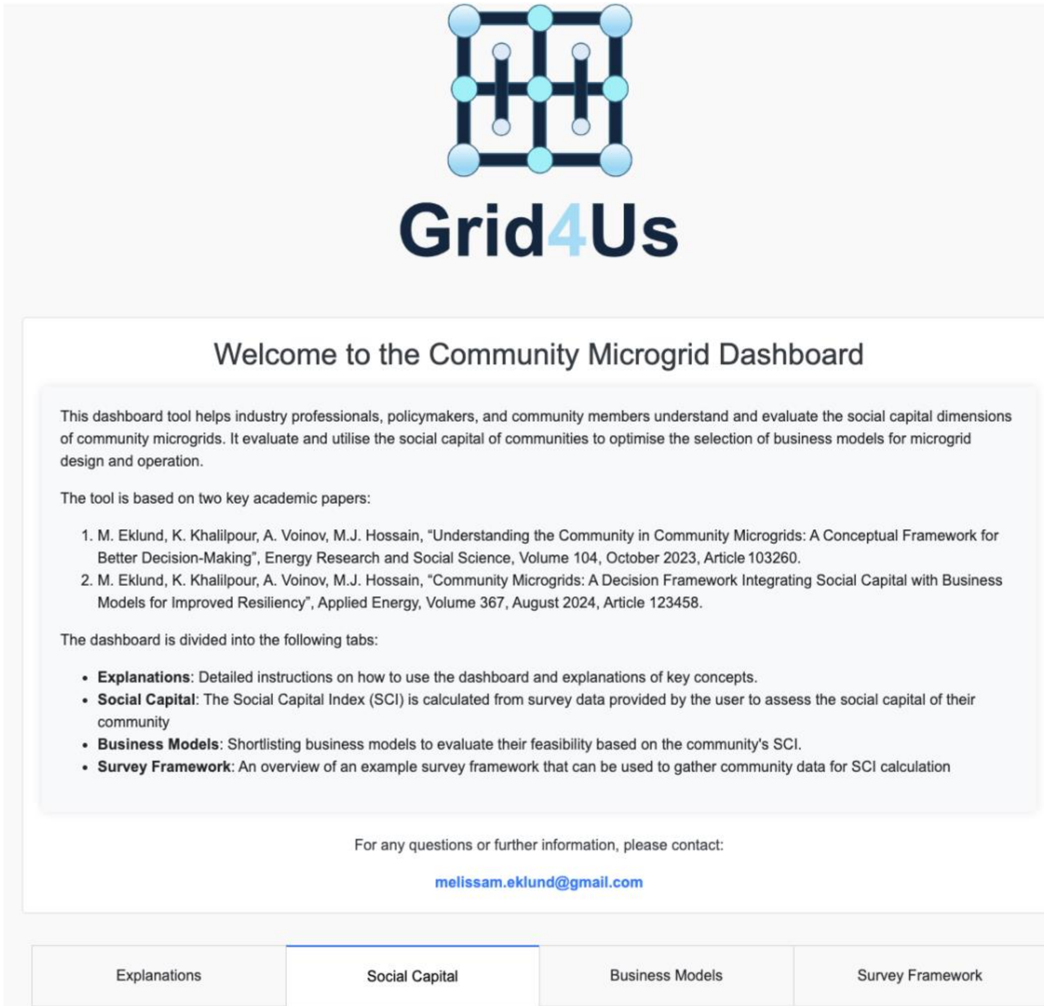


Figure 7.2. The first page of the dashboard provides a short introduction to the user.

Figure 7.3 shows the first tab of the dashboard, which contains detailed instructions and guidelines on how to utilise the dashboard effectively. This tab provides in-depth explanations of the functionalities described in the Core Functionalities section. It illustrates how users can navigate the various features and inputs to customise the analysis according to their needs.

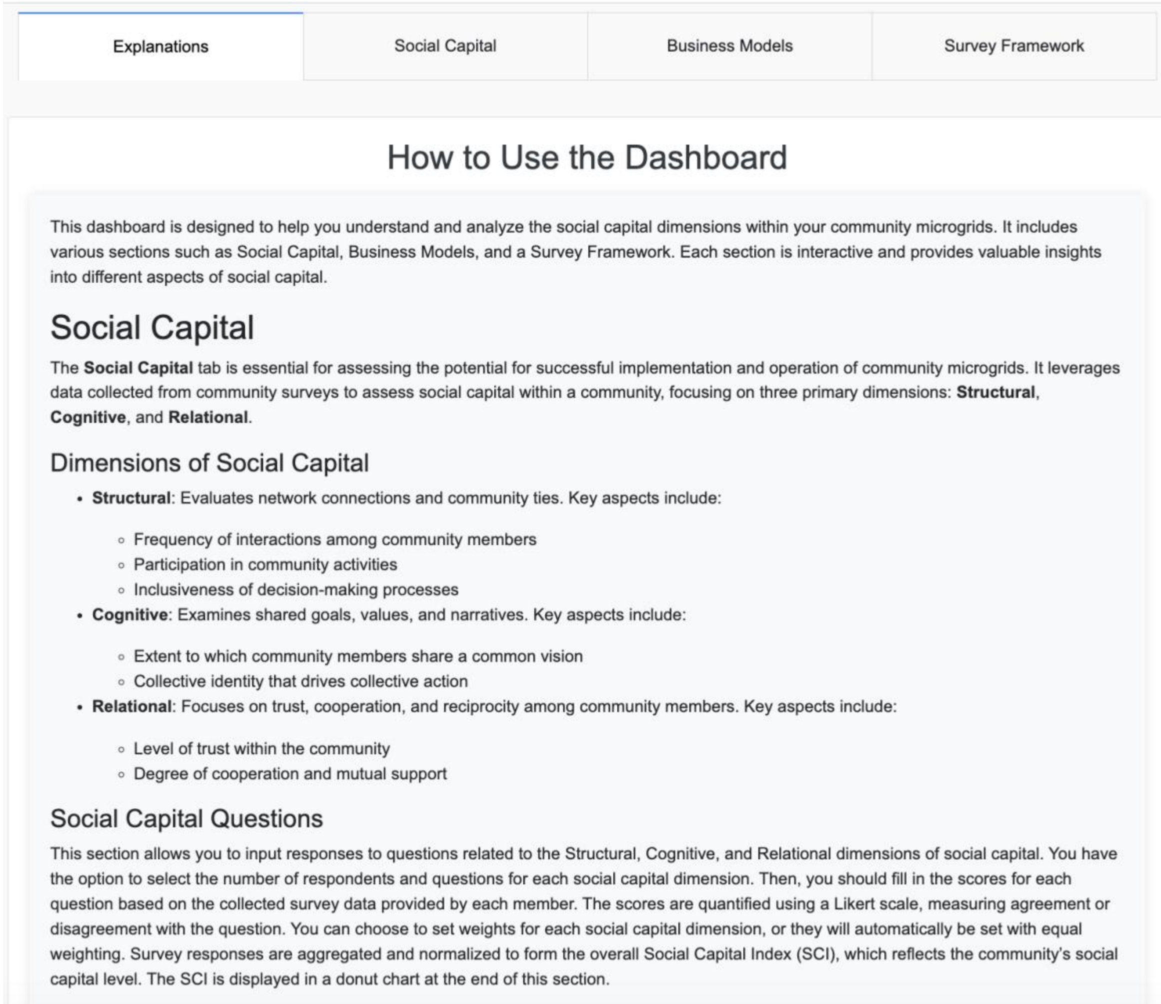


Figure 7.3. The first tab of the dashboard with detailed information on how the tool is designed and how to use it.

The second tab of the dashboard (Figure 7.4) enables users to calculate the SCI for their community by choosing one of three input methods based on their preference: a generic option, a base case, or selecting specific questions. The generic option allows users to create their own survey tailored to their community, offering customisation and flexibility for various purposes, with a layout featuring "Question n: Detail n.". Users can select the number of questions to include for each social capital dimension and the number of respondents in their community and optionally include weights. The base case option provides prefilled values by clicking the blue button, utilising an example survey framework provided in the last tab (Figure 7.8), without the need to select the number of respondents. The third method, selecting specific questions, is similar to the generic option but allows users to choose specific questions from a drop-down list for each dimension and specify the number of questions to include. Users then select the number of respondents before filling in the results from their data collection, with the option to add weights. Lastly, once all questions are filled in, the SCI will be displayed at the end of the page of this tab, as depicted in Figure 7.5.

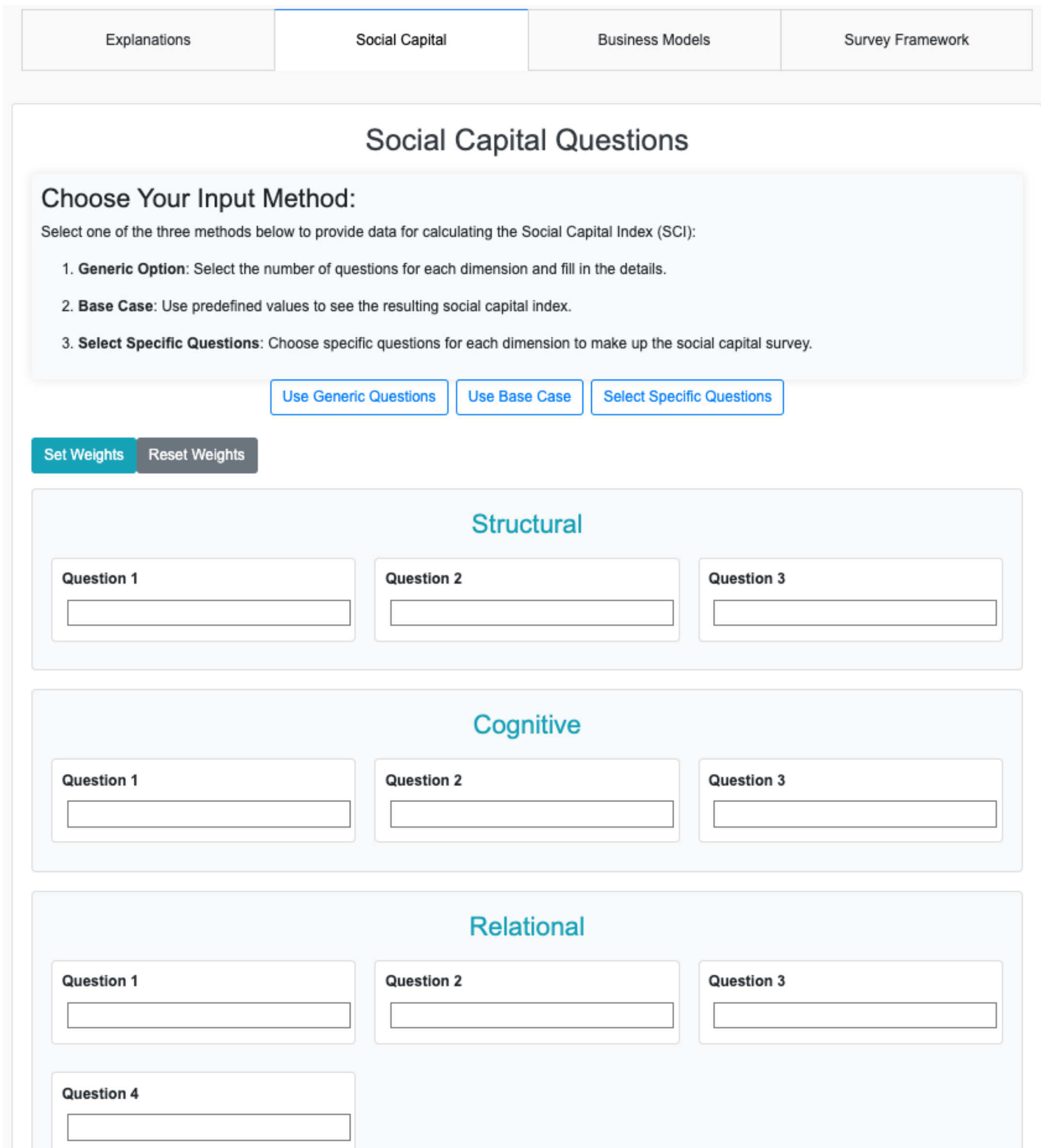


Figure 7.4. The second tab of the dashboard calculates the SCI and allows the user to customise their input based on their specific survey and community. There is also an option “Use Base Case” for users not wishing to provide survey data.

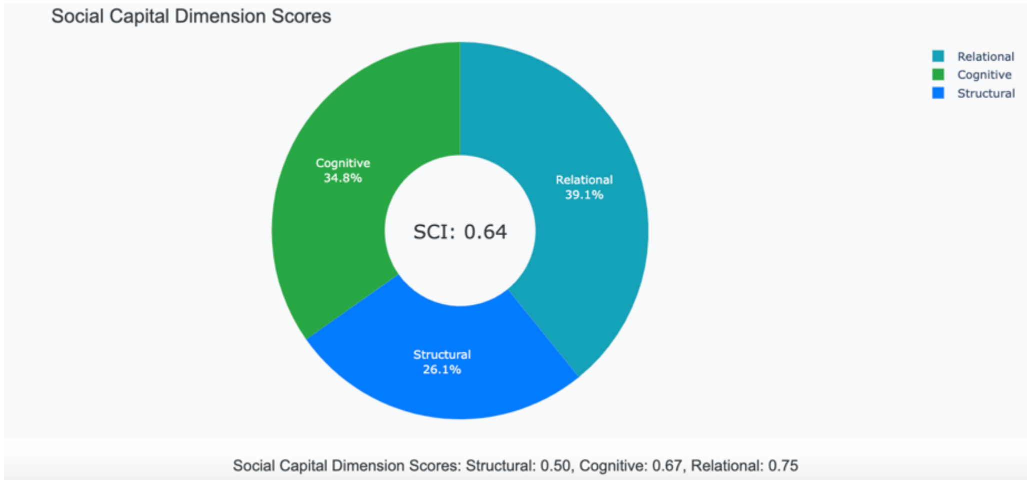
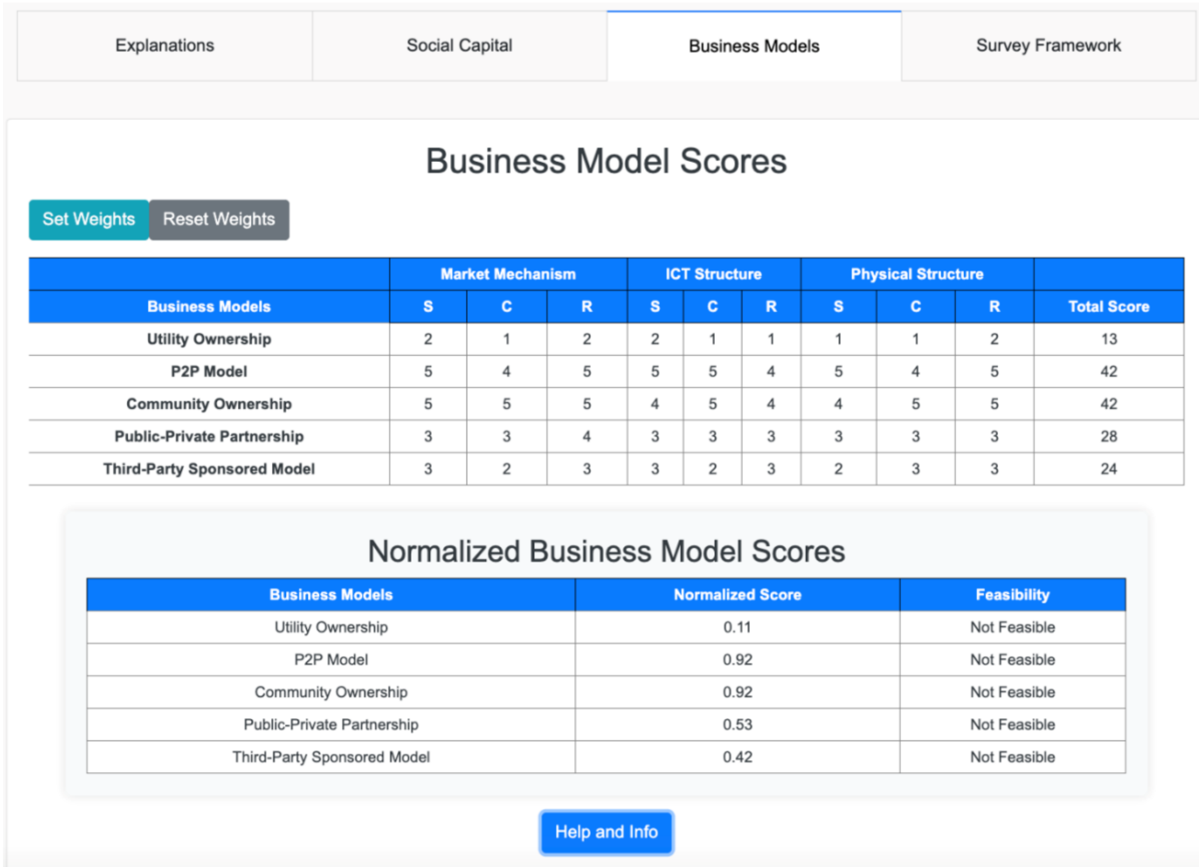


Figure 7.5. At the end of the second tab, the result of the SCI will be presented in a donut chart, which the user can export as a figure.

After the SCI has been calculated, the third tab (Figure 7.6) will shortlist the feasible BMs. The first table in this tab shows the MCDA matrix with prefilled scores and equal weighting of all dimensions (Structural, Cognitive and Relational) and categories (market mechanism, ICT structure and physical structure). However, the user can change these scores directly by clicking on the table. The user can also choose to change the weights similarly to the Social Capital tab by clicking on the set weights button and reset the weights by clicking the reset weights button. Additionally, the second table shows the normalised scores of each BM and which BM is feasible or not feasible according to the community's SCI. A help and info button is added at the end of this tab to provide further information to the user. This button provides more detailed information on the different BMs and the logic behind this tab.



	Market Mechanism			ICT Structure			Physical Structure			
Business Models	S	C	R	S	C	R	S	C	R	Total Score
Utility Ownership	2	1	2	2	1	1	1	1	2	13
P2P Model	5	4	5	5	5	4	5	4	5	42
Community Ownership	5	5	5	4	5	4	4	5	5	42
Public-Private Partnership	3	3	4	3	3	3	3	3	3	28
Third-Party Sponsored Model	3	2	3	3	2	3	2	3	3	24

Business Models	Normalized Score	Feasibility
Utility Ownership	0.11	Not Feasible
P2P Model	0.92	Not Feasible
Community Ownership	0.92	Not Feasible
Public-Private Partnership	0.53	Not Feasible
Third-Party Sponsored Model	0.42	Not Feasible

Figure 7.6. The third tab in the dashboard is where BMs are shortlisted based on their feasibility connected to the community's specific SCI.

The last tab of the dashboard (Figure 7.7) provides information on how to conduct an example to collect data needed for the SCI calculation. It gives the user a survey framework that can be used as a guide or directly as it is.

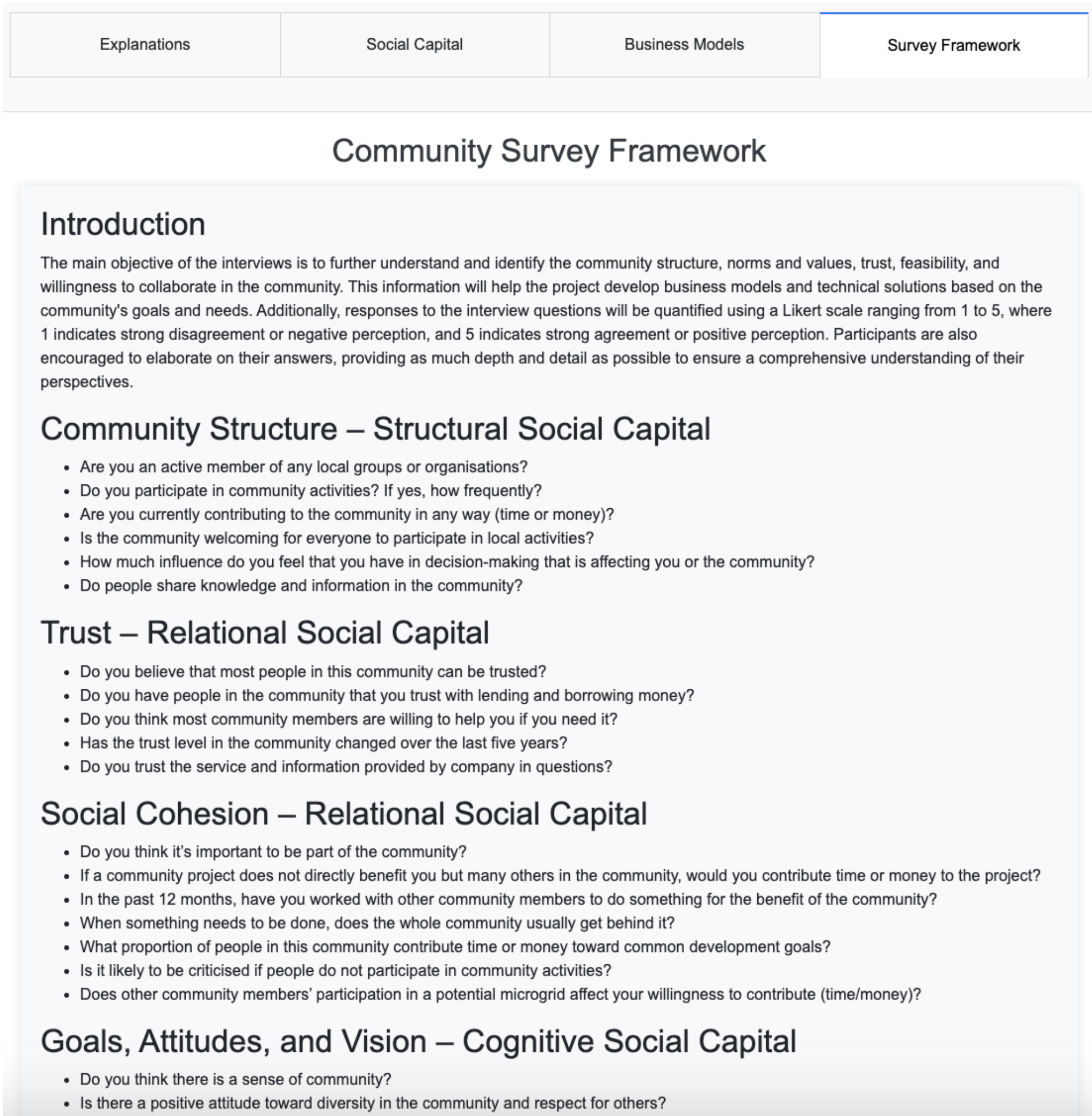


Figure 7.7. The last tab in the dashboard provides an example survey framework.

7.4 Application of the Dashboard as A Sandboxing Tool

As presented in the previous section, the dashboard is designed to facilitate policy discussion among stakeholders, communities, and industry by providing a data-driven, customisable approach to understanding and evaluating the potential of community microgrids. A discussion on how each of the main features of the dashboard can be leveraged as a sandboxing tool is provided in the subsections below.

7.1.3 Identifying Social Capital

By evaluating the social capital within a community (structural, cognitive, and relational dimensions), this tool allows the user to identify strengths and gaps in community cohesion and involvement. This data can inform discussions on how to enhance community engagement in energy projects. Further, understanding where the community stands in terms of social capital can help tailor educational and outreach programs that address specific needs, improving the likelihood of successful microgrid implementation. Consequently, targeted interventions can more easily be designed and developed.

7.1.4 Shortlisting Feasbile Business Models

By shortlisting business models that align with the community's social capital levels, the tool helps the user to consider the most viable economic and operational structures for their microgrid project. This facilitates more grounded and realistic policy formulations tailored to each community's unique characteristics. Users can use the interactive elements of the dashboard to simulate different scenarios based on varying weights and inputs, allowing for a dynamic discussion of potential outcomes and strategies.

7.1.5 Interacive Elemetens for Customisation

The ability to adjust weights and inputs according to specific community profiles or policy goals makes the tool highly interactive and engaging for different users. This encourages active participation, such as community and stakeholder engagement, in the planning process and ensures that diverse viewpoints can be considered. As new data becomes available or as community priorities shift, the tool's flexibility allows for quick adaptations, making it a valuable asset for ongoing policy evaluation and revision.

7.1.6 Visualisation and Communication of Results

The visual outputs, like the donut chart for SCI and the table shortlisting feasible business models, provide a clear, concise way to communicate complex data, making it easier for users to discuss and make informed decisions. The ability to export results as figures supports the creation of compelling presentations and detailed reports that can influence policy decisions and funding allocations. It also acts as a communication tool by allowing users to document and share their scenarios and outcomes. This can be particularly useful for policy advocacy, enabling stakeholders to present concrete scenarios to support their positions or proposals. Additionally, it can help in communicating the rationale behind certain decisions to the broader community, ensuring that all members are informed and involved.

7.1.7 Summary

By systematically assessing the factors critical to microgrid success, this tool can inform more comprehensive policy development that supports sustainable community microgrids, incorporating considerations of social dynamics alongside technical and economic factors. Further, providing a transparent mechanism for communities to see how user input affects potential business models can increase trust and buy-in, crucial elements for the success of community-focused initiatives. In summary, this tool can help with:

- Data-driven discussion
- Targeted interventions
- Customised solutions
- Scenario analysis
- Community and stakeholder engagement
- Policy adaptation and development

7.5 Conclusions

The developed dashboard offers a robust platform for integrating qualitative quantitative assessments with policy discussions, enhancing the decision-making process by grounding it in empirical data and community-specific insights. This can significantly contribute to more effective and sustainable discussions on energy policies. By utilising this tool, users can increase the feasibility of the microgrid design and operation, which would have a higher chance of being optimal for the given community. The sustainability of the community microgrid's survival and use, compared to the change of behaviour when it's already being built and decided how to divide resources. Hence, fairness aspects are already integrated into the decision and design phase of microgrid development as the social capital of the community has been integrated as a decision factor.

Future updates for this platform will focus on enhancing user experience by implementing more user-friendly features, such as expanding the data input methods and providing options for using the platform as a direct survey tool. This will include offering login access for stakeholders in charge and survey participants, thereby increasing the tool's versatility. While the current version of the tool is not designed to extract data from users, future iterations will explore this functionality, carefully considering ethical implications related to data collection and privacy. Data integrity and ethical handling will be paramount as the platform evolves to track potential trends and usage across stakeholders and projects.

The primary purpose of the platform will continue to be to serve as an enabler for various stakeholders to implement theoretical groundwork for individualisation and customisation of microgrids. Future enhancements aim to increase the platform’s usability, provide deeper insights, and empower more effective decision-making processes.

8 Conclusion and Future Research

This chapter draws conclusions from this research and provides answers to the research questions posed at the beginning of the thesis in Chapter 1. It concludes by offering recommendations for future research.

8.1 Overview of Findings

Throughout the thesis, social capital theory [63] was employed to provide an overall theoretical framework for understanding social factors in community microgrids, with the main concepts and theories introduced in Chapter 2. With its foundation in operational research, Multi-Criteria Decision Analysis (MCDA) [181] was employed in Chapter 3 to further process qualitative and quantitative knowledge from the findings in Chapter 2. Optimisation [266] and engineering techniques [53] were applied in Chapters 4 and 5 to further expand on the findings from Chapter 3. Furthermore, Chapter 5 incorporated energy justice theory [66] to enhance fairness analysis [207], utilising the methodology developed in Chapter 4. Subsequently, capacity-building theory [245] was introduced and applied in Chapter 6 to develop a cohesive strategy for the frameworks and tools established in previous Chapters. Finally, Chapter 7 introduced a dashboard tool to facilitate the practical application for different stakeholders. The findings can be summarised as follows:

Chapter 2 explored the crucial role of social context in the effectiveness of community microgrids and identified that current studies focus predominantly on isolated social factors rather than the comprehensive social fabric of communities. To address this, a theoretical-conceptual framework rooted in Social Capital Theory (SCT) was developed, which considered the structural, cognitive and relational dimensions of social capital in the planning and design of community microgrids.

The research highlighted several key community characteristics that determine community microgrids' engagement and successful operationalisation. These characteristics are integral to understanding how different dimensions of social capital influence community capability and the type of microgrid system adopted. A qualitative review of diverse studies gained key insights into the social processes, resources, and characteristics that shape community engagement with microgrids. These insights inspired the development of a novel conceptual framework that facilitates a holistic understanding of community dynamics. The framework classifies communities based on their social capabilities, which are critical in their interaction with microgrids. This direct integration of social capital considerations into the design and operation processes of community microgrids represents an innovative approach to designing and managing these systems. Further, a practical tool was developed to operationalise this framework, designed to assess social factors in communities effectively and quantitatively. This tool integrates hierarchical scales and detailed indicators based on the established framework of the World Bank, creating a tailored Social Capital Index (SCI) for community microgrids. It systematically evaluates unique social factors within communities, providing a nuanced understanding of various community types. This refined perspective facilitates more informed decision-making in the design and planning of community microgrids.

Lastly, the findings stress the need to advocate for integrating social capital considerations into the design and operation of community microgrids. Overall, this chapter contributed significantly to understanding the impact of social structures and dynamics on the success of community microgrids, offering valuable insights for practitioners and researchers in the field.

Chapters 3 to 5 explored and applied the social capital concept in selecting optimal business models for community microgrids. This was an attempt to understand how community behaviour is influenced by different business models, which shape the design and operation of the microgrid, ultimately affecting its overall performance.

Chapter 3 identified and analysed the synergy between BM components (ownership, revenue/pricing, activities and value proposition) and the corresponding market mechanism, infrastructure and ICT frameworks. Based on this understanding and evaluation of previous frameworks, a decision-support framework that delivers practical recommendations for selecting the most appropriate business models for community microgrids with respect to the community's social capital was developed.

This study revealed the intricate interplay between the technological, economic, and social dimensions inherent in community microgrids. Each business model presents a unique combination of physical structure, ICT infrastructure, and market mechanisms, reflecting distinct operational characteristics, engagement strategies, and regulatory environments. These components evolve over time and are influenced by technological advancements, market dynamics, regulatory shifts, and changes in community needs and preferences. Importantly, a successful business model must be resilient and adaptable, capable of balancing multiple, often conflicting objectives and constraints.

To integrate the complex relationships between BM components and LEMs, the framework was based on MCDA techniques to structure and synthesise the interrelations. The SCI developed in Chapter 2 was utilised as an evaluation element within the MCDA framework to guide the selection of business models and to directly incorporate the community social fabric as a focus in the decision-making process of the design and operation of the microgrid.

Lastly, the framework's robustness was illustrated through a case study, which served primarily as a decision-support tool rather than a guarantee for optimal model selection. The findings underscore how the framework provides a shortlist of business models that are more likely to be feasible and potentially optimal for the community, considering the community's initial social capital and the complex socio-technical dynamics inherent to community energy systems.

Chapter 4 further explored how to refine the selection of optimal BM for community microgrids based on their social capital and the findings in Chapter 3. An optimisation approach and a Mixed-Integer Linear Programming (MILP) model were developed to construct an integrated method for further processing and evaluating the set of shortlisted BMs based on the community's social capital. While previous research has extensively developed and applied various methodologies for computer-based models, most of these have concentrated on techno-economic design, operation, and analysis. Although some studies have incorporated and focused on social aspects, they often treat social factors in a narrow and individualistic manner, lacking a comprehensive integration and analysis of the overall community behaviour and social fabric.

In contrast, the methodology introduced in this chapter thus focuses on optimising the operation of the microgrid while considering social capital. A set of Key Performance Indicators (KPIs) were introduced to assess the impact of the community social capital post-optimisation. This nuanced approach explored the complex interplay between business models and social capital, demonstrating the relationship between community members and the microgrid design and operation. Although the integrated methodology presented in this chapter did not evaluate the long-term effects of social capital on the community, it offered a short-term, one-year evaluation that could be extended to a longer term. Additionally, the analytical framework developed goes beyond traditional quantitative approaches by incorporating KPIs highlighting qualitative dimensions of community energy initiatives. This holistic evaluation ensures that business models meet technical and financial criteria and align with the social structures they operate within.

Lastly, the findings suggest a paradigm shift from individualistic strategies to collective energy practices, highlighting the dual nature of shared energy benefits as both unifying and potentially disincentivising for personal investments in self-generation. This chapter contributes significantly to understanding how to embed and assess social factors in the operation of community microgrids. It demonstrates that while certain business models, particularly those emphasising interactive mechanisms, can significantly enhance social capital and align with community sustainability goals, the relationship between individual and collective interests is complex.

Chapter 5 expanded the findings from Chapter 4 and broadened the analysis to encompass a wider array of tariff structures. Utilising and expanding the integrated methodology from Chapter 4, this chapter focused on fairness discussion for different tariffs and business models. The findings underscore the importance of carefully designing tariff structures and selecting appropriate business models to promote fairness and social capital in community microgrids. The analysis revealed that combining different business models and tariff structures significantly influences social behaviour and the operation of the physical microgrid. Hence, it impacts the perception of fairness opportunities and outcomes.

By incorporating social capital considerations into the design and assessment of community microgrids, diverse community perspectives are more effectively acknowledged, leading to outcomes perceived as fairer and more acceptable. Policymakers and community leaders should consider these insights to foster more equitable and sustainable energy systems. By aligning tariff designs with the unique characteristics of their communities, they may enhance both operational efficiency and fairness perceptions, ultimately contributing to the success and resilience of community microgrids.

Chapter 6 built upon the frameworks and methodologies developed in Chapters 2 through 5. It proposed strategies to leverage and enhance social capital for successful implementation and sustainability community microgrid projects. An interactive approach with four integrative stages was outlined based on community capacity-building theory. Each stage was conceptually developed to build upon the preceding one, beginning with operationalising the conceptual framework presented in Chapter 2 and calculating the SCI of a specific community to provide a foundation for community capacity assessment. The subsequent stage outlined a capacity-development plan that utilised this assessment to formulate strategies for designing and operating the microgrid alongside engagement strategies and capacity-building activities.

The implementation of this plan was further explored and discussed conceptually, offering preliminary insights for industry professionals and policymakers on potential practical applications, emphasising stakeholder and community engagement. The final stage involved evaluation, emphasising that social capital is dynamic rather than static. Therefore, the SCI should be reassessed regularly to re-evaluate the business model and, consequently, the design and operation of the microgrid to accurately reflect the current state of social capital within the community.

Additionally, the findings from this chapter highlight the potential value of integrating social structure considerations with technical expertise and community capabilities. While the proposed strategies provide a conceptual foundation, their application requires further exploration. Preliminary insights suggest that engagement strategies at both individual and communal levels are sometimes essential in advancing microgrid projects. Overall, this chapter underscores the importance of incorporating a structured approach to community engagement when designing microgrid projects. Success in these projects depends on understanding community attitudes towards resource sharing and trust. Effective capacity-building initiatives should focus on individual engagement, especially for those hesitant to participate in group activities. Recognising the complexity of microgrid implementation outcomes is vital, as they can sometimes deepen existing community divisions rather than alleviate them.

Chapter 7 explored the policy implications of the frameworks and methodologies developed in previous chapters, culminating in creating a online platform designed as a dashboard and sandbox tool for policy discussions. While the platform serves as a preliminary link between the research findings and their potential application in real-world policy contexts, its practical implementation and validation remain open for future research. Through the sandboxing approach, users can conceptually explore potential challenges and opportunities, ensuring that the policies developed are robust, inclusive, and aligned with the overarching goals of sustainable and resilient community energy systems.

Moreover, this platform was not developed to be a static solution; it enables stakeholders to customise and further develop their own projects tailored to the unique needs of their communities. Consequently, it provides users with a preliminary framework to explore how empirical data and community-specific insights could inform decision-making and policy development. However, the platform's effectiveness in achieving these goals requires further testing to ensure its adaptability and relevance to diverse community policy scenarios.

Lastly, the platform has the capability of allowing data collection from actual applications in various communities. This capability enables future data collection and analysis, even if this thesis did not directly test the tool across multiple communities. However, it is important to note that no data collection will commence until all ethical considerations and applications have been thoroughly addressed and investigated. This ensures that the process adheres to the highest ethical standards, prioritising the well-being and privacy of the communities involved.

8.2 Research Contributions

The conceptual framework for Community Microgrid Development (CMD) presented in this thesis integrates a series of innovative frameworks and tools designed to address the socio-technical aspects of community microgrid projects. This framework is underpinned by the Social Capital Framework for identifying community types through the SCI encompassing several key levels of analysis and methodologies.

8.2.1 Scientific Contributions

The CMD framework (Figure 8.1) introduces novel methodologies and approaches to identify, analyse, and incorporate social aspects into the decision-making and development processes of community microgrids. This includes leveraging social capital theory and surveys to convert qualitative community knowledge into structured, processed data. This data then feeds into an MCDA framework, which identifies key elements in different BMs to evaluate the most suitable BM for communities with varying social capital levels. The next level involves utilising feasible BMs as input for an optimisation model that optimises operations according to the rules of different BMs, determining the most optimal BM based on specific community social capital levels. Finally, a capacity-building strategy is developed using the accumulated information to design a plan for increasing and monitoring social capital in the community post-implementation. Through a systematic approach, this framework aims to enhance community social capital and sustainability in the long term.

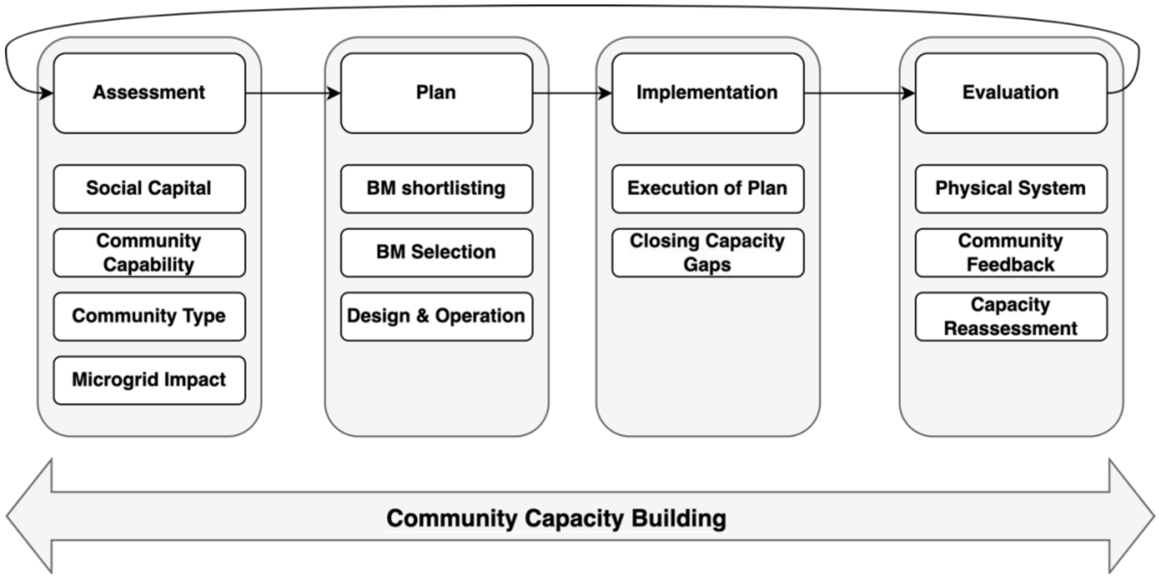


Figure 8.1. The conceptual framework for Community Microgrid Development (CMD).

8.2.2 Practical Contributions and Long-Term Impact

The frameworks and tools presented in this thesis are developed to empower various stakeholders, including communities, industry professionals, and policymakers, by providing practical resources and insights. The research demonstrates how different community types can impact and are impacted by various design and operational strategies. The creation of a freely available policy dashboard is a key contribution. This tool enhances local energy systems and promotes community engagement by offering tailored guidance based on specific community data. Stakeholders and communities can leverage this dashboard to understand socio-technical complexities, ensuring their solutions are technically sound and socially acceptable. Policymakers can use the dashboard and related tools to craft supportive, evidence-based policies that foster sustainable community microgrids.

Additionally, the findings of this thesis offer practical insights and tools that communities, industry professionals, and policymakers can use to develop and refine their systems and decision-making processes. The provided guidelines and educational resources can be customised and adapted for various contexts, enhancing the frameworks' and tools' scalability and adaptability. This comprehensive approach ensures that the frameworks remain relevant and effective across diverse applications, promoting the long-term sustainability and resilience of community microgrids.

8.3 Future Research and Recommendations

It is important to note that the primary aim of this research was to develop frameworks and tools that serve as enablers for communities, industry, and policymakers. While the work provides foundational frameworks and methodologies, it was not within the scope to conduct extensive validation or customisation across diverse contexts. Therefore, future research should focus on these aspects, leveraging these frameworks as a basis for further exploration and adaptation to individual community microgrid cases.

Future research should aim to further validate the frameworks and methodologies proposed in this thesis through extensive applications in real-world case studies. In particular, the conceptual strategies for capacity building (RQ10) and the actionable policy recommendations (RQ11) require practical implementation and empirical testing to assess their effectives and scalability. This would not only test the robustness of the developed frameworks but also provide practical insights and further refinement. By examining a diverse array of community microgrid projects, researchers can assess the applicability and adaptability of the proposed frameworks to various social, economic, and geographical contexts.

Additionally, future research should reflect on how the frameworks and tools developed in this thesis could be scaled to larger communities or applied across multiple regions. Social capital, as a critical component of this research, is highly dependent on community size and dynamics. Larger communities may exhibit more complex social structures, distributed decision-making processes, and variations in social cohesion, all of which could influence the applicability of the SCI and related frameworks. Investigating how these frameworks respond to scale—both in terms of larger populations and regional expansions—would provide valuable insights into their adaptability. Researchers should explore whether the indicators for structural, relational, and cognitive dimensions of social capital require adjustments in larger or more diverse settings and how decision-making processes shift at scale.

Specifically, future work could focus on:

1. **Comprehensive Case Studies**: Implementing and analysing the frameworks in different community microgrid settings to validate their effectiveness. This includes diverse community types, sizes, and socio-economic backgrounds, which would provide a more holistic understanding of the frameworks' applicability and adaptability.

2. **Customisation and Adaptation**: Exploring how the frameworks can be customised to meet the specific needs of individual communities. This involves tailoring the SCI and the decision-support tools to reflect unique social dynamics, cultural aspects, and community goals, ensuring that the solutions are not only technically viable but also socially sustainable.

3. **Longitudinal Studies**: Conducting long-term studies to evaluate the impact of community microgrids on social capital over time. This would involve periodic reassessment of the SCI and continuous monitoring of the community's engagement and satisfaction with the microgrid, providing valuable data on the long-term sustainability and social benefits of these projects.

4. **Technological Innovations**: Exploring the role of emerging technologies, such as blockchain and artificial intelligence, in enhancing the decision-making process and operational efficiency of community microgrids. These technologies could provide more accurate data analysis, improve transparency, and foster greater community participation and trust.

5. **Scalability and Replicability**: Examining the scalability of the proposed frameworks to larger microgrid projects and their replicability in different regions and countries. This would involve testing the frameworks in various contexts to understand the challenges and opportunities in scaling up community microgrid initiatives.

By focusing on these areas, future research can provide deeper insights and practical guidance for enabling communities, industry, and policymakers to effectively design, implement, and sustain community microgrids that are socially inclusive and technically robust.

Appendices

Appendix A

Table A. Constants and parameters for all BM scenarios

Notation	Description
α	Parameter that adjusts the weight of TRS
β	Weight factor for the QS relative to the TRS
$C^{bill,new}$	The community's current electricity bill
$C_i^{bill,new}$	Member *i*'s current electricity bill
$C^{bill,old}$	The community's electricity bill from the previous year
$C_i^{bill,old}$	Member *i*'s electricity bill from the previous year
C_t^{grid}	Cost of imported energy from the main grid at time *t*
C^{invest}	The community's the annual investment cost in DERs
C_i^{invest}	Member *i*'s annual investment cost in DERs
C_t^{mixed}	Mixed tariff in the microgrid at time *t*
C^{rev}	Total revenue of the microgrid
C^{shared}	Cost of shared electricity within the microgrid
$C^{savings}$	Total cost savings of the community
$C_i^{savings}$	Total cost savings of member *i*
DoD	Minimum depth of charge allowed for the batteries in the microgrid
E_i^{exp}	Member *i*'s total electricity export
E_i^{imp}	Member *i*'s total electricity import
E_i^{self}	Member *i*'s total self-consumption
FIT_t	Feed-in Tariff at time *t* for energy exported to the main grid
i	Index of member of set N
$L_{i,t}$	Load of member *i* at time *t*
L_t^{total}	Total load of the community at time *t*
M	A large constant used for Big-M method
η_{charge}	Charging efficiency of batteries in the microgrid
$\eta_{discharge}$	Discharging efficiency of batteries in the microgrid
R_i	Member *i*'s individual reimbursement
$S_{,i,t}$	Shared or traded energy by member *i* at time *t*
t	Time-step index of set T
TRS	Timing relevance score for member *i*
QoS_i	Quality of sharing factor for member *i*
QS_i	Quantity score for member *i*
γ_i	Member *i*'s proportional contribution to the microgrid
λ_i^{exp}	Member *i*'s export contribution
λ_i^{import}	Member *i*'s contribution from the reversed import ratio
λ_i^{self}	Member *i*'s self-consumption contribution

Table B. Decision variables for each BM scenario

Notation	**Description**	**BM A**	**BM B**	**BM C**
$B_{i,t}$	Capacity of member *i*'s battery at time *t*	√	√	√
$Bat_{i,t}^{charge}$	Battery charged by member *i* at time *t*	√	√	√
$Bat_{i,t}^{discharge}$	Battery discharged by member *i* at time *t*	√	√	√
$Bat_{i,t}^{discharge,exp}$	Battery discharged by member *i* at time *t* to be exported for either P2P trading or to community manager for either shared energy or export to main grid	-	√	√
$Bat_{i,t}^{discharge,self}$	Battery discharge for self-consumption of member *i* at time *t*	-	√	√
$Bat_{i,t}^{status}$	Binary variable indicating the operational mode of member *i*'s battery (charging/discharging) at time *t*	√	√	√
$\exp\_imp_{i,t}$	Binary variable indicating if member *i* is exporting or importing energy at time *t*	-	√	√
$G_{i,t}^{export}$	Total energy exported to the main grid by member i at time *t*	√	√	-
$G_{i,t}^{import}$	Total energy imported from the main grid by member *i* at time *t*	√	√	-
G_{t}^{export}	Total energy exported to the main grid by the community at time *t*	-	-	√
G_{t}^{import}	Total energy imported from the main grid by the community at time *t*	-	-	√
$PV_{i,t}^{export}$	PV generation from member *i* for export to the main grid at time *t*	-	√	√
$PV_{i,t}^{gen}$	Energy produced by member *i*'s PV system at time *t*	√	√	√
$PV_{i,t}^{self}$	PV self-consumption by member *i* at time *t*	√	√	√
$PV_{i,t}^{trade}$	Surplus PV energy available from member *i* for trading within the community at time *t*	-	√	-
$P_{i,t}^{net,export}$	Net energy exported to the community microgrid by member *i* at time *t*	-	-	√
$P_{i,t}^{net,import}$	Net energy imported from the community microgrid by member *i* at time *t*	-	-	√
$P_{i,j,t}^{trade}$	Energy traded by member *i* to member *j* at time *t*	-	√	-
$SOC_{i,t}$	State of charge of member *i*'s battery at time *t*	√	√	√
S_t	Amount of energy shared among community members at time *t*	-	-	√

Appendix B

Community Interview Framework

Introduction

The main objective of the interviews is to further understand and identify the community structure, norms and values, trust, feasibility, and willingness to collaborate in the community. This information will help the project develop business models and technical solutions based on the community's goals and needs. Additionally, responses to the interview questions will be quantified using a Likert scale ranging from 1 to 5, where 1 indicates strong disagreement or negative perception, and 5 indicates strong agreement or positive perception. Participants are also encouraged to elaborate on their answers, providing as much depth and detail as possible to ensure a comprehensive understanding of their perspectives.

Each interview session will take approximately 30 minutes. The researcher will maintain the confidentiality of the research records or data.

Community Structure – Structural Social Capital

1. Are you an active member of any local groups or organisations?
2. Do you participate in community activities? If yes, how frequently?
3. Are you currently contributing to the community in any way (time or money)?
4. Is the community welcoming for everyone to participate in local activities?
5. How much influence do you feel that you have in decision-making that is affecting you or the community?
6. Do people share knowledge and information in the community?

Trust – Relational Social Capital

7. Do you believe that most people in this community can be trusted?
8. Do you have people in the community that you trust with lending and borrowing money?
9. Do you think most community members are willing to help you if you need it?
10. Has the trust level in the community changed over the last five years?
11. Do you trust the service and information provided by company in questions?

Social Cohesion – Relational Social Capital

12. Do you think it's important to be part of the community?
13. If a community project does not directly benefit you but many others in the community, would you contribute time or money to the project?

14. In the past 12 months, have you worked with other community members to do something for the benefit of the community?
15. When something needs to be done, does the whole community usually get behind it?
16. What proportion of people in this community contribute time or money toward common development goals?
17. Is it likely to be criticised if people do not participate in community activities?
18. Does other community members' participation in a potential microgrid affect your willingness to contribute (time/money)?

Goals, attitudes, and vision – Cognitive Social Capital

19. Do you think there is a sense of community?
20. Is there a positive attitude toward diversity in the community and respect for others?
21. Do people share the same vision for the community's future? For example, do you believe a community microgrid is desirable (long and short term)?
22. Do people agree on priorities in the community? For example, resilience and minimising outages have been reported as priorities by the community. What does this mean for you, and would it mean that you prioritise it to pay extra to achieve this?
23. If you were part of a community microgrid, would you think it's fair that that level of engagement could result in different benefits for individual members? For example, economic benefits or physical installations of DERs (provided by the company in question) for lowering energy consumption, flexible energy usage or electricity contributed to the microgrid?
    i) Do you think it is better to have everything monetised so that everybody knows what was contributed or taken by whom? Or are you OK to have some common pool of resources that do not have to be always accounted for in $?
    ii) Do you think that if something is in common use, they will be more likely to use it? Do you think people will care for community property or try to use it as much as possible if it is free?
24. General attitudes on energy sources and renewable energy. For example, differences in installing PV, using local resources such as hydro, and focusing on non-renewables.
    i) How open are you to the project scope changing from solar to alternative options that may be more suitable?
    ii) How motivated are you to continue your involvement with the project, and how could we help with this (Communication, frequency etc.)?

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