



Evaluating the interplay of community behaviour and microgrid design through optimisation modelling in local energy markets

Melissa Eklund^{a,*}, Alexey Voinov^b, M.J. Hossain^a, Kaveh Khalilpour^a

^a Faculty of Engineering and IT, University of Technology Sydney, Australia

^b Faculty of Engineering Technology, University of Twente, the Netherlands

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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.

1. Introduction

The design and operation of community microgrids represent a vital nexus between technological innovation and social dynamics [1], intricately woven together through the mechanisms of market design and the regulatory frameworks that govern energy transactions and power flows [2]. The technological framework of a community microgrid includes key components such as Distributed Energy Resources (DERs) [3] like photovoltaic (PV) panels, energy storage systems (ESS) [4], a microgrid control centre [5], and connections to the main grid [6] (Fig. 1). This setup enables the microgrid to manage energy flows efficiently, balancing supply and demand within the community [5]. In this framework, consumers and prosumers (members who both produce and consume energy) play distinct roles [7]. Prosumers generate excess energy, which can be shared or sold within the community, while consumers primarily draw energy from the grid or local sources [7]. Standalone DERs and ESS contribute to energy resilience and efficiency by providing localised generation and storage capabilities [8]. The microgrid operates through sophisticated communication and control systems that coordinate energy flows, manage grid connections, and

ensure reliability [9]. The microgrid control centre oversees these operations [6], implementing strategies to optimise energy distribution and integrating with the broader grid as needed [6].

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 [10,11]. This balance is crucial, as the rules laid out by market design profoundly impact community behaviour [12], influencing everything from energy consumption habits to the collective pursuit of sustainability goals [13]. 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 [14]. 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 [15]. Similarly, the Isle of Eigg microgrid in Scotland achieved energy autonomy by integrating renewable energy sources with community-driven initiatives [16], addressing technical challenges while fostering ownership and participation [17].

* Corresponding author.

E-mail address: melissamikaela eklund@student.uts.edu.au (M. Eklund).

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Nomenclature	
Abbreviations	
BMA	Business Model Archetypes
BM	Business Model
CAPEX	Capital Expenditure
CSS	Collective Self-Sufficiency
DER	Distributed Energy Resource
ESS	Energy Storage System
KPI	Key Performance Indicator
LEM	Local Energy Market
MILP	Mixed-Integer Linear Programming
P2P	Peer-to-Peer
PV	Photovoltaic
SCI	Social Capital Index
SCS	Self-Consumption vs Sharing
ToU	Time of Use
Notation	
α	Parameter that adjusts the weight of TRS
β	Weight factor for the QS relative to the TRS
$B_{i,t}$	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
$Bat_{i,t}^{discharge,self}$	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
$C^{bill,new}$	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_t^{exp}	Member i 's total electricity export
E_t^{imp}	Member i 's total electricity import
E_i^{self}	Member i 's total self-consumption
$exp_imp_{i,t}$	Binary variable indicating if member i is exporting or importing energy at time t
FIT_t	Feed-in Tariff at time t for energy exported to the main grid
$G_{i,t}^{export}$	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
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
$PV_{i,t}^{export}$	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
R_i	Member i 's individual reimbursement
$S_{i,t}$	Shared or traded energy by member i at time t
S_t	Energy shared among community members at time t
$SOC_{i,t}$	State of charge of member i 's battery at time t
t	Time-step index of set T
TRS_i	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

Navigating this complex interdependency requires a deep understanding of both microgrid systems' technical underpinnings and the community's social dimensions [18]. The challenge intensifies when attempting to encapsulate these social aspects within computer-based models, which are pivotal for planning, analysing, and optimising microgrid operations [19]. Traditional computational models excel at processing the quantitative data related to physical infrastructures and energy markets [20]. However, integrating the qualitative aspects of community behaviour and social dynamics into these models presents a unique set of challenges [19,21]. Wolsink [14] 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. [19] and Dall-Orsoletta [22] 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-Orsoletta et al. [22] highlights the critical importance of considering factors such as geographical resolution, time horizon and methodological approaches when incorporating social aspects. Additionally, Lazdins and Mutule [23] 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 [24]. In the realm of optimisation, a body of work [4,25,26], including Suk et al. [27], Casalicchio et al. [28] others are pivotal. Suk et al. [27] 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. [28], 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. [29], 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 [30, 31]. Gjorgievski et al. [31], 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 [31]. Although the study acknowledges individual inputs, it falls short of delving into the complexities of social behaviour. Conversely, Moradi and Ghazizadeh [32] present a game-theory energy-sharing model within a residential microgrid that does consider individual social

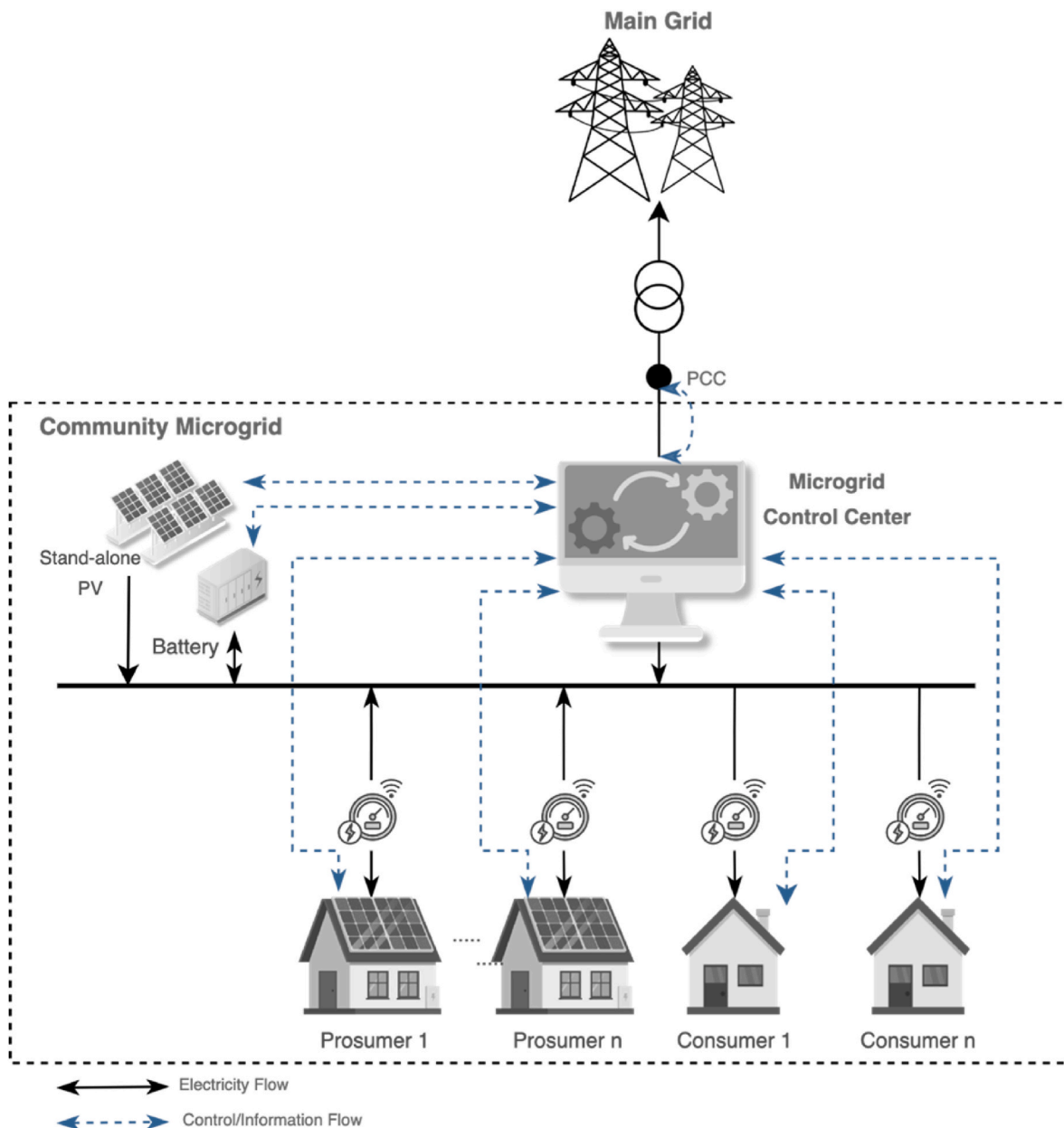


Fig. 1. Example structure of a community microgrid.

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 [33], emerges as a particularly promising tool for incorporating the social and behavioural dimensions into the analysis [32]. Notably, Paredes et al. [34] 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 [19,35]. The literature points to a predominant focus on the technical and economic optimisation of microgrids, with a tendency to marginalise the social parameters [36]. This has been noted by scholars who call attention to the scant integration of social objectives and community participation in microgrid design and planning [11,13,37].

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. [38], we utilise a set of BM archetypes that are informed by a community's Social Capital Index (SCI) as established in Ref. [39]. 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. Such an approach 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 2 details the methodology behind the development of the framework: optimisation

model and post-analysis. Section 3 presents an experimental case study for comparison of different BM scenarios. Section 4 provides the results and discussion of the case study. The paper concludes with Section 5, summarising our findings and proposing directions for future research.

2. Methodology

This section outlines the methodology used to compare various BM scenarios within the framework of a community microgrid, detailing the general characteristics and structure of the model. As depicted in Fig. 2, the method design incorporates the SCI developed by Ref. [39] to aid in selecting BMs, which subsequently influences the configuration of the LEM as elucidated in Ref. [38]. 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 BM. 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 BM from those previously presented. This, in turn, refines the understanding of the community's SCI.

2.1. BM scenarios

We have adapted the assessment framework for social behaviour and the selection of BMs from previous studies [38,39]. Specifically, Eklund et al. [38] 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 Ref. [39]. 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 social capital levels. 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 Fig. 3.

- BM A: Third-Party Ownership Model, where there is no energy sharing, and DERs may be owned by either the members or the utility.
- BM B: Centralised Peer-to-Peer (P2P) Model - System-determined energy trading amongst members.
- BM C - Community-Owned Model with bill-sharing, which adopts a cooperative approach 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 PV systems and batteries. For this paper, only the electricity consumption of the households is considered, and the heating demand is not included. 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, though this paper does not cover the communication protocols between the community manager and these markets. Detailed explanations and operational details of these models are provided in the following subsections, 2.2.1 to 2.2.3, which are dedicated to articulating the varied

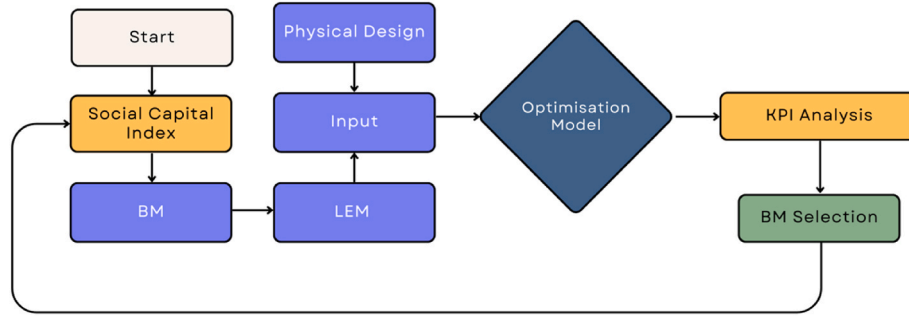


Fig. 2. Model design framework introduced in this study.

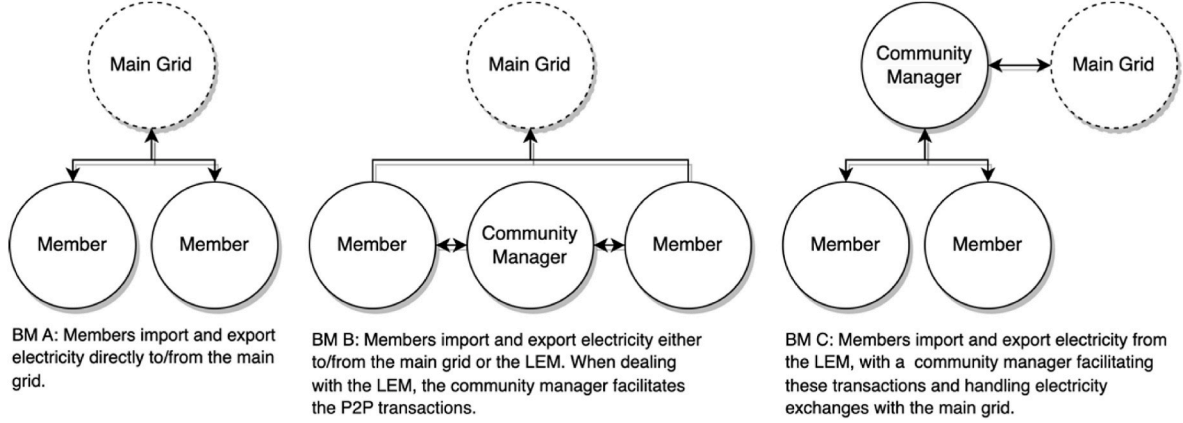


Fig. 3. Overview of three BM scenarios considered for the community microgrid.

structures and functional frameworks of each model within the community microgrid setting.

2.2. General model formulation

Our 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 our 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. The model formulation was facilitated by the PuLP package, an open-source linear programming library in Python. To solve these problems, we integrated the Gurobi optimiser [40], acclaimed for its capability to efficiently handle MILP challenges, which was essential for the intricate and expansive nature of microgrid optimisation tasks.

The specific decision variables for each BM scenario are detailed in Table 1, which provides a comprehensive overview to support the understanding of the model formulation and the subsequent equations.

2.2.1. BM 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 (\$/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 supplier. 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:

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

Where:

Z = Total cost of electricity for the community

i = Index of community members set N

t = Time-step index of set T .

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

C_t^{grid} = Cost per unit purchased electricity from the retailer at time t

FIT_t : Feed-In Tariff for electricity exported back to the retailer 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.

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

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

Where:

$PV_{i,t}^{\text{self}}$ = PV self-consumption by member i at time t

$Bat_{i,t}^{\text{discharge}}$ = Power discharged from member i 's battery at time t

$Bat_{i,t}^{\text{charge}}$ = Power charged by PV to the battery by member i at time t

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

Table 1
Decision variables for each BM scenario.

Notation	Description	BM	BM	BM
		A	B	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	Energy shared among community members 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

Equations (4) and (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 [41]. 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 ($Bat_{i,t}^{status} = 0$), Equation (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 ($t = 0$):

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

For subsequent periods ($t > 0$):

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

$$SOC_{i,t} \leq B_{i,t} \quad (6)$$

$$SOC_{i,t} \geq B_{i,t} \cdot DoD \quad (7)$$

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

$$Bat_{i,t}^{discharge} \leq M \cdot Bat_{i,t}^{status} \quad (9)$$

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 charging and discharging processes

DoD = Depth of Discharge limit

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

2.2.2. BM B: Centralised Peer-to-peer model

Similar to BM A, community members own individual 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 \$/kWh per unit. A community manager is designated to orchestrate trades between members 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 transactions 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, 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 interaction with the main grid as the primary financial consideration.

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

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 power 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 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 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.

$$PV_{i,t}^{self} - Bat_{i,t}^{discharge.self} + G_{i,t}^{import} + \sum_j P_{trade,j,i,t} = L_{i,t} \quad (11)$$

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

The battery storage constraints capturing the charging and discharging processes are equivalent to Equations (4)–(9) in BM A. However, to

account for the battery's capability to discharge for both self-consumption and trading, a new constraint is introduced in BM B. 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.

$$Bat_{i,t}^{discharge} = Bat_{i,t}^{discharge.self} + Bat_{i,t}^{discharge.exp} \quad (13)$$

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.

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

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.

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

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

2.2.3. BM C: community-owned model and bill sharing

For this scenario, 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 the 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 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 grid electricity purchases, costs for energy shared within the community, and revenues generated from electricity exported to the grid. Equations (18) and (19) delineate the interactions between the community microgrid and the main grid or retailer. These interactions are designed to accurately reflect the import of electricity to satisfy demand, the export of surplus generation, and the management of the shared energy pool.

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

$$\sum_{i=1}^N P_{i,t}^{net.export} = S_t + G_t^{export} \quad (18)$$

$$G_t^{import} = \sum_{i=1}^N P_{i,t}^{net.import} - S_t \quad (19)$$

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 power 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, $P_{net.import,i,t}$, which represents the power that each member imports from the community microgrid, as opposed to direct grid imports 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.

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

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 procured both from the main grid and from 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 electricity for consumers integrates various tariffs applicable to different sources of energy. 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.

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

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 \$/kWh for battery and PV. These rates are computed based on the capital expenditure and operational lifespan of each member's energy-producing assets. The selected tariff is, however, set below the cost of importing electricity from the main grid. 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}).

$$\gamma_i = \frac{\lambda_i^{exp} + \lambda_i^{self} + \lambda_i^{imp}}{N} \quad (22)$$

$$R_i = \frac{\gamma_i}{\sum \gamma_i} \bullet C^{rev} \quad (23)$$

2.3. Key Performance Indicators (KPIs)

Understanding the importance of social capital in the successful operation and adoption of the community microgrid is critical [39]. 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 2 presents a summary of these KPIs, and a detailed explanation is provided below.

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.

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

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.

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

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).

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

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.

$$NET = \frac{E_i^{imp}}{E_i^{exp}} \quad (27)$$

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 .

$$SCS = \frac{E_i^{self}}{E_i^{export}} \quad (28)$$

KPI - 6 - Self-sufficiency: 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.

$$SS = \frac{E_i^{self}}{L_i^{total}} \quad (29)$$

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)–(33):

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

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

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

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

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.

Table 2

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.

$Max(QoS)$ = Highest QoS score among all members.

To link the KPIs to the evaluation of social capital post-BM implementation, we utilise the conceptual framework linking social capital to the impact on the microgrid design developed in Ref. [39]. 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 3.

3. Case study

We conducted an experimental case study for a small hypothetical community of size residential households to perform a comparative analysis of the three previously introduced BM scenarios, with the focus of evaluating their dynamics, economic viability, and operational feasibility for a community microgrid. Load profiles were derived from the open-access dataset from Ausgrid [42], while PV generation profiles were generated through the NASA Merra-2 meteorological database [43] 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. Fig. 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 and 5.

Table 3
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
KPI 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

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's 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 covers an entire year with 1-h 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.

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. The costs associated with the PV and batteries are provided in Table 5, where the CAPEX includes possible rebates. Table 6 lists the specific capacities for each installation along with the annual investment cost for each member. 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 [25].

In this case study, all scenarios utilise a consistent ToU pricing strategy, with rates set at \$0.13/kWh for the off-peak period, \$0.21 A/kWh for the shoulder period, and A\$0.53/kWh for the peak period. Additionally, BM B and BM 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 [45]. 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. Results and discussion

In this section, we commence by providing 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.

4.1. 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 7. 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.

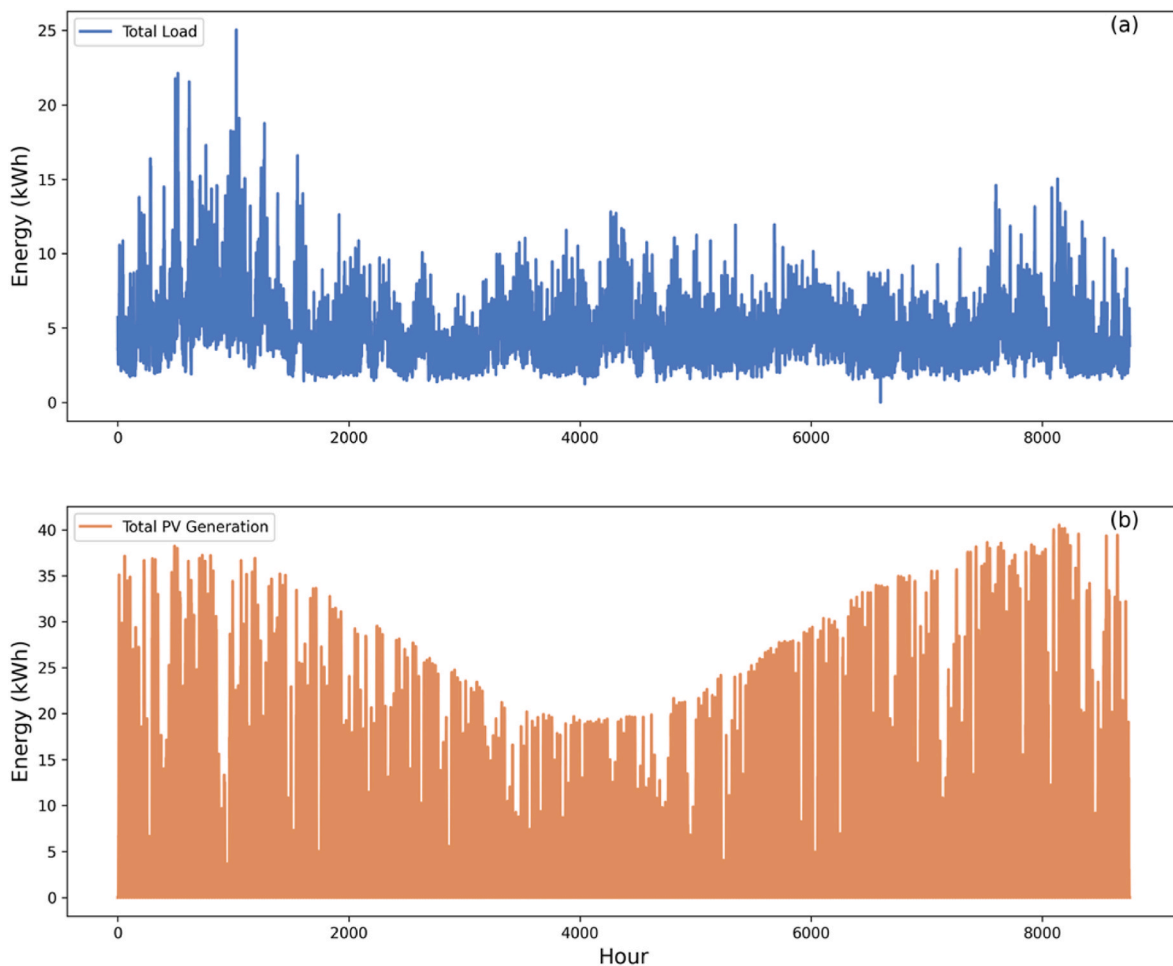


Fig. 4. Total load (a) and total PV generation (b) of the community over one year (January to December, hourly resolution).

Table 4

The annual electricity load and electricity bill for each member of the community microgrid with no community 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 5

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

	PV system	Battery	Reference
CAPEX (A\$/kW Capacity for PV, A\$/kWh Capacity for Battery)	900	1300	[44]
Planning period (years)	20	20	[25]

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, Fig. 5 illustrates the disparity between member-specific KPIs across all scenarios, highlighting the individual contributions to the microgrid’s collective goals. Meanwhile, Fig. 6 shows how the same KPI results are distributed across

Table 6

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

Table 7

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	Member	KIP 3	KIP 4	KPI5	KPI 6	KPI 7
A	0.55	0.53	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	0.65	0.6	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	0.62	0.6	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

all scenarios through a boxplot.

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's important to note that any scenario could serve this purpose to provide a tangible representation of KPI 7 findings. The heatmap in Fig. 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 Fig. 7 that member 3 contributes the most during the evening and often peak period. 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.

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.

4.2. Scenario BM A

In this scenario, members are dependent on the main grid and private 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 Fig. 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 7, the quality of sharing, is not applicable here since there is no sharing mechanism in place in BM A.

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. Fig. 9 shows varied levels of P2P engagement suggest 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.

- 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. Scenario BM C

The overall difference in the model lies in the introduction of shared energy among community members and the energy pool concept, which provides additional flexibility and cost efficiency to the community. The cost of shared energy and energy from the main grid is now included in the objective function, which takes into account not only individual members' energy usage but also their interactions with each other and with the main grid.

As seen in Fig. 10, while grid dependence 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 raises questions about the equity of the sharing mechanism.

- KPI 1 reveals the highest total cost savings, suggesting that communal ownership is the most 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.

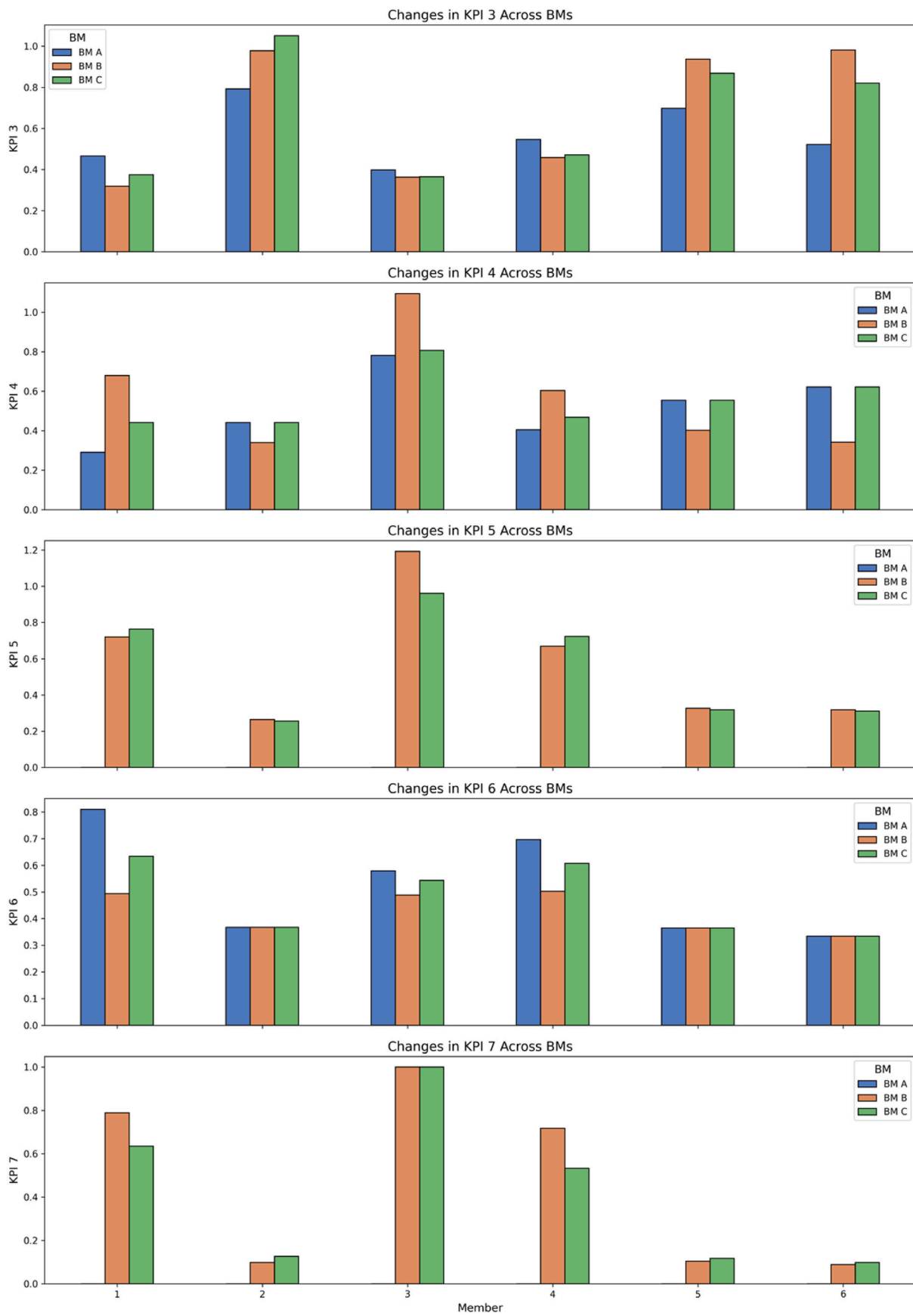


Fig. 5. Comparison of member specific KPIs (KPI 3 total cost savings per member, KPI 4 import/export ratio per member KPI 5 self-consumption vs trading/sharing ratio, KPI 6 self-sufficiency and KPI 7 quality of sharing) between scenario BM A, BM B and BM C.

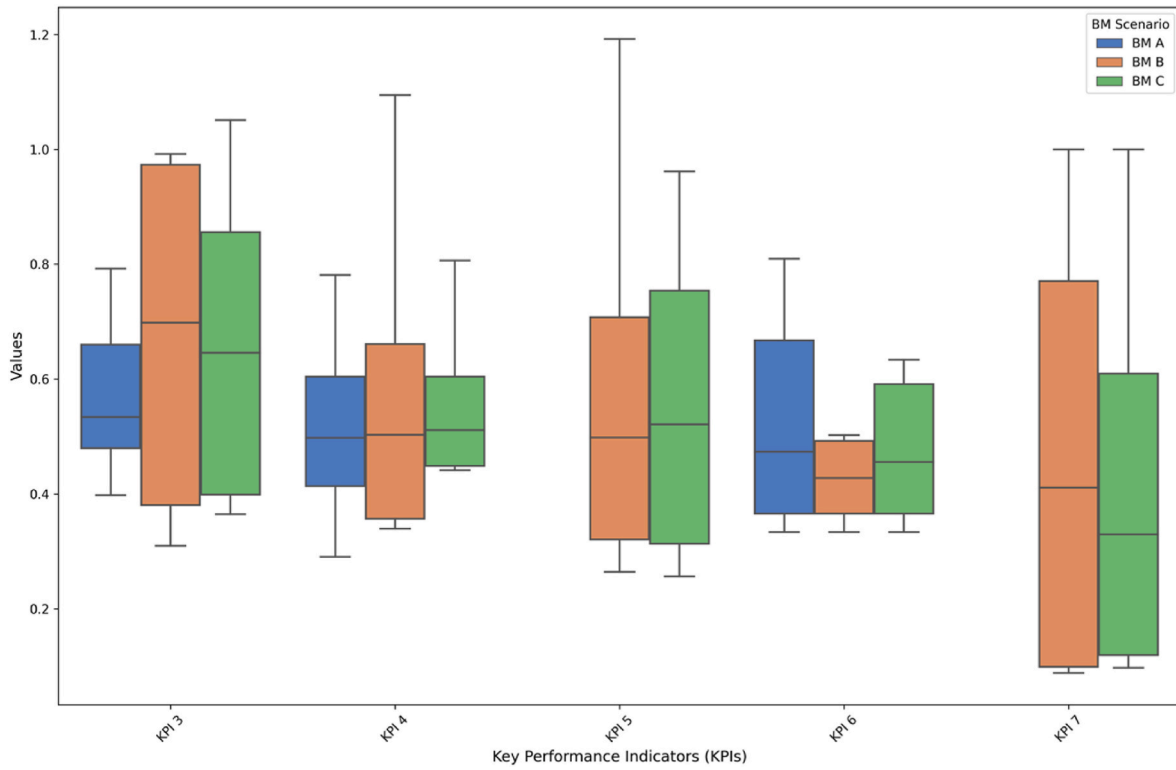


Fig. 6. Comparison of member specific KPIs (KPI 3 total cost savings per member, KPI 4 import/export ratio per member, KPI 5 self-consumption vs trading/sharing ratio, KPI5 self-sufficiency and KPI 7 quality of sharing) across scenarios BM A, BM B and BM C.

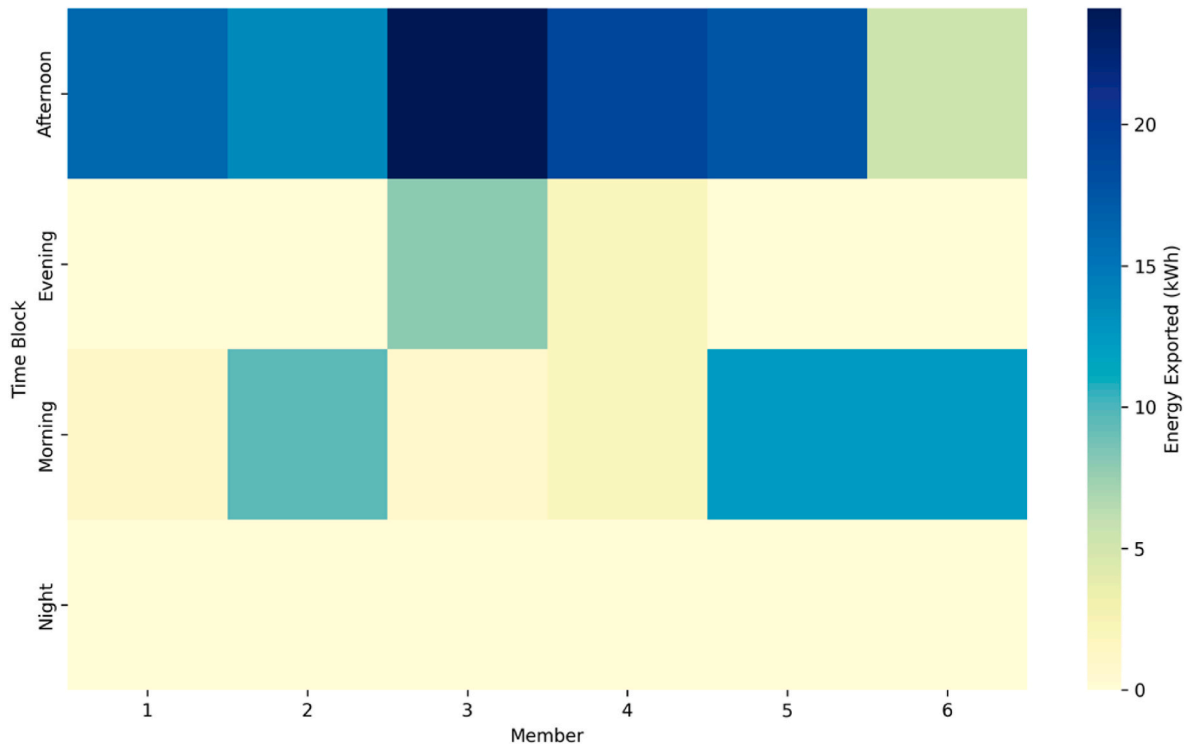


Fig. 7. Energy export by member across time blocks for BM C.

- 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

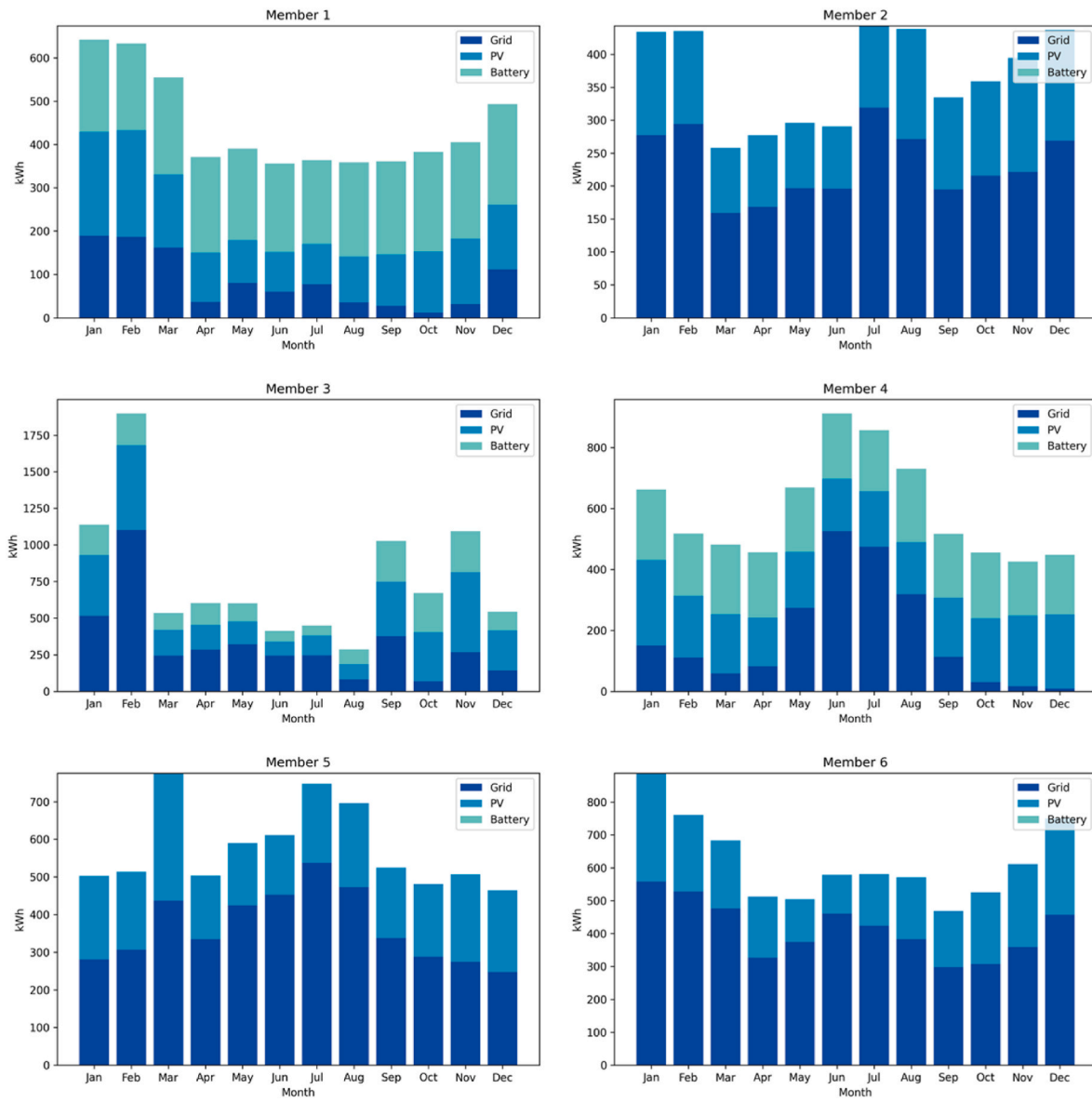


Fig. 8. Breakdown of how each member’s energy demand is satisfied during BM A.

interdependence among community members, which are central aspects of social capital.

4.5. Implications on social capital

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

4.5.1. KPI 1: total cost savings - structural dimension

BM C, showing the highest total cost savings, validates the efficacy of the community-owned 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.

4.5.2. KPI 2: collective self-sufficiency- structural and cognitive dimensions

The self-sufficiency seen in BM C illustrates a community’s ability to meet its energy needs, which likely bolsters a shared sense of identity and collaboration toward shared sustainability goals. In BM B, the moderate self-sufficiency indicates some level of collective capability but may not engender as strong a community identity as BM C. BM A, with the least self-sufficiency, may contribute least to this aspect of social capital.

4.5.3. KPI 3: individual cost savings - cognitive and relational dimensions

Individual cost savings, especially prominent in BM C, can strengthen members’ belief in the fairness and effectiveness of the microgrid, potentially increasing community engagement and cooperation. BM B presents 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.

4.5.4. 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-

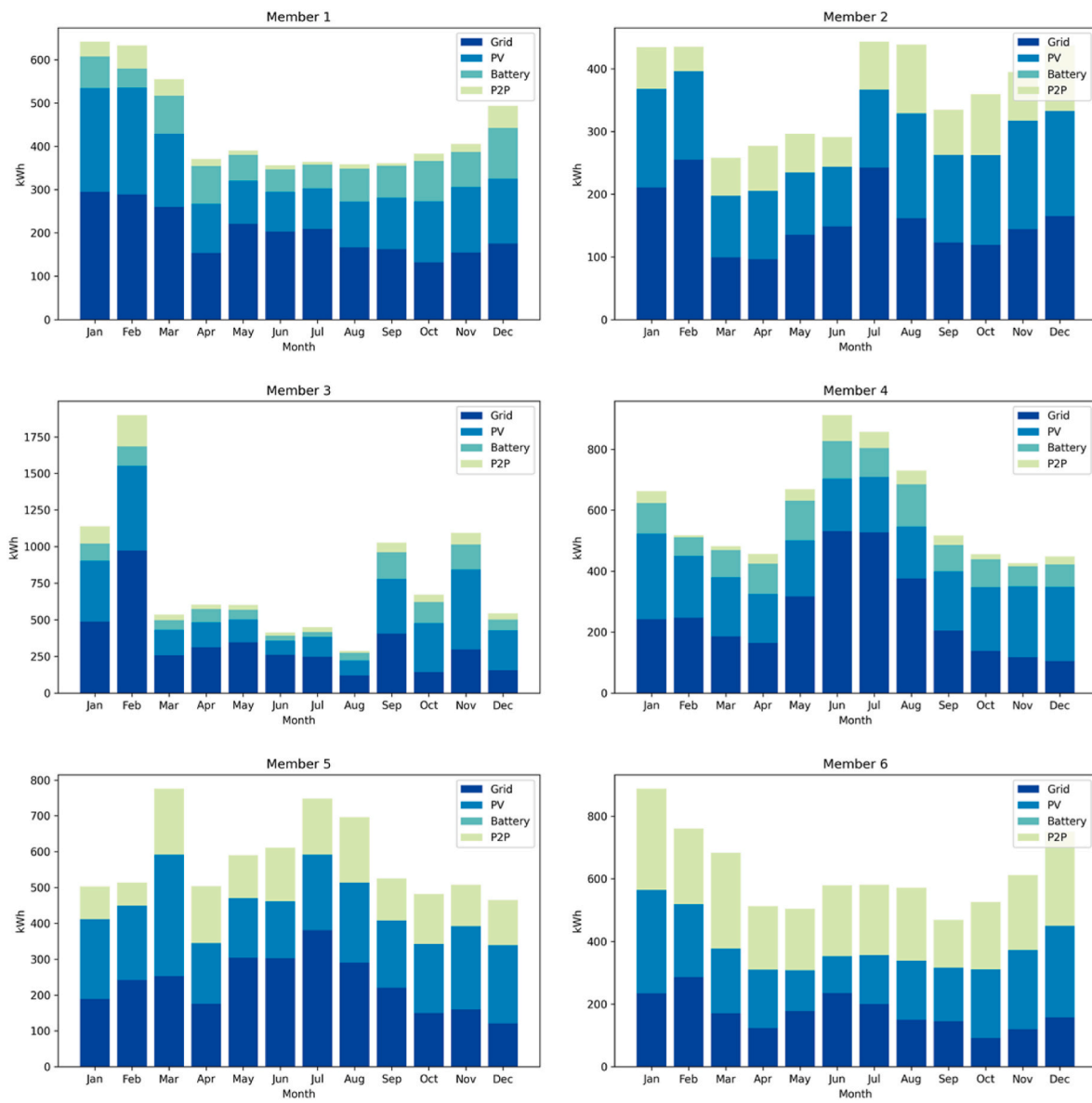


Fig. 9. Breakdown of how each member's energy demand is satisfied during BM B.

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.

4.5.5. KPI 5: self-consumption vs. sharing - relational dimension

BM C'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 sharing in BM B indicates some level of interaction and reciprocity but possibly not as strong as in BM C. The lack of a sharing component in BM A means it contributes the least to relational social capital in this context.

4.5.6. KPI 6: self-sufficiency - structural and cognitive dimensions

BM C's self-sufficiency aligns with a deeper collective understanding of sustainable practices, likely reinforcing local governance and a sense of collective competency. In BM B, variability in self-sufficiency may reflect different levels of commitment to or realisation of energy independence, with implications for shared cognitive understanding. BM A's lower self-sufficiency may limit the development of a collective

understanding of sustainability within the community.

4.5.7. KPI 7: quality of sharing - relational dimension

The high quality of sharing seen in BM C can foster a supportive community atmosphere, likely increasing the trust and quality of interpersonal relationships. In BM B, 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 C consistently supports social capital across all dimensions, reflecting its cooperative and participatory nature. BM B shows mixed results, suggesting that while the system-determined P2P trading 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 BMs 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

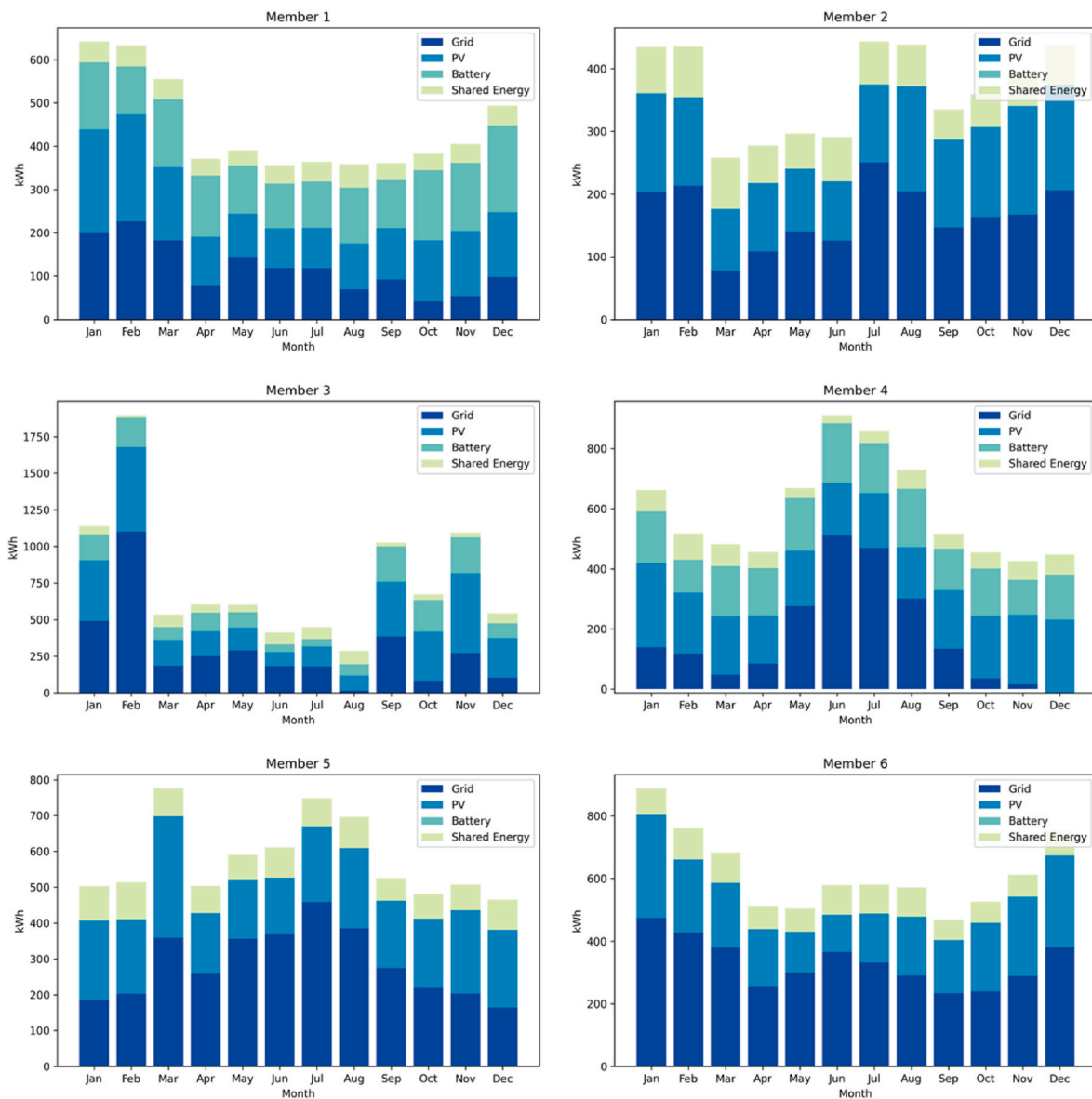


Fig. 10. Breakdown of how each member’s energy demand is satisfied during BM C.

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 C fostering the most robust social capital across all dimensions, BM B creating a variable social landscape, and BM A presenting potential challenges to building strong social capital. This analysis underscores the critical role that BM play in not only economic outcomes but also in shaping the social fabric of community-based microgrid projects.

5. Conclusion

This study highlights the nuanced interplay between BMs and social capital in community microgrids. It demonstrates that while certain BMs, particularly those emphasizing cooperative ownership and bill-sharing, 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 BMs, ensuring they not only meet technical and financial criteria but also harmonise with the social structures they operate within. By comparing three distinct BM scenarios (BM A, BM B, and BM C), we demonstrate the robustness of our model. This approach helps identify how different operational conditions 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 research to validate and apply these findings in practical settings.

CRedit authorship contribution statement

Melissa Eklund: Writing – review & editing, Writing – original draft, Visualization, Methodology, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Alexey Voinov:** Writing – review & editing, Supervision, Conceptualization. **M.J. Hossain:** Writing – review & editing, Supervision. **Kaveh Khalilpour:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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