Energy Research & Social Science 104 (2023) 103260

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Understanding the community in community microgrids: A conceptual framework for better decision-making

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ARTICLE INFO

Keywords:
Community microgrid
Community energy
Social capital
Socio-technical system

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.

1. Introduction

As the world moves towards a more sustainable future, the demand for renewable energy systems is increasing significantly [1]. This heightened demand has ignited a transformative shift towards distributed and decentralised energy systems, redefining the traditional centralised energy paradigm [2]. 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) [3]. 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 [4].

By incorporating diverse DERs, community microgrids enhance energy resilience and flexibility [5]. They reduce dependence on a single centralised power grid, which enhances community security against grid failures, blackouts, or natural disasters [6]. In the event of disruptions, microgrids can continue providing power, ensuring a consistent energy supply for critical facilities and essential services [7]. 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 [8]. However, realising these objectives is not a straightforward process [9].

The planning and design of community microgrids involve a complex interplay between various actors across different scales [10], each bringing their own perspectives and goals to the table [8]. These actors, with their diverse perspectives and goals, shape the organisational structure, strategy, and behaviour of the microgrid within the community [12]. As some members may benefit more from the microgrid than others, differences in perspectives and priorities may result in conflicts

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https://doi.org/10.1016/j.erss.2023.103260
Received 15 February 2023; Received in revised form 13 August 2023; Accepted 19 August 2023
Available online 1 September 2023

[13]. 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 [14]. 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 [14].

Previous studies such as [15–17] 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 [18]. 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 [11], and operational strategies to reflect the unique characteristics and aspirations of the community can enhance the microgrid's acceptance, participation and overall effectiveness [12]. Failure to do so can result in the microgrid not reaching its full potential and intended purpose, as highlighted in studies [19,20].

Implementing community microgrids comes with inherent challenges due to the diverse nature of communities [21]. 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 [12]. Making it difficult to establish frameworks that suit different community microgrids [12]. 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 [22].

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 [22]. The absence of comprehensive considerations of social factors poses challenges to the successful integration of community microgrids [23]. 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 [24], can result in a microgrid that does not align with the needs and behaviours of its members [25].

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. 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 [2]. 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 [26]. 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 [2]. As defined by the US Department of Energy (DOE) [3]: '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 [27]. 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 [11]. 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 [28]. This approach actively involves the local community in energy management to create social and environmental benefits [29]. Community microgrids are essentially microgrids tailored to match the unique energy needs, goals and characteristics of local communities [30]. 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 [10].

Both energy communities and community energy concepts are inherently linked with community microgrids [31]. 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 [27]. 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 [11]. 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 [32]. 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 [18].

Continuing, the concept of community in community microgrids is complex and has evolved over time [9]. A systematic review of the term "community" in community energy systems by Bauwens et al. [31] 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 [31].

In light of these findings, the definition of community microgrids proposed by Warneryd et al. [10] 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.' [10].

The definitions and concepts discussed above are summarised in Table 1 for easy reference.

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 [34], the emergence of the prosumers [35], and the operation and management of the microgrid [36]. Within this context,

Table 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.	[3]
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.	[10]
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)	[33]
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.	[12]

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 [37], as well as energy storage systems like batteries [38] and pumped hydro storage [39]. 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 [40]. 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 [36]. This comprehensive approach enhances the reliability and flexibility of community microgrids, ensuring a stable energy supply [41].

Central to this concept is the role of "prosumers", individuals or entities actively participating in both energy consumption and production [35]. 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 [42]. This aspect is further related to the unique potential for energy to not only be consumed but also exchanged or traded among community members [43]. Energy exchange or trading is facilitated and structured through various methods [44], often reflecting the governance and regulatory frameworks of the microgrid, as well as the community's preferences and goals [45]. It may adopt a collective model where pooled resources are redistributed among members [46]. Alternatively, it may operate on an individual level, where surplus energy is traded within the community microgrid, effectively creating a local energy marketplace [47].

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 [48]. A central component of the ICT structure is the microgrid central controller (MCC), which coordinates the operation of the microgrid [5]. The MCC coordinates energy production from DERs, while maintain the load balance of the community, ensuring stability within the microgrid [36]. Smart meters are another component of the ICT structure, supporting the overall operation of the community microgrid [5]. 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 [49].

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 [32]. Community members, public and private organisations, utility companies, and local governments are included in the possible participants [10]. Their responsibilities can range from overseeing energy production, ensuring efficient distribution, monitoring system and performance to managing transaction and guaranteeing regulatory compliance [10]. 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 [10].

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.

3.1. The importance of the community and social factors

3.1.1. 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. [50]. 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 [51]. This concept, originating form common pool resources (CPR), implies a shared responsibility for the resource's sustainability and the necessity of coordinated decision-making [52]. This concept underlines the importance of collective action and cooperation, especially in the context of RES which is managed and used by a community [53]. The extent to which a community microgrid operates as a 'commons' is directly influenced by the specific governance and ownership structures in place [54], 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 [20] 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 [14] 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 [55]. 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 [44]. Yet, the 'commons' concept also brings challenges, particularly due to the inherent non-excludability of CPRs [34]. 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 [56]. 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 [35]. 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 [51]. 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 [57]. 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 [20]. As a result, barriers to participation and fair benefit distribution may arise depending on the specific community [58]. This is further validated in Sperling [59], 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 [27].

3.1.2. 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 [9]. The constraints and opportunities for community microgrids are, therefore, highly affected by the behaviour and roles of these actors [29]. 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 [60].

Additionally, the level of support needed from external actors and stakeholders can vary based on the community's level of independence and experience [12]. As seen in Koirala et al. [55], 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 [19,20]. 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. [61] 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 [62]. These local leaders can provide valuable resources and support that can help to ensure the long-term sustainability of the project [61].

3.1.3. Trust

The level of participation and engagement among community members is greatly influenced by the presence or absence of trust [28]. 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 [63]. In particular, trust plays a crucial role in shaping the behavioural patterns and the long-term sustainability of community microgrids [17]. 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 [64]. 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 [27]. However, trust extends beyond internal dynamics within the community to encompass external factors, such as regulatory bodies, energy companies, and governing authorises [64]. 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 [60]. 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 [15,24].

Studies have demonstrated the indicate role trust plays in community microgrid projects, influencing peer expectations and the overall trust dynamic between actors [10]. Kalkbrenner and Roosen [65] 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. [62] 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. [66]. Walker et al. [17] 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 [17].

3.1.4. 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 [15] and responsibility are major factors in shaping the behaviour of community members and are embedded in the community's identity [21,53,59,65]. 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 [67], 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. [21]. 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 [65] 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 [65]. Overall, these findings underscore the importance of trust and social norms in determining willingness to participate in community energy initiatives.

3.1.5. Summary

The success of community microgrids is closely related to the level of community participation and engagement throughout all stages of the process [55], including decision-making, planning [67], building, maintenance, monitoring [68], education, and governance [24]. Collective action and leadership are important factors in shaping the feasibility and resilience of a community microgrid [15], 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 [65], and high levels of trust are more likely to result in successful energy projects [66]. 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 [62].

3.2. Community and social factors in the design and planning process

3.2.1. 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 [43]. Governance structures can similarly vary, encompassing energy cooperatives, corporations and no-profit associations [10]. The essence of ownership in this context extends beyond mere possession, it entails a source of control rights over the system [69]. For instance, community-owned microgrids may outsource the planning, construction, and operation of the system [54]. In such cases, even though the community has ownership, the decision-making and control might be distributed across external actors [70]. Additionally, while the community may own individual or collective DER, the physical network's ownership might still rest with the local utility company [10]. 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 [71]. The study conducted by Gui et al. [68] 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 [68]. This conclusion is further reinforced by the work of Vandazina et al. [71], 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. [72] 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 [61]. This includes factors such as the composition of both producers and consumers, which can impact the feasibility of various governance and ownership models [32]. Wolsink [20] 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 [20]. Additionally, the financial constraints of the community can also play a role in determining the feasibility of different ownership and governance [73]. For example, in emerging markets, communities may not have the funds to obtain full ownership of a microgrid [3], making mixed or third-party ownership more feasible options [71].

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 [32]. 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 [34] 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 [20,34].

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 [10]. While the endogenous regulatory framework within the community may dictate specific rules and governance structures [68], the exogenous legal and regulatory framework can either provide financial incentives or present obstacles in their development [18,43]. 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.

3.2.2. 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 [74]. However, this emphasis on technical and economic optimisation has led to a lack of understanding and consideration of social aspects [22]. Studies such as [18,68,75] 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 [25], 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 [18]. For example, Andersson et al. [76] 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 [76]. 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 [22]. For instance, Suk et al. [23] 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 [23].

3.2.3. Summary

The ownership and management of community microgrids can greatly impact the community in terms of risk, return, and responsibility [68]. 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 [61]. The success of community microgrids relies on key aspects such as effective communication and education [59], decision-making [67], conflict resolution, and stakeholder coordination [77]. The regulatory environment can either provide opportunities or pose obstacles for community microgrids and should be taken into consideration [10]. 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.

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, 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.

4. Social capital theory

Social capital has been useful in understanding relationships and community outcomes, particularly the link between societal norms and values [80]. Researchers generally agree that social capital is multidimensional and includes factors such as trust, social cohesion, social identity, networks, norms, and values [81]. Coleman (1990) [82] viewed social capital as social structures that facilitate the actions of individuals based on the behavioural norms present in social groups [82]. Putnam (1992) [83] 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 [84]. 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 [83,85].

According to Nahapiet and Ghosal [86], 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 [86].

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

Table 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	Responsibility	Social cohesion	References
✓	✓	✓		✓	✓		✓		✓	✓	[10]
	✓										[8]
✓					✓				✓		[9]
✓	✓			✓	✓			✓		✓	[11]
	✓			✓	✓		✓			✓	[18]
✓	✓			✓						✓	[19]
✓	✓	✓	✓	✓	✓	✓					[20]
✓	✓		✓	✓	✓	✓	✓			✓	[15]
✓	✓		✓	✓	✓	✓		✓	✓	✓	[16]
✓	✓	✓			✓					✓	[17]
✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	[24]
✓		✓	✓	✓	✓			✓	✓		[55]
	✓	✓	✓		✓				✓		[67]
✓	✓								✓		[68]
✓		✓	✓	✓	✓	✓	✓	✓			[14]
✓	✓				✓		✓	✓	✓		[59]
✓		✓	✓			✓					[52]
	✓								✓	✓	[35]
	✓				✓						[58]
✓		✓	✓	✓	✓	✓	✓	✓	✓		[60]
	✓	✓			✓			✓	✓		[61]
✓	✓			✓	✓					✓	[62]
✓	✓	✓	✓	✓	✓		✓				[28]
✓	✓	✓	✓					✓			[65]
✓	✓	✓	✓	✓	✓		✓	✓		✓	[66]
					✓			✓	✓		[21]
✓	✓	✓	✓		✓	✓	✓		✓	✓	[53]
✓	✓	✓		✓	✓		✓		✓	✓	[32]
✓	✓		✓				✓	✓			[34]
✓	✓			✓	✓		✓			✓	[77]
	✓								✓		[78]
✓	✓		✓	✓		✓			✓	✓	[79]
✓	✓	✓	✓	✓				✓		✓	[13]
✓	✓		✓			✓			✓		[29]

and the level of trust and cooperation [87,88]. Over time, several measurement frameworks and tools have been developed to facilitate this. For instance, Putnam [85] 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 [85]. Similarly, Onyx and Bullen [89] 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 [90] 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 [90,91].

In our upcoming exploration, we will utilise the social capital conceptualisation based on Nahapiet and Ghosal's framework [86] (see Table 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 3
Social capital dimensions from Nahapiet and Ghosal [86].

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

5. Applying social capital theory to community microgrids

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 [18]. For example, a community microgrid in a rural area may have different objectives than a community in an urban setting [12,20]. The rural community may prioritise energy independence and self-sufficiency [75], while the urban community may focus on reducing greenhouse gas emissions or increasing access to affordable energy [55]. Along with the geographical context, the social and cultural context of a community can also be influenced by factors such as the community history [59], demographics [43], and economic conditions [74].

The cognitive dimension of social capital, which encompasses shared values, beliefs, language, and narratives within a community [92], can play a crucial role in understanding the objectives and priorities of a community microgrid [14]. 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 [28]. 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 [62]. 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 [92]. The shared language and narratives can also provide a sense of unity and shared identity within the community [93], which can facilitate cooperation and collaboration towards common goals [94].

Moreover, community microgrids can promote learning and knowledge-sharing among community members [55]. 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 [32,95]. 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 [65]. 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.

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 [86]. Communities being entitled to decide upon their own microgrid infrastructure are shown to be essential for behavioural change and willingness to participate in community microgrids [20]. The decision-making in community microgrids directly influences the feasibility of collective action and cooperation [20,24]. The capabilities required to achieve this will differ depending on the community structure [77].

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 [86]. Communities with democratic structures increase social interaction between their members and facilitate cooperative behaviour in community microgrids [14]. The density and connectivity of social interactions increase the accessibility of resources between members and empowerment to participate in a community microgrid [96]. This is further supported by the study conducted by Bush and McCormick [16] 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 [16].

The development of community microgrids can also have a transformative effect on the social structures of the community [32]. The creation of organisations or groups for participation in the microgrid can provide social structures and ties that foster further cooperation and trust. [17] This, in turn, can influence the establishment of networks and norms that encourage support and engagement [92]. In addition, communities with strong network ties and configurations facilitate better access to information and knowledge for individuals within the community [55,81,91]. 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 [10,18,55,78]. 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.

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 [63]. 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 [79]. It provides a deep understanding of the community and the level of cohesivity, which can help to prevent conflicts [34,55,81,91]. Trust towards local government or businesses, such as utility owners, can further guide what type of community microgrid solution is feasible [34,77].

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 [13]. The social need to be an active part of a community has especially been highlighted to be a motivator for participation in sustainable projects [14]. 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 [32]. Additionally, social norms, such as reciprocity and expectation of collaboration, play a crucial role in fostering cooperation among community members [28]. These norms can stimulate participation and contributions to the shared resources, which is essential for effective resource management [34]. 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 [28]. Community energy projects can bring together individuals from different backgrounds and perspectives, working together towards a common objective [14], thus fostering the development of new relationships and strengthening the sense of community [97].

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 [97], making it easier to tailor energy initiatives that align with the community's unique social and cultural context [25]. Structural social capital helps to understand the community structure, its roles, rules, precedents, and procedures [90], with communities having democratic structures and strong social ties being more likely to participate in community microgrids [14]. Relational social capital is crucial in determining the likelihood of community members to pursue goals collectively [53] and is dependent on the quality of relationships, level of trust, social norms and obligations, and level of cohesiveness [63]. 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 [14]. 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 [92]. In this way, community microgrids go beyond merely addressing energy needs, they can also strengthen the social fabric of a community.

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 Fig. 1.

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.

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 [98]. 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

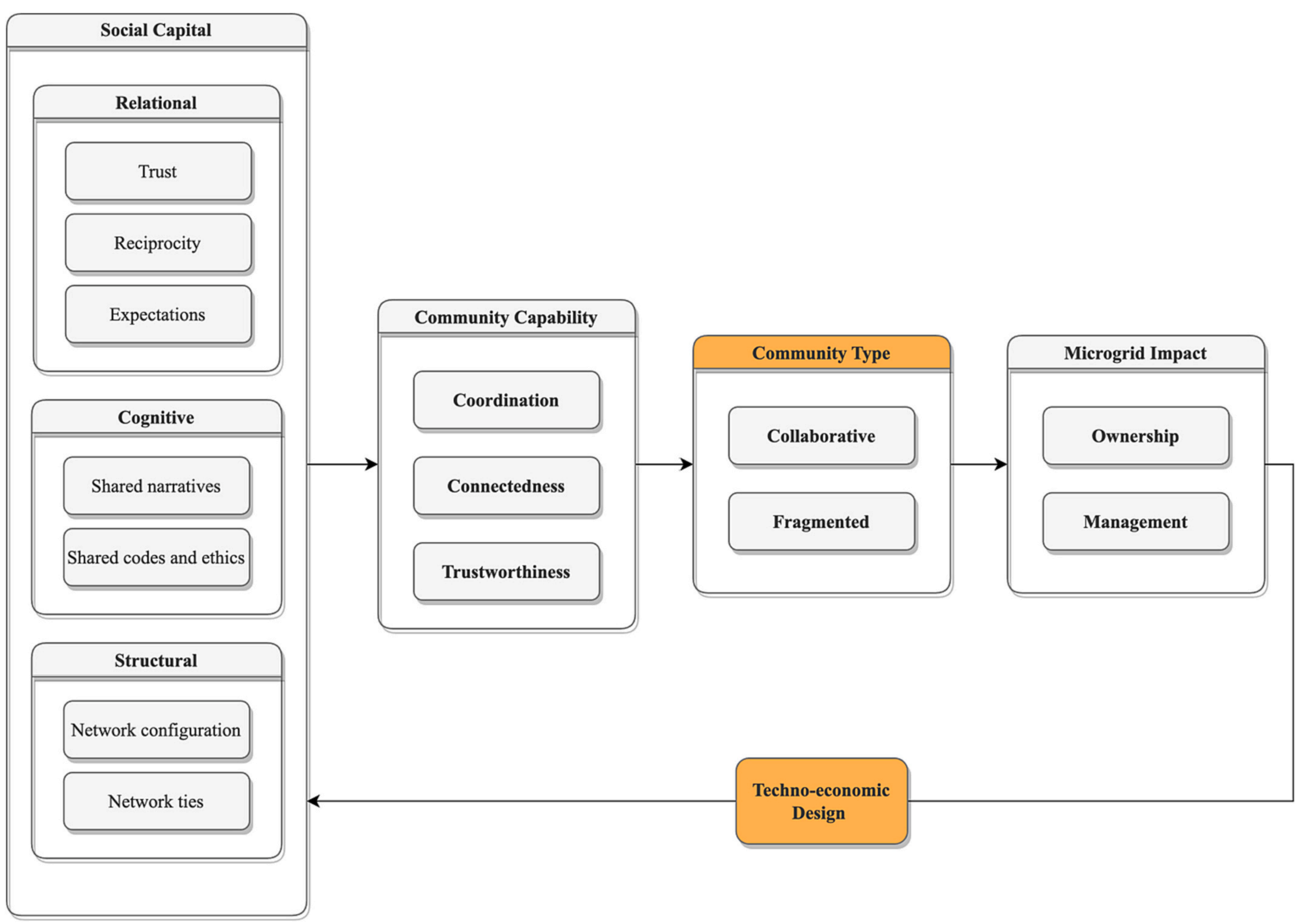

Fig. 1. The conceptual framework linking the theoretical foundations of social capital to the impact on microgrid design.

through collective action and social processes [97]. 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. [99], emphasises three interconnected elements of community capability: what communities have, how communities act and for whom communities act (Fig. 2). This framework emphasises the importance of understanding the assets, actions, and beneficiaries within a community.

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 [28]. By assessing a community's social capital, one can obtain a better understanding of its ability to work together and attain common objectives [92]. 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".

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 [100] 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 [100].

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 [101]. 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 [97]. "Fragmented" refers to a situation where the community is not functioning properly or effectively [102] due to a lack of social capital [92]. 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 [92]. 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. Fig. 3 visually represents these intricate dynamics of social capital, emphasising the significance of each dimension and their collective influence on the community.

6.4. Community microgrid impact

An important aspect to consider during this process is the ownership and governance structure of the microgrid [10]. The choice of ownership can also greatly impact the way the microgrid operates [20], as well as the level of community involvement and participation [29]. 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

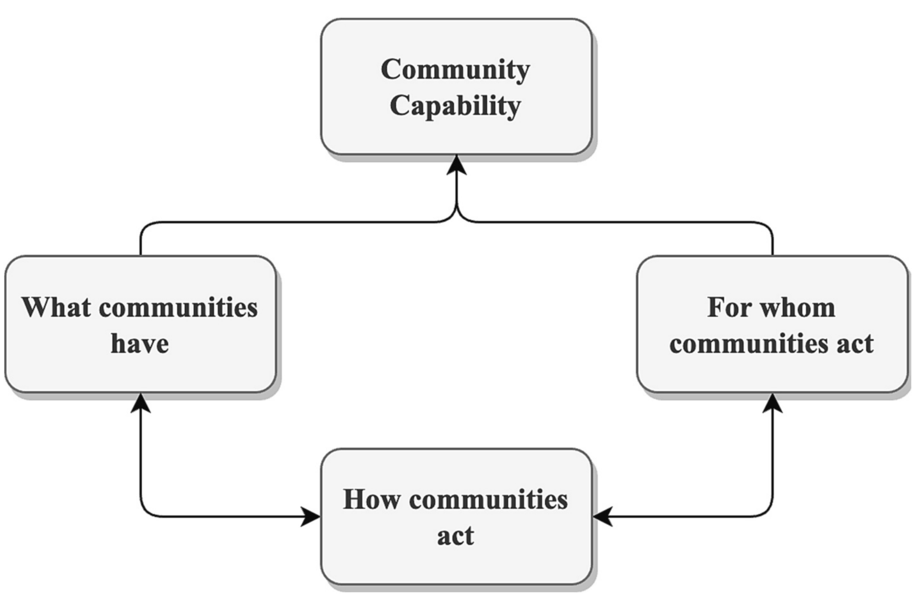

Fig. 2. Illustration of community capability (adapted from George et al. [99]).

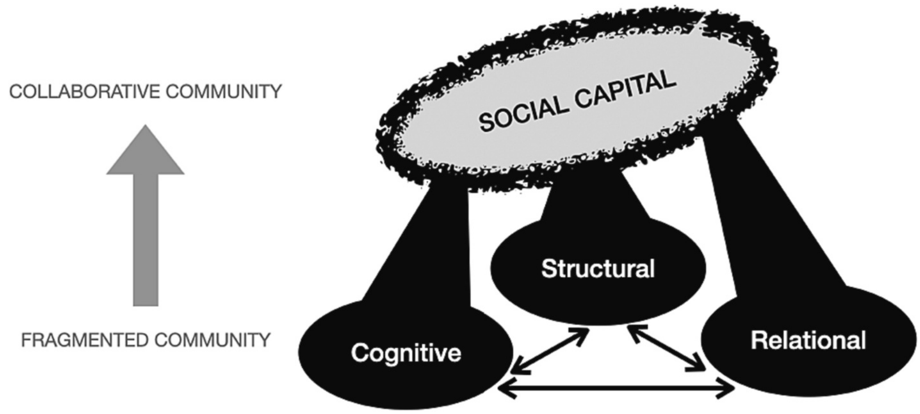

Fig. 3. The relationship between social capital and community type (Source, Authors).

information flow, and trust among members, may foster cooperation and sustainable behaviour [10,86]. Communities with these characteristics may be well-suited for community-owned microgrids [78], which can lead to greater engagement and participation from community members, as well as a greater sense of ownership and responsibility [15]. 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 [68]. 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 [2,8]. The study by Broska [14] 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 [20]. Fig. 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.

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 [68]. This, in turn, influences the technical design and overall feasibility of the community microgrid [78] 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 [78], 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 [68], 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

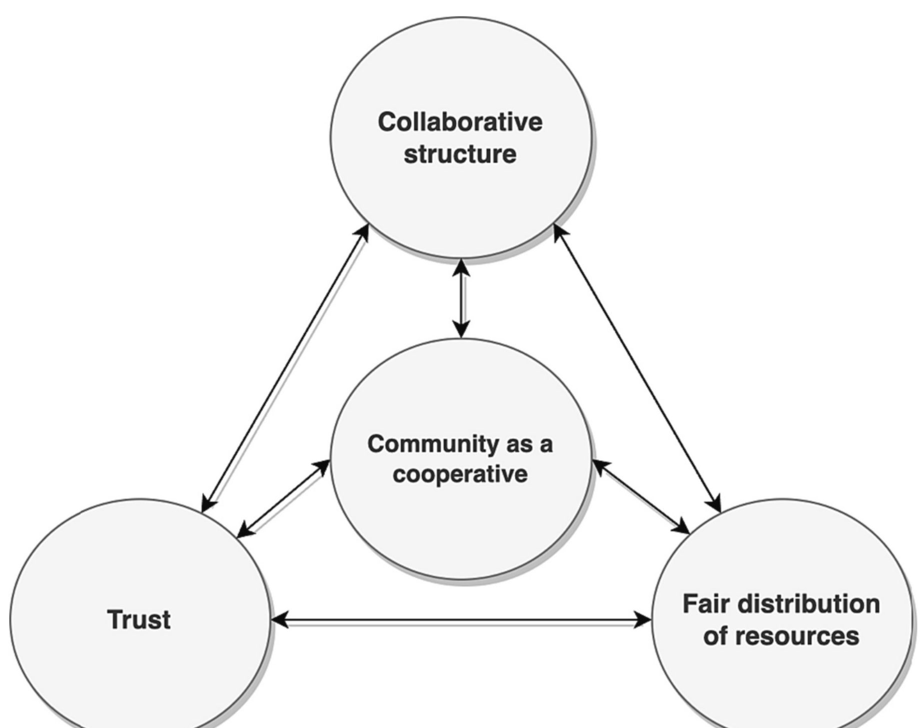

Fig. 4. Illustration of key elements for cooperative community microgrids (Source, Authors).

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.

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 Fig. 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 [90] 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.

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 Fig. 5. More specifically, the foundation of the first two layers of our scale lies in Nahapiet and Ghoshal's established framework [92]. These layers represent the core dimensions and their

Fig. 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).

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 [90] 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 Fig. 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) [103]. 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.

Our 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 Fig. 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.

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 microgrids.

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

No data was used for the research described in the article.

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