How to build Resilient Community Energy Systems? Lessons from Malawi and Ethiopia

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How to Build Resilient Community Energy Systems? Lessons from Malawi and Ethiopia

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Abstract

This paper defines the notion of realising Resilient Community Energy Systems (R-CES) through community capital to withstand against unforeseen natural hazards, climate change induced risks and socio-political disruptions. It evaluates the interrelationship between different stages of CES project implementation with development of community's resilience in the form of social, human, economic, physical and natural capital. This study employs empirical research by carrying out case study analysis of CES projects deployed in risk prone regions of Malawi and Ethiopia. Three CES projects, two in Malawi and one in Ethiopia have been examined through qualitative analysis of data collected through semi-structured interviews with CES project stakeholders. Case studies analysed the role of different stakeholders in planning, installation, and operation of projects and evolution of the community's resilience during phases of project implementation. In-depth critical analysis of cases demonstrates, how community's evolved resilience in different forms of community capital enables them to cope with unforeseen shocks/ disruptions encountered over the period of CES operation. Comparative analysis of cases proposed the novel R-CES framework defining seven key components of community capital to realise R-CES in practice. The proposed framework provides recommendations and best practices to CES project developers, managers and community representatives to implement CES projects in a way strengthening community capital to realise a resilient community and sustainable infrastructure.

Keywords: Community Energy; Resilience; Community Capital; Disruptions

1. Introduction

Community Energy Systems (CES) are decentralized energy initiatives involving a high degree of community participation in ownership, management and benefit sharing. Such initiatives typically utilize locally available resources and involve renewable energy sources like solar, wind, and micro-hydro for energy generation (Walker and Devine-Wright, 2008). CES are often characterised as community-centric clean energy initiatives and play a pivotal role in the wider sustainable energy transition, especially in countries with large gaps in energy provision. Countries with low electrification rates in sub-Saharan Africa are facing the dual challenge of providing universal electricity access to promote development activities while mitigating carbon emissions to combat global climate change (Mulugetta *et al.*, 2022). Moreover, these countries lack access to clean cooking sources and are highly dependent on biomass and other polluting fuels for domestic cooking needs. CES have emerged as a sustainable solution to provide clean, reliable, and equitable energy access to energy-deprived populations in these countries (Samarakoon, 2020; Ambole *et al.*, 2021). Such systems have proved to be instrumental in providing last-mile access to remote and vulnerable communities.

Countries like Malawi, Mozambique, and Zambia, in South-East Africa, are highly prone to natural disasters and climate change-related risks. In the last few years, cyclones Idai and Freddy caused massive destruction across communities living in risk-prone regions in these countries (Disasters Emergency Committee, 2019). Concurrently, Ethiopia and Eritrea have experienced massive displacement of communities due to civil war and socio-political conflicts in recent years. Communities residing in displacement settings and vulnerable regions in such countries often experience humanitarian crises and are deprived of basic life services of electricity, cooking, drinking water, and healthcare (Miller, 2024).

Supplying reliable electricity access to the populations residing in rural, remote and vulnerable settings in such countries through a centralised grid remains a challenge. Lack of public infrastructure and limited ability to restore and maintain the system after frequent disruptions further limits their ability to reach scattered settlements (Gebreslassie and Cuvilas, 2023). Remote and vulnerable communities in such regions thus need Resilient - Community Energy Systems (R-CES), which can cope with unforeseen disruptions/ risks through their underlying local capacity. Such systems are particularly relevant in risk-prone areas as these could be repaired quickly and locally, unlike centralised grid extension, which frequently involves a complex and lengthy restoration process. R-CES does not refer to the system's resilience solely in terms of its technological/ infrastructural capacity. It mainly concerns with the community's resilience to withstand unforeseen shocks/ disruptions (To and Subedi, 2019). In fact, technological/ infrastructural capacity is a component of community's physical capital (Vallecha and To, 2024).

Previous literature has analysed varied cases of deployment of CES to address socioeconomic development of energy-deprived and vulnerable communities in risk-prone regions (Antwi and Ley, 2021; Gebreslassie, 2024). However, there were reported to be several CES projects which lacked sufficient resilience to cope with potential risks and disruptions and became dysfunctional after a short period of operation (Berger, 2017; Zigale, Muleta and Mohammed, 2019; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2023). Few studies have explored how to build R-CES which could sustain the functionality of the energy system during disruption while developing a community's capacity to cope with it. Since implementation of CES typically involves the local community's participation in project deployment and operation, the foundation for building R-CES lies in the formation of community's resilience. One way to examine community resilience against unforeseen disruptions is to assess its social, economic, physical, natural and human capital (Carmen *et al.*, 2022).

This paper defines a conceptual model to assess community resilience through different forms of the community's capital and their interrelationship with CES implementation stages. The model demonstrates that the manner of community involvement influences how community capital is gained and strengthened in different areas and, hence, whether CES implementation contributes to delivering community resilience. Critical qualitative analysis of three CES cases from Malawi and Ethiopia demonstrate different aspects of resilience and instances of system's failure. Comparative analysis of community capital across three cases and communities' responses towards managing disruptions leads to the development of R-CES framework.

The proposed R-CES framework suggests seven key components of community capital which CES developers/ managers should consider while implementing a CES project to make it resilient against unforeseen shocks/disruptions. Four out of seven key components correspond to human and social capital of a community, suggesting higher significance of these forms of community capital to realise R-CES in practice. Thus, CES stakeholders should focus on strengthening the community's social and human capital right at the inception of CES implementation process. This could be achieved by mobilising the community and inculcating technical and project management skills through active community participation in CES project planning, installation and operation stages.

This paper is organised as follows. Section 2 presents the contextualisation of resilient CES through different forms of community capital. It explains the conceptual model to analyse the interrelationship between CES implementation stages and community resilience development. Following a brief discussion of the methodology for selection of CES projects and case study analysis in section 3, we then put this approach into practice in Section 4, which presents case study analysis of CES projects from Malawi and Ethiopia. Sections 5 and 6 present discussions and conclusions of the study, respectively.

2. Contextualising Resilient Community Energy Systems (R-CES)

CES are community-centric decentralised energy systems that entail an active role for local communities in project implementation and benefits generated out of the project (Walker *et al.*, 2010). Understanding of CES requires interpretation of 'community' in relevant context. We refer this definition of 'community' by Huang *et al.* (2017, p712), "community is a social unit (a group of people) that has something in common, such as norms, values, identity, and often a sense of place, which refers to being situated in a given geographical area (e.g. a village, town, or neighbourhood)". There exist numerous definitions of CES based on this context. As defined by Walker and Simcock (2012, p194), "community energy systems refer to electricity and/or heat production on a small, local scale that may be governed by or for local people or otherwise be capable of providing them with direct beneficial outcomes".

Over the last few years, a growing literature has examined the evolving role of CES to achieve sustainable energy access for all (Süsser, Döring and Ratter, 2017; Gebreslassie and Cuvilas, 2023). The concept of CES likely emerged from energy secured geographies in Europe and the USA where CES aimed towards citizen led initiatives for sustainable energy transition and climate action (Walker and Devine-Wright, 2008; Brummer, 2018; Gorroño-Albizu, Sperling and Djørup, 2019). However, their relevance seemed to be equally important with respect to least electrified and developing countries of Global South. Interestingly, there reported to be cases of integrated community energy systems, community microgrids and prosumer community groups in countries of developing Asia, all of which share commonalities having community as a key actor in such initiatives (Thapar, Sharma and Verma, 2017; Khalid *et al.*, 2023; Shastry and Rai, 2025).

Existing literature has described the potential importance of community microgrids for enhancing electric grid resilience through their inherent capability of islanding and supplying critical services to local communities during extended grid outages following an extreme event or disruption (Hussain, Bui and Kim, 2019; Mutani *et al.*, 2021; Hafeznia and Stojadinović, 2024). Moreover, their role was mainly reported to enhance the resilience of energy system. However, few studies have explored the role of CES in building community resilience beyond infrastructural resilience (Hotaling, Bird and Heintzelman, 2021; Michael, Ben and Mike, 2021). Though some studies have examined the impact of CES deployment towards development of community capacity in addition to electric infrastructure resilience, their focus remained limited towards enhancing physical capacity of the community (Shapira, Shibli and Teschner, 2021; Khalid *et al.*, 2024).

This study addresses this gap by evaluating the effects of different stages of CES implementation on all forms of community capital and impact of evolved community's capacity to realize R-CES through empirical research. In addition to infrastructural capacity, which is a component of the community's physical capital, this study demonstrates the impact of CES implementation over community's social, human, economic and natural capital which makes it resilient against unforeseen hazards or disruptions. Since earlier studies discussed multiple instances of CES project failures due to lack of community capacity to withstand unforeseen shocks/ events (Berger, 2017; Vallecha and Bhola, 2019; Zigale, Muleta and Mohammed, 2019), there is a need to understand the notion of R-CES through the lens of community resilience.

2.1 What do we mean by Resilient Community Energy System (R-CES) ?

R-CES could be characterised as decentralised and people-centric energy systems with an underlying capacity to withstand any unforeseen shocks and disruptions (Mazur *et al.*, 2019; To *et al.*, 2021). These initiatives typically involve active participation of the local community in energy production and consumption along with managing and upkeep of these systems (Joshi and Yenneti, 2020). Central to R-CES is a resilient community which can withstand and adapt to unforeseen events. There exist numerous definitions of community resilience. As defined by Community and Regional Resilience Institute (CARRI, 2013, p10) "Community resilience is the capability to anticipate risk, limit impact and bounce back rapidly through survival, adaptability, evolution and growth in the face of turbulent change." The Community-Based Resilience Analysis (CoBRA) framework proposed by the United Nations Development Program (UNDP) characterises community resilience in terms of its capacity in the form of social, human, economic, physical and natural capital (UNDP Drylands Development Centre, 2016). Other frameworks such as the Sustainable Livelihood Framework focus on similar dimensions (Department for International Development, 1999; Mayunga and Peacock, 2010). Figure 1 represents these dimensions, explained in the following sections.

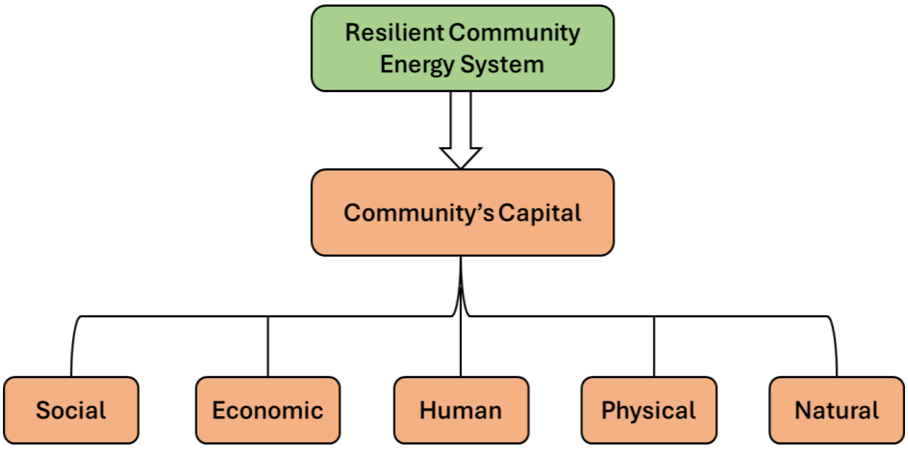

Figure 1 Community's capital defining Resilient CES (Source: Author's own)

Human capital

A community's human capital is its workforce's capacity to produce goods and services by utilizing other forms of capital to sustain economic production. The UK Government's Department for International Development (DFID) defines Human Capital as 'the sum of skills, knowledge, labour and good health that together enable people to pursue different livelihood strategies and achieve their livelihood outcomes' (UNDP Drylands Development Centre, 2016, p6). The two main components of human capital are educational attainment and good health (Sen, 2001). Education requires adequate knowledge, skills, training, and experience to be imparted to the working-age population for an effective labour force. The health and physical ability of people are needed to use any available resources effectively (Department for International Development, 1999; Sen, 2001; Doussard and Yenigun, 2022).

Social capital

Social capital is the degree of connectedness and cooperation among community members. Different features of social organisation define social capital, including the constitution of networks of individuals with shared interests, membership of formalised groups and relationships of trust among community members to promote cooperation during adverse events (Pretty and Ward, 2001). Strong social bonds and community ties enable weaker and more vulnerable sections of society to locate and utilize shared resources during disruption. A network of communities allows the transfer of information and resources for better preparedness and mitigation strategies to counter potential risks and hazards (Mayunga and Peacock, 2010; Boston *et al.*, 2024) .

Economic capital

The economic capital depends on the availability of financial resources and income-generating streams through businesses, industries and landholdings. At the household level, economic capital depends on savings, income, remittances, and credit (Neveu, 2018). A community with a strong economic capital will have greater means to absorb the impacts of disruption and facilitate rapid recovery through the use of financial resources for livelihood outcomes. For example, access to cash and credit enables people to avail basic amenities like food and shelter post-disruption and enables mobility. Resilience in terms of economic capital relies not only on the amount of resources but also on their diversity. Communities with diverse income streams and easier access to credit and state transfer benefits (i.e. pensions, hazard insurance, etc.) are more resilient to unforeseen disruptions (Norris *et al.*, 2008; UNDP Drylands Development Centre, 2016).

Physical capital

The physical capital of a community consists of the basic infrastructure that supports it, such as roads, electricity, telecommunications networks, water supply and sanitation. It also includes the built environment, including houses, public buildings (i.e., schools, police stations, hospitals, libraries, museums, and government buildings), parks, and any other type of public and collectively shared space. Physical capital is crucial for disaster recovery. For example, public infrastructure like roads, telecommunications, electricity and hospitals act as lifelines while absorbing the impacts of disasters and reaching a new normal state by speedy recovery. The presence of manufacturing units and local industries enables the community to produce goods and services and recover rapidly through economic crisis induced post disruption (Mayunga and Peacock, 2010; Koliou *et al.*, 2020).

Natural capital

Natural capital relates to the availability of natural resources, such as land, water, forest cover, biodiversity and other natural endowments necessary for inhabitation. It also includes environmental resources like solar irradiance, wind, and other renewable energy sources that a community could harness for clean energy production and use. Sometimes natural and physical capital are indistinguishable. The availability of natural resources becomes critical while recovering from an abrupt disruption, especially for a population whose livelihood relies on resource-based activities like farming, fishing, and mining (UNDP Drylands Development Centre, 2016; Cafer, Green and Goreham, 2019).

2.2 Interrelationship between Community Energy Systems and Community Resilience

We propose the existence of a close association between stages of CES implementation and development of community resilience. As CES involve the local community as a major actor in one or more of the project implementation stages, development and operation of the project directly or indirectly contribute to the development of community's capital. Commissioning a CES project typically involves three stages: planning/conceptualization, installation and operation. The community's involvement in each of these stages contributes to building one or more forms of community capital which is the measure of community's resilience (Dimitris Kitsikopoulos, 2023; Vallecha and To, 2024). For instance, involving the community in project planning results in developing the community's human and social capital because it develops the community's energy system planning and funding acquisition skills and raises awareness of renewable energy sources and environmental security. It mobilizes the community and helps to strengthen the social bond and decision-making capacity among community members.

The community's involvement during installation and operation inculcates engineering system design knowledge, grid maintenance and customer management skills. Community members engagement as workforce in project implementation stages generates local employment and builds economic capital. New electricity-driven businesses and industries create livelihood opportunities and diversify income streams for people thus enhancing economic resilience (Berka and Creamer, 2018; Dimitris Kitsikopoulos, 2023). The development of electricity distribution grid infrastructure and subsequent growth and expansion of communication facilities builds physical capital of the community. It also contributes to conserving natural capital, for example, preventing deforestation. The availability of electricity reduces the demand for wood and solid biomass for cooking and domestic energy consumption, which subsequently reduces deforestation and enhances the natural forest cover in the region. Reduction in usage of traditional polluting fuels after electrification improves the air quality and improves the health and well-being of the community (Lai *et al.*, 2024).

Figure 2 shows the conceptual model representing interrelationship between stages of CES implementation and development of different forms of community's capital (Vallecha and To, 2024). The relationship between CES implementation and community resilience opens opportunities for multiple positive feedback loops because when community capital develops, it benefits the project, thus enhancing the opportunities for further development of the community's capital. The development of the community's capital continues during project operation, and the combined effect is an increased capacity to withstand any unforeseen disruptions/risks.

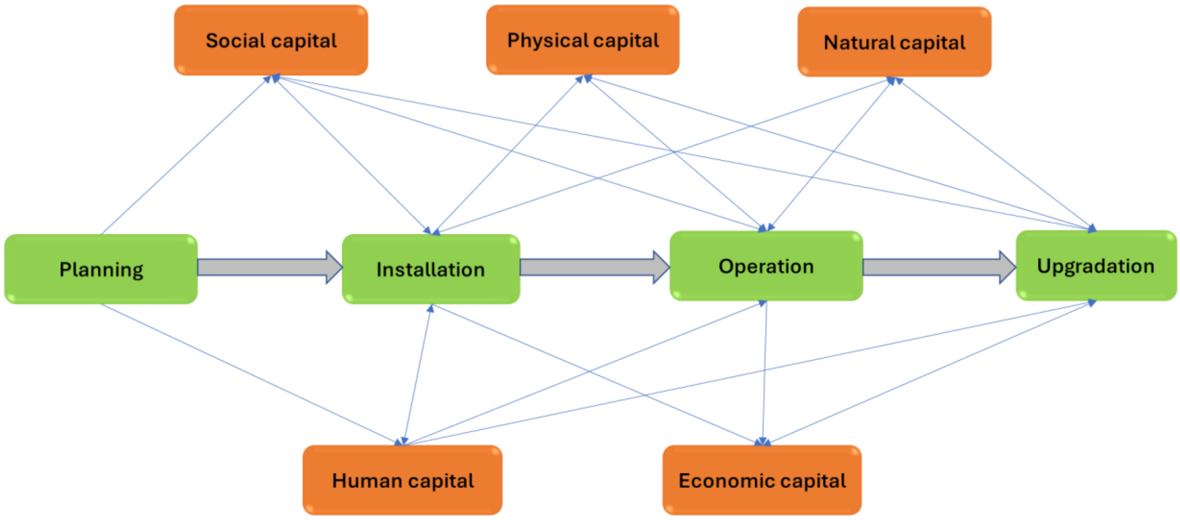

Figure 2: Conceptual model showing interrelationship between CES implementation stages and forms of community's capital (Source: Adapted from (Vallecha and To, 2024))

3. Methodology

The interrelationship between stages of CES implementation and their impact on community capital has been evaluated through case study analysis of CES projects deployed in different contexts. The team of authors selected two countries, Malawi and Ethiopia for in-depth analysis, seeking to compare national contexts that face similar geographical challenges regarding exposure to disaster risks, but with different responses to the development of community energy. Interestingly, both countries have primarily rural population. Malawi is a landlocked country in southeastern Africa, sharing borders with Zambia, Mozambique, and Tanzania. Geographically, Malawi is prone to natural hazards and climate change-related risks like cyclones and floods. Recently, cyclones Freddy and Idai have claimed thousands of lives and displaced millions of people (Disasters Emergency Committee, 2019; Department of Disaster Management Affairs, 2022). In Malawi, the impacts of these events on electricity networks was so significant that it took nearly a year to fully restore the services of the crucial generation project of Kapichira hydroelectric power station after catastrophic cyclone damage (EGENCO, 2023).

Ethiopia is particularly vulnerable to climate change-induced risks such as, droughts, floods and landslides. (World Bank, 2019). Concurrently, the country faces risks from political and armed conflicts. From 2020 to 2022, a war erupted in the Tigray region, and conflict continues in some areas (Human Rights Watch and Amnesty International, 2022). Two projects were selected in Malawi and one in Ethiopia, representing different conditions of vulnerability. In Malawi, the Chipopoma Micro-hydro power project and the Mdyaka Solar-Wind Hybrid project were selected which provide electricity in risk-prone regions that frequently face natural hazards. In Ethiopia, the Tabia Selam project was selected which is in the Tigray region prone to conflict, drought and environmental degradation. Figure 3 represents the location of project sites selected for case studies on maps of respective countries.

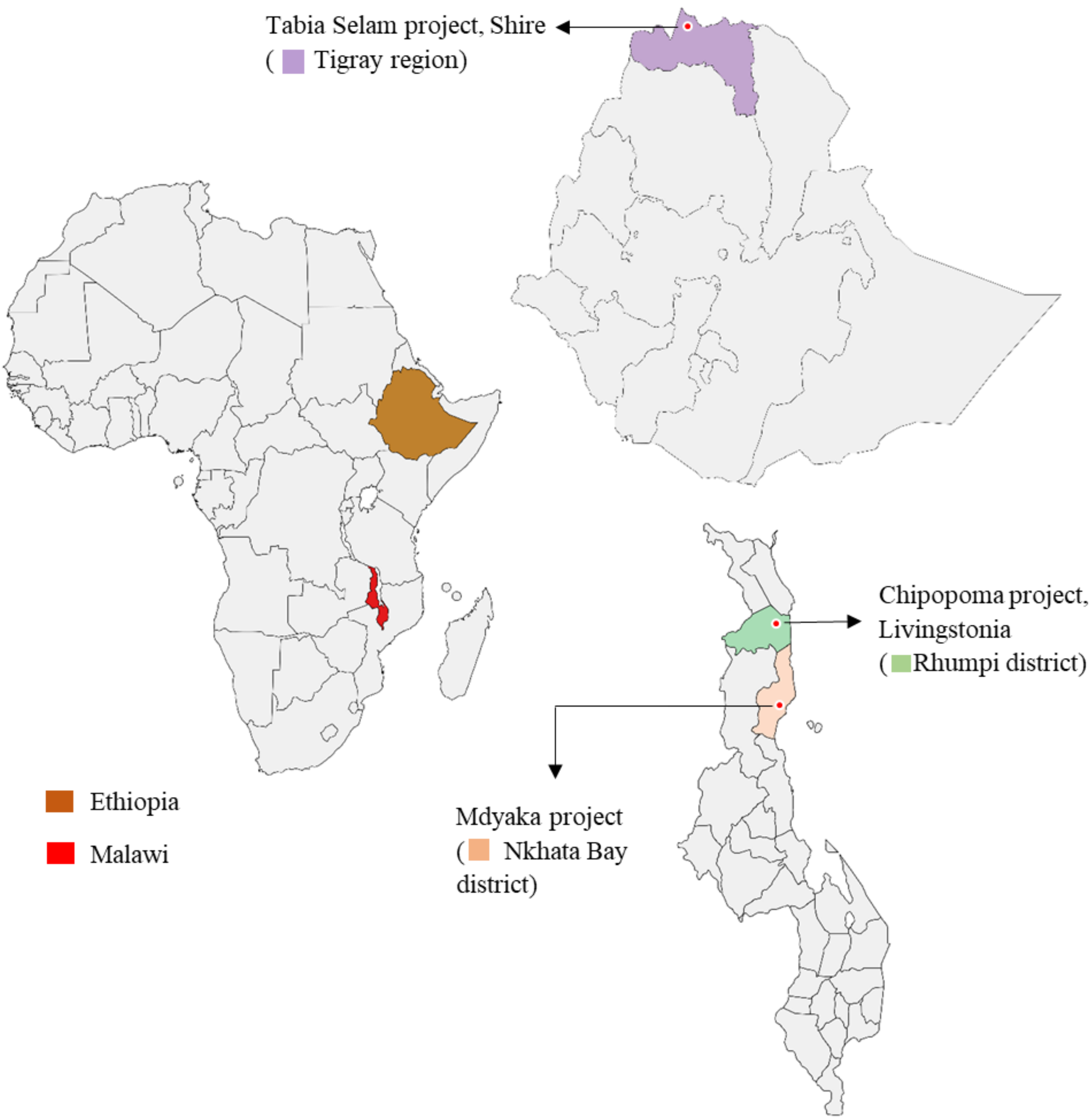

Figure 3 Map of Africa, Ethiopia and Malawi illustrated with project sites selected for case studies

Primary data was collected through stakeholders' interviews during field visits and complementary interviews through telephone. The interviewee's sample included project developers, project managers, members of advisory boards and other project committees, and local representatives. The sample targeted interviewees who could explain the lived experience of community energy. For Chipopoma project, the respondents were Director of Chipopoma Power and a member of Energy Committee. In the case of the Mdyaka project, a village chief and a former member of the Energy Committee were interviewed. For the Tabia Selam project, a member of the project implementing agency, and the regional administrator were interviewed. Additional data was collected from project plans, budgets, tender documents, maps, and other project documentation. The analysis integrated the data into case study accounts that would explain the development of projects and how their managers and communities faced unforeseen disruptions.

Each case was examined in terms of how CES projects had contributed to developing the community's capital and how such capital was mobilised during unforeseen events. Relevant components of community's capital sharing commonalities across the cases were extracted under social, economic, human, physical and natural dimensions. Accordingly, the impact of CES implementation stages on community's capital was evaluated by assessing their effects on different components. Tables 1-3 present the effects of CES implementation stages on different components of community's capital, where '+1' indicates visible positive effect of planning/ installation/ operation stage towards respective component. '-1' and '0' indicates negative and no significant effect on respective components during project implementation stages. These effects were assessed by analysing the data available through stakeholders' interviews and secondary sources.

Following this, a comparative analysis of cases was carried out by evaluating the net impact of CES implementation stages by aggregating the effects on all components of community's capital in the respective dimension. Table 4 presents the comparative analysis of cases indicating net increase or decrease in the respective forms of community's capital during project implementation stages. Comparative analysis of cases leads to the extraction of key components of community's capital that require support and strengthening in order to realise R-CES in practice.

4. Community Energy Case Studies

4.1 Case Study 1 – Chipopoma micro-hydro system, Malawi

The Chipopoma Micro-hydro Power Project is located in Livingstonia, a small town in Rhumpi district of northern Malawi. The power plant is situated close to Manchewe waterfalls and supplies electricity to the Manchewe community. It was developed by the local community with financial support from international development organisations. The formal planning of the project was started in 2015 when one of the villagers took the initiative to develop a micro-hydropower system using the natural stream of water flowing through the Manchewe waterfall. After sharing his vision with village representatives, he formed a network of volunteers in the community to realize the project. They approached various funding agencies and development organisations and eventually secured funding from UNDP, the Titus Foundation and the U.S. Embassy in different project stages.

After securing some initial rounds of funds and technical training support from UNDP, residents of Manchewe started installing the power plant in 2017. They formed a local not-for-profit body, 'Chipopoma Power' which acts as the Village Energy Committee (VEC) responsible for decision-making about the project's development and operation, including handling any community issues, needs and complaints. The project takes its name from 'Chipopoma,' an alternative name for the Manchewe waterfall. Due to lack of prior experience in power plant installation, community members were experimenting and learning simultaneously through their hit-and-trial approach. They approached technical experts who advised them in technical design and procurement of specific equipment. Nevertheless, the community effectively designed and constructed the turbine locally and procured machinery like generators, transformers, and switchgear from national and international suppliers. Technical training provided by the UNDP to local community members enabled them to establish a local power distribution infrastructure. The Chipopoma powerhouse with penstock carrying water to the turbine is shown in figure 4.

In 2019, Chipopoma Power extended the power lines to connect the first few households and started supplying electricity to community members. As of 2024, the project operates a 53 kVA generator supplying power to nearly 120 households, a school, a maize mill, two lodges, and a few commercial establishments. Users pay a one-time installation charge of 35,000 MWK ($20.3)[1] for a new connection. The charge covers the cost of extending the power line from the distribution system to the user's house. Users are charged with a flat tariff system, for which they need to pay 3500 MWK ($2.03)/month for using electricity from the micro-hydro system. The tariff covers the maintenance and operational cost of running the entire microgrid system. There is a plan to upgrade the project to connect more than 400 households and commercial establishments in the region.

(a) Powerhouse

(b) Penstock carrying water to the turbine

Figure 4 Chipopoma Power project at Manchewe (Source: Author's own)

4.1.1 Impact on the community's capital

The implementation of the Chipopoma project strengthened the community's capital in different forms. Since the concept of a micro-hydropower system was initiated by local community members, their participation from project planning to the operation stage improved

[1] $ = 1,724.13 Malawian Kwacha (MWK)

the community’s technical competency and project management skills at an advanced level. The project emphasises inclusiveness; currently, 10 out of 13 members in the Village Energy Committee (VEC) are women. Playing a role in tariff collection and power plant maintenance, community members developed customer management skills and capacities to enhance local governance. The Chipopoma project thus contributed to building the human and social capital of the Manchewe community.

Resulting new access to the power supply encouraged the development of electricity-driven businesses like maize mills, vegetable oil extractors, and coffee bean dryers. These projects have increased local employment opportunities and reduced people’s drudgery to fetch these services from distant markets. Businesses like barber shops, grocery stores, and hotels were upgraded, enhancing their profit margin. Households reduced their expenditure on kerosene and charcoal for lighting and cooking. New employment opportunities, upgraded businesses, and the increase in disposable income in households built the economic capital of the community. The procurement of different electricity-driven appliances like televisions, refrigerators, mobile phones developed the physical capital beyond the establishment of mini-grid distribution infrastructure and the powerhouse.

The Chipopoma project also enhanced the community’s natural capital. The availability of electricity reduced local demand for fuel wood, charcoal and other polluting fuels for cooking and other domestic applications, thus helping protect existing forests, which over the time are expected to increase the natural tree cover and improve air quality in the region. Table 1 presents the Chipopoma micro-hydro power project implementation stages and their impact on different components of community’s capital relevant to assess community’s resilience to withstand unforeseen disruptions.

Table 1: Effect of CES project implementation stages on components of community’s capital

Community’s capital dimensions	**Component of community’s capital**	**Project implementation stages and their effects on community’s capital**		
		Planning	**Installation**	**Operation**
Human	Funding acquisition skills	**+1**	**0**	**+1**
	Awareness towards renewable energy systems and climate change	**+1**	**+1**	**+1**
	Energy system planning skills	**+1**	**0**	**+1**
	Engineering system design knowledge	**+1**	**+1**	**0**
	Powerhouse operation and monitoring skills	**0**	**0**	**+1**
	Tariff collection and customer management skills	**0**	**0**	**+1**
	Health and wellbeing improvement	**0**	**0**	**+1**

	Improvement in primary education	**0**	**0**	**+1**
Social	Community mobilization	**+1**	**+1**	**+1**
	Strengthening of social bond	**+1**	**+1**	**+1**
	Formation of Village Energy Committee	**0**	**+1**	**+1**
	Group decision making capacity	**+1**	**+1**	**+1**
Economic	Generation of local employment	**0**	**+1**	**+1**
	Development of electricity driven businesses like maize mill, oil extractor, etc	**0**	**0**	**+1**
	Saving in expenditure on fossil fuel	**0**	**0**	**+1**
	Service upgradation and profit enhancement by electrifying existing businesses, such as travel lodge, barber shops, etc	**0**	**0**	**+1**
Physical	Electricity generation and distribution infrastructure	**0**	**+1**	**+1**
	Upgradation of household's physical capital through electric appliances	**0**	**0**	**+1**
	Establishment of communication channel through Television and mobile phones	**0**	**0**	**+1**
	Development of roads for transportation and local infrastructure	**0**	**0**	**0**
Natural	Natural forest cover	**0**	**0**	**+1**
	Air quality	**0**	**0**	**+1**
	Land and water resources	**0**	**0**	**0**

'+1' '-1' and '0' indicate 'positive', 'negative' and 'no significant effect' of CES implementation stages on components of community's capital

4.1.2 Managing disruptions

The operation of the micro-hydropower system at Manchewe has not been smooth because of several natural and socio-technical disruptions since operations started in 2019. Several lightning strikes and thunderstorms have caused damage to the microgrid infrastructure. In 2021, one of the transformers was blown out due to lightning strikes, costing 3.5 million MWK ($2030) to repair. The VEC arranged funding for the repair through the Titus Foundation. Moreover, lack of technological resources and knowledge in the community caused issues of phase imbalance and turbine breakout. Phase imbalance is a phenomenon that occurs due to uneven distribution of single-phase loads on the same power system. It may result in severe damage of generator and other equipment in the powerhouse. Turbine breakout is the term used for damage/ wear and tear in turbine parts.

In 2023, powerhouse machinery had frequent turbine breakouts and significant wear and tear in other equipment due to phase imbalance and design inefficiencies. The VEC carried out repairs but decided to operate the power plant at reduced capacity to minimise the risk of further breakouts. The VEC also approached different technical institutes and networks of organisations to acquire technical training and funds for installing breakers and protection systems against lightning. The GCRF-funded CESET project based at the University of Sheffield, together with Loughborough University and Addis Ababa University, provided technical support and a small grant to install protection devices and real-time monitoring systems, making the project more resilient to certain natural hazards and technological failures.

Additionally, the flat tariff system proved to be inefficient in generating sufficient revenue to connect additional consumers. Those connected consume unlimited power, leaving limited capacity to accommodate new connections and creating tensions among the community. Lack of working capital limits the VEC, which needs to procure poles and wires to extend distribution infrastructure to connect scattered households. The VEC procured funding for prepaid meters and a new billing system through a grant provided by the UNDP but currently facing practical challenges to implement it due to lack of technical experience. The current funding model barely covers day-to-day operations and routine maintenance and depends on voluntary work. The community is not maintaining any disaster recover funds, meaning that recovering from an unforeseen disruption will require external funding. Figure 5 shows the timeline of the project with implementation stages, instances of unforeseen events and present functionality.

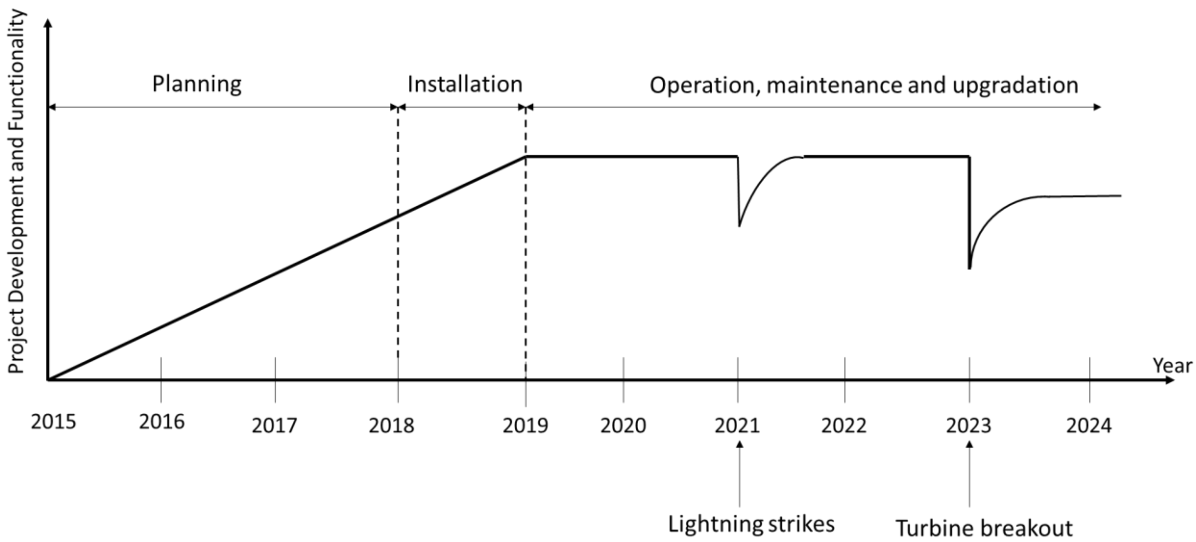

Figure 5 Project implementation stages, unforeseen events and functionality status (Source: Authors' own)

4.2 Case Study 2: Mdyaka Solar-Wind Hybrid System, Malawi

Mdyaka is a village in the Nkhata Bay district of northern Malawi. The Department of Energy (DoE), now Ministry of Energy, Government of Malawi installed a solar PV-Wind hybrid energy system in 2009 to supply electricity to 150 households. The project was one of the six pilot solar-wind hybrid energy systems implemented by the Department of Energy to demonstrate the application of renewable energy-based off-grid systems to electrify remote and rural communities. These projects were planned with an installed capacity of 20-25 kW to supply electricity to 100-150 households located within 1-km radius of the energy system. However, none of the projects are functional presently. The Solar PV-Wind hybrid mini-grid at Mdyaka was a 20 kW system for 150 consumers. The DoE officials accelerated planning to install a solar-wind hybrid mini-grid at Mdyaka in 2007. They surveyed Mdyaka in 2008 and installed the mini-grid in 2009. The DoE was responsible for arranging necessary funding for equipment, machinery and distribution infrastructure. The local community had little role in planning and installation and was not included in major decision-making. They were excluded in defining the criteria for selecting 150 beneficiaries and developing a business model for sustainable operation and maintenance of the system.

Consumers at the Mdyaka mini-grid had an unmetered supply and were not charged any tariff for their electricity consumption. The electricity was available only from 5 pm to 11 pm for lighting, mobile phone charging and watching television. Other high-energy-consuming appliances, such as induction stoves and refrigerators, were not allowed. There was an agreement between the DoE and consumers regarding system maintenance. The government was responsible for any significant technical issues and scheduled maintenance. The local community was responsible for looking after the security of equipment and machinery deployed in the powerhouse. Each household contributed 100 MWK ($0.058) per month to cover the cost of a security guard and replacement of bulbs installed for lighting the powerhouse. Since the government agency planned and installed this project, it was expected that the government would be responsible for any major maintenance and operational issues. The project functioned well for a few years after installation but became inoperative in 2013 due to unforeseen events and the community's limited capacity to cope with them.

4.2.1 Impact on the community's capital

Since community participation was minimal in the case of the Mdyaka Solar-Wind hybrid system, it similarly had a limited effect on the community's capital amid the process of project implementation. There was almost no community involvement during project planning and installation. Community members lacked and never developed any planning and design skills, but a few of them learned to operate the powerhouse and monitor the system.

Lack of community involvement during planning and installation meant that there was little mobilisation of community networks. As some households were connected and others were not, social bonds were weakening among community members. The project developers defined the selection criteria for beneficiaries, and community members perceived that they were not inclusive. The growing sense of discrimination among villagers harmed their collective decision-making capacity. The group of households connected to the mini-grid formed a small committee to collect monthly contributions from households to cover the cost of security guards. However, their role was not extended beyond it.

As a result of these dynamics, the project planning and installation had no significant effect on the community's economic capacity. However, the community's savings on fuel for lighting and domestic applications contributed to building households' economic capital during project operation. The purchase and use of different electric appliances during successful project operations contributed to building the physical capacity of households. However, de-functional assets and abandoned mini-grid infrastructure restricted the community from utilizing the engaged land and negatively influenced the community's physical capital. Table 2 presents the impact of CES implementation stages on Mdyaka's community capital.

Table 2: Effect of CES project implementation stages on components of community's capital

Community's capital dimensions	**Component of community's capital**	**Project implementation stages and their effects on community's capital**		
		Planning	**Installation**	**Operation**
Human	Funding acquisition skills	**0**	**0**	**0**
	Awareness towards renewable energy systems and climate change	**0**	**0**	**+1**
	Energy system planning skills	**0**	**0**	**0**
	Engineering system design knowledge	**0**	**0**	**0**
	Powerhouse operation and monitoring skills	**0**	**0**	**+1**
	Tariff collection and customer management skills	**0**	**0**	**+1**
	Health and wellbeing improvement	**0**	**0**	**0**
	Improvement in primary education	**0**	**0**	**0**
Social	Community mobilization	**0**	**0**	**0**
	Strengthening of social bond	**-1**	**-1**	**-1**
	Formation of Village Energy Committee	**0**	**0**	**+1**
	Group decision making capacity	**0**	**-1**	**-1**
Economic	Generation of local employment	**0**	**0**	**+1**
	Development of electricity driven businesses like maize mill, oil extractor, etc	**0**	**0**	**0**

	Saving in expenditure on fossil fuel	**0**	**0**	**+1**
	Service upgradation and profit enhancement by electrifying existing businesses, such as travel lodge, barber shops, etc	**0**	**0**	**0**
Physical	Electricity generation and distribution infrastructure	**0**	**+1**	**+1**
	Upgradation of household's physical capital through electric appliances	**0**	**0**	**+1**
	Establishment of communication channel through Television and mobile phones	**0**	**0**	**+1**
	Development of roads for transportation and local infrastructure	**0**	**0**	**0**
Natural	Natural forest cover	**0**	**0**	**+1**
	Air quality	**0**	**0**	**+1**
	Land and water resources	**0**	**0**	**0**

'+1' '-1' and '0' indicate 'positive', 'negative' and 'no significant effect' of CES implementation stages on components of community's capital

4.2.2 Managing disruptions

Several natural hazards have impacted the solar-wind hybrid system at Mdyaka in recent years. Lightning strikes are frequent in the region. In 2012, a lightning strike damaged the inverters in the powerhouse, which were repaired by the Energy Department's (DoE) technicians. In 2013, another lightning surge hit one of the windmills, partially damaging the turbine and traversing through inverters and batteries in the powerhouse, blowing out major equipment in the powerhouse and affecting the consumers connected with the system.

The intensity of this event was so severe that nearly 20 people got electric shocks in the connected households and had to be hospitalized. Many households reported damage to their appliances as well. Such an event could have been avoided if the DoE had proactively installed protection devices like lightning arrestors when similar but less severe events were experienced before the 2013 event. After this event, the energy system became inoperative, requiring significant repair and replacement of damaged equipment. Since major maintenance and repair was the responsibility of the Energy Department, consumers waited for the government's intervention to resume the project operation. However, no action was taken by the government for the next few years.

Community members tried to reinstate the project on their own. However, their inability to arrange funds and lack of technical experience restricted them from undertaking any repair. In 2018, government officials visited the site and detached solar panels from the mounting structures to use them at another site. By then, the batteries were already disposed of, and the costs of repairing the powerhouse and distribution infrastructure were too high to be feasible.

Figure 6 represents the project timeline with various instances of disruptions and stages of project implementation.

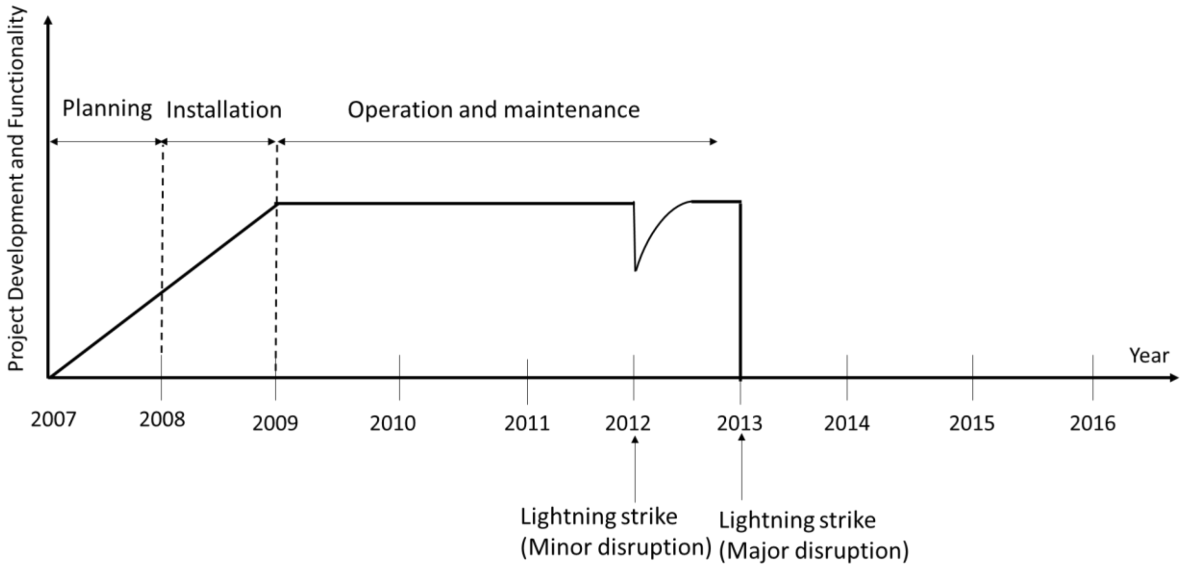

Figure 6 Project implementation stages, unforeseen events and functionality status (Source: Authors' own)

From 2013 to 2019, the community did not have any electricity supply and was dependent on traditional means of lighting, including kerosene. The lack of resilient energy system design, business model, community involvement in project implementation and equitable access to electricity supply failed this project. In 2019, the national grid entered the village, providing electricity connections to willing consumers who could pay for connection charges and household wiring. Presently, around 40% of the households in the village are connected to the national grid supply. Broken windmills, panel mounting structures, and powerhouse establishment of solar-wind hybrid system are still lies abandoned there as shown in Figure 7.

Figure 7 Abandoned Solar PV-Wind mini grid infrastructure at Mdyaka (Source: Author's own)

4.3 Case Study 3: Tabia Selam Solar-PV Water Pumping System, Ethiopia

Ethiopia has faced a significant water crisis over the past many years due to an uneven distribution of water sources, variable rainfall patterns and extreme weather events (UNICEF, 2022). Around 60 million residents in Ethiopia lack access to safe drinking water, which accounts for nearly half of the country's population (World Bank, 2023). The water crisis intensifies in conflict-prone regions as conflict reduces access to water resources. 'Tabia Selam' is a small village in the Shire district of the North-Western Zone of the Tigray region in Ethiopia. The residents of Tabia Selam did not have easy access to safe drinking water and used to walk miles to fetch drinking water from distant locations.

In 2021, World Vision, an International Non-Governmental Organization (NGO), installed a community-centred solar PV water pumping system to meet people's drinking water requirements. After a year of planning and consultation with the local community, World Vision successfully installed the project in 2022. The project has a capacity of 2kW and serves 55 households in Tabia Selam. The community participated actively during project installation by offering labour force and localized resources such as sand, gravel, food, and shelter to project partners.

After installation, the community took charge of operating the system by forming a Village Energy Committee (VEC), comprising of six members, three of whom are women, responsible for the operation, maintenance, and administration of the system. Additionally, they have one security guard and one female operator who assists with daily water distribution and collecting the money from users. Initially, users were charged 0.25 ETB ($ 0.002)[2] for using 20 litres of water, which was gradually raised to the present tariff of 1 ETB ($ 0.008) for 20 litres. The revenue generated through tariff collection covers the expenses for maintenance and salary of operators and security personnel.

4.3.1 Impact on the community's capital

Active participation of the community during project installation and operation developed the community's technical competency and project management skills. Access to safe drinking water has had a significant positive impact on the community's health and well-being. It saved the everyday drudgery of people who had to collect drinking water from far-located sources. It also improved the status of primary education among village children as they no longer needed to walk long distances to fetch water for their families and now could devote more time to their studies. The community's project management strengthened the members' social bond and generated local employment opportunities for system operators, technicians and security guards.

Furthermore, establishment of solar water pumping unit developed the community's assets in the form of physical capital. It also contributed to conservation of natural resources as establishment of this system resulted in more uniform utilization of underground water sources. Earlier the community was dependent on underground water sources located in nearby areas putting additional burden of their drinking water needs on single source. Table 3 presents the effect of different project implementation stages on community's capital of Tabia Selam.

Table 3 Effect of CES project implementation stages on components of community's capital

Community's capital dimensions	**Component of community's capital**	**Project implementation stages and their effects on community's capital**		
		Planning	**Installation**	**Operation**
Human	Funding acquisition skills	**+1**	**0**	**+1**
	Awareness towards renewable energy systems and climate change	**+1**	**+1**	**+1**
	Energy system planning skills	**+1**	**0**	**0**
	Engineering system design knowledge	**+1**	**+1**	**0**
	Power system operation and monitoring skills	**0**	**0**	**+1**
	Tariff collection and customer management skills	**0**	**0**	**+1**
	Health and wellbeing improvement	**0**	**0**	**+1**

[2] $ = 114.94 ETB

	Improvement in primary education	**0**	**0**	**+1**
Social	Community mobilization	**+1**	**+1**	**+1**
	Strengthening of social bond	**+1**	**+1**	**+1**
	Formation of Village Energy Committee	**0**	**+1**	**+1**
	Group decision making capacity	**+1**	**+1**	**+1**
Economic	Generation of local employment	**0**	**+1**	**+1**
	Development of electricity driven businesses like maize mill, oil extractor, etc	**0**	**0**	**0**
	Saving in expenditure on fossil fuel	**0**	**0**	**+1**
	Service upgradation and profit enhancement by electrifying existing businesses, such as travel lodge, barber shops, etc	**0**	**0**	**0**
Physical	Electricity generation and distribution infrastructure	**0**	**+1**	**+1**
	Upgradation of household's physical capital through electric appliances	**0**	**0**	**0**
	Establishment of communication channel through Television and mobile phones	**0**	**0**	**0**
	Development of roads for transportation and local infrastructure	**0**	**0**	**0**
Natural	Natural forest cover	**0**	**0**	**0**
	Air quality	**0**	**0**	**0**
	Land and water resources	**0**	**0**	**+1**

'+1' '-1' and '0' indicate 'positive', 'negative' and 'no significant effect' of CES implementation stages on components of community's capital

4.3.2 Managing disruptions

The community solar-PV water pumping system in Tabia Selam took an unexpected turn after few months of its operation. In November 2022, the system encountered a deliberate attempt of theft and destruction because of armed conflict and social unrest due to Tigray War in Ethiopia. The robbery of PV panels and partial damage to other equipment made the system inoperative immediately after the incident. During the Tigray war, it was extremely difficult to protect the equipment installed outside from extremists' actions. After this incident, the community failed to procure new PV panels to rejuvenate the system due to lack of funds. As the water pumping system had been installed just a few months before this unforeseen event, the VEC did not have any disaster recovery funds because of the short period of project operation. However, community members were continuously trying to reach out to donors, development organisations and officials of regional government by utilizing their social and human capital developed during project implementation stages.

War conditions, social unrest and broken supply chains in the region created hurdles for the community to reach potential agencies and technical partners which could support them to resume system operation. Through villagers' persistent efforts and support provided by the Tigray regional government, the community eventually managed to restore the system to its original state with external financial and technical support provided by World Vision. The system resumed its functionality in June 2023 after a disruption of seven months. This ended the residents' ordeal of walking more than three hours every day in an insecure environment to fetch drinking water from far-located sources. The system was reported to be working fine with its original functionality at the end of 2023.

Figure 8 represents the project timeline, showing instances of disruption and stages of project implementation. The restored system is shown in figure 9.

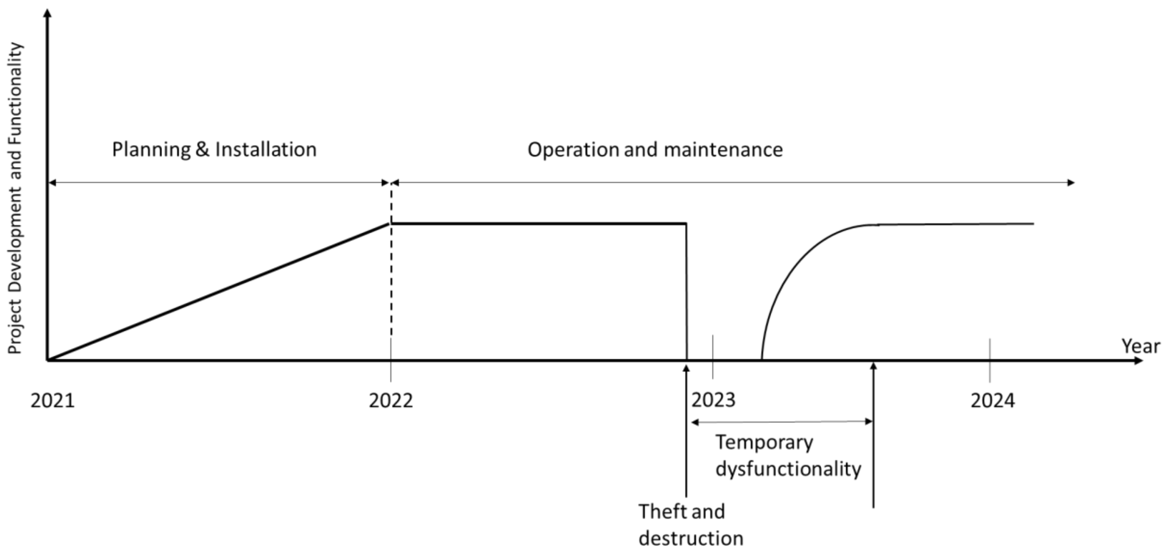

Figure 8 Project implementation stages, unforeseen events and functionality status (Source: Authors' own)

(a) Solar PV panels powering water pump (b) Power electronic controller

Figure 9 Solar-PV Water Pumping System at Tabia Selam, Shire (Source: Author's own)

5. Discussions

5.1 Comparison of cases

The case studies of CES deployed in varied geographical and socio-political contexts of Malawi and Ethiopia revealed various incidences of unforeseen disruptions/ shocks which a typical CE project encounters during the course of its operation. The critical analysis of cases explained how communities responded against such unforeseen disruptions and managed to recover and adapt through resilience developed during project implementation stages. For instance, the Chipopoma micro-hydro system in Malawi faced multiple lightning strikes and turbine break-outs, temporarily affecting the project's functionality. However, the community's resilience developed in the form of social and human capital during project implementation helped in the quick recovery from the destructive effects of such events. The community's skills and networks enabled them to arrange the necessary funds and technical support to cope with such events successfully.

Similarly, the community solar-PV water pumping system at Tabia Selam in Ethiopia faced deliberate theft and destruction, which resulted in the system's dysfunctionality for seven months. Anticipating and avoiding such events many times appeared to be beyond the community's capacity. However, the community's evolved resilience in the form of social and human capital once again enabled them to secure financial and technical support to recover from such unforeseen events and restore the system's intended functionality. On the contrary, in the case of the Mdyaka Solar-Wind hybrid system, the community did not succeed in restoring the system's functionality owing to the weak social, human and economic capital of the community. The lack of community participation in project implementation stages did not provide enough opportunities for people to develop their technical and management skills. The lack of community mobilization and inclusion of limited households in the village to become the project's beneficiaries developed a notion of discrimination among villagers and weakened their social bond. This limits the community's resilience and its ability to recover from unforeseen events and disruptions.

Table 4 shows the comparative analysis of CES cases discussed, concerning dimensions of the community's capital, the type of disruptions faced by these projects and their present functional status. Net increase/ decrease in community's capital was evaluated by aggregating the effects of CES implementation stages on all components of community's capital within each dimension represented in Tables 1-3. Positive value of aggregated effects indicates net increase while negative value indicates net decrease for respective dimension of community's capital. For instance, aggregating the effects on all components of social capital for Chipopoma case results in value of '11', which is positive (greater than zero), indicating increase in social capital.

There observed to be a net increase in all forms of community's capital in the case of the Chipopoma micro hydro and Tabia Selam solar-PV water pumping system project. However, Mdyaka solar-wind hybrid system reported net decrease in social capital. This does not necessarily mean that projects which do not report a net increase in all forms of community capital are unable to recover from unforeseen disruptions and vice-versa. It is apparent from case analysis that there is a slight development in the community's human and economic capital in case of Mdyaka, but it is much lower as compared to the case of Chipopoma and Tabia Selam. Active community participation in project implementation stages in case of Chipopoma and Tabia Selam resulted in significant development of the community's capacity to cope with unforeseen disruptions faced during project operation.

Table 4 Comparative analysis of cases

Case Studies	**Community's capital**					**Type of disruption**	**Present status**
	Human	**Social**	**Economic**	**Physical**	**Natural**		
Chipopoma micro-hydro system	⇧	⇧	⇧	⇧	⇧	Lightning strikes, turbine breakout	Functional with reduced capacity
Mdyaka solar-wind hybrid system	⇧	⇩	⇧	⇧	⇧	Lightning strikes	Dysfunctional
Tabia Selam solar-PV water pumping system	⇧	⇧	⇧	⇧	⇧	Theft and destruction	Functional with initial installed capacity

⇧ represents net increase; ⇩ represents net decrease in community's capital during project functionality

5.2 Realising Resilient Community Energy Systems

Comparative analysis of cases revealed significance of certain key components of community's capital for realising Resilient Community Energy System (R-CES). These key components are extracted by comparing their role in determining resilience of CES cases analysed. CES stakeholders should pay attention to these components during the project implementation stages. These key components constitute the framework to realise R-CES in practice as explained below and represented in figure 10.

Engineering system design, maintenance and operational skills

Communities with sound engineering knowledge and system operation skills recover quickly following an unforeseen disruption, rather than communities with little technical know-how. This is evident in the case of Chipopoma, where the community managed to recover quickly after facing lightning strikes and turbine breakout issues. Thus, CES developers should consider involving community members in a way that maximises their engineering knowledge and system operation skills during the project implementation stages.

Financial management and networking skills

Since CES projects are typically operated and managed by the local community, community members should be adequately trained in project management, especially finances. They should know how to design optimal tariff and connection fees, which cover maintenance charges, operators' salaries and disaster recovery funds. The community should learn basic funding acquisition and networking skills to communicate effectively with development agencies, utilities, and NGOs and seek external support in situations beyond the community's control. CES project implementers should impart these project management skills to community members by involving them in project's planning and operation.

Community mobilization

Community mobilization is the process of developing a shared vision among community members. It involves bringing together all individuals, groups and sections of society to accomplish a common objective. It raises awareness among community members, strengthens their participation in project management and makes them accountable for the project's sustainability. Realizing resilient CES requires community mobilisation right from the project planning/ conceptualization stage. It involves consulting the community for utilization of local resources like land, water, labour force, etc., during project implementation. The community is further engaged in tariff determination and financial management. It is apparent through case studies that CES projects, such as Chipopoma and Tabia Selem, which mobilised their communities during project implementation, showed enhanced resilience to withstand unforeseen disruptions.

Constitution of strong Energy Committee

CES projects' successful management and operation is dependent on local governance and community's decision-making capacity. This can be achieved by constituting a strong and democratic energy committee representing all sections of society which could cater needs of all including most vulnerable individuals/ groups in the community. Energy committee plays a critical role in realizing resilient CES. It is responsible to take any pro-active actions needed to anticipate a potential risk and minimize its impact. Energy committee is a formal decision-making body to take any responsive action to absorb the severity of a disaster and to develop a recovery plan to restore the project's functionality. It is further responsible to take necessary decisions for transforming the project to an adaptive capacity for avoiding similar destruction from future events.

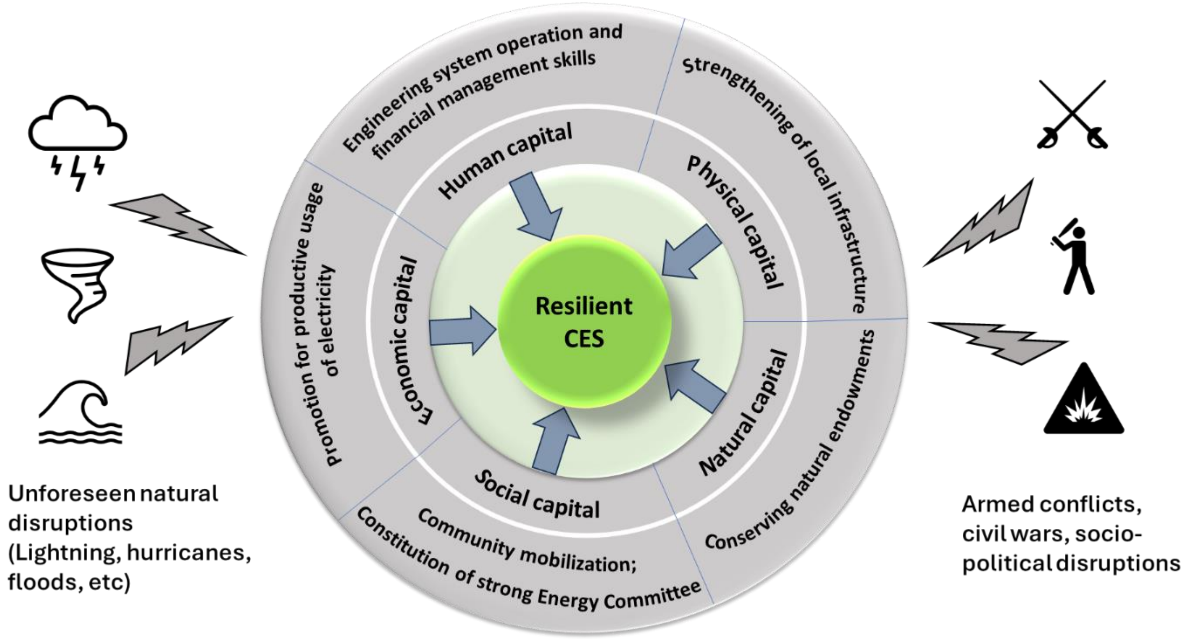

Figure 10 Resilient Community Energy Systems (R-CES) Framework (Source: Author's own)

Promotion for productive usage of electricity

Though CES are basically aimed to provide reliable and clean electricity access to under-served households, they are equally relevant in driving small scale businesses and livelihood applications. For instance, solar-PV water pumping system in Tabia Selam is a community energy system dedicated to serve drinking water requirements of local residents. Similarly, Chipopoma power is supplying electricity not only to households but also commercial establishments like maize mill, barber shops, travel lodge, etc. Development and service upgradation of such businesses contributes to building the economic capital of community by generating local employment and creating diverse income streams for residents. This helps community to recover rapidly through economic crisis post disruption. CES developers should promote development of electricity driven businesses and make reasonable arrangements for productive usage of electricity by consulting local community while planning CES implementation.

Strengthening of local infrastructure

Implementation of CES in a region directly or indirectly contributes in development of other forms of local infrastructure such as telecommunication, internet, healthcare centres, etc. which acts like a lifeline to recover rapidly following an unforeseen disruption. Moreover, development of small and medium scale enterprises mitigates supply chain challenges raised following a disruption. CES stakeholders should consider development of local facilities such as radio, internet, hospitals, schools, community centre, roads and transportation. All these forms of community's physical capital enable community to rapidly produce goods and services for recovering fast through an economic breakdown following a disruption. Availability of public infrastructure and communication channels further enhances the reachability of relief work and external aid, thereby minimising the immediate impact of disruption.

Conserving natural endowments

Since CES typically utilizes locally available natural resources for energy generation, their very existence depends on availability and balance of natural resources in the region. For instance, a micro-hydro power CES can't continue to operate seamlessly unless there is a stream flow of water through the source supplying water to the system. Communities engaged in such projects used to construct embankments and plant trees to conserve the water flow. Moreover, severity of natural disasters could be reduced by adopting environmental conservation methods. For example, impact of floods due to heavy rainfall could be absorbed by increasing natural tree cover in the region. Conservation of natural endowments not only reduce the impact of natural hazards but also contributes in maintaining the functionality of CES, making them resilient against unforeseen events. CES stakeholders should pay enough attention towards conserving natural resources and controlling their pollution by making proper arrangements for safe disposal of damaged/ end-of-life equipment used in CES implementation.

6. Conclusion

Community Energy Systems have emerged to become a promising solution to provide clean, reliable and last mile electricity access across remote and risk prone regions in Africa and driving a broader sustainable energy transition in the Global South. However, making CES resilient against unforeseen shocks/ disruptions has been a matter of concern as some of such initiatives were reportedly failed to maintain their functionality while coping with disruptions. In-depth case study analysis of CES projects implemented in different geographical and socio-political contexts in two countries revealed, 'building community's resilience' is the key to realise Resilient CES (R-CES). It implies resilience of CES likely depends on the way, they have been implemented. Community's capacity in the form of social, human, economic, physical and natural capital is the measure of its resilience to withstand against unforeseen events/ disruptions.

This study evaluated development of different components of community's capital during CES project implementation stages through empirical research. Novel contribution is the case study analysis demonstrating interrelationship between stages of CES implementation and community's capital. Comparative analysis of cases explained the effect of community's evolved resilience to cope with unforeseen disruptions and proposed a framework to realise R-CES based on seven key components of community's capital. Critical analysis of cases revealed that community's participation in CES implementation stages is the basis to develop all forms of community's capital. However, CES developers/ managers should know the ways of effective community participation for realising a resilient CES. CES implementers must ensure to develop community's human capital by imparting technical and project management skills among community members. They should take care of maintaining uniformity in benefit sharing of CES project across different sections of society leaving no scope for discrimination.

CES developers should pay enough attention towards community's mobilisation, strengthening of social bond and decision-making capacity of members. They should involve community by making reasonable arrangements for productive usage of electricity. Provisions should be made to supply electricity to shops, small businesses, agriculture and other livelihood applications to enhance community's economic capital by promoting diversified income generating streams. Further, CES stakeholders should consider development of robust engineering system design and strengthening of local infrastructure by taking into account any potential risks/ disruptions to energy system. They should disseminate knowledge and awareness among community members to protect their physical and natural capital as these become the lifeline to recover quickly following an unforeseen disruption.

These practices/ recommendations for realizing R-CES are derived through case studies undertaken in this study. There might likely be the case that some factors sound critical in determining the resilience of one project but not for others. Additionally, there is a scope of including new factors in R-CES framework sharing commonality in other CES projects in future. However, their association with broad dimensions of community's capital would remain same. In general, it could be inferred, strengthening community's capital in every possible way leads to the realisation of R-CES in practice.

Further, this study analysed the effect of CES implementation stages over components of community's capital through qualitative assessment as this approach suits well with respect to the data available for case studies. However, this study could be taken to more quantitative level by grading the effects on a Likert scale and asking the respondents to rate them. Their responses could be analysed through multi criteria decision making techniques to evaluate the optimum strategy for deployment of resilient CES within a region/ community setting. This requires an advanced research plan and data collection approach which could be explored in future studies.

Data Availability Statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Ethical Statement

The authors confirm that appropriate ethical approval and consent was obtained for the interviews conducted in this work.

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Conflict of interest

The authors have no personal conflicts of interest. Likewise, they are responsible for the publication of this paper.

References

Ambole, A. *et al.* (2021) 'A Review of Energy Communities in Sub-Saharan Africa as a Transition Pathway to Energy Democracy', *Sustainability*. Available at: https://doi.org/10.3390/su13042128.

Antwi, S.H. and Ley, D. (2021) 'Renewable energy project implementation in Africa: Ensuring sustainability through community acceptability', *Scientific African*, 11, p. e00679. Available at: https://doi.org/https://doi.org/10.1016/j.sciaf.2020.e00679.

Berger, T. (2017) 'Practical constraints for photovoltaic appliances in rural areas of developing countries: Lessons learnt from monitoring of stand-alone systems in remote health posts of North Gondar Zone, Ethiopia', *Energy for Sustainable Development*, 40, pp. 68–76. Available at: https://doi.org/https://doi.org/10.1016/j.esd.2017.07.001.

Berka, A.L. and Creamer, E. (2018) 'Taking stock of the local impacts of community owned renewable energy: A review and research agenda', *Renewable and Sustainable Energy Reviews*, 82, pp. 3400–3419. Available at: https://doi.org/https://doi.org/10.1016/j.rser.2017.10.050.

Boston, M. *et al.* (2024) 'Community resilience: A multidisciplinary exploration for inclusive strategies and scalable solutions', *Resilient Cities and Structures*, 3(1), pp. 114–130. Available at: https://doi.org/https://doi.org/10.1016/j.rcns.2024.03.005.

Brummer, V. (2018) 'Community energy – bene fi ts and barriers : A comparative literature review of Community Energy in the UK , Germany and the USA , the bene fi ts it provides for society and the barriers it faces', 94(June), pp. 187–196. Available at: https://doi.org/10.1016/j.rser.2018.06.013.

Cafer, A., Green, J. and Goreham, G. (2019) 'A Community Resilience Framework for community development practitioners building equity and adaptive capacity', *Community Development*, 50(2), pp. 201–216. Available at: https://doi.org/10.1080/15575330.2019.1575442.

Carmen, E. *et al.* (2022) 'Building community resilience in a context of climate change: The role of social capital', *Ambio*, 51(6), pp. 1371–1387. Available at: https://doi.org/10.1007/s13280-021-01678-9.

CARRI (2013) *Definitions of Community Resilience: an Analysis*, *Carri Report*. Available at: http://www.resilientus.org/library/CARRI_Definitions_Dec_2009_1262802355.pdf.

Department for International Development (1999) *Sustainable livelihoods guidance sheets*.

Department of Disaster Management Affairs (2022) *MALAWI: Tropical Storm ANA Situation Report - 2*.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (2023) *Rehabilitation of Micro-Hydropower Plants in Ethiopia Enabling Energy Cooperatives to Power Rural Communities*.

Dimitris Kitsikopoulos, C.V. (2023) *The Social Impact of Energy Communities in Greece*. Available at: https://www.rescoop.eu/uploads/rescoop/downloads/Social-Impact-of-EC-in-Greece_EN_FINAL.pdf.

Disasters Emergency Committee (2019) *2019 cyclone IDAI appeal final report*. Available at: https://www.dec.org.uk/sites/default/files/media/document/2021-10/DEC_Idai Report final_21_HR_SP_AW.-compressed.pdf.

Doussard, M. and Yenigun, O. (2022) ‘From Capital to Capabilities: Human Development Theory and New Directions in Economic Development’, *Journal of Planning Education and Research*, 44(3), pp. 1542–1555. Available at: https://doi.org/10.1177/0739456X221091434.

EGENCO (2023) *EGENCO Restores Kapichira*. Available at: https://www.egenco.mw/egenco-restores-kapichira/#:~:text=Although Kapichira Power Station has,Company ten billion Malawi Kwacha.

Gebreslassie, M.G. (2024) ‘The Role of Community Energy and the Challenges in a State-Led Model of Service Provision in Ethiopia BT - Community Energy and Sustainable Energy Transitions: Experiences from Ethiopia, Malawi and Mozambique’, in V. Castán Broto (ed.). Cham: Springer Nature Switzerland, pp. 147–169. Available at: https://doi.org/10.1007/978-3-031-57938-7_7.

Gebreslassie, M.G. and Cuvilas, C. (2023) ‘The role of community energy systems to facilitate energy transitions in Ethiopia and Mozambique’, *Energy Systems* [Preprint]. Available at: https://doi.org/10.1007/s12667-023-00640-w.

Gorroño-Albizu, L., Sperling, K. and Djørup, S. (2019) ‘The past, present and uncertain future of community energy in Denmark: Critically reviewing and conceptualising citizen ownership’, *Energy Research & Social Science*, 57, p. 101231. Available at: https://doi.org/https://doi.org/10.1016/j.erss.2019.101231.

Hafeznia, H. and Stojadinović, B. (2024) ‘Resilience-based decision support system for installing standalone solar energy systems to improve disaster resilience of rural communities’, *Energy Strategy Reviews*, 54, p. 101489. Available at: https://doi.org/https://doi.org/10.1016/j.esr.2024.101489.

Hotaling, C., Bird, S. and Heintzelman, M.D. (2021) ‘Willingness to pay for microgrids to enhance community resilience’, *Energy Policy*, 154, p. 112248. Available at: https://doi.org/https://doi.org/10.1016/j.enpol.2021.112248.

Huang, Z. *et al.* (2017) ‘Planning community energy system in the industry 4.0 era: Achievements, challenges and a potential solution’, *Renewable and Sustainable Energy Reviews*, 78, pp. 710–721. Available at: https://doi.org/https://doi.org/10.1016/j.rser.2017.04.004.

Human Rights Watch and Amnesty International (2022) *“We Will Erase You from This Land” Crimes Against Humanity and Ethnic Cleansing in Ethiopia’s Western Tigray Zone*. Available at: https://www.hrw.org/sites/default/files/media_2022/06/ethiopia0422_web_0.pdf.

Hussain, A., Bui, V.-H. and Kim, H.-M. (2019) ‘Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience’, *Applied Energy*, 240, pp. 56–72. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2019.02.055.

Joshi, G. and Yenneti, K. (2020) ‘Community solar energy initiatives in India: A pathway for addressing energy poverty and sustainability?’, *Energy and Buildings*, 210, p. 109736. Available at: https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109736.

Khalid, R. *et al.* (2023) ‘Towards equitable and inclusive energy systems for remote off-grid communities: A socio-technical assessment of solar power for village Helario in Tharparkar, Pakistan’, *Renewable and Sustainable Energy Transition*, 4, p. 100067. Available at:

https://doi.org/https://doi.org/10.1016/j.rset.2023.100067.

Khalid, R. *et al.* (2024) 'Community energy and socio-technical infrastructure resilience: analysis of mini/micro hydro power projects in Khyber Pakhtunkhwa, Pakistan', *Environmental Research: Infrastructure and Sustainability*, 4(3), p. 35015. Available at: https://doi.org/10.1088/2634-4505/ad7886.

Koliou, M. *et al.* (2020) 'State of the research in community resilience: progress and challenges', *Sustainable and Resilient Infrastructure*, 5(3), pp. 131–151. Available at: https://doi.org/10.1080/23789689.2017.1418547.

Lai, P.S. *et al.* (2024) 'Household Air Pollution Interventions to Improve Health in Low- and Middle-Income Countries: An Official American Thoracic Society Research Statement', *American Journal of Respiratory and Critical Care Medicine*, 209(8), pp. 909–927. Available at: https://doi.org/10.1164/rccm.202402-0398ST.

Mayunga, J. and Peacock, G.W. (2010) *The Development of a Community Disaster Resilience Framework and Index in edited report, Advancing the Resilience of Coastal Localities: Developing, Implementing and Sustaining the Use of Coastal Resilience Indicators*. Available at: https://doi.org/10.13140/RG.2.2.23402.75201.

Mazur, C. *et al.* (2019) 'A holistic resilience framework development for rural power systems in emerging economies', *Applied Energy*, 235, pp. 219–232. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2018.10.129.

Michael, B., Ben, S. and Mike, H. (2021) 'Use of Advanced Microgrids to Support Community Resilience', *Natural Hazards Review*, 22(4), p. 5021012. Available at: https://doi.org/10.1061/(ASCE)NH.1527-6996.0000449.

Miller, S. (2024) *Scars of War and Deprivation: An Urgent Call to Reverse Tigray 's Humanitarian Crisis*. Available at: https://d3jwam0i5codb7.cloudfront.net/wp-content/uploads/2024/02/Ethiopia-Report-MAR-2024.pdf.

Mulugetta, Y. *et al.* (2022) 'Africa needs context-relevant evidence to shape its clean energy future', *Nature Energy*, 7(11), pp. 1015–1022. Available at: https://doi.org/10.1038/s41560-022-01152-0.

Mutani, G. *et al.* (2021) 'An energy community for territorial resilience: Measurement of the risk of an energy supply blackout', *Energy and Buildings*, 240, p. 110906. Available at: https://doi.org/https://doi.org/10.1016/j.enbuild.2021.110906.

Neveu, E. (2018) '347Bourdieu's Capital(s): Sociologizing an Economic Concept', *The Oxford Handbook of Pierre Bourdieu*. Edited by T. Medvetz and J.J. Sallaz. Oxford University Press, p. 0. Available at: https://doi.org/10.1093/oxfordhb/9780199357192.013.15.

Norris, F.H. *et al.* (2008) 'Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness', *American Journal of Community Psychology*, 41(1–2), pp. 127–150. Available at: https://doi.org/10.1007/s10464-007-9156-6.

Pretty, J. and Ward, H. (2001) 'Social Capital and the Environment', *World Development*, 29(2), pp. 209–227. Available at: https://doi.org/https://doi.org/10.1016/S0305-750X(00)00098-X.

Samarakoon, S. (2020) 'The troubled path to ending darkness: Energy injustice encounters in Malawi's off-grid solar market', *Energy Research & Social Science*, 69, p. 101712. Available at: https://doi.org/https://doi.org/10.1016/j.erss.2020.101712.

Sen, A. (2001) *Development as Freedom*. United States: Oxford University Press.

Shapira, S., Shibli, H. and Teschner, N. (2021) 'Energy insecurity and community resilience: The experiences of Bedouins in Southern Israel', *Environmental Science & Policy*, 124, pp. 135–143. Available at: https://doi.org/https://doi.org/10.1016/j.envsci.2021.06.006.

Shastry, V. and Rai, V. (2025) 'Beyond the business case: Impacts and resilience post-adoption of decentralized renewable energy for rural livelihoods', *Energy for Sustainable Development*, 84, p. 101600. Available at: https://doi.org/https://doi.org/10.1016/j.esd.2024.101600.

Süsser, D., Döring, M. and Ratter, B.M.W. (2017) 'Harvesting energy: Place and local entrepreneurship in community-based renewable energy transition', *Energy Policy*, 101(C), pp. 332–341. Available at: https://econpapers.repec.org/RePEc:eee:enepol:v:101:y:2017:i:c:p:332-341.

Thapar, S., Sharma, S. and Verma, A. (2017) 'Local community as shareholders in clean energy projects: Innovative strategy for accelerating renewable energy deployment in India', *Renewable Energy*, 101, pp. 873–885. Available at: https://doi.org/https://doi.org/10.1016/j.renene.2016.09.048.

To, L.S. *et al.* (2021) 'A research and innovation agenda for energy resilience in Pacific Island Countries and Territories', *Nature Energy*, 6(12), pp. 1098–1103. Available at: https://doi.org/10.1038/s41560-021-00935-1.

To, L.S. and Subedi, N. (2019) 'Towards community energy resilience', in *Energy Access and Forced Migration*, pp. 81–91. Available at: https://doi.org/10.4324/9781351006941-8.

UNDP Drylands Development Centre (2016) *Community Based Resilience Analysis (CoBRA) Conceptual Framework and Methodology*. Available at: https://www.undp.org/publications/cobra-conceptual-framework.

UNICEF (2022) *Water Crisis in the Horn of Africa: UNICEF Advocacy Brief*. Available at: https://www.unicef.org/media/126006/file/water-crisis-horn-africa-2022.pdf.

Vallecha, H. and Bhola, P. (2019) 'Sustainability and replicability framework: Actor network theory based critical case analysis of renewable community energy projects in India', *Renewable and Sustainable Energy Reviews*, 108, pp. 194–208. Available at: https://doi.org/10.1016/j.rser.2019.03.053.

Vallecha, H. and To, L.S. (2024) 'Community Energy and Community Resilience: A Multi-Dimensional Perspective BT - Community Energy and Sustainable Energy Transitions: Experiences from Ethiopia, Malawi and Mozambique', in V. Castán Broto (ed.). Cham: Springer Nature Switzerland, pp. 23–44. Available at: https://doi.org/10.1007/978-3-031-57938-7_2.

Walker, G. *et al.* (2010) 'Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy', *Energy Policy*, 38(6), pp. 2655–2663. Available at: https://doi.org/10.1016/j.enpol.2009.05.055.

Walker, G. and Devine-Wright, P. (2008) 'Community renewable energy: What should it mean?', *Energy Policy*, 36(2), pp. 497–500. Available at: https://doi.org/https://doi.org/10.1016/j.enpol.2007.10.019.

Walker, G. and Simcock, N. (2012) ‘Community Energy Systems’, in S.J.B.T.-I.E. of H. and H. Smith (ed.). San Diego: Elsevier, pp. 194–198. Available at: https://doi.org/https://doi.org/10.1016/B978-0-08-047163-1.00598-1.

World Bank (2019) *Disaster Risk Profile: Ethiopia*. Available at: https://www.gfdrr.org/sites/default/files/publication/ethiopia_low.pdf.

World Bank (2023) *Promoting Sustainable and Equitable WASH in Ethiopia*. Available at: https://www.worldbank.org/en/news/feature/2023/11/10/promoting-sustainable-and-equitable-wash-in-ethiopia#:~:text=Despite these strides%2C approximately 60,22 million continuing open defecation.

Zigale, T.T., Muleta, T.N. and Mohammed, M.J. (2019) ‘Assessment of Cause of Huluka Micro Hydro Power Scheme Failure and Estimation of Its Potential’, *International Journal of Research -GRANTHAALAYAH*, 7(8), pp. 292–300. Available at: https://doi.org/10.29121/granthaalayah.v7.i8.2019.672.