Sustainable rural electrification through community-managed mini-grids: Evidence from Tanzania

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approved dissertation by
Irene Fredolin Ngoti
born on 30.10.1988 in Kilimanjaro, Tanzania

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First supervisor:
Dr. Lars Holstenkamp, Leuphana University, Lüneburg, Germany

First reviewer:
Prof. Dr. Claudia Kemfert, Leuphana University, Lüneburg, Germany

Second reviewer:
Prof. Dr. Burkhard Hehenkamp, University of Paderborn, Germany

Third reviewer:
Prof. Dr. iur. Thomas Schomerus, Leuphana University, Lüneburg, Germany

The individual contributions to the cumulative dissertation project are or will be published as follows:

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Author's address:
Leuphana University Lüneburg
Faculty of Sustainability
Universitätsallee 1
21335 Lüneburg
Germany
[redacted]

Dedication

To my beloved parents, Fredolin Ngoti and Domithila Minde;

and to my beloved daughters, Aracely and Adrielle.

I love you.

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Abstract

Mini-grids are progressively promoted as a viable solution for rural electrification in Sub-Saharan Africa. Yet, experiences show mixed results, with some struggling to survive and some failing or ceasing operations prematurely. This dissertation integrates evidence from East Africa using the institutional analysis and development (IAD) framework, Agrawal's enabling conditions, a sense of ownership analytical framework, and the coupled infrastructure systems (CIS) framework to examine the sustainability and success of containerised solar mini-grids, specifically community-managed ones. It first analyses the sustainability factors independently (Chapters II to IV) and then the contributing factors for the failure of community-managed mini-grids (Chapter V).

The first research aim of this dissertation–analysing the institutional frameworks governing mini-grid development and operations in Uganda and Tanzania and identifying key factors contributing to sustainable rural electrification is addressed in Chapter II. In this chapter, mini-grid actors' interactions, institutional and socio-cultural factors affecting mini-grid sustainability, and comparative mini-grid institutional performance between Uganda and Tanzania were analysed. This chapter gives a macro-level understanding of mini-grid institutions by utilizing the IAD framework from a micro-level. The findings in this chapter demonstrate complex multi-level interactions among mini-grid actors and institutional inefficiencies that can lead to mini-grid failure if not addressed.

Chapters III and IV were both involved in addressing the second research aim–investigating the effects of institutional arrangements and community sense of ownership on the sustainable management of community-based mini-grids in Tanzania. This chapter offers an understanding of mini-grids' sustainability from a micro level by focusing on community-managed mini-grids. With the aid of Agrawal's enabling conditions and a sense of ownership analytical framework, respectively, strong rules enforcement on maintenance management, and a strong sense of ownership (through tariff payment, decision making, and participation) among mini-grid users are found to be vital for mini-grid sustainability.

To identify and analyse the key factors contributing to the failure of solar community-managed mini-grids in Tanzania, Chapter V utilised the CIS framework that demonstrated community-managed mini-grid systems as coupled infrastructure systems. With the help of causal loop diagrams, findings in this chapter show failure of mini-grids is due to the interdependencies

across technical, institutional, social, and political (external) factors. While all examined cases exhibited financial challenges in terms of having insufficient balances for maintenance, they were also subjected, with varying intensity, to non-compliant behaviour in paying tariffs, the absence of mini-grid legal ownership, and local political interference. Long-term sustainability of community-managed mini-grids therefore needs to be approached through a systemic lens.

Zusammenfassung

Mini-Grids werden zunehmend als praktikable Lösung für die Elektrifizierung ländlicher Gebiete in Subsahara-Afrika gefördert. Die Erfahrungen zeigen jedoch gemischte Ergebnisse: Einige kämpfen ums Überleben, andere scheitern oder stellen ihren Betrieb vorzeitig ein. Diese Dissertation integriert Erkenntnisse aus Ostafrika unter Verwendung des „institutional analysis and development“(IAD) -Framework, der „Agrawal's enabling conditions“, eines analytischen Rahmens für das Gefühl der Eigenverantwortung, und des coupled infrastructure systems (CIS) -Framework, um die Nachhaltigkeit und den Erfolg von containerisierten Solar-Mini-Grids, insbesondere von gemeinschaftlich verwalteten, zu untersuchen. Zunächst werden die Nachhaltigkeitsfaktoren unabhängig voneinander analysiert (Kapitel II bis IV) und anschließend die Faktoren, die zum Scheitern von gemeinschaftlich verwalteten Mininetzen beitragen (Kapitel V).

Das erste Forschungsziel dieser Dissertation – die Analyse der institutionellen Rahmenbedingungen für die Entwicklung und den Betrieb von Mini-Grids in Uganda und Tansania sowie die Ermittlung der wichtigsten Faktoren, die zu einer nachhaltigen ländlichen Elektrifizierung beitragen – wird in Kapitel II behandelt. In diesem Kapitel wurden die Interaktionen der Akteure im Bereich der Mininetze, institutionelle und soziokulturelle Faktoren, die die Nachhaltigkeit von Mini-Grids beeinflussen, sowie die institutionelle Leistung von Mini-Grids in Uganda und Tansania vergleichend analysiert. Dieses Kapitel vermittelt ein makroökonomisches Verständnis der Mini-Grid -Institutionen unter Verwendung des IAD-Frameworks auf Mikroebene. Die Ergebnisse dieses Kapitels zeigen komplexe Interaktionen auf mehreren Ebenen zwischen den Akteuren im Bereich der Mini-Grids sowie institutionelle Ineffizienzen auf, die zum Scheitern von Mini-Grids führen können, wenn sie nicht behoben werden.

Die Kapitel III und IV befassen sich beide mit dem zweiten Forschungsziel – der Untersuchung der Auswirkungen institutioneller Regelungen und des gemeinschaftlichen Verantwortungsgefühls auf die nachhaltige Verwaltung von gemeinschaftsbasierten Mini-Grids in Tansania. Dieses Kapitel bietet ein Verständnis der Nachhaltigkeit von Mini-Grids auf der Mikroebene, indem es sich auf gemeinschaftlich verwaltete Mini-Grids konzentriert. Mit Hilfe von Agrawals analytischem Rahmen für förderliche Bedingungen und Eigenverantwortung wurde festgestellt, dass eine strenge Durchsetzung von Regeln für das Wartungsmanagement und ein starkes Gefühl der Eigenverantwortung (durch Tarifzahlung,

Entscheidungsfindung und Beteiligung) unter den Mini-grid-Nutzern für die Nachhaltigkeit von Mini-Grids von entscheidender Bedeutung sind.

Um die Schlüsselfaktoren zu identifizieren und zu analysieren, die zum Scheitern von solarbetriebenen, von der gemeinschaftlich verwalteten Mini-Grids in Tansania beitragen, wurde in Kapitel V das CIS-Framework verwendet, welches gemeinschaftlich verwaltete Mini-Grid-Systeme als gekoppelte Infrastruktursysteme darstellt. Mit Hilfe von Kausalschleifendiagrammen zeigen die Ergebnisse in diesem Kapitel, dass das Scheitern von Mini-Grids auf die gegenseitigen Abhängigkeiten zwischen technischen, institutionellen, sozialen und politischen (externen) Faktoren zurückzuführen ist. Während alle untersuchten Fälle finanzielle Herausforderungen in Form unzureichender Mittel für die Instandhaltung aufwiesen, waren sie auch in unterschiedlichem Ausmaß mit nicht konformem Verhalten bei der Zahlung von Tarifen, dem Fehlen eines rechtlichen Eigentums an den Mini-Grids und lokalen politischen Einmischungen konfrontiert. Die langfristige Nachhaltigkeit von gemeinschaftlich verwalteten Mini-Grids muss daher aus einer systemischen Perspektive betrachtet werden.

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ADA	Austrian Development Agency
CBM	Community-based mini-grids
CIS	Coupled Infrastructure Systems
CLD	Causal Loop Diagrams
CPR	Common-Pool Resources
ERA	Electricity Regulatory Authority
ESMAP	Energy Sector Management Assistance Programme
EWURA	Energy and Water Utilities Regulatory Authority
FBO	Faith-based Organizations
FGDs	Focus Group Discussions
IAD	Institutions and Development
M&E	Monitoring and evaluation
NDP	National Development Plan
NEMA	National Management Environment Authority
NEMC	National Environment Management Council
NGO	Non-profit Organization
O&M	Operations and maintenance
PV	Photovoltaics
RA	Research Aim
REA	Rural Energy Agency
REF	Rural Energy Fund
RESP	Rural Electrification Strategy and Plan
RoI	Return on Investment
ROR	Rate of Return
SDG	Sustainable Development Goal
SES	Social-Ecological Systems
SPP	Small Power Producers
SSA	Sub-Saharan Africa
TANESCO	Tanzania Electricity Corporation
TZS	Tanzanian Shillings
VEC	Village Energy Committee
WRI	World Resources Institute

Chapter I: Framework chapter

1. Introduction

According to SDG 7, access to affordable, reliable, sustainable, and modern energy is a universal right, applicable to both rural and urban populations. The latest statistics from the World Bank (2023) indicate that most of the top 20 countries with the largest electricity access deficits come from the Sub-Saharan Africa (SSA) region. The pace of rural electrification in this region still lags behind that in urban areas, indicating that challenges related to electricity access deficits are most likely severe in rural SSA. The gap between rural and urban electricity access has led to significant investment in rural electrification initiatives and improvements in energy regulatory and policy frameworks to accommodate alternative solutions to national grid extensions for rural areas. One viable alternative to the national grid-based electrification is mini-grids (Blimpo & Cosgrove-Davies, 2019; Yadoo & Cruickshank, 2012). This shift is driven by mini-grids' ability to accommodate low-productive end uses and dispersed rural populations (Blimpo & Cosgrove-Davies, 2019; Palit & Chaurey, 2011), which is financially unattractive for national grid electrification. A mini-grid typically refers to a small-scale electricity generation and distribution system (ranging from 10 kW to 10 MW) that is isolated from the national grid, supplying energy to a limited number of customers. Though the term is at times used synonymously with microgrid, there is no consensus definition. In rural SSA, mini-grids are often implemented through private entities, communities, national utilities, and hybrid ownership models.

With abundant renewable energy sources in SSA, mini-grids are potential candidates to narrow the electricity access deficits in rural households. Despite their promises, mini-grids face multiple hurdles, social-economic, technical, financial, and institutional, that threaten their sustainability. These hurdles have called for a growing body of research seeking to uncover the causes, consequences, and offer practical solutions to secure mini-grid sustainability across different ownership models (Katre et al., 2019; Poudel et al., 2022). This dissertation contributes to the literature by focusing specifically on the community-managed mini-grids whose benefiting communities are responsible for operation and management (Maier, 2007; Palit & Chaurey, 2011).

Studies have shown that community-managed mini-grids are less driven by profit motives, highly involve respective communities in operation and management, and are, to a large extent, financed by donors, development agencies, and respective governments, making them optimal solution for rural electrification, probably more so than private, public and hybrid mini-grids (Duran & Sahinyazan, 2021). In countries like Tanzania, donors in collaboration with respective governments have introduced community demonstration projects that allow community involvement in mini-grid governance to facilitate electrification and adoption of renewable energy through mini-grids. These projects aim to stimulate local empowerment and a sense of ownership, allow customisation to local community needs, such as electricity demand, willingness, and ability to pay, and create a foundation for potential replication in other underserved rural communities.

It is important to note that this approach to rural electrification, while beneficial in many ways, faces institutional challenges particularly in the domains of management and decision-making processes (Yadoo & Cruickshank, 2012), for instance, maintenance management, which calls for collective action institutional arrangements, which may not be guaranteed in every community of mini-grid users (Karumba & Muchapondwa, 2017). If institutional frameworks supporting community-managed mini-grids are not set at the national level, then implementation at the community level may be affected, especially when community mini-grid users have neither prior experience in managing such systems nor a supporting structure in place. As a result, some community-managed mini-grids may struggle and even fail to achieve long-term sustainability. This dissertation makes the first contribution by analysing institutional frameworks governing mini-grid implementation, operation, and the sustainability implications. This is done by looking at the rules, regulations, and policies on the mini-grid sector from the macro level using Tanzania and Uganda as case studies (Chapter II). Subsequently, we dive into the micro level, examining the sustainability of community-managed mini-grids in Tanzania (Chapters III-V).

Energy governance characterises community-managed mini-grids as common-pool resources (CPRs) (Gollwitzer et al., 2018; Greacen, 2004; Wolsink, 2012) following seminal studies by Baland & Platteau (1996), Ostrom (1990), Wade (1988) and later by Agrawal (2001), who provide conditions for the successful management of communally owned resources such as forestry, fisheries, and grazing lands. Several authors have analysed mini-grids as CPRs and how they can be sustainably managed by applying the enabling conditions framework by Agrawal (2001) (see (Gollwitzer et al., 2018) and partial application of the framework by Ostrom (1990); Wade (1988) (see (Karumba & Muchapondwa, 2017; Kirubi Charles Gathu, 2009; Maier, 2007). The aforementioned literature has moderately analysed the role of institutional arrangements–rules that govern individual and collective choices regarding the management of CPRs (Greacen, 2004; Ostrom, 1986; Yan Tang, 1991), which are determinants for the sustainable management of CPRs, including community mini-grids. The analysis conducted in these studies is based on overall mini-grid management with no systematic analysis of interactions, relationships, and applicability of institutional arrangements for sustainable maintenance management of community-based mini-grids–arguably a central aspect for the long-term functioning of mini-grid systems. The second contribution of this dissertation is therefore a micro-level institutional analysis based on "Agrawal's (2001) enabling conditions framework" that was modified from the institutional framework developed by Baland & Platteau (1996), Ostrom (1990), Wade (1988). Institutional arrangements factors–a subset of the enabling conditions framework that facilitate the sustainable management of community-managed mini-grids are systematically analysed.

Another underexplored yet crucial aspect of sustainable community-managed mini-grids is the psychological dimension–specifically, mini-grid users' sense of ownership. The role of sense of ownership as a factor that facilitates the sustainable management of community mini-grids is implicitly stated in some literature (Katre et al., 2019; Maier, 2007). Pierce et al. (2001) define a sense of ownership as a psychological state in which people feel that a particular community infrastructure system is "theirs". A sense of ownership, which in the mini-grid context is defined as a psychological state in which mini-grid users feel that the mini-grid infrastructure system is theirs, fosters a common vision of governance among mini-grid users (Kumar et al., 2009), enhancing their sense of responsibility and contributing to successful mini-grid management (Madriz-Vargas et al., 2015). Despite its positive impact on sustainable mini-grid management, a sense of ownership remains insufficiently theoretically and empirically tested in mini-grid governance. There is not only inadequate qualitative or quantitative analysis of the relationship between a sense of ownership and sustainable mini-grid management, but also a lack of theoretical analysis of the factors through which a sense of ownership among users develops toward mini-grid. The literature on rural electrification through mini-grids would therefore benefit from this study, in addition to institutional factors that affect the sustainable management of community mini-grids, psychological aspects among mini-grid users that also contribute to the sustainable management of mini-grids. We, therefore, seek to identify factors behind mini-grid users' sense of ownership, which in turn affect mini-grid management, as well as analyse how community involvement in decision-making processes, monitoring, formulating, and enforcement of rules instill a sense of ownership among users, which in turn facilitates sustainability.

Despite its potential, the community-managed mini-grid model in Tanzania that was introduced through demonstration projects has experienced significant implementation challenges. 13 out of 14 mini-grid established projects (see Section 3.2) had failed within a short operation period. Some studies associate community-managed mini-grid failure with technical, economic, environmental, institutional, and social factors (Katre et al., 2019; Warneryd et al., 2020). Various approaches to analysing the factors contributing to the failure of community-based mini-grid projects have been employed, implying that there is no one-size-fits-all solution. This creates a need for more theory-driven analyses to provide more insights for improving future initiatives and deriving more sustainable outcomes for community-based mini-grids. This dissertation additionally contributes to that body of knowledge.

This dissertation enriches the general literature on sustainable rural electrification through community-managed mini-grids by performing a multidimensional empirical institutional analysis and psychological dimension– mini-grid users' sense of ownership analysis, of mini-grid (un)sustainability. A case of Uganda and Tanzania is used for the macro-level analysis of the mini-grid institutional frameworks in order to be used further for microanalysis. At the micro level, a case of demonstration projects in Tanzania that involve community-managed mini-grids is used first because of the sustainability challenges facing rural electrification through this model, which may soon cease to exist (see Section 3.1). Second, the analysis of the sustainability of such demonstration projects has the potential to increase renewable electricity access to other rural areas in the country that have no access.

2. Research question and aims

To understand the status quo of sustainable rural electrification through community-managed mini-grids in East Africa, this dissertation addresses the following overarching research question:

What are the key factors influencing the sustainability and success of community-managed mini-grids for rural electrification in Tanzania?

This dissertation, therefore, integrates insights from four research articles explored in Chapters II to V, with the following specific research aims, each providing a unique perspective in answering this research question:

The **first** research aim (RA1) addressed in Chapter II sets the ground for Chapters III to V by **analysing the institutional frameworks governing mini-grid development and operations in Uganda and Tanzania and identifying key factors contributing to sustainable rural electrification.** This aim allows for a comparative study of mini-grid institutions in Uganda and Tanzania to understand how different regulatory and institutional setups impact the sustainability of rural electrification projects. Analysing institutional structures in these two countries also provides insights from the macro level on how sustainability in rural electrification through mini-grids is approached before proceeding further to the micro level. Aspects such as the energy policy landscape and challenges related to mini-grid deployment by systematically utilising the Institutions and Development (IAD) framework are explored.

Building on this, the **second** research aim (RA2) **investigates the effects of institutional arrangements and community sense of ownership on the sustainable management of community-based mini-grids in Tanzania. This aim integrates insights from** Chapters III and IV to examine how the institutional arrangements and the community's sense of ownership work together to influence the management and sustainability of mini-grids. It does this by conducting an empirical investigation at the micro level in community-managed mini-grids in Tanzania.

Based on Chapter V, the third research aim (RA3) is to identify and analyse the key factors contributing to the failure of solar community-managed mini-grids in Tanzania by using the coupled infrastructure systems (CIS) framework. This aim seeks to diagnose and understand the common reasons behind the failures of community-managed mini-grid systems in Tanzania. The CIS framework is employed to uncover the causes of mini-grid failure by analysing the interrelationships between the infrastructure built from mini-grid systems.

To address the corresponding aims, this framework chapter synthesises the findings and contributions of the four individual chapters of this dissertation into four key insights, collectively answering the overarching research question. Section 3 presents this study's research approach, including the case study regions. Section 4 provides an overview of each chapter's aims and methods. Section 5 presents key findings and contributions of each subsequent chapter, while lessons learnt are in Chapter 6. Chapter 7 concludes the framework chapter by giving an outlook for future research.

3. Research approach

This section begins by providing background information on the mini-grid projects that form the basis of this dissertation (section 3.1). Then, it discusses the case study regions covering the corresponding mini-grid projects and the reasons for their inclusion in analysing rural energy sustainability for mini-grid management (section 3.2).

3.1. Background

The concept of solar community-managed renewable energy included in this dissertation was, for the first time, introduced by the government of Tanzania through the Ministry of Energy and Minerals in partnership with donors in the year 2014 through the implementation of 14 containerised solar demonstration projects in 10 villages across three regions in Tanzania (Odarno et al., 2017). Apart from electrifying rural areas that are far from the national grid and not scheduled to be connected by the Rural Energy Agency (REA) and the Tanzania Electricity Corporation (TANESCO) in the near future, another objective was to emulate this model to other unelectrified communities in other parts of the country at an affordable price, thereby promoting the diffusion of this new renewable energy technology. It should also be noted that the houses in the selected village should be close together and have sufficient electricity consumption capacity to match the production. The other objective of this model was to allow community involvement in managing the mini-grids. Beneficiary communities were involved in governance issues on these mini-grid projects by overseeing management matters and ensuring the overall security of mini-grid assets. Therefore, a Village Energy Committee (VEC) was selected by respective community members, who collaborated with the company responsible for maintaining the overall mini-grid systems. The VEC was working under respective village councils, which were all under the Ministry of Energy and Minerals. The VEC also managed financial matters like tariff collection. In this mini-grid model, formal rules existed governing the mini-grids. The Ministry of Energy and Minerals provided a guidance book that included rules and duties for every part responsible for running mini-grid projects in the respective communities. Such rules relate to finances, maintenance, dos and don'ts of VEC, electricity users, the village council, the company responsible for maintenance, and even the ministry itself. The community members were also allowed to modify the rules governing their mini-grids as the projects moved along. The guidance book with rules was provided to each member connected to the mini-grid project from the beginning.

Various governance challenges relating to institutional arrangements may arise in the mini-grid implementation phase, threatening the sustainability and success of community-managed mini-grids. Issues like illegal connections, the existence of non-tariff payers among users, power misuse among VEC and mini-grid technicians, nepotism, and poor leadership, among others, emerge, resulting in the failure of many of these mini-grid projects (Ngoti, 2024a, 2024b). Very few mini-grids have managed to supply electricity for a longer time (more than three years), and these are considered successful and sustainable cases in this study. The variations in rules enforcement, adjustment, and other institutional setups are potential sources for the differences in sustainability outcomes in each project. Investigating the institutional factors for such variations is one key interest of this dissertation. Contrary to privately-owned mini-grid models, where investors are highly likely to get returns because of the nature of their business model and, hence, positive impact on their sustainability, there are hardly any profits generated to community-managed mini-grids under the studied demonstration projects, which weakens their financial sustainability. As a result, the sustainability of these projects may also rely on the robustness of institutional arrangements at the local level–where variations in how rules governing the mini-grid users are enforced become key determinants for projects' success or failure. Therefore, strong management supported by a robust institutional framework setup becomes the main pillar for sustaining community-managed mini-grids.

In addition, creating an environment that promotes a sense of ownership when designing and implementing community-managed mini-grid policies and programs like the ones under this demonstrative project elsewhere in Tanzania is vital. Otherwise, it would be hard to attract supporting donors for similar projects if the current projects fail and no specified causes, remedies, and solutions are analysed in the literature. Since this model is still useful for electrifying underserved rural communities in Tanzania, it is hoped that the findings in this dissertation provide valuable insights to address the gaps in the community-managed mini-grids through the described demonstration projects so they can be revived and implemented sustainably elsewhere in Tanzania. As mentioned earlier, Uganda is included in this dissertation for a comparative institutional assessment of mini-grid sectors alongside Tanzania. The comparison aims to analyse sustainability outcomes, construct a diagnostic framework that captures the causal interactions among actors and the influence of exogenous contexts, and to analyse the mini-grid institutional frameworks from the national level and see how these frameworks can be applied to specific mini-grid typologies, particularly community-managed models (see Chapter II).

3.2. Case study region

The data used to analyse community-managed mini-grids in this study was collected in containerised solar projects located in four villages in three regions of Tanzania: Dodoma, Katavi, and Tabora. The four villages are among 10 villages that benefited from demonstration projects explained in section 3.1. Dodoma, Katavi, and Tabora regions all have natural potential for solar power generation and high solar radiation, with 27.7%, 36.1%, and 18.1% distribution of rural households connected to electricity, respectively (National Bureau of Statistics, 2020). Table 1 lists all villages that benefited from the demonstration containerised solar mini-grid projects.

Table 1: Containerised solar mini-grids under the demonstrative project in Tanzania, 2015-2024

Region	**District**	**Ward**	**Village (Mini-grid name)**	**Number of containers**	**Operational status**
Dodoma	Kongwa	Lenjulu	Lobilo	1	Non-operational
		Chitego	Leganga	1	Operational*
			Ngutoto	1	Operational*
		Makawa	Silale	1	Operational
Tabora	Uyui	Tura	Tura	2	Non-operational
		Loya	Loya	2	Non-operational
		Lutende	Lutende	1	Non-operational
Katavi	Mlele	Nsenkwa	Nsenkwa	2	Non-operational
		Ilela	Mapili	1	Non-operational
		Ilunde	Ilunde	2	Non-operational

*Failed and later revived. Currently operating, but management is no longer under the served communities but Non-governmental Organisation.

The coloured mini-grids in Table 1 are the study cases. The operational mini-grid cases (Silale and Leganga mini-grids) were selected specifically to answer the second research aim addressed in Chapters III and IV. These were the only surviving mini-grids when data collection was conducted. The coloured non-operational cases explored the third research objective addressed in Chapter V. Ilunde mini-grid was selected because, up to the period in which data was collected, there was no national grid electrification connected to the area. Villagers were using a home-based solar system. Loya was selected because of the information that the national grid arrived at the mini-grid site while it was still operating, but in the field, it turned out that national grid electrification was immediately introduced after the mini-grid stopped operating. Each mini-grid container has the capacity to generate 13.75 kWp and was able to supply electricity to 60 customers only. Institutions (i.e., churches, mosques, schools, police stations, village offices), businesses (i.e., shops, bars), and normal household users are the three types of customers connected to electricity in each village. Figure 1 shows an overview of the case study locations.

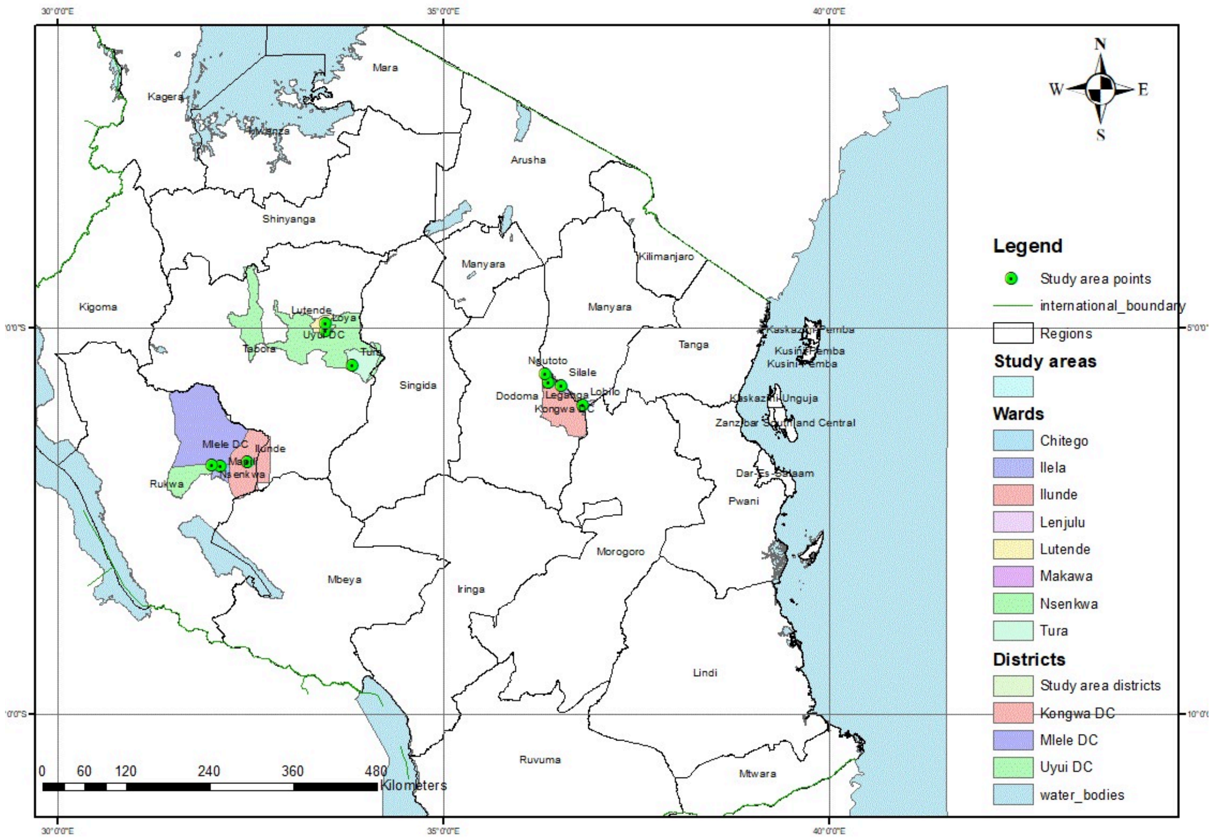

Figure 1: The case study regions

4. Chapter overview

This section presents an overview of the aims and methods of Chapters II to V, which are four research articles that are interconnected in the sense that they are collectively designed to bring forth a comprehensive understanding of the factors associated with sustainable and successful management of rural electrification through community-managed mini-grid projects. The four research articles use different theoretical and analytical frameworks to address different aspects of this overarching research problem by considering institutional designs, community/mini-grid user engagement, and the interaction between social and technical mini-grid systems.

The empirical analyses rely on existing literature review data and semi-structured questionnaires with open-ended questions collected from local people in the case study regions. The analysis for the first research objective was mainly done based on existing literature review data to extensively mine what is available in the literature and contribute to the current literature by applying the IAD framework to mini-grid institutions. The semi-structured, in-depth interviews with key informants were conducted between May and June 2022, and these were used to address the second research aim (see Chapters III and IV). Another in-depth, semi-structured interview round was conducted in July 2023 to address the third research aim (see Chapter V). In-depth semi-structured interviews facilitated a deep understanding of the sustainability of community-managed mini-grids, which included rich and detailed responses from mini-grid users' experiences, beliefs, and attitudes that are hardly captured by quantitative data analysis.

Chapter II: An IAD framework analysis of mini-grid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania

This chapter addresses RA1: "To analyse the institutional frameworks governing mini-grid development and operations in Uganda and Tanzania and identify **key factors contributing to sustainable rural electrification". The IAD framework was systematically utilised to conduct a comparative analysis of mini-grid institutions in Uganda and Tanzania by identifying and mapping actors involved in the mini-grid sector and assessing their roles and interactions across different mini-grid implementation stages.** Based on the literature review on the sustainability of mini-grid institutions starting from a general developing country context, followed by case studies specific to Uganda and Tanzania, mini-grid regulations and policy outcomes were evaluated. The chapter examined the energy regulatory framework, policy landscape, and challenges related to mini-grid deployment. The chapter was, therefore, able to provide socio-cultural and institutional insights that affect mini-grid sustainability. In addition, it underlined the interventions and policy strategies that can address the root of institutional inefficiencies to enhance the sustainability of the mini-grid sector. Chapter II formed a base for the overview of mini-grid institutional frameworks at the national level.

Chapter III: Institutional arrangements and sustainable maintenance management of community-based mini-grids in Tanzania

Chapter III is an empirical study conducted in Tanzania to address RA2: "To **investigate the effects of institutional arrangements and community sense of ownership on the sustainable management of community-based mini-grids in Tanzania**". The chapter explicated a maintenance management model practiced in the two solar community mini-grids (Leganga and Silale in Table 1) using data from 18 semi-structured interviews with village energy committee members, electricity users, technicians, and local leaders. The chapter also presented an institutional arrangements assessment for the maintenance management of the two mini-grids and analysed how rules, sanctions, and accountability for community mini-grid maintenance affect the corresponding maintenance and, hence, mini-grid sustainability outcomes. This analysis was facilitated by (Agrawal, 2001) institutional arrangements- enabling conditions for managing common-pool resources. These institutional arrangements were coded using MAXQDA 2022 following the interview responses. This chapter analysed the mini-grid institutional frameworks from a micro-level by looking at the rules, roles, and responsibilities of community-based mini-grid stakeholders and governance structure. Therefore, the focus on institutional arrangements in this chapter aligns with the IAD framework analysis in Chapter II, specifically on how the rules in use in the institutional setup affect mini-grid sustainability outcomes.

Chapter IV: The role of sense of ownership in rural community mini-grid management: qualitative case study from Tanzania

This chapter also addresses RA2, "To **investigate the effects of institutional arrangements and community sense of ownership on the sustainable management of community-based mini-grids in Tanzania**". Silale and Leganga mini-grids were the cases studied in this chapter. The research data used was collected through 18 semi-structured interviews with 6 village energy committee members (3 members from each mini-grid), 8 normal electricity users (3 from Leganga and 5 from Silale), 1 technician maintaining both mini-grids, and 3 village council leaders (2 from Leganga and 1 from Silale). The chapter empirically analysed the psychosocial aspects of mini-grid management, focusing on the role of a sense of ownership among community members. A theoretical framework for psychological ownership was presented to analyse the mechanism behind the sense of ownership in the mini-grid context and how it affects community mini-grid management. A systematic qualitative analysis of the mini-grid development lifecycle to the sense of ownership was also conducted to determine the essential mini-grid phase in which the sense of ownership matters for the successful management of rural community mini-grids.

Chapter V: Exploring the causes for failure in community-managed mini-grids containerised solar mini-grids: A coupled infrastructure system framework analysis

Chapter V is an empirical study focusing on RA3, **"To identify and analyse the key factors contributing to the failure of community-managed mini-grids in Tanzania by applying** a coupled infrastructure systems framework." Four mini-grids–Silale, Leganga, Ilunde, and Loya- were included for analysis in this chapter. In addition to the data collected from Leganga and Silale mini-grid that answered RA1 and RA2, focus group discussions with respective village project leaders and users were conducted separately in both Ilunde and Loya to collectively gain insights regarding the failure of these projects which had occurred some time before data collection. A systems thinking approach was applied across all four cases by first identifying key contributing factors (variables) for failure within mini-grid subsystems using five types of infrastructure under the CIS framework. These variables were then used to develop causal loop diagrams (CLDs) in order to visualise interrelations, cascading effects, and potential feedback loops influencing system dynamics and sustainability outcomes.

Commonalities and differences between the frameworks

Focus on the understanding and enhancing sustainability of mini-grids–specifically community-managed ones–as the centre for this dissertation, is explored by the IAD framework, institutional arrangements, sense of ownership, CIS and analytical frameworks. Each of these frameworks contributes a unique analysis of mini-grid systems dynamics and shares overlapping objectives and perspectives on the sustainability and success of mini-grid systems. Commonalities and differences among the frameworks employed in this dissertation are thus explained below.

The IAD framework serves as a diagnostic instrument for troubleshooting mostly institutional and governance-related matters concerning mini-grid (un)sustainability. It provides a broader lens for understanding the interactions of rules in use, biophysical conditions, and community attributes, and how they interact in the action arena, where mini-grid stakeholders make decisions.

Institutional arrangements (Enabling conditions for sustainable management of CPRs analytical framework) focus on the narrow scope of designing and enforcing rules in use pertaining to mini-grid matters (maintenance management in this dissertation). It therefore emphasises the local rule-in-use and their roles in enabling or hindering collective action towards mini-grid management. Together with the IAD, both frameworks use rules in use in understanding mini-grid governance and (un)sustainability, but their differences lie in scope and depth of analysis.

The sense of ownership analytical framework is used to understand how mini-grid users perceive and relate to mini-grid system by explicitly digging into their social interactions and psychological behaviours. A stronger sense of ownership among users fosters rule compliance and responsibility towards the mini-grid.

The CIS framework goes beyond institutional and governance aspects by conceptualizing mini-grids as coupled infrastructure composed of social, technical, and environmental subsystems when explaining the (un)sustainability status of mini-grids. Together with IAD, both frameworks identify the interplay of institutional, social, and technical systems aspects, although the IAD framework digs deeper within CIS's institutional system aspect by giving insights into governance and policy structures. Together with the sense of ownership, both frameworks emphasise on the social interaction behaviours and dynamics among mini-grid users. The sense of ownership framework is therefore integrated in the CIS framework as social system infrastructure, to provide mini-grid users' behaviour and community dynamics influence on sustainability.

Each framework thus provides unique analytical viewpoints of challenges, solutions, and understanding of mini-grid sustainability. They all focus on mini-grid sustainability by figuring out causes for system failures, analysing mini-grid governance (through an institutional analysis lens), technical reliability (via maintenance management), and social dynamics. However, CIS framework serves as an overarching structure by integrating variables from the preceding frameworks to explain how failure of the mini-grid system is the result of the interrelated failure of subsystem components, e.g., failure in one subsystem (i.e., social) can affect another subsystem (i.e., institutional). Together, all frameworks form a comprehensive approach to answer the overarching research question for this dissertation while offering robust solutions for community-managed mini-grids' sustainability. Figure 2. gives an overview of this dissertation.

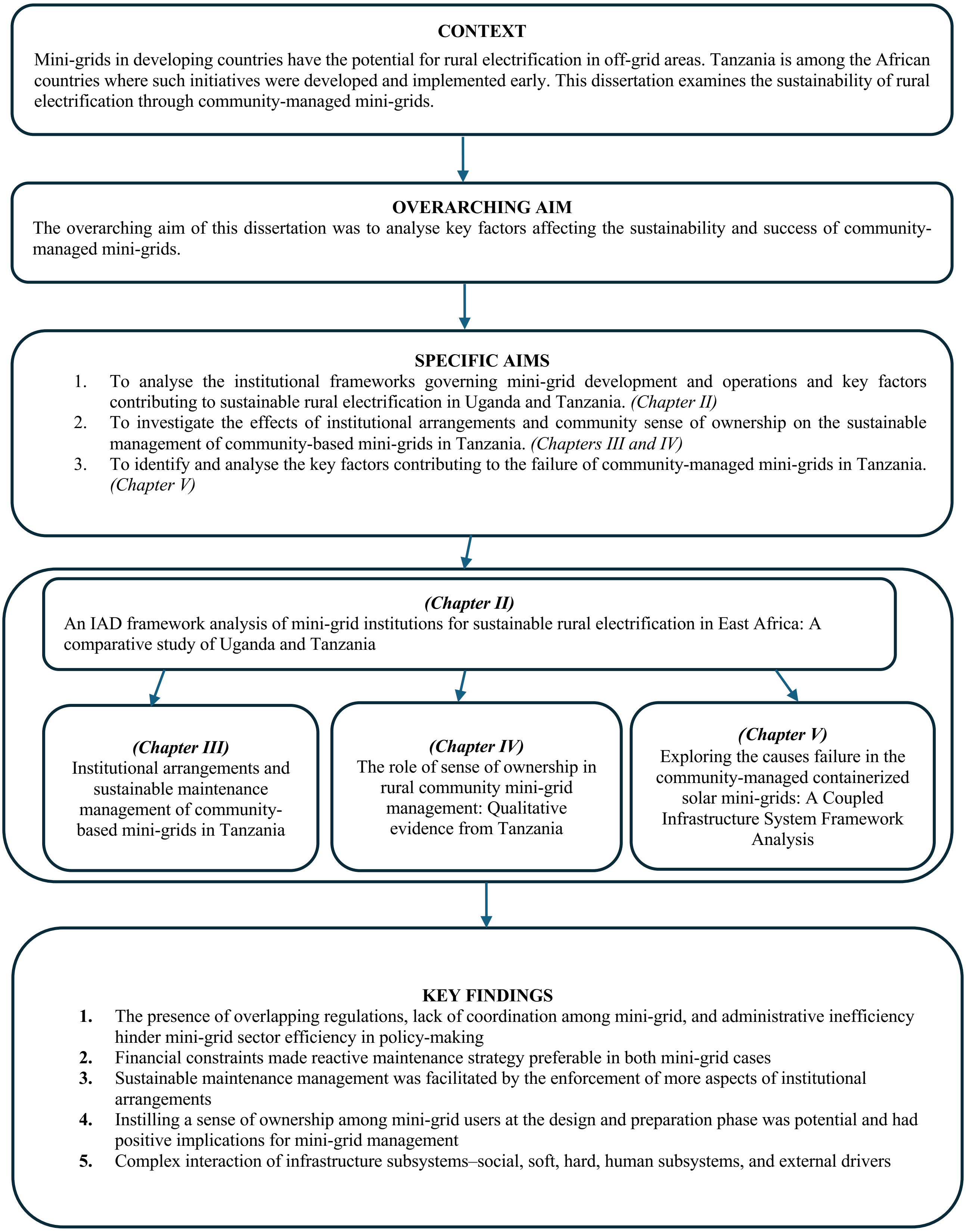

Figure 2: Concise summary of the dissertation

5. Key findings and contributions

This section summarises key findings from Chapters II-V along with contributions (Figure 2).

Chapter II: An IAD framework analysis of mini-grid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania

Based on the application of the IAD framework on mini-grid institutions in Uganda and Tanzania, we first presented findings from the mini-grid action arenas before comparative institutional analysis of mini-grid sectors of the two countries. On the mini-grid action arenas, the results showed the existing complex nature of institutional settings of multiple actors (i.e., developers, operators, investors, service providers, rural communities, regulators) and interdependent regulatory/policy environment (i.e, energy/electricity, environment, financial, labor, health and safety, rural development). Actors interact at multiple levels and activities, and different policy situations overlap with each other, which results in a complex actor network, infinite possible actor interactions and choices, multiple centers of decision-making, and a complex mash-up of rules governing all the interactions. The IAD framework was therefore able to simplify the identified complex situation into a more understandable institutional setting.

Comparative institutional assessment of Uganda and Tanzania's mini-grid energy sectors showed overlapping regulations and a lack of coordination among mini-grid actors, hindering sector efficiency in policy-making (Uganda being more vulnerable to this than Tanzania). Administrative inefficiency in terms of numerous approvals required, longer approval timelines, and corruption was also found in both countries. The results also showed that both countries had set regulated tariffs that failed to reflect the actual cost of electricity production in rural areas, making mini-grid projects financially unviable without government subsidies. The existence of less cumbersome rules, the digitalisation processes and requirements in the mini-grid sector, and the promotion of participatory policy-making that accommodates practical knowledge existing in local communities would channel significant advancement towards sustainable outcomes in Uganda's and Tanzania's mini-grid systems.

This chapter provides a theoretical contribution by providing a systematic approach to understanding complex interactions among actors and institutions in the mini-grid sector. It thus contributes to the theoretical discourse on mini-grid institutional frameworks. The chapter also provides a practical contribution that could cater to stakeholders and decision-makers adopting flexible strategies to adapt the IAD framework and apply it to local conditions to address challenges faced by different mini-grid user communities.

Chapter III: Institutional arrangements and sustainable maintenance management of community-based mini-grids in Tanzania

In both studied mini-grid cases, reactive maintenance was preferred to preventive and predictive maintenance strategies because of financial restraints. This, however, did not guarantee similar implementation outcomes for both mini-grids. Mini-grid maintenance was mainly financed through tariffs, and a stable maintenance fund positively impacted mini-grid maintenance sustainability. On the side of institutional arrangements, the results showed that executing more elements of institutional arrangements facilitates more sustainable outcomes for mini-grid maintenance management, and the opposite outcome occurs when fewer elements are enforced. Implementing institutional arrangements for sustainable maintenance management required collective action from mini-grid users and their leaders, not just technical personnel. This collective approach to institutional arrangements has significant implications for the sustainable governance of mini-grids if implemented for maintenance and other mini-grid management components like generation and distribution, metering, operations, and financial management.

This chapter makes an empirical contribution to the sustainable community-based energy governance literature and the common pool resources literature by focusing on maintenance, which is primarily considered from a technical perspective. However, this chapter analyses it from an institutional angle. Practically, the chapter provides an empirically grounded maintenance management model from two solar community-managed mini-grids in Tanzania to reflect realities on the ground. This model could be a relevant tool for stakeholders and policymakers to improve and implement mini-grid operations in similar contexts.

Chapter IV: The role of sense of ownership in rural community mini-grid management: Qualitative evidence from Tanzania

Analysis of factors affecting the sense of ownership among community mini-grid users showed that initial tariff payments, as a significant form of self-investing in the mini-grid was a critical factor. Users became more quickly attached to the mini-grid when they paid for tariffs from the beginning of the project than those who paid tariffs later. Low participation in decision-making (controlling ownership of the mini-grid route) on managerial, financial, and technical matters among users was also found to negatively affect the sense of ownership and vice versa. A sense of ownership among users was found to be higher when the mini-grid is positively affected by more factors (sense of ownership routes) compared to that of mini-grid users with fewer factors. The design and preparation phase was found to be an essential phase for instilling a sense of ownership among mini-grid users. Less community engagement in this phase, for instance, negatively affected the sense of ownership among users. A strong foundation of a sense of ownership in this phase was thus found to be the foundation of a stronger sense of ownership in the later stages of the mini-grid cycle, which also positively affects mini-grid management.

This chapter makes theoretical, empirical, and practical contributions. The chapter extends the psychological ownership framework concept (initially and mostly explored in organizational literature) to the context of community energy projects and analyse how a sense of ownership affects mini-grid management and sustainability. An analytical framework from the psychological ownership framework was developed in a mini-grid context. This analytical framework provides a structured approach for future research analysis of other infrastructure projects. The chapter makes practical contributions by providing energy practitioners with the necessity for fostering a sense of ownership and not just legal ownership, when developing community mini-grid models for their long-term sustainability. It further emphasises the importance of designing energy-related policies that promote a sense of ownership. The chapter also generates empirical insights on how a sense of ownership can promote sustainable management (as in Silale mini-grid) or lead to project failure (as in Leganga mini-grid).

Chapter V: Exploring the causes for failure in community-managed mini-grids containerised solar mini-grids: A coupled infrastructure system framework analysis

The failure of the mini-grid cases in this chapter is attributed to a complex interaction of infrastructure subsystems–social, soft, hard, human subsystems, and external drivers. This implies that an intervention to secure the sustainability of the mini-grid system must address this multifaceted system, rather than targeting a single system in isolation. The findings in this chapter further indicate the common existence of insufficient financial balances for maintenance purposes across all mini-grids, although the intensity varied by case. Importantly, the issue of inadequate maintenance funds was not a standalone issue; rather, caused by poor functioning of other infrastructure subsystems, such as non-compliance with tariff payments, local political interference, and the absence of clear legal ownership structures. With the help of CLDs, these factors were visually identified as critical disruptors. The analysis further revealed that the reinforcing feedback loops identified by the CLDs were prolongedly unaddressed due to delayed interventions. Such neglect resulted in unexpected compounding consequences– insufficient balances in the maintenance funds, low community involvement, poor rule enforcement, and tariffs nonpayment users' behaviours. The unaddressed feedback loops, thus, functioned as silent killers for these community-managed projects.

The chapter contributes theoretically to the energy literature by offering a systemic explanation of failure in community-managed mini-grids. By using the CIS framework and the help of the CLDs, it uncovers the intricate and interdependent networks of social, soft, hard, human factors, and exogenous drivers, thereby advancing a detailed analysis for the failure of community-managed energy projects.

6. Lessons learnt from chapters II to V

These chapters provide cumulative insights into the institutional, psychological, and infrastructural dimensions that structure the sustainability of community-managed mini-grids in East Africa. Through the integration of four frameworks: the IAD framework, institutional arrangements, sense of ownership, and the CIS analytical frameworks, a holistic analysis of sustainability factors and challenges for rural electrification through mini-grids was conducted. The following are key lessons that emerged from these chapters.

Institutional coherence and regulatory coordination are vital for a sustainable mini-grid sector. Policies, legal framework, government agencies, and regulatory bodies in the mini-grid sector should have proper alignment and collaboration on their actions, procedures, and decisions. This will minimise the possibility of poor coordination among actors and administrative inefficiencies that hinder the good performance of the mini-grid sector.

Implementation of institutional arrangements fosters sustainable maintenance of community-managed mini-grids. Effective implementation of rule enforcement, graduated sanctions for noncompliance, and the accountability of mini-grid users and leaders significantly contribute to good mini-grid governance and long-term sustainability. Conversely, partial or limited implementation of institutional arrangements is unlikely to secure mini-grid sustainability.

Raising a sense of ownership among mini-grid users is a vital yet often overlooked determinant of community-managed mini-grid sustainability. A sense of ownership should be instilled among users before mini-grid construction. This process should start during initial surveys and needs assessments, where users begin developing a psychological connection to the project. It is therefore important for the mini-grid developers, funders, and policymakers to recorgnise and incorporate this factor when formulating mini-grid policies.

The systemic and interdependent nature of community-managed mini-grid sustainability. The focus on community-managed mini-grid sustainability should simultaneously be on social (users' interactions and behaviours), soft (rules and norms–institutional factors), hard (physical infrastructure), human (knowledge about the system), and external factors (local politics). All factors are equally significant in contributing to sustainability; none is to be prioritized at the expense of the others.

7. Outlook

Sustainable and reliable electricity supply in rural areas has become a significant focus of the modern development agenda. This dissertation contributes to this agenda by providing a comprehensive multi-level analysis of institutional (institutional arrangements), technical (maintenance management), and socio-cultural (community governance and sense of ownership) dimensions affecting the sustainability of rural electrification through community-based mini-grids. The integration of findings from Chapters II-IV explained the intricate relationship between the dimensions mentioned above and the interdependencies between them from an infrastructure system perspective in Chapter V to show how they affect the sustainability of rural community mini-grids. These dimensions were therefore examined across different levels, both micro-macro, through the regulatory framework (Chapter II) to the micro level community governance and engagement (Chapters III-V). These chapters thus provided a comprehensive understanding of the various factors that contribute to or hinder the sustainability of community mini-grids.
Despite contributions, it is worth noting that the study was limited by the paucity of comparative analysis for community-managed mini-grids from other renewable resources and the lack of quantitative data in the analysis, which could provide broader insights into mini-grids' sustainability. However, this dissertation's findings, insights, and limitations open direction for future research. First, this dissertation made a theoretical contribution by deriving an analytical framework in a mini-grid context from the psychological ownership framework, which can be used to assess other mini-grid ownership models, aside community-managed model used in this dissertation. Future research could further analyse the sense of ownership by employing quantitative data, which could provide statistically grounded insights that qualitative methods could not provide in this dissertation. Second, the method and approaches employed in this dissertation could be applied to other mini-grids with renewable sources such as hydropower, biomass, and wind. Third, this dissertation presented a

detailed analysis of rural community voices about governance of energy community projects, which come as pilot projects, their success, and failure. Future studies could investigate how these results can best be applied as guidance for future similar pilot projects in terms of psychological and legal ownership settings, exit strategies, and energy rules settings that accommodate community-based projects. Regulatory measures that accommodate smooth ownership transitions could reduce or eliminate the bad management of donor-funded community mini-grid projects. This goes hand in hand with developing monitoring and evaluation frameworks for mini-grid projects funded by the governments, international organisations, and non-governmental organisations, to keep tabs on their performance to ensure sustainability. Availability of data from such frameworks can form a base that is vital for the policy-making and design of future projects.

Chapter II: An IAD framework analysis of mini-grid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania

Abstract

Mini-grids offer a viable solution for extending electricity access to underserved areas beyond the reach of main-grids. Their sustainability is crucial for rural electrification prospects in Sub-Saharan Africa. Using Ostrom's IAD framework, we conduct a socio-cultural and institutional analysis of mini-grids across their development stages. We map sector actors and their respective roles in the mini-grid sector providing a framework of their interactions and choices towards sustainable outcomes. We further present a comparative institutional assessment of Uganda and Tanzania's mini-grid sectors; analyzing outcomes and constructing a diagnostic framework of the causal actor interactions and exogenous contexts hindering sector sustainability. Our study reveals the inherent challenge posed by the complex interdependencies within the mini-grid sector and its relationship with adjacent sectors. It further uncovers significant institutional inefficiencies in the mini-grid sectors of Uganda and Tanzania. We advocate a flexible solution strategy, wherein, regulators strategically modify the adaptable components of the IAD framework considering the specific root causes of problems. This approach allows for targeted interventions through precise adjustments to effectively address underlying issues. Additionally, we emphasize the importance of policy integration mechanisms with adjacent sectors and a policy design process that incorporates the core values of sector actors.

Keywords: Mini-grid sustainability, Institutional analysis, IAD framework, Rural energy policy, Regulatory framework, Sub-Saharan Africa

JEL classification: D02, D04, E02, Q48

1. Introduction

Mini-grids have been posited as economically viable options for driving electricity access in underserved areas beyond the reach of main grids (Ahlborg & Hammar, 2014a; Motjoadi et al., 2020a). In Sub-Saharan Africa, with some of the lowest electrification rates in the world (IEA et al., 2022), the viability and sustainability of mini-grids is central to the achievement of SDG7 - sustainable energy for all by 2030. While technical and financing factors in the study of mini-grid sustainability are important (Katre et al., 2019; Peters et al., 2019a; Poudel et al., 2022; Zebra et al., 2021), the institutional framework within which mini-grids operate is just as important (Palit & Kumar, 2022; Ulsrud et al., 2018) and is the focus of this paper.

Institutions refer to systems of established prevalent social rules, norms, and shared strategies that structure human behaviour and social interactions (Knight, 1992). They can be as formal as laws, policies and regulations or as informal as cultural norms or standard operating procedures. They create incentives for desired behaviour in repetitive situations (Crawford & Ostrom, 1995) and are critical in governance of situations that require coordination among large groups of individuals (Hurwicz, 1994).

We utilize the Institutional Analysis and Development (IAD) framework defined by E. Ostrom (Kiser & Ostrom, 2000; E. Ostrom, 1986, 1990, 1999; E. Ostrom et al., 1994; L. Ostrom et al., 1993) to analyse the institutions governing mini-grid implementation and operation. The IAD framework has been valuable in analysing and designing of policy and institutional interventions in a wide range of political-economic situations (Polski & Ostrom, 1999). It has been utilized to analyze mini-grids as common pool resources (Gollwitzer et al., 2018; Gollwitzer & Cloke, 2018; Greacen, 2004; C. G. Kirubi, 2009; Maier, 2007; Wolsink, 2012). The Social-Ecological Systems (SES) framework (extended IAD) has also been used to explain community mini-grids (Holstenkamp, 2019a; Sanchez & Tozicka, 2013; Yadoo & Cruickshank, 2010). In this paper, we apply the IAD framework as a tool for analysing institutions and evaluating policy effectiveness in the mini-grid context.

Previous works on mini-grid policy frameworks have focused mainly on the nature of institutional structures (Deshmukh, 2013; Franz et al., 2014) while others have examined ownership structures as a key sustainable factor of mini-grid implementation (Duran & Sahinyazan, 2021a, 2021c). Several have mentioned in passing the regulatory environment to point to challenges facing the roll-out of mini-grids (Mondal et al., 2010; Ohunakin et al., 2014; Peters et al., 2019a; Shyu, 2012) without necessarily going in depth into particular regulations and their implications. In contrast, our study goes beyond surface-level analysis, undertaking a comprehensive cause-and-effect examination of the underlying rationale behind local actor choices and patterns of interaction as well as a rigorous structural analysis of mini-grid sector policies in a bid to explain sector outcomes.

Uganda and Tanzania, two of the least electrified countries in the world (IEA et al., 2022), have adopted off-grid electrification in a bid to achieve a leapfrog on their rural electricity access targets (Banura, 2022; Odarno et al., 2017). We use these two countries as case studies in our analysis of mini-grid sectors in East-Africa, addressing three research questions: (1) What are the key institutional and socio-cultural considerations driving sustainability outcomes in mini-grid systems? (2) What are the crucial actor choices and patterns of interaction contributing to or in the way of desired sector outcomes? (3) What are the sustainability implications of Uganda and Tanzania's mini-grid sector policies?

The rest of the paper is organized as follows: In section 2 we present an overview of the IAD framework and how it is uniquely applied in answering our research questions. In section 3 we apply the IAD framework to the general mini-grid context to establish the institutions and socio-cultural factors driving mini-grid sector outcomes and go on to map the actors, their roles, positions and choices across the mini-grid development phases of financing, planning, and implementation. In section 4, we present a comparative and diagnostic institutional assessment of Uganda and Tanzania's mini-grid energy sectors and in section 5, policy implications and conclusion.

2. Methodology

2.1. The IAD Framework

The IAD framework is quite versatile and applicable to a variety of research questions pertaining to human decision making (Hess & Ostrom, 2005). It provides an overall view of a complex system while allowing for focus on certain areas of interest (Oakerson, 1992), but also, assigns the many variables within the reference context into categorical groups, locating these groups within a foundational structure of logical relationships (McGinnis, 2011a). Figure 3 highlights the logical links and interdependencies between the main categories of the IAD framework. *Exogenous variables* constitute the biophysical characteristics, attributes of community and rules-in-use. The *action arena* is composed of the core actors and their interactions or action situations. Outcomes are *dependent variables* with feedback influence on the action arena and exogenous variables.

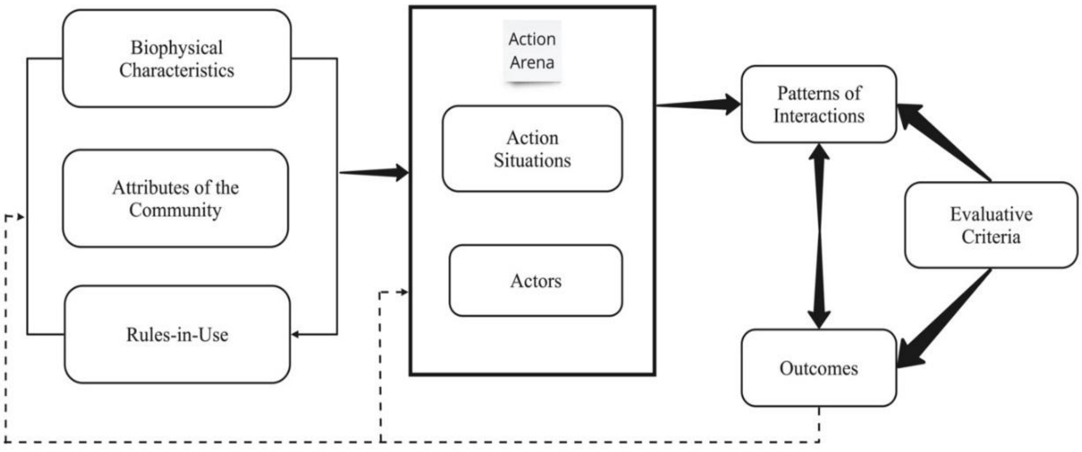

Figure 3: IAD Framework. Source: Kiser and Ostrom, 1982

The action arena is the core of the IAD Framework useful in analysing dilemmas in processes of institutional change (Hess & Ostrom, 2005). Actors' patterns of interactions within the action arena are borne out of a combination of the exogenous context, actors' choices and incentives and their actions (Ibid). Here, actors observe information, choose courses of action, engage with each other in patterns of interaction, and realize outcomes from their interactions (McGinnis, 2011a).

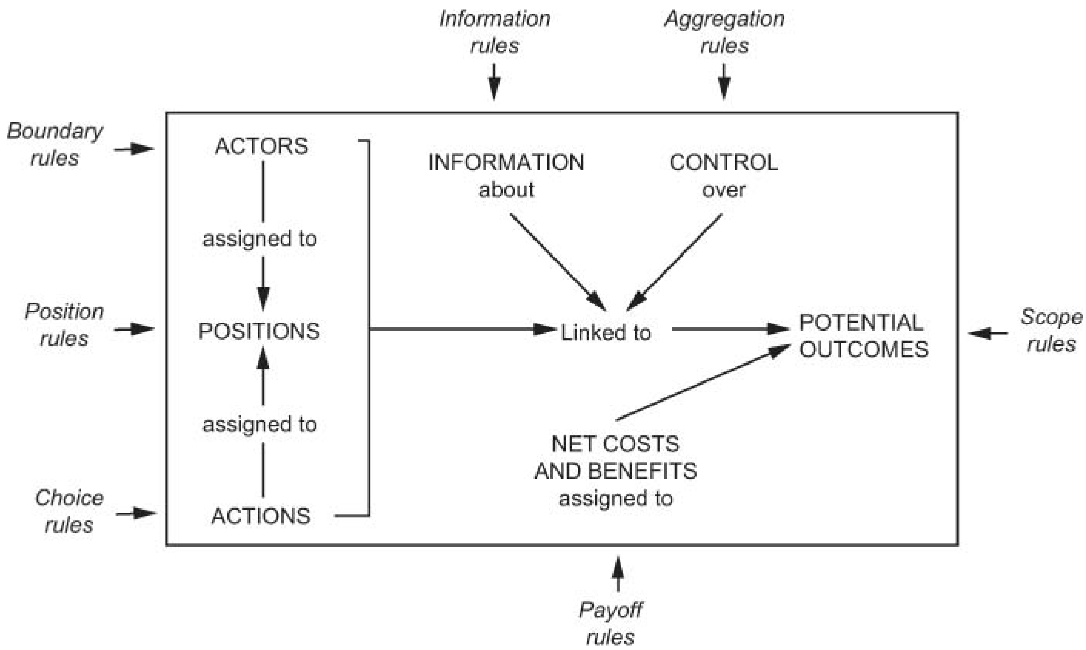

Figure 4: Rules-in-use in the exogenous context directly affecting the action arena (Source: Ostrom 2005)

The action situation, contained within the action arena, is detailed in Figure 4. It specifies the nature of relevant actors, the resources and choices at their disposal and essentially approximates the "rules of the game" (E. Ostrom et al., 1994). The rules-in-use (boundary rules, position rules, choice rules, information rules, aggregation rules, scope rules and payoff rules), are exogenous variables giving structure to and directly affecting the action situation. This here, is the institutional focus of this study. The IAD framework is useful in analysing rules-in-use across all levels of social interaction and choice; from the Constitutional, Policy and Operational levels (Cole, 2017). At the operational level, individuals interact with each other and the physical/material resource making day-to-day choices that affect resource access and use (Hess & Ostrom, 2005). At the policy level, in addition to regulations being made, collective- choice rules determine who is eligible to make the rules and how rules may be changed (Polski & Ostrom, 1999). At the constitutional level are legal-political rules defining who can and cannot participate in making collective choices at the policy level. The choices made at each of these levels of social interaction have outcomes that can affect the exogenous context – biophysical conditions, community attributes, and rules at other levels (Cole, 2017).

2.2. IAD Framework Materialization

We performed a *literature review* related to the sustainability of mini-grid institutions starting from a general developing country context, followed by case studies specific to Uganda and Tanzania. It involved a keyword search of SCOPUS, Google Scholar and general internet databases for academic and grey literature including research articles, government agency reports and policy documents, international energy agency databases and regional mini-grid development agency reports. Included were those studies and reports providing insights into the regulatory frameworks, policies, and institutional arrangements enabling or hindering mini-grid sustainability in the region[1]. Thematic data extracted from the selected literature were analyzed for common themes, patterns and trends (See Appendix B). The study utilized stakeholder insights synthesized from a variety of regional mini-grid development agency reports ensuring region-specific applicability of research findings.

The IAD framework has been typically adopted for the analysis and understanding of complex institutional arrangements (Altomonte & Guinto, n.d.; Lestari et al., 2018; Nigussie et al., 2018; Oh & Hettiarachchi, 2020) or to the analysis of existing policies (Imperial & Yandle, 2005; Shah & Niles, 2016). In the former, the analysis is focused on identifying the institutional factors that contribute to the problem or issue (E. Ostrom, 1990). It is forward-looking aiming to inform the development of new policies or interventions to address the problem. In the latter, the focus is on evaluating the

[1] Results of literature review search and associated document sets to be available upon request.

effectiveness of the policies and identifying opportunities for improvement (Polski & Ostrom, 1999). Here, analysis is backward-looking aiming to inform the revision or improvement of existing policies.

For research questions (1) and (2), we adopt the IAD framework to analyse the institutional and socio-cultural considerations at work in the mini-grid sector. Starting with the specific political-economic context - mini-grid sustainability, we work forwards through the framework in Figure 3; describing the physical and material attributes of the context, proceeding through community attributes, rules-in-use, action arena(s), patterns of interaction, and outcomes respectively. For question (3), we adopt the IAD framework as a diagnostic tool, working backwards through Figure 3 to reaffirm or revise policies, evaluate policy outcomes, and understand the information and incentive structures of different policies. The steps are summarized in Figure 5. Applying both approaches to the problem adds robustness to the methodology - providing comprehensive understanding of the institutional context, allowing for anticipation of unintended consequences and the design of context-relevant policies.

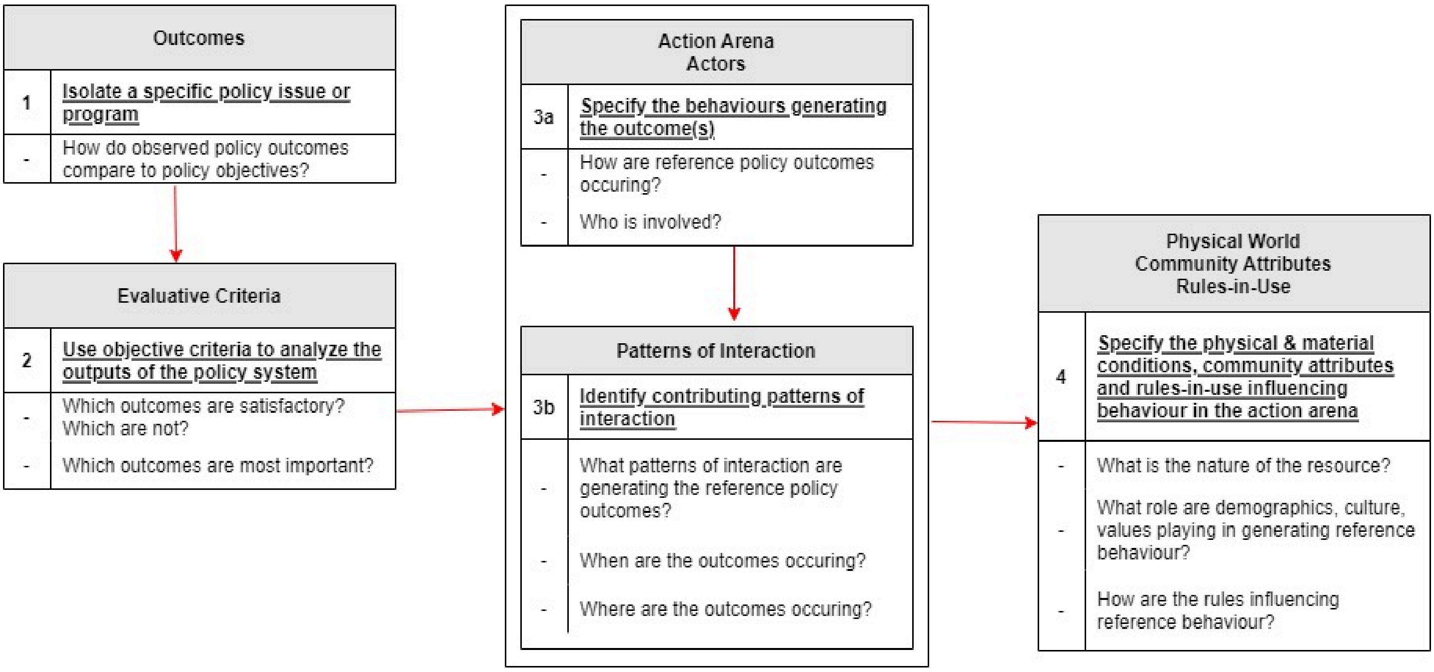

Figure 5: Diagnostic application of IAD framework. Source: Authors. Abstracted from(Polski & Ostrom, 1999)

3. IAD Framework Analysis of the Mini-grid Sector

3.1. Institutional and Socio-Cultural Analysis of the Mini-grid Context

We use the IAD framework to decompose the mini-grid institutional context into its component parts to understand how actors against a backdrop of technical, social and economic constraints interact together so as to produce desired outcomes. Figure 6 shows core mini-grid variables structured into a relational schema that is the IAD framework.

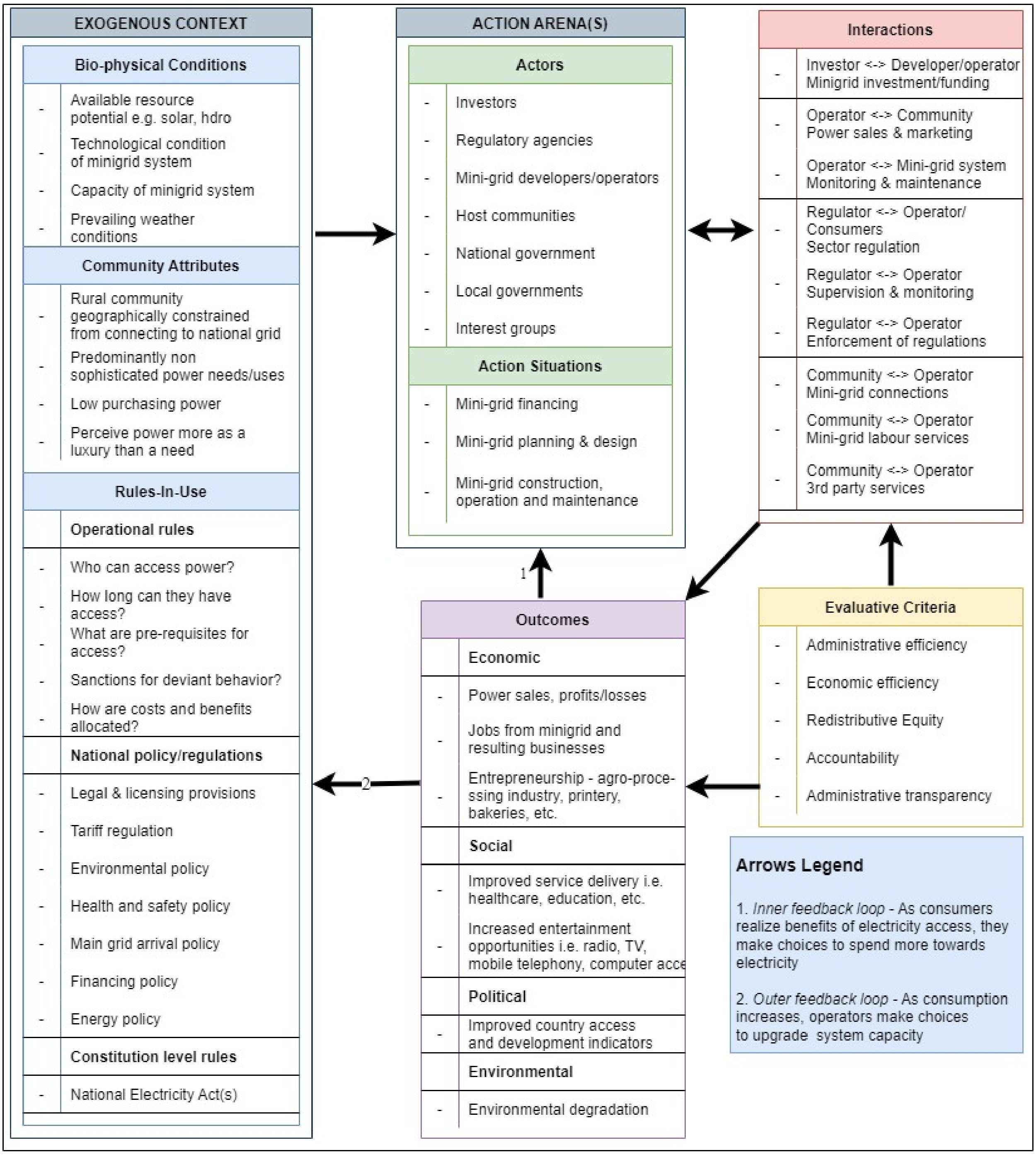

Figure 6: IAD framework structure of core mini-grid institutions. Source: Authors

In the *exogenous context* are the factors with potential to limit or support the dynamics within the action arena. *Biophysical conditions* are physical, biological, technical and capacity constraints of the mini-grid resource; *community attributes* are defining characteristics of the community that pertain to using and managing the mini-grid resource (Gollwitzer et al., 2018).

The *Rules-in-use* in Figure 4 are at three levels (Cole, 2017): At operational level, individuals interact with each other and the mini-grid making day-to-day choices. There is a combination of boundary rules and payoff rules determining who is eligible to connect, how they get connected, prerequisites for accessing power once they are connected, sanctions for breaking the rules e.g. disconnections and fines, and how costs and benefits are allocated among grid users (Gollwitzer et al., 2015a). At the policy level, regulators craft regulations for the operators and consumers while the mini-grid operator sets the rules of service for consumers. At the constitutional level are position rules that establish who can issue mini-grid licenses and craft governing policy for the sector.

At its centre, Figure 6 lists the central *actors*: Investors are private, local governments, donor/development partner agencies or host communities funding mini-grid implementation. Regulators are autonomous agencies including electricity regulatory authorities, rural electrification agencies, etc. who regulate, supervise and monitor operations. The role of the central government is through the legislature making policy and government ministries e.g. Ministry of Energy facilitating sector funding as well as creating an enabling environment (Akinlabi & Oladokun, 2021). Local governments provide permitting and local approvals for mini-grid operations. Host communities are target consumers of power and resource partners in mini-grid implementation. Interest groups including NGOs, donors, development partners are usually invested in influencing policy.

The *Interactions* box lists only a subset of a myriad of possible interactions among these actor groups. They are grouped into four main functional arenas of interaction: First, mini-grid resource appropriation involving interactions of consumers with the mini-grid resource in the sale and purchase of power and interactions of the mini-grid resource system with the biophysical context in terms of resource generation. Second, the rule-making arena where different rule-making agencies interact to draft governing rules for the sector. Third, the resource maintenance arena involving interactions on the part of the operator, consumers and the resource system pertaining to maintenance and lastly, the monitoring and supervision arena in which the operator, consumers and regulator interact to ensure compliance to established rules.

Outcomes are generated at the juncture of action situation outcomes, actors' choices and interactions and exogenous impacts. There are a number of mini-grid outcomes including social, political and economic impacts on the host communities. Via feedback loops, these outcomes impact back onto the exogenous variables and action situations gradually changing the overall system response. Mini-grid outcomes influence the choices and decisions of actors via the inner feedback loop e.g. improved economic prospects drive decisions to consume more power, and outcomes influence gradual changes in the exogenous variables via the outer loop, e.g. increase in sales profits influences decisions on further investments in capacity upgrades (Gollwitzer et al., 2018).

Evaluative criteria are applied by sector actors and external observers to assess system achievements against objectives. For the mini-grid context applicable criteria may include: economic efficiency, administrative efficiency, redistributional equity, and administrative transparency.

3.2. Action Arenas in the Mini-grid Implementation Context

Building on the mini-grid institutions and social-cultural context presented in section 3.1, we now explore the action arenas that make up the three main stages of the mini-grid implementation cycle – *Mini-grid Financing*, *Planning and Design,* and *Implementation*. For each stage of mini-grid implementation, we systematically examine the core actors, the rules or institutions at play, key information requirements, and net costs and benefits, all of which feed into actors' choices and ultimately the outcomes. These three action arenas may happen simultaneously or in sequence such that the outcomes of one arena become important inputs for the next action arena (McGinnis, 2011b).

3.2.1. Mini-grid Financing

In this arena, mini-grid investments are motivated and funded. Information on business plans, grid ownership models and risk assessments are prepared as input into investment decisions. Investments come from private investors, donor organizations, governments, direct from the target mini-grid communities or a hybrid combination of 2 or 3 sources. The source of investment determines the mini-grid ownership model, the payback and Return on Investment (RoI) requirements. In Table 2 we classify key actors into 3 categories: investors, regulators and developers. We specify what information these different actors require in the execution of their respective roles, the possible choices they can make while accounting for the rules at play and the resulting net costs and benefits.

The rules referenced in Table 2 are the policies and guidelines in place to guide actors' choices and behaviours. They are the institutions governing who investors can be and the roles of the different actors (position rules). They set the terms of interaction governing the actors (choice rules). They structure the mini-grid market towards profitability for private players via mini-grid tariff policies and government concessions/subsidies (pay-off rules).

Table 2: Analysis of mini-grid financing action arena.

Actors (Roles)	Information requirements	Choices	Net Costs & Benefits	Outcomes	Rules
Investors (Financier) - Private - Government - Community	- Local tax rates - Approved tariff regime - Available government concessions, subsidies - Investment Payback period - Local currency rates - Local interest rates - Business plan(s) - Business risk assessments - Licensing procedures	- How much to invest - How long to invest - Choice of mini-grid ownership model - What rate of return to expect - Direct involvement in operations or delegation?	- Cost of investment - Potential investment gains or losses - Ownership stake in a mini-grid asset	Private/public/community investment	**Boundary rules** -> Mini-grid investments must fit in designated areas as per master plan **Position rules** -> Regulatory agencies are mandated by law to license sector investors **Choice rules** -> Investor/operator compliance with all license T&Cs, Guidelines & Directives **Information rules** -> Mandatory regular financial reporting to the regulator **Payoff rules** -> Minimum expected pay back period and Return on Investment -> Regulator approved tariff regime
Regulator (Regulator/ Licensor) - Regulatory agencies - Government agencies	- Target mini-grid location and fit in master plan - Source of investment (local/foreign) - Business ownership, operation structure(s)	- To approve license or not - Financing support in terms of concessions, subsidies	- Achievement of electrification master plan(s) - Direct energy sector development	- Mini-grid operation licenses - Mini-grid concessions, subsidies (if any)	
Mini-grid Developer (Developer)	- Local tax rates - Approved tariff regime - Available government concessions, subsidies - Investment Payback period - Local currency rates - Local interest rates - Government electrification master plan(s)	-Choice of investor/partners - Choice of payback terms	- Mini-grid funding - Business profit share	- Mini-grid funding - Investment partnerships - Profit share and payback agreements	

Funding in the private sector model is from private equity and commercial loans and in the government/utility-based model, it comes directly from government or via subsidies (U.S.A.I.D., 2018a, 2018c). In the community-based model, local communities own, operate and maintain the mini-grids, sometimes receiving external help with financing, design and installation (Ibid). Similarly, different regulatory actors, even in cooperation, bring differing policy arenas (economic, environmental, energy, political) into play as part of mini-grid governance.

The physical and material characteristics within the exogenous context influence the financing action arena constraining institutional arrangements there-in. This includes local resources and capabilities related to investor attraction and raising of requisite capital including local currency rates, commercial interest rates, cost of capital, local tax rates (Bhattacharyya & Palit, 2016; U.S.A.I.D., 2018a). These are external to the mini-grid sector but ultimately affect the decisions actors make in this action arena. Socio-cultural community attributes pertinent to the financing arena include a community's attitude to money, accepted patterns of behaviour, respect for the rule of law, consumer preferences, which inform future mini-grid market prospects (Bhattacharyya, 2018; Madriz-Vargas et al., 2015; Ulsrud et al., 2018). The entire exogenous context factors into the net costs and benefits which are weighed by investors in determining whether to invest, the right level of investment, and the duration and rate of RoI to set.

3.2.2. Mini-grid Planning & Design

In this phase, feasibility studies, technical designs and specifications, impact assessments, market analysis and operator licensing happen. The central mini-grid planning actors are the energy/electricity regulatory agencies in charge of licensing and reulatory oversight (Akinlabi & Oladokun, 2021). They ensure consumer protections, favourable RoI conditions for investors and collaborate with other agencies in the arenas of environment, land, labour, health and safety to drive the mini-grid agenda.

Another key planning role is that of local governments - intermediaries between host communities and mini-grid developers, responsible for community mobilization of needed resources e.g. land, local labour, coordinating engagement efforts between the community and developers, and mediation in case of disputes. Existence of regulations that are necessary, efficient and effective is fundamental to ease complexity of interactions between all actors in the planning and design stage as many projects are abandoned here (Bhattacharyya & Palit, 2016; U.S.A.I.D., 2018b). Regulations inform land procurement and settlement processes, choice of service territories, tariff regimes, mini-grid concessions, etc.

Table 3 brings to light the multiple policy arenas at play in the mini-grid implementation process. Apart from energy/electricity regulatory agencies, we find agencies from other policy arenas of finance, environment, land, health and safety wielding sufficient power to impact mini-grid implementation (Deshmukh, 2013). These agencies are autonomous but inter-dependent, sharing information at different stages of the mini-grid planning and design process. Without approval documents from local tax authorities, environmental agencies, local leadership in the host communities and the physical planning and health offices respectively, the electricity regulatory agency cannot proceed to issue a mini-grid license (E.R.A., 2020).

Table 3: Analysis of Mini-grid Planning & Design Action Arena

Actors (Roles)	Information requirements	Choices	Net Costs &Benefits	Outcomes	Rules
Regulatory agencies (Regulator/ Supervisor/ Licensor) - Rural electrification agencies - Environmental protection agencies - Standards assurance agencies - Tax authorities	- Project Feasibility studies - Environmental impact assessments - Resettlement and compensation plans (if any) - Proof of license fees payments - Proposed tariff plan - Proposed Technical design - BoQs	- Approve feasibility reports & assessments or not - Approve license or not - Approve tariff plan or not	- Consumer protection - Environmental protection - Protection of community interests	- Mini-grid operation licenses	**Boundary rules** -> Licensing as a prerequisite to grid implementation **Position rules** -> Clear team roles based on defined job descriptions **Choice rules** -> Adherence of designs to set technical and environmental standards - **Information rules** -> Submission of feasibility studies, impact assessments to regulator for approvals
Community (Target consumers/ Host community/ Landlord) - Community leaders - Local government representatives - Local community	- Clear resettlement & compensation plans (if any) - Planned product and service portfolio	- Support or sabotage mini-grid plans	- Improved social & economic prospects - Improved job prospects	- Local project acceptance	
Mini-grid Developer (Business planner/ Feasibility assessor/ System designer/ Licensee/ Developer)	- License fees structure - Applicable technical & quality standards - Applicable environmental regulations	- Choice of contractors - Choice of suppliers - Choice of system design - Choice of operating model	- Direct costs in terms of license fees and feasibility report approval fees - Direct costs of operation	- Completed planning phase - Fully designed mini-grid plans	

3.2.3. Mini-grid Implementation - Construction, Operation & Maintenance (O&M)

The implementation phase covers the actual execution in terms of mini-grid construction and O&M. Construction brings together project developers, implementation partners, sub-contractors, service providers, regulatory monitors, local tax authorities, etc. In the construction phase emphasis is on procurement, contracting and mini-grid site set-up making local labour, health & safety and contract laws important. Key attention is paid to materials and installation standards, quality assurance and environmental considerations as dictated by local regulations (Moner-Girona et al., 2018).

O&M brings together mini-grid operators, technical staff, marketing and sales, customer support as well as the host community. Table 4 provides a summary of the action arena in this stage. The interactions between these different groups are governed by regulation and consumer agreements. Agreements specify expected tariff rates, minimum service level requirements, roles and responsibilities of both the operator and the power consumers. Regulators in this stage have a monitoring and supervision role, enforcing tariffs, service territories, service and environmental standards.

Table 4: Analysis of Mini-grid Construction, Operation and Maintenance Action Arena

<table>
<tr><th>Actors (Roles)</th><th>Information requirements</th><th>Choices</th><th>Net Costs & Benefits</th><th>Outcomes</th><th>Rules</th></tr>
<tr><td>Mini-grid operator
(System installers/
Monitoring agents/
Maintenance agents/
Sales& marketing agents)</td><td>- Technical installation standards
- System performance reports
- Power sales reports
- Financial reports
- Customer complaints reports</td><td>- Choice of local capacity building or external expat hires
- Choice to subcontract operations or use in-house team
- Choice of power tariffs</td><td>- Cost of local training & capacity building
- Cost of sales</td><td>- Return on investment
- Local support capacity
- Sustainable operations</td><td rowspan="3">Boundary rule
-> Customer connections limited to approved geographical area(s)

Position rules
-> Regulatory agencies are mandated by law to monitor operations

Choice rules
-> Clear team roles based on defined job descriptions

Information rules
->Mandatory regular performance & financial reporting to the regulator

Payoff rules
-> Prepaid or postpaid payments
-> A Commensurate number of power units is received</td></tr>
<tr><td>Regulator
(Regulator/
Supervisor/
Monitor/
Enforcer)</td><td>- Sale prices/tariffs
- Customer complaints and resolution procedures
- Technical system design(s)
- Mini-grid performance reports</td><td>- Choice to penalise operator breaches or not
- When and how much to inspect
- Choice to review obsolete policies</td><td>- Direct costs of monitoring & supervision
- Standard system installations</td><td>- Consumer protections
- Environmental protections
- Up to date sector policies</td></tr>
<tr><td>Community
(Consumers/
Customers/
Labour/
Business partners)</td><td>- Sale prices/tariffs
- Operator service level agreements
- Service complaints handling procedures
- Mini-grid jobs on offer
- Available partnership opportunities</td><td>- Choice to take up jobs on mini-grid
- Choice of business partnerships with operator
- Choice to connect to mini-grid
- When and how much to consume</td><td>- Direct electricity costs
- Added jobs
- Added business opportunities</td><td>- Electricity access for the community
- Improved social, economic prospects</td></tr>
</table>

3.3. Synthesis of Findings from the Mini-grid Action Arenas

The following themes emerge from the mini-grid action arenas described in sections 3.2.1-3.2.3: the institutional complexity introduced by actor interactions from multiple levels of activity and multiple policy arenas; the overarching role of the regulator and the impact of adjacent action situations/arenas on the mini-grid sector.

3.3.1. Institutional Complexity

The IAD framework presents a simplified view of what is otherwise a complex institutional setting of multiple actors with divergent interests in multiple overlapping action arenas subject to several levels of rules. Actor interactions happen at multiple levels, and policy situations overlap with each other so that activities in one, affect activities in another. What is abstracted by the framework is a diversity of possible mini-grid ownership/management models – private, government, community, hybrid; the full scope of internal mini-grid actors – developers, operators, financiers, suppliers, service providers; and a plurality of regulatory/policy arenas at play – energy/electricity, environment, financial, labour, health and safety, rural development, etc., each with different policy objectives and reporting lines. Together they make for a complex actor network, infinite possible actor interactions and choices, multiple centres of decision making and a complex mash up of rules governing all the interactions. Figure 7 highlights the range of policy arenas at play. It emphasizes the crucial need for consultation, coordination, and communication among the different policy arenas to address challenges posed by their inter-connectedness.

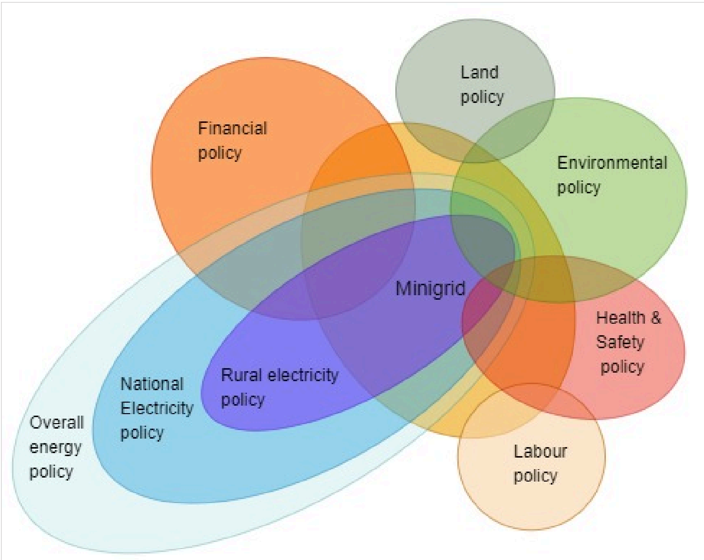

Figure 7: Nested, inter-dependent mini-grid policy arenas. Source: Authors

3.3.2. Regulation in the Mini-grid Sector

An analysis of all action arenas highlights the enormous role of the regulator across all 3 stages of mini-grid implementation – regulating, licensing, monitoring, supervising. Mini-grids lend themselves to regulation – they are central to governments' plans to provide universal access to electricity and their nature of service requires regulation in terms of technical and quality standards. In addition, host community attributes (see Figure 3) indicated by rural settlements, low population density and low purchasing power (Ogeya et al., 2021) necessitate forms of price subsidization and control . With regulation, rules are externally imposed by government, enforced by use of penalties, to alter the economic behaviour of actors.

The fast pace of scientific innovation, social change, environmental challenges and the impetus for rural economic development in the mini-grid sector necessitate sound regulatory frameworks capable of facilitating well-functioning power markets; attracting needed private investment and creating strong institutions to cope with the inter-connectedness of sectors (Bhattacharyya & Palit, 2016).

3.3.3. Mini-grid Adjacent Situations/Arenas of Influence

Each action situation in the mini-grid context is inter-connected with adjacent action situations whose outputs influence the social, economic, cultural, and institutional conditions for actors within it (McGinnis, 2011b). Any changes in the outcomes of any one action situation potentially have serious and continuing effects throughout this complex system of inter-connected action situations (McGinnis, 2011a). Adjacent sector impacts on the focal mini-grid action arenas can be positive, creating powerful synergies in combination with internal sector dynamics to drive sector growth or they can also be strongly negative that they offset crucial gains arising from internal efficiencies.

Key among adjacent action arenas is the technological innovation action arena. There is an ongoing energy transformation driven by fast technological advancements that are lowering costs, improving system performance and facilitating integration of emerging renewable technologies in the mini-grid sector (I.R.E.N.A., 2017). Similarly, the climate change action arena nested over multiple levels from local, national, to international levels is important in its influence on energy policy (Jean-Baptiste & Ducroux, 2003). Renewable energy mini-grids have become a strategic focus for sector actors; reflected in increased technological innovation budgets at the international and national levels, and more investor friendly mini-grid policies and regulations. The main-grid is another influential arena with direct influence not only on the prioritization of mini-grid related resources, choice of mini-grid technology, siting/location, mini-grid tariff, but also specific policies like main-grid arrival policy (Nkiriki & Ustun, 2017).

Mini-grid action arena(s) are nested within the local and national political action arena(s). Mini-grid actors, their choices and interactions occur within the context of a political framework that determines the central players, how effective they can be, in addition to fixing the rules of the game. The political system creates the regulatory agencies, delegating them power to execute their tasks, but also, key leadership roles are political appointees. Crucially, the nature of the political regime in terms of accountability, political stability and control of corruption will (dis)incentivize private investments necessary for sector growth (Mallon, 2006).

4. Comparative Institutional Analysis of Uganda and Tanzania’s Mini-grid Sectors

In this section we undertake a systematic, comparative institutional assessment of Uganda and Tanzania’s mini-grid energy sectors. We describe their mini-grid regulatory frameworks, evaluate the resulting sector outcomes and then work backwards to diagnose the actor interactions and exogenous context most responsible for these outcomes. We then draw conclusions on the sustainability of their mini-grid institutions.

4.1. Overview of Uganda and Tanzania’s Mini-grid Regulatory Context

Key in the countries’ mini-grid sectors is government’s central role in the determination of mini-grid sites and the licensing and pre-approval roles of the regulatory authorities including Uganda’s Electricity Regulatory Authority (ERA), the Rural Electrification Agency (REA(U))[2] and the National Management Environment Authority (NEMA) as well as Tanzania’s Energy and Water Utilities Regulatory Authority (EWURA), her Rural Energy Agency (REA(T)) and the National Environment Management Council (NEMC). ERA and EWURA are responsible for overall regulation and licensing including tariff setting, sector supervision, disputes settlements, etc; REA(U) and REA(T) are responsible for coordination of government-, donor-funded and private sector-led rural electrification programmes and NEMA and NEMC play an environmental protection role.

The two countries have long defined mini-grid regulatory and policy frameworks for rural electrification although Tanzania had a strong head start over Uganda. Historically, their governments prioritized grid extension over distributed energy in their long-term electrification policies. It is only after 2008 that Tanzania established its REA(T) (Odarno et al., 2017) and adopted the Small Power Producers (SPP) framework to encourage low-cost investment in mini-grids. This led to doubling of her mini-grid numbers and made her a regional leader in mini-grid development (Ibid). Prior to 2013 when REA(U) was established (SE4All, 2020), Uganda relied on the Electricity Act of 1999 and the Rural Electrification Strategy and Plan (2013-2022) which emphasised grid extension. Even afterwards, it continued lagging Tanzania in terms of mini-grid policies till 2020 when it adopted its first targeted mini-grid policy and regulatory framework (The electricity (isolated grid system) regulations of 2020), focusing on development of diversified mini-grid renewable energy sources. A comparison of the two mini-grid regulatory frameworks is presented in Table 5.

[2] REA(U) was functionally absorbed into Ministry of Energy and Mineral Development in 2021

Table 5: A comparative assessment of Uganda & Tanzania's regulatory frameworks

A.	**Mini-grid Financing**	
1.	Mini-grid investment laws and policies	Uganda's Rural Electrification Strategy and Plan specifies Government's energy investment plans plus the areas earmarked for mini-grid investment and development Tanzania's National Investment Promotion Policy and Rural Energy Act incentivize investment on diversified energy sources and promote Tanzania´s rural electrification.
2.	Financial support for mini-grids investors	To drive sector growth, in **both countries**, Rural Energy Agencies (REA) manage Rural Electrification Fund(s) to subsidize the capital costs of rural electrification projects.
3.	Last mile power connections	In **both countries,** REA utilizes results-based financing to incentivize last mile electricity connections in partnership with private service providers (GoU, 2018)
4	Mini-grid sector investments	In **Uganda**, all electricity sector investments require pre-approval by ERA to protect consumers from exorbitant tariffs (ERA, Electricity Regulatory Authority, 2013). **Tanzania**, on the other hand, has deregulated the investment approval process(United Republic of Tanzania, 1996).
5.	Main grid arrival to mini-grid sites	**In both countries**, **o**perators can continue selling to existing isolated grid customers, sell to the main grid or terminate operations in which case they would qualify for compensation **Uganda has** no specific compensation criteria while **Tanzania** specifies compensation if main grid arrival happens within 2-15 years post mini-grid commencement (GoU, 2020) (Tenenbaum et al., 2014).
B.	**Mini-grid Planning and Implementation**	
1.	Mini-grid licensing	In **both countries**, separate regulatory approvals are required from electricity regulatory authority, rural energy agencies, environmental protection agencies and local government. Licensing fees are tiered based on the grid capacity (GoU, 2014). License exemption thresholds differ, < 2MW for **Uganda**; < 1MW for **Tanzania** (SE4All, 2020)
2.	Technical standards and designs for mini-grids	**Both countries** have specific regulations on mini-grids technology, technical standards and codes relevant for design, construction, operation and maintenance of mini-grids.
3.	Health and safety matters	**Both country regulations** provide for the general safety, health and welfare of employees in addition to obligations on electricity providers on overall safety. See Appendix 1
5.	Customer and quality of service protections	In **both countries** mini-grid quality-of-service is enforced by the electricity regulatory authority and in addition a reporting channel is provided to consumers to file service complaints.
6.	Environmental protection	In **both countries**, autonomous environmental agencies coordinate, monitor, regulate and supervise all environment impacting activities including mini-grid licensing and operations.
7.	Decommissioning of mini-grid	**Uganda** issues specific guidelines on mini-grid decommissioning. See Appendix 1 **Tanzania** however, lacks specific regulations on mini-grid decommissioning.

4.2. Uganda & Tanzania's Mini-grid Sector Outcomes

We examine mini-grid sector outcomes in the two countries with a focus on current numbers of mini-grid connections, growth rates and mini-grid survival rates, comparing them against the policy objectives in the respective policy frameworks. Table 6 summarizes latest available[3] mini-grid data for Uganda and Tanzania.

[3] Current country specific mini-grid data for both Uganda and Tanzania from government agencies and established sources are limited and incomplete which restrains precise triangulation of mini-grids numbers.

Uganda's rural electricity access stands at 13% against national access of 26%, while Tanzania's rural access stands at 19% against national access of 38% (I.E.A., 2020). From Table 6, Uganda's mini-grid market is much less mature than that of Tanzania. Uganda has however seen significant growth of ≈200% over the last 3 years, jumping from 16 to 48 operational mini-grids between 2020 and 2022 (E.S.M.A.P., 2022) . There has been an improvement in the mini-grid outlook but sector developments still severely lag government set rural electricity access targets of 26% by 2022, 51% by 2030, and 100% by 2040 specified in the Rural Electrification Strategy and Plan (RESP) of 2013-2022. In addition, the survival of existing mini-grids is a concern. As of 2020, out of 34 mini-grids, only 16 were confirmed as operational and 18 had unknown status; a survival rate of ≈47% (U.O.M.A., 2020). Systemic problems still hinder sector growth including limited access to capital, an uncertain regulatory environment, limited private sector participation and poor mini-grid economics (SEforALL, 2019; U.O.M.A., 2019, 2020, 2021, 2022).

As of early 2016, Tanzania had 109 mini-grids, of which only 77 were confirmed to be operational, 14 non-operational and 18 with unknown status; a mini-grid survival rate of ≈71% (A.M.D.A., 2018; Odarno et al., 2017). A total of 66 mini-grids were subsequently registered between 2017 and 2021 (E.W.U.R.A., 2018, 2019, 2020, 2021, 2022), which makes a total of 175 registered mini-grids in Tanzania (See Table 6). While Tanzania posts much better numbers than Uganda, her mini-grid market growth has slowed on account of weak enforcement of existing regulations, frequent rule changes and mixed signals from the government which have made players wary of developing new projects (E.S.M.A.P., 2022; SE4All, 2020).

Table 6: Uganda & Tanzania cumulative annual mini-grid numbers, connections and growth rates.

Mini-grid types	**Uganda**			**Tanzania**					
	2020[a]	**2021[b]**	**2022[c]**	**< 2016[d]**	**2016/17[e]**	**2017/18[f]**	**2018/19[g]**	**2019/20[h]**	**2020/21[i]**
Fossil Fuel	0	0	0	19	19	19	19	19	19
Hydro	6	6	2	49	49	49	50	50	50
Biomass	3	3	3	25	25	25	25	25	25
Solar	6	9	42	13	16	20	39	62	78
Hybrid	1	1	1	3	3	3	3	3	3
Total	**16j**	**19j**	**48j**	**109k**	**112**	**116**	**136**	**159**	**175**
Connections	**4,000**		**>20,000**	**184,000**			**187,298**	**193,955**	**199,951**

Missing fields – Unable to find information in that category.
The grand total for mini-grids and connections in Tanzania, are authors' compilation from the cited sources.
[a] (UOMA 2020); [b] (UOMA 2021); [c] (UOMA 2022); [d] (Odarno et al. 2017); e (EWURA 2018); [f] (EWURA 2019); [g] (EWURA 2020); [h] (EWURA 2021); [i] (EWURA 2022)
[j] Only includes mini-grids with confirmed operational ststus ~18 mini-grids have unknown operational status.
[k] Number includes 14 non-operational mini-grids and 18 mini-grids of unknown status.

4.3. Key Action Arenas, Causal Patterns of Interactions & Exogenous Context

The outcomes presented in section 4.2 reveal low mini-grid numbers, poor rates of mini-grid survival and sector growth rates that lag set government targets. The outcomes are generated out of actor interactions in the mini-grid market, permitting and administration, and mini-grid policy making arenas. We compare how policies, interest group preferences, agency mandates, as well as exogenous context in the two countries shape the reported sector outcomes.

4.3.1. Mini-grid market

Equity considerations. Uganda and Tanzania's mini-grid markets are characterized by government intervention in the form of regulated tariffs (SE4All, 2020). Mini-grid developers are unable to set cost-reflective tariffs that recoup installation costs and operating expenses within a rural household's ability to pay for electricity. The mini-grid context is that of rural, remote, poor communities. Motivated by equity considerations, regulators seeks to shield consumers from high electricity bills (Mottram, 2022); matching mini-grid tariffs to main-grid tariffs irrespective of the levelized cost of mini-grid electricity (Andreoni et al., 2022; Raisch, 2016; SE4All, 2020). Governments compensate for the low tariffs by providing un-sustainable capex subsidies to mini-grid developers and address affordability challenges via direct subsidies to consumers in terms of free-connections policies (Odarno et al., 2017; Pérez-López, 2020).

Mini-grid financing. Uganda's Rural Energy Fund (REF) was established in 2007 to fund electricity access projects to rural communities through the development of mini-grids. The program, funded by the World Bank and the government of Uganda, offers financial incentives to private mini-grid developers consisting of upfront capital subsidies of up to 50% (Hoeck et al., 2022; Lane et al., 2018). Tanzania's REA(T) runs a similar incentive program for private developers funded by the government of Tanzania covering a capital subsidy of up to 75% (Melnyk & Kelly, 2019) and its Rural Based Financing program offers subsidies of $500 per connection (Phillips et al., 2020). Tanzania's program offers higher developer financing than Uganda's program possibly accounting for the higher investment attraction in their mini-grid sector. Additionally, Tanzania's program is managed by a single agency, REA(T) (Willcox & Cooper, 2018), while Uganda's program is managed by multiple agencies (REF, REA(U), Uganda Electricity Generation Company Limited) which leads to greater administrative complexity (Twesigye, 2019) that would hinder investment attraction in the sector.

Mini-grid tariffs. In-spite of these financing mechanisms, studies in these countries have found the levelized cost of electricity to be as high as 1.5-times the set mini-grid tariff (SE4All, 2020; U.O.M.A., 2021). According to Uganda's tariff policy, ERA should set power tariffs by determining operator revenue requirements and applying a Rate of Return (ROR) regulation (E.R.A., 2006). ERA, however, imposed a mini-grid tariff cap of 0.30 USD/kWh slightly higher than the main-grid tariff of ≈0.22 USD/kWh but still lower than the cost reflective rate of ≈0.50 USD/kWh, forcing it to apply expensive top-up subsidies (Pérez-López, 2020). Electricity Act also specifies the principle of cost reflective tariffs, but increasing public and political pressure has handicapped EWURA making flexible tariff setting a sensitive topic (SE4All, 2020). TANESCO-run rural mini-grid networks are unable to fully reflect costs in the tariff (Odarno et al., 2017). In both countries, sector regulators are not setting tariffs based on realistic and economic costs of electricity not only hindering investment attraction but also affecting the sustainability of existing mini-grids.

4.3.2. Mini-grid Licensing & Supervision Regimes

Sector reforms. Both Uganda and Tanzania's energy sectors underwent a devolution of functional and fiscal responsibilities from central to sub-national governments or agencies (Curristine et al., 2007; Tumwesigye et al., 2011). Political power was decentralized from national level ministries to jurisdiction specific governmental agencies. As discussed in section 3.4.1, there are many aligned but also potentially competing interests and goals at play in the licensing and supervision arena – national versus rural energy access goals, economic development goals, environmental protection, land & natural resource considerations, etc. The interests are overseen by distinct semi-autonomous offices with different reporting lines and differing mandates (See Table 7) causing a level of incoherence and overlaps (Wabukala et al., 2022). Each has its own requirements and they do not coordinate on delivery timelines (SE4All, 2020). The absence of a recognized intra-agency coordination role and/or mechanism, lack of institutional clarity and un-awareness on the part of the different agencies of the relative ranking of governments' priorities results in bureaucratic redundancy, gridlock, agenda turf wars, which challenge efficiency of implementation (Aly et al., 2019; Andreoni et al., 2022; Fazekas et al., 2021; Tumwesigye et al., 2011; Wabukala et al., 2022).

Table 7: Required approvals and responsible authorities involved in mini-grid licensing.

Required Approvals	**Responsible Authority**	
	Uganda	**Tanzania**
Mini-grid operation		
Registering Mini-grid	ERA	TIC
Registering with the Tax authority	URA	TRA
Getting provisional license/registration	-	EWURA
Getting license/ certificate of exemption	ERA	EWURA
Getting letter of intent (if SPP/VSPP wants electricity to DNO	-	TANESCO
Environmental approval		
Environmental impact assessment and feasibility study approved by the authority	NEMA	NEMC
Confirmation that intended site is appropriate for Mini-grid development(also called strategic area in Tanzania)	REA	DNO
Review and approval by water sources and/or irrigation authority	DWRM	Regional water basin office
Land and natural resource usage rights		
Proof of land ownership or permission to use the land (lease)	REA	Village/Local governments
Approval to use specified amount of water or identified natural resource in the intended site	NEMA	Regional water basin office
Getting construction or building permits (example for hydro power projects)	DWRM	District or Municipal Council
Community or local governments involvement		
Approval or proof for business conduction in the locality and about tariff application which is due to be submitted to the authority	Local government	Local government

Administrative efficiency. Regulatory processes in the two countries, of mini-grid license application, tariff approvals, environmental impact assessment approvals, etc. are characterized as cumbersome, expensive and time consuming (SE4All, 2020) revealing a level of institutional inefficiency. Table 7 summarizes the different levels of approvals required for mini-grids development in Uganda and Tanzania. With more than ten approvals to obtain, mini-grid performance from both countries is hindered by inefficient and inter-agency gridlock procedures (Ibid), a stumbling block for investment attraction. In addition, is the issue of corruption in the energy sectors of both countries with both governments scoring low in terms of controlling the vice (Aly et al., 2019; Andreoni et al., 2022; Fazekas et al., 2021; Tumwesigye et al., 2011; Wabukala et al., 2022).

The licensing process for mini-grid operators differs slightly between the two countries. The time it takes to apply for requisite licenses, concessions and environmental approvals is substantial (EEP Africa, 2018) taking ≈18 months for Uganda (U.O.M.A., 2022) and ≈14 months (Adamopoulou et al., 2022) for Tanzania. In Uganda, according to Electricity (Isolated Grid Systems) Regulations, 2020, mini-grid operators generating >2MW must obtain a license prior to operation. All systems <2MW must obtain a license exemption certificate, a process which mandates prior social and environmental impact assessment approvals and takes a minimum of 180 days (E.R.A., 2020; Kapika & Eberhard, 2013). This points to redundant and cumbersome transaction costs in Uganda's process. In Tanzania, mini-grid operators must obtain a license for systems >1MW, but the process is simpler for smaller power producers (SPPs) <1MW where requirement is simply registration with the regulator. Registration, unlike licensing, is for information purposes only and does not require regulatory approval (Tenenbaum et al., 2014a). This concept of light-handed regulation for SPPs may account for higher investment attraction in Tanzania.

4.3.3. Mini-grid Policy Making

Mini-grid sector complexity. The complexity of the energy sector discussed in section 3.3.1 directly impacts the processes and outcomes of policy making. There are various levels of government involved in mini-grid policy making in Uganda and Tanzania: government ministries including Energy, Economic Planning, Environment, Water resources, etc., governmental agencies for electricity sector regulation and rural electrification, in addition to the involvement of interest groups – NGOs, donors, development partners. Based on the breadth of interests involved, policy decisions, are highly likely to be hijacked by politics rather than being supported by science (Aly et al., 2019).

Policy making approach. The economic power wielded by external interest groups (donors and NGOs) in the process gives them a powerful platform to influence the direction of policy and how it is made. They have used this platform to advocate a participatory policy making approach (Rodriguez & Komendantova, 2022) that invites users/consumers of policy to identify, develop, and decide directly on policy proposals via consultative or participatory means (Rietbergen-McCracken, 2017). Both countries have adopted a mix of top-down regulation and participatory approaches. In Uganda, the government and regulatory authorities playing a central role in policy formulation and implementation but ERA's website also shows efforts to involve stakeholders in the policy making process through public consultations and other participatory processes. Similarly, EWURA's website notes the key role played by Tanzania's government, but also reports a focus on involving stakeholders, including communities, NGOs, and the private sector, in the policy making process. Despite these efforts, there are still challenges to promoting greater civil engagement in energy policy making in the two countries including limited resources and capacity among civil society organizations, and a lack of transparency in policy making processes (Guma, 2017).

Policy changes. Over the last two decades (or so), both Uganda and Tanzania have made efforts to develop and implement policies to support the deployment of mini-grids. In Uganda, there have also been several changes to these policies, with updates and revisions made in response to changing priorities and market conditions. The RESP, launched in 2001, has since seen its fourth revision, the latest coming in 2019 with the support of NRECA International. Tanzania's government has also implemented policies and initiatives over the same period. However, there has been greater stability in mini-grid policy in Tanzania over the last decade, with fewer significant changes or revisions. The higher level of certainty in Tanzania's mini-grid sector could account for its relatively higher private mini-grid investments.

4.4. Sustainability Implications of Uganda & Tanzania's Mini-grid Institutions

Institutional sustainability is defined as an institution's ability to coordinate or organize human interaction in the long term towards achieving specific sustainability goals (Pfahl, 2005). Institutional sustainability relies not only on the existence of documented rules and regulations but also on the practicability of their implementation. Our analysis in sections 4.2 and 4.3 has established that the current mini-grid institutions in the two countries are not producing the desired sector outcomes. Figure 8 highlights the logical links from our IAD framework analysis of Uganda and Tanzania's energy sectors

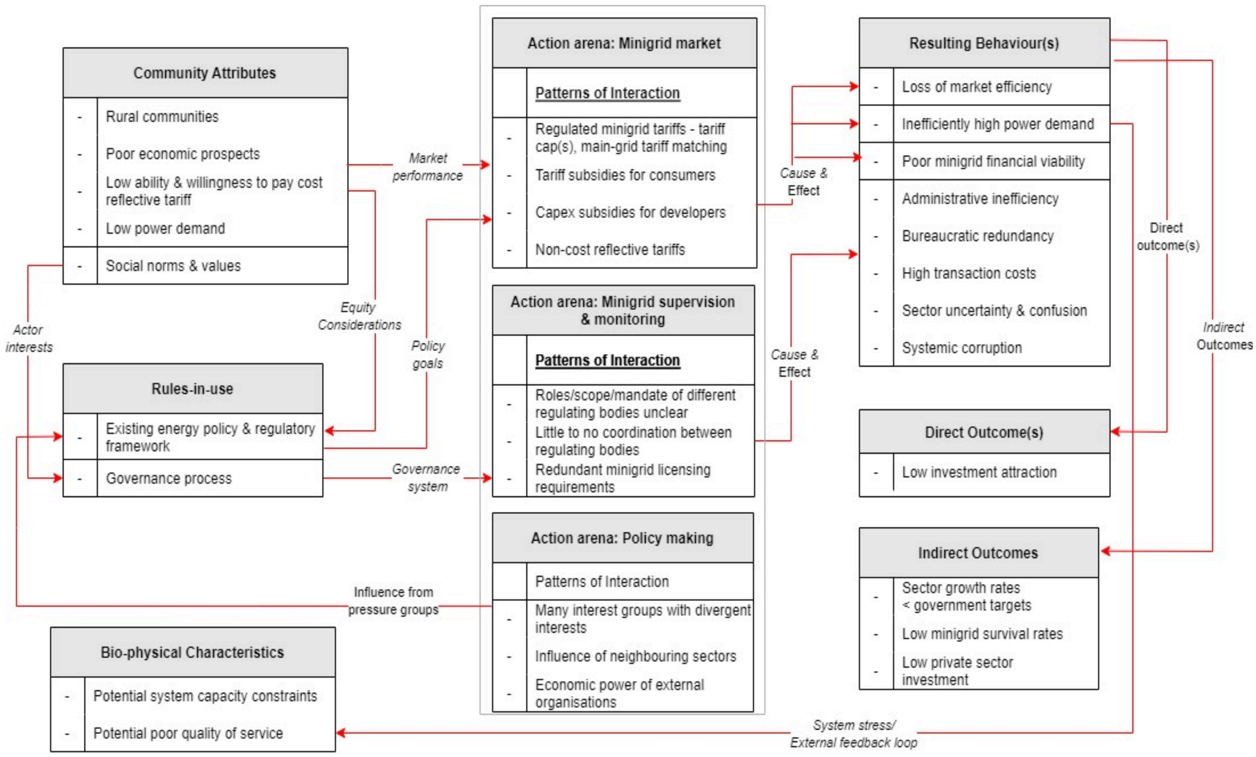

Figure 8: Logical links from IAD framework analysis of Uganda & Tanzania energy sectors.
Source: Authors

4.4.1. Institutional efficiency

The inefficiencies in the mini-grid institutional frameworks of these countries described in sections 4.3.1 and 4.3.2 have the potential to spur short-term and long-term negative feedback loops. In the short-term, institutional process issues like poor administrative efficiency and corruption would drive potential investors to abandon the license application process before its conclusion. In the longer-term, inflexible non-cost reflective tariff policies without sufficient supportive financing would drive operators to abandon live projects on account of their poor economic viability.

Curristine et al. (2007) found functional and political decentralization (agencification) beneficial for efficiency if accompanied by appropriate fiscal and political decentralization. It improves the efficiency and responsiveness of the public sector when it brings decision making closer to the user communities (Treisman, 2002). There are however major risks with agencification, including the exposure of governments to financial risks and increased incentives for political patronage and corruption (Curristine et al., 2007; Treisman, 2002). Section 4.3.2 highlights corruption as one of the key stumbling blocks affecting institutional efficiency in Uganda and Tanzania's energy sectors. In the absence of strong political will and punitive legal frameworks to control corruption, the vice may undermine any useful gains that would accrue from a robust mini-grid regulatory framework (Wabukala et al., 2022).

4.4.2. Mini-grid market design

With inflexible non-cost reflective tariffs and insufficient support financing, mini-grid operations cannot be profitable and operations such as these will likely collapse without the support of external grants. Regulated tariffs are distorted by grant subsidies and cross-subsidies at the expense of efficiency and cost recovery. In addition, artificially low subsidized tariffs stimulate inefficiently high-power demand, which puts pressure on the system capacity and the quality of service for all users. The impact on mini-grid operations is poor performance and quality of service that is transferred directly to consumers. These are external feedback loops on the system making it un-sustainable. However, if mini-grid tariffs were not capped, there is a risk that electricity prices offered by mini-grid operators may be unaffordable for many rural households. This could limit power demand potentially leading to the failure of mini-grid projects.

4.4.3. Integrated Policy Making

Described in sections 3.3.1, 3.3.3 and 4.3.3, energy issues and consequently energy policy cut across jurisdictional boundaries, governance levels, and policy domains. The decision making in Uganda & Tanzania's sector is made more complex by the fragmentation and decentralization of decision-making centres (see section 4.3.2). There is an increased number of actors involved in the policy process together with the increasing role of NGOs, special interest groups and agencies necessitating cooperation, coordination and integrated policy making to achieve robust policies. Policy integration is an agency-driven process of multi-dimensional policy within a governance system directed at addressing a cross-cutting policy problem in a holistic manner (Candel & Biesbroek, 2016). It transcends the boundaries of established policy fields and individual departments (Meijers & Stead, 2004); linking between different departments in public agencies (horizontal integration) or between different tiers of government (vertical integration) or a combination of both (Ibid). However, organizations involved may differ in terms of institutional structures and practices, historical contexts, priorities, etc., making consensus elusive. Policies qualifying as integrated will be comprehensive - recognizing a broader scope of policy consequences in terms of time, space, actors and issues, and consistent –applicable at all policy levels and government agencies (Meijers & Stead, 2004).

4.4.4. Participatory Policy Making

The process of how the rules are made and updated and who has responsibility for making the rules is important in determining the sustainability of mini-grid institutions. E. Ostrom, (1993) advocates participatory decision making as key to the sustainability of institutions. Those most affected by the rules must have a say in making and modifying those rules (E. Ostrom, 1993) . Negative consequences are bound to arise when external rules that don't match the local context are imposed (Cox et al., 2010). In the mini-grid case, the actors most affected, operators and consumers, should contribute in the formation and modification of mini-grid policy as early as at ideation stage. These stakeholder groups hold valuable contextual knowledge on what works and what doesn't. Involving them would drive policy acceptance, ownership and accountability among resource users which has a direct link to the sustainability of desired outcomes.

4.4.5. Alignment of social norms and cultural values.

In the socio-cultural context, human behaviour is driven by personal, professional, cultural characteristics. Such specific characteristics of personality are values (Schwartz, 1992). Values are durable internal individual criteria for evaluation; on the other hand, social norms are external to the actors, developed because of long-term interaction between actors (Hechter, 1993). Actor behaviour is determined not only from the constraints emanating from the context in which they are embedded but also by actors' evaluations of the alternative outcomes (Ibid). At implementation, policies get co-opted and altered in order to serve the goals, values and assumptions of those using them (Muers, 2018). Thus, any sustainable institutions, policy or regulatory designs must ensure a level of consistency between the intended institutional values and the socio-cultural values of actors. From our findings, the current mini-grid market design of regulated tariffs seems to be at odds with the overall governmental goal of attracting private investments into the sector. The intended values in a regulated non-cost reflective tariff are more likely to attract NGOs and charities than private investors. Further, an analysis of the governance inefficiencies in 4.2.2 single out corruption which is an outcome of actors' core values. Where sector actors have a short-term view, maximise their individual interests at the expense of a thriving mini-grid sector, the result is corrupt institutions characterized by unnecessary bureaucracy and unending gridlock.

5. Conclusion and Policy Implications

We set out to find the key institutional and socio-cultural considerations driving (un)sustainable outcomes in mini-grid systems; the driving actors' choices and patterns of interaction and the sustainability implications of Uganda and Tanzania's mini-grid policies. Our findings on mini-grid institutions highlight two main considerations for sustainability: First, the challenge posed by the the complexity and inter-connectedness of the mini-grid sector and adjacent sectors. Second, the potential positive and/or negative impact(s) from adjacent sector arenas on the focal mini-grid action arenas. In addition, we found the ability of Uganda and Tanzania's mini-grid institutions to coordinate key actor interactions in the long term for achievement of specific sustainability goals to be hindered by institutional inefficiencies, distorted power markets on account of strongly regulated tariffs and a policy design process that is not accounting for the socio-cultural values of sector actors.

5.1 Policy Insights and Recommendations

5.1.1 Reshape patterns of interaction; transform outcomes

Section 4.3.2 highlights problematic patterns of interaction in the administration of Uganda and Tanzania's mini-grid sectors. Poor inter-agency coordination, redundant-highly bureaucratic processes and corrupt actor behaviours have created gridlock and administrative inefficiencies, frustrating efforts to ramp up private investment. The robust solution is a combination of strategies aimed at streamlining actor interactions towards influencing their choices/behaviours and consequently outcomes. Among possible strategies is:

(1) Change of rules: Regulators must *Simplify*. The more complex and cumbersome rules/processes are, the more pressure on actors to circumvent the same. Simplifying regulatory processes could mean consolidating regulations to reduce redundancy or *standardisation* of processes to reduce complexity.

(2) Change of actor incentives: *Digitizalization* of processes and requirements is a must to drive transparency, compliance and convenience at lower transaction costs. It crucially minimizes unnecessary face-to-face interactions, reducing opportunities for personal bias, favoritism and corruption.

(3) Change of information flows: Regulators could consider implementation of oversight mechanisms including *public reporting and disclosure* as a way to drive greater transparency and accountability

(4) Change of actors: Regulators could utilize training programs, mentoring, and other forms of *capacity building* to change mindset of actors targeting to alter underlying actor incentives and ultimately patterns of interaction.

This method allows for targeted interventions to effectively address underlying issues.

5.1.2 Integration in policy making and implementation

Section 4.3.1 reveals a distorted mini-grid market that is reliant on un-sustainable government subsidies, a result of 'fixed' community attributes and external environment in the low economic prospects of mini-grid communities and consumers' low ability to pay. In 3.3.1 and 3.3.3, we describe mini-grid energy policy as a cross-sectoral policy arena affecting and affected by decisions taken in adjacent policy arenas including main-grid, climate, development, economy, environment, land, labour, etc. Adjacent sector impacts will either combine with focal sector dynamics to re-inforce desirable outcomes or cancel out crucial gains arising from focal sector efficiencies. This cross-sectoral character affects how energy policy is proposed, adopted, and implemented. Successful rural energy policies cannot be developed nor implemented in isolation from adjacent policy arenas. Policy integration where rural energy policy is designed and implemented alongside complementary or interdependent community development policy including transport, communications, health, education services, etc. would be a more cost-effective approach for governments in the region. This would leverage funds from multiple sectors but also, will be better able to facilitate growth of viable and sustainable mini-grid energy markets independent of long-term government stabilization programs.

5.1.3 Structures for participatory policy making

Given the diversity and heterogeneity of policy actors, the formulation and adoption of mini-grid policy can either be hampered or advanced by the policy making process. All the participatory processes of cross-sectoral cooperation, coordination and policy integration can be meaningless and counterproductive if they are conducted in an unstructured way. There must be intentional mechanisms to take account of feedback and draw on a wide variety of qualitative and quantitative data so that decisions are not based solely on politics but also on scientific expert knowledge and practical knowledge existing in local communities.

5.1.4 Values adoption to drive institutional change

Section 4.4.5 discusses the impact of a potential mismatch between host community core values and the values informing mini-grid policy. It reveals the existence of feedback loops between *community attributes* and *rules-in-use*. Rather than being driven by set policies, sector outcomes are driven by how individual actors apply the underlying processes. Because core values can evolve over time, where changes are pervasive enough, there is potential to induce institutional and policy change. By utilizing the outer feedback loop between outcomes and exogenous context and embedding adaptive learning processes, policy makers can drive values adoption; positively altering expected patterns of behaviour and consequently outcomes. To achieve this, policy makers must strengthen the feedback mechanism with capability to sense and capture process outputs. It requires that policy implementation is accompanied by targeted monitoring of output indicators and where value discordances are detected, corrective learning or policy adaptation can be activated.

5.2. IAD framework contribution

The mini-grid institutional context is a complex system of divergent actor interests from multiple inter-dependent regulatory actors coming from different policy arenas. The strengths of the IAD framework lie in its structured approach, providing a useful frame of reference to analyze this complexity. It has been successful in allowing for a tailored examination of the unique challenges and opportunities within the mini-grid institutional context. However, a weakness is that under one broad brush ‘Rules-in-use’ it does not distinguish between internally-generated and externally-imposed rules overlooking important distinctions in their specific impacts on actor interactions. Overall, the IAD framework has served as a foundational structure to develop theories and support a deeper understanding of mini-grid institution sustainability.

5.3. Study limitations and future research

It is worth noting that the study is limited by the paucity of verified mini-grid numbers data for triangulation purpose for Uganda and Tanzania. However, methodological triangulation was achieved through the use of multiple sources of data reducing the risk of bias and providing a more robust basis for our conclusions. Further research in form of a comprehensive survey of mini-grid operators and users in these countries, in addition to in-depth interviews and focus group discussions with key stakeholders, is required to fill in the information gaps.

6. Declarations

Author Contributions: Individual author contributions were as follows: Conceptualization, L.D.N.; methodology, L.D.N. and H.A.S; formal analysis, L.D.N., H.A.S and I.F.N.; writing—original draft preparation, L.D.N., H.A.S. and I.F.N.; writing—review and editing, L.D.N. All authors have read and agreed to the published version of the manuscript.

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Appendix A

This contains detailed compilation of Uganda and Tanzania's mini-grid policies and regulations as referenced in section 4.

A.	**Mini-grid Financing**	
	Uganda	**Tanzania**
1	Mini-grid investment laws and policies	
	Uganda's Rural Electrification Strategy and Plan (RESP) of 2013-2022: seeks to prioritize service areas on key social, economic and political metrics as determined by the government **National Development Plan (2010/11-2014/15) and Second National Development Plan (NDPII) 2015/16 – 2019/20:** outline the national plan on energy sector investment **Electricity Investment Approval and Verification Guidelines of March 2013:** provides guidance on the electricity sector approvals.	**National Investment Promotion Policy of 1996**: encourages investment on diversified energy sources for sustainable electricity supply. It also calls for investment from private sector **Rural Energy Act of 2005:** seeks to secure investment, resource mobilization and promote rural electrification. **Electricity Act of 2008:** outlines how authorities should set tariff that enhance investors to recover their investment costs.
2	Financial support for mini-grids investors	
	Energy Policy for Uganda of 2002: establishment of REF for loans and grant provision to rural electrification programs	**Rural Energy Act of 2005:** securing funds for qualified mini-grid developers
3	Last mile power connections	
	Uganda's electricity connections policy, 2018-2027: aims to address challenges of high connection charges and lack of incentives for service providers to make timely and cost affordable connections	**Tanzania Energy Development and Access Expansion Project implemented between 2003 and 2015:** To facilitate last mile power connections to rural customers
4	Main grid arrival to mini-grid sites	
	Uganda's Electricity Isolated Grid System, 2020 regulation: Outlines options are available to operators in the event of mini-grid arrival to mini-grid site	**The Electricity Development of Small Power Projects Rules of 2014 to 2020:** outline guidelines for compensation of interconnection when main grid reaches mini-grid

B.	**Mini-grid Planning and Implementation**	
1	Specific rules and regulations for mini-grid development	
	Uganda's Electricity Isolated Grid System, 2020 regulation: provides overall regulations pertaining mini-grid existence in Uganda	**The Electricity Development of Small Power Projects Rules of 2014 to 2020:** governs regulatory matters and procedures relating to the development of small power projects
2	Mini-grid licensing	
	Electricity Act of 1999: established ERA to manage licensing matters within the electricity sector **Uganda's Electricity Isolated Grid System, 2020 regulation:** outlines mini-grid licensing procedures	**Electricity License Fees Amendment regulation of 2014:** specifies licensing fee for different energy capacity systems **The Electricity Development of Small Power Projects Rules of 2014 to 2020:** specifies mini-grids procedures for license
3	Technical standards and designs for mini-grids	
	Uganda's Distribution Line Construction Guidelines, 2017: aims to provide guides guideline on all matters pertaining technical system designs for electricity systems to ensure safety of both customers and constructors **Uganda's Electricity Isolated Grid System, 2020 regulation:** specifically provides rules to be adhered for mini-grids implementation and operation	**Electricity Generation, Transmission and Distribution Activities Rules of 2019:** aims to provide guidance on technical standards and codes relevant for design, construction, operation and maintenance of mini-grids. **Electricity Grid and Distribution Codes of 2017:** provides guidance on mini-grids technology, construction and tariff issues related to sale of power.
4	Health and safety matters	
	The Occupational Safety and Health Act 2006: points out what should be done by mini-grid operators to ensure safety of their employees and customers **Electricity (Safety code) regulation 2003:** specifies safety requirements that must be adhered to by mini-grid licensees **The Electricity (Code of Quality of Service) Regulations 2020:** specifies regulations that must be followed by both service provider and consumer to ensure delivery and consumption of quality electricity services	**The Electricity General Regulations Act 2011-20:** aims to protect consumers from dangers that may arise from electricity and related activities. **The Occupational Health and Safety Act No. 5 2013:** seeks to enhance general safety, health and welfare of electricity sector employees
5	Customer services and protection	
	Know Your Right regulation of 2015: meant for customers' protection against under-quality services from electricity providers **The Electricity (Tariff Code) Regulations:** Provide customers with fair and reasonable price structures consistent with maintenance of a financially and operationally secured electricity supply system.	**EWURA Consumer Complaints Settlement Procedure Rules, 2020:** Ensures customers are well served and can be able file complaints on matters pertaining electricity services.
6	Environmental matters pertaining mini-grid deployment	

	The National Environment Act, No. 5 of 2019: aims to coordinate, monitor, regulate and supervise all activities pertaining to the environment including management of hazardous chemicals and biodiversity offsets; addressing environmental concerns arising out of petroleum activities and midstream operations, among others **Uganda Electricity Decommissioning Power Systems Installations Guidelines, 2018:** aims to protect environment from inoperative mini-grids	**Environmental Management Impact Assessment and Audit Amendment Regulations, 2018:** seeks to provide guidance on environmental impact assessment matters including activities to be undertaken during construction, operation and decommissioning of the project. **The Electricity General Regulations Act 2011-20:** aims at ensuring environmental protection from electricity production, transmission, supply and installation. Also to guide actors to comply with their industry best practices
7	Decommissioning of mini-grid	
	Uganda Electricity Decommissioning Power Systems Installations Guidelines, 2018: provides guidance specifically to decommissioning of mini-grids systems that have stopped operating for whatever reason in order to protect environment	**Environmental Management Impact Assessment and Audit Amendment Regulations, 2018**: provide general guidance on decommissioning of any system that no longer operates to protect the environment

Appendix B

Summary of Research data themes and sample reference literature arising from literature review

Summary themes			
Category	**Sub-Category**	**Key Themes**	**Examples of literature**
IAD framework	IAD methodology	IAD applied to analysis of problems	(Gollwitzer & Cloke, 2018); (Altomonte & Guinto, 2022.); (Lestari et al., 2018); (Nigussie et al., 2018); (Oh & Hettiarachchi, 2020); (Shah & Niles, 2016)
	Mini-grid IAD context	Sector actors, roles, patterns of interaction, community attributes	(Gollwitzer et al., 2015a); (Gollwitzer et al., 2018); (Akinlabi & Oladokun, 2021); (Hoeck et al., 2022)
		External environment	(Bhattacharyya & Palit, 2016); (Madriz-Vargas et al., 2015); (Jean-Baptiste & Ducroux, 2003)
Policy frameworks	Regulatory Environment	Policy requirements	(Bhattacharyya & Palit, 2016)
		Mini-grid external environment	(Bhattacharyya & Palit, 2016); (Madriz-Vargas et al., 2015); (I.R.E.N.A., 2017)
		Mini-grid financing	(SE4All, 2020)
		Mini-grid Planning and design	(Akinlabi & Oladokun, 2021); (Madriz-Vargas et al., 2015)
		Mini-grid implementation	(Madriz-Vargas et al., 2015)
		Mini-grid policies	See Appendix A for details

East Africa mini-grid context	Uganda's mini-grid sector	Regulatory challenges and barriers	(SE4All, 2020); (Nkiriki & Ustun, 2017); (Kapika & Eberhard, 2013)
		Mini-grid sector Outcomes	(Twesigye, 2019); (Wabukala et al., 2022); (Hansen, 2015); (E.R.A., 2020); (SE4All, 2020); (U.O.M.A 2019 - 2022)
	Tanzania's mini-grid sector	Mini-grid policies	See Appendix A for details
		Regulatory challenges and barriers	(SE4All, 2020); (Ngowi et al., 2019); (Tenenbaum et al., 2014a)
		Mini-grid sector Outcomes	(EWURA 2018 - 2022); (Odarno et al., 2017); (U.O.M.A 2019 – 2022); (Mottram, 2022); (SE4All, 2020); (E.S.M.A.P., 2022)

Chapter III: Institutional arrangements and sustainable maintenance management of community-based mini-grids in Tanzania

Abstract

This article presents empirical research on the maintenance management model for containerised solar community-based mini-grids and corresponding institutional arrangements. It employs Agrawal's (2001) "institutional arrangements" subset of enabling conditions and examines its applicability in explaining the sustainability of maintenance management of community mini-grids. The paper analyses and synthesises distinctive sustainability experiences from two solar community mini-grids in Tanzania. Using data from 18 semi-structured interviews with village energy committee members, electricity users, technicians and local leaders, the paper explicates a maintenance management model practised in the two mini-grids. The paper further presents institutional arrangements assessment for the maintenance management of the two mini-grids and analyses how rules, sanctions and accountability for community mini-grids maintenance affect the corresponding maintenance sustainability outcomes. The study found reactive maintenance to be a dominant maintenance strategy and is complemented by insufficient balances in the mini-grids' maintenance funds. Proper enforcement of maintenance rules, implementation of arranged graduated sanctions, and presence of low-cost adjudication coupled with the accountability of mini-grid leaders can potentially enhance the maintenance sustainability of community mini-grids. The paper concludes that, institutional arrangements for communally owned mini-grids need a collective interactive approach among local users for sustainable mini-grids maintenance.

Keywords: Operational sustainability, Community energy governance, Maintenance practices, Tanzania

1. Introduction

The global agenda on access to affordable, reliable, sustainable, and modern energy (SDG 7) through renewable technologies has gained significant attention in recent years. Rural communities in global south countries, such as Tanzania, with low global electrification rates (IEA et al., 2022), have benefited from this agenda through mini-grids, which emerged as a promising solution (Blimpo & Cosgrove-Davies, 2019; IEA et al., 2022; Motjoadi et al., 2020b; Tenenbaum et al., 2014b). As an alternative solution to principal grid electricity, different mini-grid ownership models, such as private, utility, community, and faith-based, in Tanzania offer electricity generation and distribution from decentralized renewable energy sources (Odarno et al., 2017).

Community-based mini-grids model, whose benefiting communities are responsible for managing financial and technical mini-grids matters (Katre et al., 2019), is both a notable ownership model in electrifying rural communities (Bhattacharyya & Palit, 2016; Cust et al., 2007; Dauenhauer et al., 2020; Maier, 2007) and a tenable approach for institutionalising, managing, and organising rural mini-grids. Community-based mini-grids as common pool resources (CPRs) (Gollwitzer et al., 2018; Maier, 2007) call for respective communities to collectively operate and manage mini-grids willingly (e.g., collecting tariffs, mini-grid maintenance, electing energy committees in most cases) to enhance the system's sustainability. Despite its potential to electrify developing countries' rural communities, this model faces technical and financial (Gollwitzer et al., 2018; Greacen, 2004; Katre et al., 2019; Mgonja & Saidi, 2017), sociocultural, and political (Dauenhauer et al., 2020; Gollwitzer et al., 2018; Potisat, 2019) hurdles. Previous works on technical factors that affect mini-grid sustainability have focused mainly on technical installations, maintenance management, designs, and performance (Haney & Burstein, 2013; Mgonja & Saidi, 2017), which rely on the engineering field, while others have examined socio-technical designs for mini-grid implementation (Ahlborg & Sjöstedt, 2015; Ulsrud et al., 2015). Whilst the aspects above are well researched, institutional aspects (Gollwitzer et al., 2015b, 2018; C. Kirubi et al., 2009; Tang, 1991) for managing community-based mini-grids from a technical angle have not received significant attention. Limited studies have pointed to the role of institutional arrangements in overall mini-grid management (Gollwitzer et al., 2018) and maintenance funds (Maier, 2007), but have not extensively delved into analysing their interactions, relations, and applicability for decentralised mini-grid management units like maintenance.

This paper, therefore, goes beyond by undertaking an insightful analysis of institutional arrangements for community mini-grid management and examining their applicability to maintenance sustainability outcomes. Institutional arrangements refer to rules that govern individual and collective choices regarding the management of CPRs (Greacen, 2004; E. Ostrom, 1986; Tang, 1991). Institutional arrangements have received enormous attention in the literature associated with local organisation and management of natural resources, including mini-grids (Agrawal, 2001; Gollwitzer et al., 2018; Keisang et al., 2021; E. Ostrom, 1990). Once designed by small local communities, institutional arrangements are determinants of the sustainable management of CPRs (Baland & Platteau, 1996; E. Ostrom, 1990; Wade, 1989). This also applies to managing community mini-grids (Agrawal, 2001; Gill-Wiehl et al., 2022; Gollwitzer et al., 2015b, 2018; Maier, 2007). This paper, therefore, examines mini-grid maintenance management and later utilises the "institutional arrangements" subset of the enabling conditions analytical framework developed by Agrawal, (2001) (see shaded enabling conditions in Figure 9) to analyse mini-grid maintenance management. The remaining Agrawal's enabling conditions are excluded from analysis but captured in other mini-grid literature contexts (see (Gollwitzer et al., 2018; Karumba & Muchapondwa, 2017; C. Kirubi et al., 2009)). Partial application of enabling conditions for sustainable management of mini-grids is also found in (Gollwitzer et al., 2018; Karumba & Muchapondwa, 2017; Maier, 2007), who prove that the nature of a specific study and its variables determine what to include from enabling conditions, and (Wolsink, 2012) who contends that institutional management of mini-grids relies on trust, the existence of regulations and boundaries, rules formulation and compliance which are partly included in the enabling conditions.

By using two solar community mini-grid cases in Tanzania, this paper aims first to examine maintenance management practices employed in these mini-grids. The paper thus presents a maintenance management model for rural community mini-grids in Tanzania. Secondly, the paper investigates whether the existing institutional arrangements using Agrawal (2001) analytical framework are applicable in explaining the sustainability of maintenance management of these mini-grids. As such, the paper attempts to contribute to the institutional analysis of technical aspects of mini-grid management while focusing on maintenance. Doing so helps shed light on future research that enabling conditions analytical framework by Agrawal (2001) can correspondingly be applied to a specific management component for the sustainability of communally owned resources.

2. Framework for analysing community-based mini-grids institutional arrangements and maintenance management

This paper uses the insights of Gollwitzer and others in (Gollwitzer et al., 2018) which explain 17 refined enabling conditions (see dotted lines in Figure 9) from 33 conditions that were initially developed by Agrawal (2001) to explain the sustainable management of CPRs in mini-grids context.

Our focus is only on institutional arrangements (6 out of 17 enabling conditions applicable for sustainable management of mini-grids. See shaded enabling conditions in Figure 9) due to the nature of the study's outcome variable, maintenance management. Mini-grid maintenance faces dynamics that cannot be fully addressed by all 33 enabling conditions or 17 refined enabling conditions for sustainable mini-grid management. Focusing on institutional arrangements enabling conditions facilitates the effective analysis of mini-grid maintenance management.

Institutional arrangements point out to collective action pertaining to rules formation, rules enforcement, accountability, and procedures put in place for governing resource users, which are all central to the mini-grid maintenance management considerations this paper seeks to delve into.

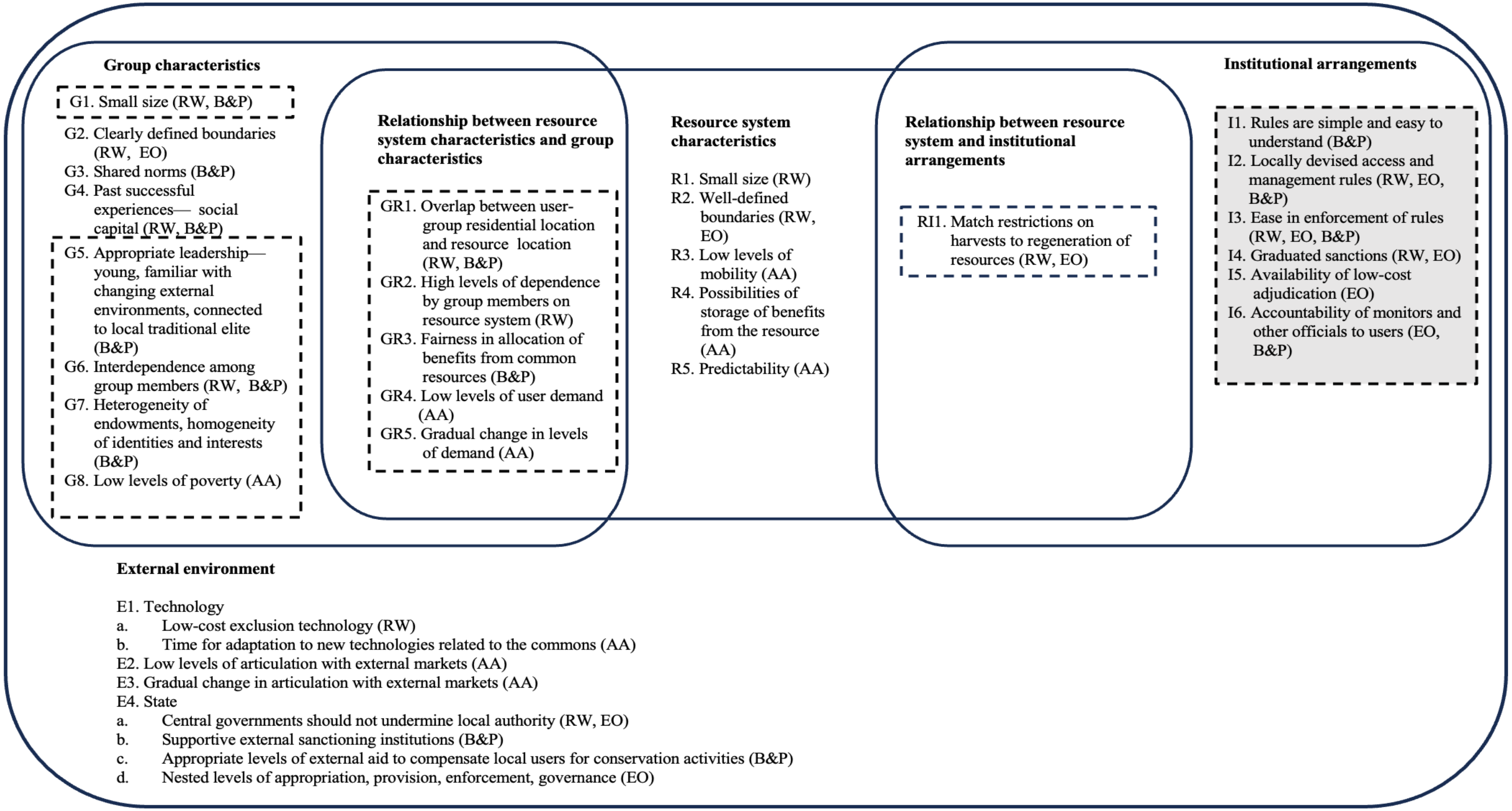

Figure 9: Agrawal (2001) -Analytical framework: 33 Enabling conditions for sustainable management of CPRs.

The enabling conditions in the dotted line are a refined analytical framework developed and tested by (Gollwitzer et al., 2018) precisely for the mini-grids context. Those in the shaded area are the conditions for analysing sustainable maintenance management in this paper.
Key: Conditions established by RW => (Wade, 1989); EO=> (E. Ostrom, 1990); B&P => (Baland & Platteau, 1996); AA => (Agrawal, 2001).
Source: Author based on Agrawal (2001) and Gollwitzer et al. (2018).

The layout of who makes decisions, sanctions, and monitors, in addition to what practices to perform or not, is well set under institutional arrangements. Institutional arrangements complement these key elements and are analytically explained in Figure 9. Rules that are simple and easy to understand (I1), which in mini-grid maintenance context implies that all users should clearly understand all maintenance rules. Locally devised access and management rules (I2) - which concern users' participation in formulating new rules or amendment of old ones regarding maintenance. Easy enforcement of rules (I3) by all users is also essential. Presence of graduated sanctions (I4) to all rules breakers towards mini-grid maintenance. The availability of low-cost adjudication (I5) becomes more useful because of graduated sanctions among users. Lastly, monitors and other officials must be accountable to users (I6) in all matters concerning mini-grid maintenance management. Institutional arrangements (I1-I6) are thus the focal of this paper in facilitating the exploration of un(sustainable) maintenance management of mini-grids. The remainder of this section presents the conceptual framework for analysing mini-grid maintenance management to construct its corresponding model and further link it back to the analytical framework of institutional arrangements-enabling conditions.

2.1. Mini-grid maintenance management

Understanding the concepts of mini-grid maintenance and management elements pertaining to mini-grid maintenance is fundamental for answering the first research question for this paper. (Carlo & Arleo, 2017) define maintenance as "the combination of all technical, administrative, and managerial actions during the lifecycle of an item intended to retain it in or restore it to a state in which it can perform the required function." Maintenance is therefore inevitable for the mini-grid's technical well-being regardless of the mini-grid ownership model and mini-grid energy sources (solar, wind, biomass, diesel, geothermal, hydropower) (Boruah & Chandel, 2023; Keisang et al., 2021). Substantial practicability of maintenance is, however, more apparent in private-owned mini-grids than community-owned mini-grids (Peters et al., 2019b; Tenenbaum et al., 2014a; Zebra et al., 2021) mainly due to the nature of the business model and different operational and maintenance approaches employed by each of these mini-grid models. This makes community-based mini-grid more vulnerable to maintenance sustainability, among other reasons that make this model central for this paper. Implicitly, there is no "one size fits all" theory on maintenance management including for mini-grid maintenance management. In that instance, the paper starts by decoding maintenance management in a mini-grid context, then works forward by linking it to institutional arrangements in Figure 9 (see Sub-section 2.2). This paper's maintenance management analysis is based solely on rural solar photovoltaics (PV) community-owned mini-grids in the two case studies.

Mini-grid maintenance management identifies what mini-grid parts need maintenance, maintenance strategies, associated responsible maintenance personnel (Adetona et al., 2020), operating maintenance funds, and maintenance schedules related to the mini-grid (Maier, 2007; Mgonja & Saidi, 2017). Solar mini-grid maintenance activities cover two principal areas: Plant-related maintenance activities and site maintenance activities. Plant-related maintenance activities are specifically related to the parts that run the mini-grid, such as solar panels, charger controllers, inverters, batteries, and cables (Adetona et al., 2020; AFREA, 2010; Al-Akori, 2014). On the other hand, site maintenance activities include keeping the area around and inside the mini-grid clean and painting the mini-grid container (for containerised solar mini-grids). Mini-grid maintenance personnel should be well-trained and knowledgeable of the mini-grid system inside out (Adetona et al., 2020; Zebra et al., 2021). Maintenance in this aspect starts with the people before the mini-grid itself (Adetona et al., 2020). Depending on the mini-grid ownership model or organisational arrangement, maintenance personnel can be either in-house (employed by the mini-grid owner) or a third party (external contractor) (see (AFREA, 2010; Keisang et al., 2021)).

There are three common maintenance strategies: reactive, preventive, and predictive maintenance. Reactive or corrective maintenance responds explicitly to failures in the system (Carlo & Arleo, 2017), whereas preventive maintenance is usually scheduled to stave off failures (Carlo & Arleo, 2017; S. A. Kumar & Suresh, 2006; Sanz-Bobi, 2014). Depending on activeness in attending to maintenance, maintenance occurring immediately after a system failure is regarded as immediate maintenance. The one conducted in the future or later, even when the system has broken down, is called deferred maintenance (Solar Power, 2018). The management approach to the maintenance strategies identified differs across mini-grids (Maier, 2007; Sanz-Bobi, 2014). Predictive maintenance involves actions performed to evaluate the state of the PV system, forecast, and recommend appropriate repair or replacement measures before a system failure (Keisang et al., 2021; Solar Power, 2018).

Mini-grid maintenance scheduling includes organising all the logistics related to maintenance. It indicates what maintenance activities and types should be carried out, by whom, and when

(S. A. Kumar & Suresh, 2006). Establishing a maintenance schedule from the mini-grid commissioning is essential (Adetona et al., 2020). Another important element of mini-grid maintenance management is the availability of an active maintenance fund, especially for communally managed mini-grids (Maier, 2007), to ensure sustainable maintenance (Al-Akori, 2014; Thangaraj & Velury, 2016).

2.2. Linking analytical framework of enabling conditions and solar community mini-grids maintenance management

In the last step of the analysis, this section highlights the link between Agrawal's (2001) institutional arrangements-enabling conditions described in Section 2 and mini-grids maintenance management in Sub-section 2.1. The consideration of institutional arrangements (I1-I6) focuses on their applicability to solar community mini-grid maintenance management. These institutional arrangements, as central to this study, refer to the rules governing and structuring relationships among users of the CPR (Maier, 2007; Oakerson, 1990). It is clear that the first three elements of institutional arrangements (I1-I3) entirely speak to rules (i.e., rules that are simple and easy to understand (I1); locally-devised access and management rules (I2); easy enforcement of rules (I3)). As the centre, the rules in managing CPRs are disintegrated into three levels that are demonstrated to affect decision-making arrangements and outcomes (e.g., maintenance management) in using CPRs (Oakerson, 1990): 1) operational rules, which directly control and affect the use of resource system; 2) collective choice rules, which indirectly affect operational choices through formulation, changing and implementing operational rules collectively by resource system's decision-makers; and 3) constitutional choice rules, which involve the decision-making arrangement external to local resource system users, are used to formulate collective choice rules and in turn affect operational rules.

In solar community mini-grid maintenance, operational rules control who can participate in such maintenance; in this case, it is a technician with equipped knowledge to perform maintenance tasks. Restricted access to the inside of the mini-grid's control room allows only people listed under the constitutional choice rules, which can be mini-grid operators, technicians, village energy committee (VEC) members, and/or local village council leaders. The inside of the mini-grid container or control room is out of bounds for normal users, as they are not directly involved in mini-grid system maintenance. Instead, they undertake mini-grid site maintenance activities depending on the decision-making arrangements. The rules also specify the do's and don'ts of qualified maintenance participants. Furthermore, they specify how mini-grid maintenance is financed and governed, mainly through tariff collections deposited in the mini-grid maintenance fund (Maier, 2007). Operational rules also accommodate rewards or sanctions for participants connected to the mini-grid maintenance, such as penalties for illegal connections that may affect the mini-grid and defaulting users refusing to pay tariffs for maintenance. The success of operational rules in this context may be measured by their ability to ensure sustainable mini-grid maintenance management (Edwards & Steins, 1998).

Collective choice rules are associated with collective decisions made by electricity users, their officials, and/or external authorities in formulating mini-grid maintenance management policies. These rules are derived from the constitutional level (Edwards & Steins, 1998; E. Ostrom, 1990), in this case through the mini-grid constitution adopted by mini-grid users, the company, and/or public electricity utility authority. Operational rules are, therefore, not self-generating but depend on a collective body of decision-makers (Edwards & Steins, 1999). For rural mini-grid maintenance management, electricity users and their leaders may partly formulate, change, and implement collective rules, whereas external authorities largely dominate the formulation of these rules (Edwards & Steins, 1999).

Mini-grid maintenance management constitutional rules are derived from the general constitution (if available) made by the mini-grid owners depending on the ownership model or constitution made directly by an external energy-related authority specific to running mini-grids. The constitution defines all matters of mini-grid governance, including mini-grid maintenance management. It stipulates who is eligible for mini-grid maintenance, their roles and responsibilities, and how to finance it. At this stage, the specified terms of reference for mini-grid maintenance management provide ground for establishing, changing, and implementing collective choice rules. In addition, mini-grid users may depend directly upon constitutional rules for legislation and operational rules enforcement (Edwards & Steins, 1998). Implicitly, it is challenging to isolate collective and constitutional rules while analysing the local organisation for natural resource management (Rasmussen & Meinzen-Dick, 1995).

As mentioned earlier, these rules affect the decision-making arrangement of mini-grid maintenance and their associated outcomes. They guide the rest of institutional arrangements enabling conditions (12-I6). Thus, they need to be simple and easy to understand (I1) by all the stakeholders involved, either directly or indirectly, with mini-grid maintenance management to govern sustainably mini-grid maintenance.

In relation to clear and straightforward rules (I1), locally devised access and management rules (I2) in the mini-grid maintenance context depend on the extent to which electricity users can formulate and adjust maintenance rules. These rules can either be new or adapted from external constitutional rules. These rules also set the extent to which they are easily enforceable among mini-grid users (I3). Graduated sanctions (I4) should be imposed to minimise damages connected to mini-grid maintenance. Illegal connections and the use of banned appliances that negatively affect mini-grid systems calling for maintenance are associated with sanctions. The sanctions primarily include penalties and electricity disconnection (Maier, 2007). Some mini-grid maintenance-related sanctions may be challenging to operationalise and enforce. For instance, it is difficult for the VEC, who have no expert knowledge about mini-grid, to prove that the technician has intentionally tempered with mini-grid system parts to attract a maintenance service fee. Because of the likelihood of mini-grid maintenance rule breakers, low-cost adjudication (I5) is essential. In most cases, the VEC collaborates with the village council ethics committee to deal with such incidents. Finally, monitors and other officials must be accountable to electricity users (I6) to ensure proper management of the mini-grid maintenance for sustainable operations.

3. Methodology

3.1. Case study selection

The empirical case studies were conducted at Leganga and Silale mini-grids in the Dodoma region. Leganga and Silale were among ten villages that benefited from mini-grid projects through Tanzania's Ministry of Energy and Minerals. Initially, the Ministry of Energy and Minerals signed a contract with Elektro Merl Company from Austria to install the mini-grids, connect all targeted customers, and be responsible for supplying electricity services and providing maintenance services to both mini-grids. The company also consulted the respective villages' energy committees (selected by electricity users) on the mini-grid project management. The village energy committee (VEC) and the village government were the supervisors and guardians for both mini-grid projects per guidelines developed by the Ministry of Energy and Minerals. Information about operations and management for both mini-grid projects was detailed in the guidance book and handled over to mini-grid users by the Ministry of Energy and Minerals. The respective villages took over entire mini-grid operations and management following an expired contract with Elekro Merl Company. VEC was responsible for managing financial matters, specifically tariff collections, during and after Elektro Merl Company's operations. In addition, VEC was responsible for convening and conducting committee meetings and gatherings with electricity users, administering electricity connections, controlling illegal connections, and usage of banned electric appliances.

Both mini-grids share similar attributes in relation to technical configuration, financial structure (funder and availability of maintenance fund), management arrangements (community-based decision-making arrangements), and number of electricity customers (see Table 8). Despite the similarities, the two cases exhibit distinctive sustainability outcomes of maintenance management, which is a critical aspect of the analysis of this study. Silale mini-grid sustained its operations, whereas the Leganga mini-grid ceased operations three years after its commissioning. The Silale mini-grid is allegedly the only operational community-based mini-grid in Tanzania whose operation and maintenance are solely executed by the respective community.

Table 8: Characteristics of the mini-grid case studies

	Silale	**Leganga**
Location	Makawa ward, Kongwa district	Chitego ward, Kongwa district
Year commissioned	2015	
Initial Owner	Donor-funded, community	
Maintenance personnel	Elektro -Merl Company, community (hired technician)	
Generation technology	Solar PV containerised system	
Installed capacity	15kilowatt peak (kWp)	
Metering technology	Load limiter	
Number of connections	60	
Customer types	Households, small businesses, and institutions (school and church)	
Financial management	Community through village energy committee	
Maintenance fund	Present and sustainable	Present and unstainable
Operational status	Still operating though with struggles	Stopped operating in August, 2018
Current operations	Run by community up-to-date	Run by ELICO Foundation since 2021

3.2. Data collection and analysis

The research is based entirely on qualitative interviews and observation to gather potential information related to the research questions from the field. In all, the study conducted 18 semi-structured in-depth interviews with key informants: VEC, village council leaders, mini-grid technicians, and normal household users, who are involved either directly or indirectly with mini-grid maintenance management and institutional arrangements. The data for both mini-grids was collected between May and June 2022. The interviews covered technician who serviced and maintained both mini-grids. The same technician also served as a tour guide during all field visits. Official and relevant information related to each mini-grid site was provided by the village chairperson and VEC members who were present during field visits. These interviewees were all directly connected with mini-grid institutional arrangements and maintenance management. As such, they provided resultant data that enriched the study. Interviews with normal electricity customers relied on snowball sampling; these consumers were indirectly and partly involved in the mini-grid institutional arrangements and maintenance management.

The study used Kiswahili language—universally accessible in Tanzania—in all the interviews with transcription following later with the aid of MAXQDA 2022, a software package for qualitative data analysis and mixed methods research.

The study deployed a codebook based on theory-driven and data-driven codes during data analysis. Specifically, the study had three rounds of coding to capture all the codes related to the institutional arrangements as per the analytical framework of enabling conditions by Agrawal and mini-grid maintenance management elements described in Sub-section 2.1. This triad of coding facilitated the analysis of data within the studied framework. Moreover, the interviews for the two mini-grids were coded and analysed separately to capture respective data for each case before collating to compare and contrast the results and findings. All the ethical standards of research have been adhered to in conducting this study. Participation in this study was voluntary, with informed consent obtained from all the participants. No compensation was provided to the participants for their involvement. Hence, there was no inducement to influence their participation and views.

4. Results

In this section, the framework for analysing community-based mini-grid institutional arrangements and maintenance management (Section 2) is applied to the empirical data to assess its efficacy. Maintenance management for Silale and Leganga mini-grids is first assessed to establish its model, followed by applying the institutional arrangements-enabling conditions (Figure 9) to test their applicability to the assessed mini-grid maintenance management model. The conclusion on the sustainability outcomes of mini-grid maintenance management is then drawn.

4.1. Maintenance management model(s) for Silale and Leganga mini-grids

The framework presented in Section 2.1 reveals that mini-grid maintenance management encompasses maintenance activities and types, maintenance staff, maintenance plans, and maintenance funds. Based on these components, this sub-section undertakes systematic analysis and derives a practical maintenance management model of Silale and Leganga mini-grids.

4.1.1 Maintenance personnel

Silale and Leganga shared one principal technician who was directly responsible for maintenance activities, strategies, and implementing maintenance plans for both mini-grids. The technician was first hired by Elektro Merl Company and continued to work with both villages later after the company's contract to oversee O & M for both mini-grids expired. Before starting the mini-grid maintenance job, the technician was rigorously trained. The technician was recognised by users in both mini-grids as the principal technician. The Silale mini-grid had two local technicians (one a member of VEC), whereas Leganga had one local technician. The local technicians performed tasks external to mini-grid containers, such as fixing fallen electricity poles and burnt electric devices connected to the mini-grids, like limiters and connectors. They also performed wiring works and connected electricity meters in customers' houses. The mini-grid system maintenance, on the other hand, was the specific responsibility of the principal technician:

> *"The people who manage plant maintenance are technicians. I am the only responsible plant technician, but for small tasks outside the plant, like burnt bulb holder, etc., in people's houses, there are local technicians" (Interviewee 1).*

However, local technicians' tasks were done in consultation with the principal technician via phone (as confirmed by respondents 6, 9, and 15). The principal technician acknowledged having trained local technicians to minimise transport costs to execute such small tasks. This arrangement was responsive to the financial difficulties in running the mini-grids following the departure of Elektro Merl Company, and the technician had to attend to only fundamental matters pertaining to mini-grid maintenance. Despite the experience with maintenance works related to mini-grids, the principal technician admitted to being unable to fix some issues:

> *"There are things that I cannot do when they happen; for example, if the tri-power or inverter fails, I will write a report. Today, on June 12, 2022, the container has shut down. The problem is that the tri-power has failed, so I will write details there, turn off*

the plant, disconnect other things, close the plant, and inform the ministry" (Interviewee 1).

4.1.2. Maintenance activities

Both mini-grid cases had two similar types of maintenance activities: plant or system and site maintenance. Plant maintenance activities involved checking or responding to invertor functionality status, removing non-functional batteries to create a functional series, updating software, fixing broken limiters and broken solar panels, and cleaning the panels. In other words, plant maintenance activities mostly entailed applying technical knowledge while handling them. During the Elektro Merl management, the technician carried out all the plant maintenance activities as part of his job description. Later, mini-grid users in Silale and Leganga were involved in cleaning the solar panels to save costs of paying technicians to do the job. The technician, however, provided guidance on how to clean the panels, and later, VEC continued to supervise the work. On the other hand, site maintenance activities, such as removing grass around the mini-grid surroundings for the two cases, were mainly performed by customers under the supervision of VEC. Meanwhile, the technician periodically painted the external walls of the mini-grid containers during the company's operations.

4.1.3. Maintenance strategies

In both cases, the implementation of maintenance strategies was more proactive during the Elektro Merl Company's management than in the aftermath when communities took over the power grid's control. Then, preventive and predictive maintenance were the predominant maintenance strategies performed by the technician. These strategies generated a well-functioning system with no major breakdowns in the first three operational years of both Silale and Leganga mini-grids. *Interviewee 1 explained*:

> "*As a technician, I worked in two periods. During the first period, I worked with the company that constructed and managed the project. My responsibilities were cleaning and checking for any issues in the container twice a month. If there were no issues, I signed a report and left…"*
>
> *"When you get there, you check the inverter; you check the charging system, you read the report; after that, you check whether there is any challenge; if there is none, you sign, you write a report on what you have done […]".*

"*Since we constructed it [mini-grid] in 2015, it was just functioning well. There were no technical problems, only cleanliness issues. Once I arrived there, I just had to tighten the batteries. But there were no issues or troubles…"*

After the company left, VEC in both mini-grids had to manage overall O&M. There was no contract between the two villages and the technician. Due to financial challenges, there was a substantial change in maintenance strategies adopted for both mini-grids. Corrective maintenance was, therefore, the dominant maintenance strategy employed, especially in Silale; the Leganga mini-grid stopped operating only a few months after the company left. Respondents shared the following views:

"*After that, I started working with the village. So, the village's routine was not like when the company was in operation, where I had to go to the container twice a month… But I don't have a contract with them, meaning I didn't sign a contract for them to pay me every month. But they said that if the container breaks down, they would call me, and I would go work, and we would agree on how much they would pay me*" (Interviewee 1).

"*For example, if a fault occurs and the container shuts down, you call the technician*" (Interviewee, 4).

"*…in most of his[technician's] trips, he only comes when the container stopped working. When it has a problem, eh! Then you will see him often*" (Interviewee, 3).

Additionally, immediate maintenance was commonly done by the technician whenever any fault needed fixing, particularly when the spare parts were available. With inaccessible spares like batteries, deferred maintenance was the only option. As mentioned earlier, due to financial constraints, preventive and predictive maintenance were rarely undertaken in both mini-grids under the VEC management despite the principal technician underscoring their significance:

"…after Elektro Merl left and they were the ones paying my salary by then, I only go when a problem occurs. However, I told them that given the condition of the container, I should come at least once a month to clean and check it, read reports to know what is going on, to ensure that it continues to survive. But once you tell them, they take it as if you are going to waste their money on transport costs and other expenses…they say the container still functions. Why all that? […]" (Interviewee 1).

To save transport costs and the wage payable to the technician conducting preventive or predictive maintenance, VEC found it economical to stick with the corrective maintenance strategy, not knowing how damaging that could be to the sustainability of the mini-grids' maintenance.

4.1.4. Maintenance schedule

The study found the existence of a maintenance schedule for Silale and Leganga mini-grids during the management of Elektro Merl Company. Specifically, the technician reported having monthly and quarterly schedules for mini-grid maintenance. The technician was required to conduct plant maintenance and write a feedback report twice every month. This schedule was to be followed regardless of the mini-grid plant's status, even when there was no problem. Quarterly maintenance was also conducted with specific activities such as painting the mini-grid container and cleaning the solar panels. Other respondents corroborated the technician's claim about the described maintenance schedule. However, the respondents reported that the mini-grid management under VEC could no longer sustain the initial arrangements of the maintenance schedule mainly due to financial constraints. In consequence, they preferred to have maintenance based on arising breakdowns in the mini-grids:

> "*... we wish to have the technician come every month. But due to our [current financial] situation, if we say we collect money and distribute it monthly for the technician to come, it becomes difficult.*" (Interviewee 9)

4.1.5. Maintenance fund

The initial arrangement regarding the financial management of the two mini-grids was to open bank accounts to deposit monthly electricity fees collected. These bank accounts were treated as maintenance funds. The accounts were opened soon after mini-grids began operating and were managed by VEC members of respective mini-grid projects. Guidelines for maintenance management funds were accessible in the mini-grid guidance book, making them familiar to users, leaders, and technicians. The money deposited in the maintenance fund was mainly from monthly electricity tariffs and connection fees for new customers (Silale). The primary expenditure of the maintenance fund was to finance mini-grid maintenance. The respondents identified other recurring expenditures: the technician's wage and transport costs (more in Silale), VEC allowance, VEC transport costs to deposit and withdraw money, and panel cleaners (Leganga). Silale also had a one-time expenditure on building the mini-grid fence. In addition, Silale used the maintenance fund to finance a school construction project in the village. This expenditure was not associated with the mini-grid maintenance. The respondents acknowledged having been involved in funding the village project with the promise of getting a refund from the village council. The money was, however, not reimbursed as promised by the village council.

Despite having maintenance funds in both mini-grids, benefits and sustainability outcomes vary. Implementing the maintenance fund represented a significant and positive step towards managing the Silale mini-grid by facilitating maintenance activities whenever the need arose. Up to field visit dates, this maintenance fund for Silale had money, though a small amount, for managing the mini-grid without external financial assistance. The respondents reported that having a maintenance fund was beneficial to the users, and with the help of VEC, the maintenance management of the mini-grid was successful:

> "*[The maintenance fund] account has helped. For example, to a certain extent, the money we collected at the beginning of the project was very high. It was high before we started the plant's maintenance activities. Depositing money in the account was advantageous since it was moderately consumed. Even when the money was consumed, it was not much and was safe in the account. If there was no account, money could be in our pockets and could easily be spent, and we would not have any money. So, the account has helped us to protect the project"* (Interviewee, 3)

In the Leganga case, due to free electricity consumption in about seven months since the mini-grid's commencement, savings in the maintenance fund lagged far behind their counterparts at Silale. In addition, the consumers at Leganga needed to be more consistent in settling their electricity tariffs. A few months after Elektro Merl left, the mini-grid stopped operating and required maintenance, which could not be done partly because of the insufficient balance in the maintenance fund. The Leganga mini-grid was eventually shut down. Insufficient balance in the maintenance fund emerged as one reason behind the failure. Participants in Leganga also acknowledged that the maintenance fund could be more useful if users consistently paid their electricity tariffs since day one of the mini-grid commencement.

4.1.6. The existing maintenance management model

The maintenance management model displayed in Figure 10 is based on what was practiced when the communities at both Leganga and Silale independently operated the two mini-grids without the Elektro Merl Company:

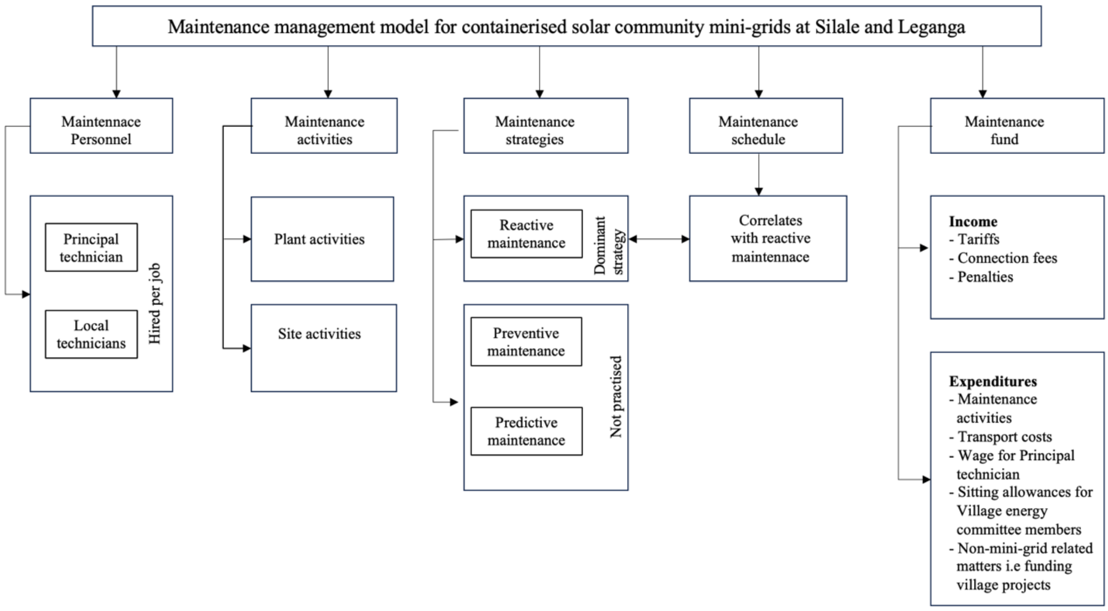

Figure 10: Maintenance management model for Silale and Leganga -solar community microgrids

The model presents five essential aspects of mini-grid maintenance management and their corresponding elements. Maintenance personnel are hired based on the maintenance needs that arise. This practice amounts to reactive maintenance, which emerged to be the dominant maintenance strategy employed in both mini-grids. Because of this reactive maintenance strategy, having no mini-grid maintenance schedule was preferred. As Section 4.1.3 has indicated, the maintenance strategy in force depended on the non-contractual hiring of the principal technician and having no maintenance schedule because of budgetary constraints associated with the maintenance fund. As Figure 10 further illustrates, only three income sources existed for the mini-grid maintenance fund, and the main income stream came from electricity tariffs. The expenditures, however, were reported to be high compared to the income collected because of the low tariffs, among other reasons (See Section 4.2).

The nature of the maintenance management model presented implies that making preventive and predictive maintenance strategies as dominant strategies and having a maintenance schedule are essential for good maintenance practice in the investigated solar community-owned mini-grids. Leganga and Silale have similar maintenance management models, except for the poor maintenance fund management in Leganga, which resulted in dissimilar sustainability outcomes. The only source of income in Leganga was tariff fees, which was also found to be unstable. Silale, on the other hand, had more sources of income for its maintenance fund (tariffs, connection fees to new customers, and penalties), which positively contributed to its sustainability compared to Leganga.

4.2. Applying institutional arrangements as enabling conditions for sustainable maintenance management of Silale and Leganga mini-grids

This section applies Agrawal's (2001) institutional arrangements (Figure 9) to the empirical data to assess their applicability as enabling conditions for the sustainable maintenance management of solar community mini-grids. This study reveals that the existence and application of institutional arrangements are essential in fostering sustainable management of the mini-grid system and its corresponding management units, such as maintenance.

It also emerged during this study that the existence of local rules that are simple and easy to understand (I1) about maintenance management is essential to reinforce the sustainability of community mini-grid. As described in Section 2.2, CPR management rules fall under three levels: operational, constitutional, and collective. Mini-grid maintenance rules in both Silale and Leganga cut across from constitutional to operational levels while overlapping with the collective action rules. In both cases, constitutional choice rules are formal written rules that detail all matters[4] relating to the two mini-grid projects. It was constitutionally stated who is involved with mini-grid maintenance and their responsibilities. Users in both mini-grids acknowledged the existence of guidelines specifying all constitutional choice rules. Further, they admitted to having implemented most of the rules from the guidebook at both collective and operational levels. The guidelines were externally developed by the Ministry of Energy and Minerals. In both cases, mini-grid users directly relied on this guidebook for legislation and enforcement of maintenance operational and collective rules.

Operational rules for mini-grid maintenance only allowed the technician, village chairperson, and VEC members to enter the container for maintenance. The rules further outline the do’s and don’ts for the maintenance team. For example, the technician could not connect power to consumers illegally without VEC clearance. Additionally, for maintenance, the technician must enter the inside of the container accompanied by at least one VEC or the village chairperson. These maintenance operational rules were diligently enforced (I2) at both Leganga and Silale mini-grids:

[4] For instance, overview of the project, operational and management procedures of project e.g., VEC election procedures and their roles, maintenance fund and its management, tariff collections and procedures, and procedures to enter inside the mini-grid container.

> *"… the guidance document from the Ministry is good. When the technician comes to open the container, he must be accompanied by one or two village leaders. On his entrance is a book that he must sign, stating the date, time, and purpose of his visit. But the leaders should see it"* (Interviewee, 4)

Moreover, the existence of maintenance rules (I1) was accompanied by locally devised access and management rules and enforcement of rules (I2 and I3). This facilitated the creation of sanctions rules for stubborn customers and the adjustment of electricity prices, which directly affected the maintenance fund. In both cases, monthly electricity fees were initially set based on constitutional choice rules, where three categories of users were based on watts usage. The groups were: 1) 100 watts, who pay 5,000 -10,000 Tanzanian shillings (TZS); 2) 250 watts, who pay 10,000 -20,000 TZS; and 3) 500 watts who pay 15,000 – 20,000 TZS. The rules specify that the electricity fees collected would sustain the management of the mini-grids. At Silale, the respondents (3,5,7,9) corroborated that the original set-up prices per the guideline book were only implemented in the first few months. Later on, consumers collectively agreed to lower the tariffs per watts usage under the collective choice rules; that is, electricity consumers and VEC locally devised the rule regarding tariffs and enforced the new tariffs. The tariffs were lowered to a flat rate of 3,000 TZS regardless of the number of watts consumed. VEC and village council facilitated this collective arrangement action among users as part of efforts aimed to sustain the maintenance fund somewhat even though the savings gradually decreased:

> *"…that guidance book contains everything, including equipment with their prices, costs of consuming electricity are written there. But the electricity users revised them and arranged the ones that they can afford"* (Interviewee, 3)

Constitutional tariff rules were thus revised through collective actions and new tariffs were operationalised. Constitutional rules regarding the maintenance fund expenditures at Silale, were violated when village leaders, VEC, and users collectively agreed to fund the school construction project by loaning the village with an agreement to refund. This action negatively affected the maintenance fund. Respondents shared their doubts about the sustainability of the maintenance fund in case major mini-grid maintenance was to happen because the money was never refunded. The data, however, suggested a robust implementation of collective choice rules at Silale compared to Leganga.

Besides creating and enforcing maintenance rules, the findings suggest drawbacks in implementing constructed graduated sanctions (I4) against mini-grid maintenance. Sanctions include warning letters and, later, electricity disconnection to rules breakers (e.g., users who refuse to pay tariffs), as well as fines in monetary form for illegal connections. These sanctions affected mini-grid maintenance indirectly through maintenance funds. Therefore, the existence and enforcement of such sanctions positively affected maintenance funds and, eventually, general mini-grid maintenance. Even though the sanctions focused on electricity users, technicians and VECs who are directly involved with mini-grid maintenance should have been included. There were no sanctions against the technicians and VEC if they practiced anything that could jeopardise mini-grid maintenance (e.g., intentional tempering with the mini-grid system by a technician, non-payment of tariffs by VEC). This calls for accountability of mini-grid monitors and officials to users (I6) but was impractical for the two cases. At Leganga, the respondents mentioned that VEC was not accountable to users in various ways, e.g., they were not paying tariffs, which made some users refuse to pay. Moreover, Silale was found to have a more dedicated and accountable VEC than Leganga.

To have sustainable maintenance management of both mini-grids, participants suggested external management by the company as before (i.e., during Elektro Merl governance). The company could administer the maintenance management independently and facilitate low-cost adjudication (I5) with minimal/no biases or fear of what users would say because of pure work relationships with the consumers. This experience was hardly practiced at Leganga due to kinship between some VEC members/village leaders and the mini-grid's customers. This affected the decision-making of mini-grid VEC members/village leaders and led to poor electricity tariff management since defaulting consumers were not held accountable, negatively affecting the mini-grid maintenance fund and general mini-grid maintenance. The mini-grid required maintenance, and the maintenance fund had insufficient balance to solve the problem:

> *"The final step was to try to take the list (stubborn electricity customers) to the ward council. But now it has come to the point where if we take it to the council, the committee will be blamed…you know, only family members live here. It is a close-knit community"* (Interviewee, 16).

Other users at Leganga mentioned that poor tariff collection for maintenance purposes was due to disrespectful and frightening answers from users, which made VEC despair to collect tariffs. Inadequate implementation of graduated sanction (I4), pitfalls with rule enforcement (I3), and insufficient accountability of VEC in monitoring maintenance management, especially the maintenance fund (I6), forced the Leganga mini-grid to be shut down. This happened only after three years of operation under the VEC management. The enforcement of rules, implementation of graduated sanctions, low-cost adjudication, and accountability of mini-grid monitors and officials (I3 – I6) as enabling conditions for maintenance management were minimally implemented at Leganga and yet could explain the status of its unsustainability.

Silale, on the contrary, sustainably managed the mini-grid maintenance independently for more than four years, ever since Elektro Merl Company left. With low-cost adjudication availability (I5), VEC at Silale accountably executed graduated sanctions and other rules of mini-grid maintenance, which were collectively and constitutionally constructed. Based on empirical data, institutional arrangements, as enabling conditions, were more applied for sustainable maintenance management of the Silale mini-grid than the Leganga one, which partially applied the institutional arrangements in mini-grid maintenance and, as a result, experienced failure.

5. Discussion and Conclusion

This paper explores the existing maintenance management model and the applicability of institutional arrangements as enabling conditions for sustainable maintenance management of solar community mini-grids in Tanzania. The findings from Leganga and Silale highlight two aspects of sustainable maintenance management of communally owned mini-grids. First, the existence of a similar maintenance management model across mini-grids does not guarantee similar implementation results. Second, it is true that institutional arrangements are enabling conditions for sustainable maintenance management of mini-grids. However, their partial implementation does not guarantee sustainability outcomes. Therefore, implementing more elements of institutional arrangements facilitates more sustainability outcome for mini-grid maintenance management.

Regarding the maintenance management model, reactive maintenance, for instance, is the dominant maintenance strategy in both mini-grid cases. This strategy was preferable to others mainly due to financial constraints (S. A. Kumar & Suresh, 2006). It was, therefore, financially feasible to conduct maintenance only after system breakdowns. Calling the technician once the problem arose was cost-effective because it implied less transport costs incurred and wage payment, which could otherwise be spent on the technician undertaking maintenance based on a specific schedule. As a result, unscheduled maintenance became more desirable than scheduled maintenance. Inadequate and poor management of maintenance funds are also found to have a negative impact on mini-grid maintenance and, hence, overall mini-grid sustainability. In relation to previous studies on the sustainability of mini-grid projects in developing countries, the findings support the positive impact of maintenance funds on the maintenance sustainability of rural community mini-grids (Maier, 2007; Mgonja & Saidi, 2017) and proper maintenance management as a key function for mini-grid sustainability (Al-Sultan & Duffuaa, 1995; Carlo & Arleo, 2017). It is thus evident that healthy maintenance for community-based mini-grid does not only require technician's attention but also interactions and awareness among mini-grid users, VEC, and village leaders on how essential maintenance is for mini-grid sustainability and how they collectively set decision-making arrangements that support proper maintenance management.

Users, VEC, and village leaders of both mini-grids served as vessels that indirectly affected the maintenance sustainability through institutional arrangements. The Leganga case, for instance, demonstrated how poor enforcement of rules, high failure rates to practice graduated sanction, and inadequate accountability of VEC and village leaders made maintenance sustainability of their mini-grid complex. There was abuse of rules with no action to combat it, which contributed to poor maintenance fund management and, consequently, the mini-grid failure as soon as the mini-grid project was left in the hands of electricity customers (see (Peters et al., 2019a)). Empirical evidence also shows that the unavailability of a sustainable maintenance fund and poor management emerged as contributing factors to mini-grid failure. Incidentally, the community mini-grid failure occurred shortly after donors exited (Al-Akori, 2014; Peters & Sievert, 2015; Thangaraj & Velury, 2016), which exposes the funding and operational gap. Silale, on the other hand, sustainably managed mini-grid maintenance because of the increased awareness that prevailed among mini-grid users and their leaders. This study revealed how successful institutional arrangements as enabling conditions are for sustainable maintenance management of the Silale mini-grid. However, locally devised rules could not have a positive impact on mini-grid maintenance all the time, as evidenced when there was a collective agreement to use some amount in maintenance fund as a loan to facilitate village matters that are unrelated to the mini-grid.

Furthermore, the maintenance fund emerged as a central aspect of community mini-grid maintenance. Through enforcement of maintenance rules, the presence of low lost adjudication together with leaders' accountability allowed users and mini-grid leaders to agree mutually on sustaining the maintenance fund for the mini-grid's sustainability. However, it was also observed that the penalties related to mini-grid maintenance mainly targeted normal electricity consumers. In other words, the technicians, VEC, and village leaders could not be held responsible per the rules if they did anything that endangered mini-grid maintenance. In line with (Maier, 2007; E. Ostrom, 1990), it is essential to note that the actual enforcement of rules affecting mini-grid maintenance was an additional effective determinant for the sustainable management of the Silale mini-grid compared to the one at Leganga. Also, having penalties without enforcing them amounted to a waste of effort. Therefore, implementing all (more) elements linked to institutional arrangements demonstrates more sustainability for mini-grid maintenance management, and the opposite outcome occurs when fewer aspects are applied.

Based on the findings, it is apparent that the sustainability of maintenance management for rural community mini-grids in Tanzania mostly suffers from insufficient maintenance funds and associated poor decision arrangements. Impliedly, components of mini-grid maintenance management largely depend on the maintenance fund. Sufficient balance in the maintenance funds facilitates the smooth running of maintenance activities, strategies, schedules, and technician operations, which signals sustainable maintenance management. The study, therefore, calls for incorporating suitable maintenance strategies such as preventive maintenance, capacity-building related to the maintenance, and electronic tariff collection model in rural mini-grid business models. Also, for capacity-building, targeting locals as maintenance trainees is imperative. In addition, institutional arrangements play a positive role in maintenance management since their absence could have contributed negatively to sustainability outcomes for both case studies from the early stage.

Overall, this paper has empirically contributed to the sustainable energy literature by analysing institutional arrangements of mini-grid management while focusing on maintenance. This paper has demonstrated that Agrawal's (2001) enabling conditions apply to the overall sustainable management of mini-grids as CPRs and corresponding mini-grid management units. Compared to other principles for analysing the sustainability of CPRs (Baland & Platteau, 1996; E. Ostrom, 1990; Wade, 1989), Agrawal's analytical framework categories are context-specific based (Figure 9). This context sensitivity enhances the applicability and adaptability of the framework to diverse mini-grid settings and management. Implementing a collective approach of institutional arrangements, for instance, at the local level, among users, to mini-grid management units such as the maintenance (as applied in this paper) and operation unit, metering and the financial unit, and generation and distribution unit, among others, is relevant for the realisation of sustainable governance of mini-grids as CPRs.

Table 9 summarises case studies that have utilised subcategories and conditions from Agrawal (2001) in their analysis. This table gives an overview of how few cases have utilised Agrawal's Agrawal (2001) analytical framework and how the framework can be partially applied in different contexts concerning mini-grids. This study has uniquely contributed to this analytical framework with the systematic application of institutional arrangements (I1-I6) to the mini-grid maintenance context. The findings indicate how applicable institutional arrangements are in determining the sustainability of communally owned mini-grids by focusing on mini-grid maintenance management.

Table 9: Summary of literature that applied enabling conditions in analysing sustainable management of mini-grids

Enabling conditions utilised	Brief study description	Country	Ref.
- Group characteristics (G1, G5-G8) - Relationship between resource system characteristics and group characteristics (GR1-GR5) - Institutional arrangements (I1-I6) - Relationship between resource system and institutional arrangements (RI1)	Explores how mini-grids are CRPs. Refines [25] framework to the ones applicable to mini-grids management in developing countries.	Kenya	(Gollwitzer et al., 2018)
Heterogeneity of endowments, homogeneity of identities and interests (G7)	Effects of heterogeneity of different groups of mini-grid users on the sustainability of community-based mini-grids.	Kenya	(C. G. Kirubi, 2009)
Institutional arrangements (I1-I6). (Not systematically applied)	Reasons for successes and failures of 27 community-based micro hydro. Mini-grid maintenance experiences.	Pakistan	(Maier, 2007)
Easy in enforcement of rules (I3)	Institution building challenges from institutional context.	Tanzania	(Ahlborg & Sjöstedt, 2015)
Institutional arrangements (I1-I3). (Not systematically applied)	Analysis on institutional conditions that favours social acceptance of distributed generation in smart grids.	-	(Wolsink, 2012)
- Resource system (R1 and R2) - Group characteristics (G1, G2, G4, G5, and G7) - Institutional arrangements (I1-I6) - External environment (E4a and E4b)	Role of individual characteristics, institutional arrangements, and other conditions on management of micro hydro schemes.	Kenya	(Karumba & Muchapondwa, 2017)

Furthermore, this paper has developed an empirical maintenance management model (Figure 10) that demonstrates the maintenance management practices of community mini-grids in rural Tanzania.

It is also worth noting that this study is limited by the absence of respondents from Elektro Merl Company and the Ministry of Energy and Minerals, who were responsible for the birth of studied cases. However, alternative valuable information was collected through a guidance book from the Ministry of Energy and Minerals, written explicitly for the studied mini-grid cases, and an interview with the mini-grid technician, a former Elektro Merl employee. Further research involving comparative analysis for community-based mini-grids that use different energy sources, such as hydropower, biomass, and solar, is required to examine their maintenance management sustainability outcome once the enabling conditions framework is applied.

Data availability

Data will be made readily available upon request.

Chapter IV: The role of sense of ownership in rural community mini-grid management: Qualitative evidence from Tanzania

Abstract

Background

The majority of mini-grids in Tanzania are managed by private entities, faith-based institutions, and the government. In contrast, a limited number of mini-grids under community management strive to survive. Although the concept of "sense of ownership" is considered crucial for mini-grid sustainability in developing countries, there is limited theoretical exploration of the factors that drive this concept and its effects on community mini-grid management. This paper assesses the relationship between the sense of ownership among electricity users and the effective management of two solar community-based mini-grids with different sustainability experience.

Results

A sense of ownership plays a role in establishing the decision-making process of mini-grids among village energy committee members toward sustainable or unsustainable management. The mechanisms behind the sense of ownership among community members toward managing mini-grids are largely expedited by the strong leadership of village energy committee members, community participation in decision-making and resource mobilisation, especially in the preparation, design and implementation phases of mini-grids.

Conclusions

A sense of ownership is found to influence the effective management of community mini-grids in Tanzania. When designing mini-grid project policies and programs that target respective communities as prospective owners, energy practitioners and policy-makers should consider creating an environment that nurtures a sense of ownership.

Keywords: Community mini-grids, Community participation, Community management, Sustainability, Solar, Ownership

1. Background

The electricity access rates in sub-Saharan Africa are among the lowest despite an increase in global electricity access between 2010 and 2020. In fact, a projected 670 million people will continue to lack access to electricity, with 9 out of 10 people expected to live in sub-Saharan Africa (IEA et al., 2022). Over the past decade, mini-grids[5] have provided more reliable electricity than national utilities among rural communities in Africa due to the existing sparse rural population (Blimpo & Cosgrove-Davies, 2019), less frequent or lengthy outages and voltage fluctuations (SE4All, 2020), and fewer challenges with transmission and distribution networks (E.S.M.A.P., 2022). Tanzania is a sub-Saharan country with a robust mini-grid regulatory framework that supports investments in different mini-grid ownership models. These models encompass private entities, communities, national utility, hybrids (Odarno et al., 2017; SE4All, 2020), and faith-based organisations (Odarno et al., 2017). Community-based mini-grids (CBMs) stand out as unique models whose operation and management rely on beneficiary local communities (Maier, 2007; Palit & Chaurey, 2011). Local community involvement in the mini-grid preparation and design phase[6] is thought to facilitate both smooth management (Gill-Wiehl et al., 2022; Tran, 2013) and long-term sustainability of mini-grids (Katre et al., 2019), which further creates a strong sense of ownership among users (Thema et al., 2020).

A sense of ownership, which is defined as a psychological state in which people feel that a particular community infrastructure system is "theirs" (Pierce et al., 2001), and is, however, revealed to enhance the effective management of community infrastructure, such as water systems (Ambuehl et al., 2021; Marks et al., 2013) and community mini-grids (Madriz-Vargas et al., 2015). A sense of ownership arguably develops a common vision among electricity users towards mini-grid governing (A. Kumar et al., 2009) and increases their sense of responsibility, which can be associated with successful management (Madriz-Vargas et al., 2015). However, no qualitative or quantitative analysis has yet examined the role of a sense of ownership in rural mini-grid community management. Moreover, prior research has partially highlighted the causes of a sense of ownership among mini-grid users without detailed theoretical analysis. This study, therefore, seeks to fill both research gaps by using the cases of Leganga and Silale

[5] A mini-grid is a small-scale electricity generation system (from 10kW to 10MW) isolated from the main grid, that distributes energy to a limited number of customers.
[6] Other phases in mini-grid life cycle are implementation together with monitoring and evaluation.

in Tanzania to primarily analyse the role of a sense of ownership in community mini-grid management. To achieve this, the study specifically uses the following guiding research questions: (RQ1) Which factors affect a sense of ownership among CBM users? (RQ2) in which mini-grid phase does a sense of ownership among users arise? To answer these research questions, this paper focuses on CBMs whose respective community members are responsible for all plant management practices.

This article makes two main contributions to the literature. First, while previous studies on CBMs management have focused on institutional aspects to manage maintenance (Maier, 2007) and overall mini-grid management (Gollwitzer et al., 2018; Warneryd et al., 2020), technical aspects (Greacen, 2004), and financial aspects (Katre et al., 2019), this study contributes to both the community mini-grids and psychological ownership literature by using the "routes" to theoretical psychological ownership framework to analyse the mechanism behind the sense of ownership in the mini-grid context. This paper then develops an analytical framework of the sense of ownership routes for rural community mini-grids. Second, a systematic qualitative analysis of the mini-grid development lifecycle in relation to the sense of ownership is conducted to determine the most important mini-grid phase in which the sense of ownership matters for the successful management of rural community mini-grids.

The remainder of this article is organised as follows. The "Conceptual framework" section presents conceptual guidance on analysing a sense of ownership in community mini-grid management. The methods used are outlined in the "Methods" section. The results of the empirical analysis are presented in the "Results" section, followed by a detailed discussion in the "Discussion" section. Finally, the "Conclusions" section concludes the paper.

2. Conceptual framework: Sense of ownership in community mini-grid management

2.1. Conceptual background of sense of ownership

This paper provides a theoretical basis for understanding the sense of ownership to explain its role in community mini-grid management. A sense of ownership among users of different resources is one of the essential catalysts for sustaining different infrastructures (Madriz-Vargas et al., 2015; Marks et al., 2013). It is also a powerful component among employees of both public (Asatryan, 2006; Mahsud & Jinxing Hao, 2017) and private organisations (Farahani et al., 2019) and individual households (Marks & Davis, 2012) and a significant factor for policy and programmes (Pickford et al., 2016) in different sectors. Nevertheless, few studies have provided a theoretical framework for the relationship between sense of ownership and the sustainable management of rural community mini-grids. The organisational and behavioural sciences provide a useful theoretical umbrella for explaining the gap identified.

Pierce et al. (2001) define a sense of ownership as a "state in which individuals feel as though the target of ownership (material or immaterial in nature) or a piece of it is "theirs". Later, it was argued that a sense of ownership is expressed in feelings and explanations related to the words 'my or mine and our' towards the target (Pierce et al., 2003). As such, a sense of ownership indicates an individual's possessiveness and connection to the target as his or her own. In other words, an individual has recognition, beliefs, and thoughts towards the target. This target can be a company, organisation, project, idea, or output. Pierce et al. (2003) further clarified that such possessiveness can also be expressed towards people. One of the seminal studies conducted by Furby (1978) also used possessive attitudinal words such as 'my, mine and our' as measurements associated with a sense of ownership. Van Dyne & Pierce (2004) used the same vocabulary and created a seven-item instrument to measure a sense of ownership. Several empirical studies have developed other instruments to quantitatively measure a sense of ownership by adding new criteria based on Van Dyne & Pierce (2004), for instance, Avey et al. (2009), who constructed 12 items (Dawkins et al., 2017).

The sense of ownership theory is further advanced to cover the collective sense of ownership, which involves the shared mentality among group members who regard themselves as 'us' and develop feelings of ownership towards a target as theirs (Pierce & Jussila, 2010). Pierce & Jussila (2010) define a collective sense of ownership as "collective (feeling) that this target (or a piece of that target) of ownership is collectively 'ours'" and further claim the near impossibility of a collective sense of ownership to existence without an individual's sense of ownership existence. Implicitly, feelings of collective ownership of a shared target start at the individual level. This study uses the possessive expressions pronouns 'my, mine, our, or theirs' (Pierce et al., 2001, 2003) in analysing a sense of ownership and considers both positive and negative possessive statements as attitudinal measurements of a sense of ownership, as stated by (Furby, 1978; Pierce et al., 2001, 2003). The paper also applies 'our' to indicate individuals' collective sense of ownership. A detailed sense of ownership exploration is given in the Subsection "Data analysis."

2.2. Factors enabling a sense of ownership

Pierce et al. (2001) theorise three main causal paths through which individuals develop a sense of ownership towards a target: self-investing in the target, having control over the target, and intimately knowing the target. These routes explain how a sense of ownership comes to exist among individuals toward the target.

Self-investing in the target is linked to the money or time an individual spends either working or taking care of the target, energy or skills set applicable during physical labour provision, and interests in the target (Mahsud & Jinxing Hao, 2017; Pierce et al., 2003). Individuals who expend their energy, time, and care in producing goods and services tend to become possessive towards what they work for and the corresponding targets. Even though these individuals may not be legal owners of the target, a sense of ownership is likely to arise (Pierce et al., 2001; Thema et al., 2020). As Dawkins et al. (2017) contend, a sense of ownership is self-driven, unlike legal ownership, which normally sets boundaries from its set. A sense of ownership can, hence, exist exclusively without legal ownership (or vice versa) or can coexist (Etzioni & Street, 1991; Furby, 1980) but originates and depends on the feelings of individuals towards the target (Pierce et al., 2003). This conception of a sense of ownership distinguishes it from legal ownership, as the former is perceived by the person whose feeling is expressed, whereas the latter is based on legality (Pierce et al., 2003).

Having control over the target can also cause a sense of ownership because individuals can make decisions that affect the outcomes of a given target, including shouldering enormous obligations and being responsible for influencing strategies that may induce the development of feelings of control over the target and, hence, a sense of ownership (Pierce et al., 2001). Subsequently, having control over a certain idea and work to yield the desired outcome, for example, an organisation, may increase the sense of ownership towards a particular organisation even when an individual is not a legal owner.

Ultimately, knowing the target is connected to how well individuals possess sufficient knowledge of a target by associating with it. Knowledge may be acquired through long- or short-term attachment to the target, although the more individuals associate with a particular target, the more knowledge is extracted and the more the sense of ownership may develop (Pierce et al., 2001, 2003). The resultant knowledge may increase personal interests and, eventually, feelings of responsibility towards the target. The routes explained here tend to independently cause a sense of ownership, although going through more than one route can occasion a greater sense of ownership (Pierce et al., 2003).

2.3. Conceptualising a sense of ownership in the mini-grid context

As already stated, a sense of ownership is a feeling a person has towards something or target (such as project, company, organisation) as his or her own. This study treats mini-grids as the target of ownership since, from their inception, different stakeholders (donors, investors, developers, government agents, community members, etc.) are involved. As noted earlier, Tanzania has five common mini-grid ownership models: private entities, community, national utility (owned by government), hybrid and faith-based organisations. Community-based mini-grids, the main concern of this study, are managed, owned, operated, and maintained by local community members. Thus, community members' sense of ownership of mini-grids is defined as a psychological state in which electricity users have an impression and feelings that the mini-grid is their own. No studies have discussed the role of a sense of ownership in community-based mini-grid management in-depth; therefore, this study addresses this gap.

Mini-grid development involves various phases in its lifespan. The three common phases that are considered and highlighted in this study are preparation and designing, implementation, and monitoring and evaluation. In the preparation stage, the donor, investor, or community identifies the location and community for the envisaged mini-grid, collaborating with the governmental energy agency. This stage covers discussions and agreements on the needs assessment, the boundaries of who is going to benefit from the project, project values between community members and the developer or investor, and the follow-up of licence approvals. The community also participates in this phase financially or non-financially by offering land to construct mini-grids. Empirical evidence affirms that this phase is crucial for developing ownership among community members in both community energy projects (Ortiz et al., 2012; Terrapon-Pfaff et al., 2014) and noncommunity-owned projects (A. Kumar et al., 2009; Madriz-Vargas et al., 2015), as a collective vision geared towards the successful management of mini-grid projects has developed (Tran, 2013). Mini-grid design—also under the first phase—involves mostly a mini-grid's technical aspects and financial feasibility planning. The salient features at this stage include the choice of technology for application in correlation with the energy sources available and size, the preparation of sustainable technical operational plans, and the development of a sustainable business model for running the mini-grids (Madriz-Vargas et al., 2015). Mini-grid developers and communities are mostly involved in this phase, together with the respective energy regulatory agencies, which are responsible for reviewing and approving the licence and feasibility study. The community can decide to support or sabotage mini-grid plans during the preparation and design phase.

Implementation is an action phase that entails installing the mini-grid at the site and operationalising it. The phase also covers operations and maintenance (O&M). The mini-grid operator can be in-house (i.e., the community can manage O&M matters by hiring technicians within the locality) or outsourced. Moreover, the tariff design agreed upon during the design phase is also applicable in this phase. Furthermore, the operator, community members or both can execute this phase of a mini-grid project independently or collaboratively, depending on the mini-grid ownership model. Community members can engage in this phase by providing communal labour during construction. Additionally, community members' participation in decision-making during this phase may promote a sense of ownership (Marks & Davis, 2012). Finally, the monitoring and evaluation (M&E) phase helps check for user satisfaction levels, socioeconomic impacts of the mini-grid, and electricity reliability status. Since the community sense of ownership may develop in any of these phases, this study examines the phase(s) in which a sense of ownership arises and matters the most.

Based on the theoretical foundation explained in the previous subsection, this subsection further presents the mechanisms behind a sense of ownership in the mini-grid context, which are summarised in the developed analytical framework (see Figure 11). Self-investing in the mini-grid constitutes the initial monetary investment that electricity users contribute to managing mini-grid O&M. This contribution is mostly in the form of tariffs and capital costs. There are also nonmonetary contributions from community members, such as providing land for installing the mini-grid and offering manual labour during the construction stage without pay. Users can also care for mini-grids by cleaning the panels without payment, cleaning the surroundings of the mini-grid, and watching out for jeopardising events against mini-grids, such as throwing stones at the panels. These are some forms of investment that electricity users dedicate to mini-grids, which can increase their sense of ownership. Resource mobilisation is another form of self-investment in mini-grids carried out by electricity users independently (for community-owned mini-grids) and/or by mini-grid operators collaborating with electricity users (for private, faith-based and community-owned mini-grids). This resource mobilisation can occur because users mobilise funds for O&M by paying tariffs and setting rules to guide them in managing the mini-grid.

The ownership of mini-grids is controlled by users involved in the mini-grid's decision-making, for example, on the amount of tariffs to pay, the adjustment of tariffs and the selection of energy committee members. This correlates with convening meetings for users to discuss mini-grid matters. In addition, electricity users have control over mini-grids by perceiving that they have influenced mini-grids since the preparation phase and can accept or refuse their houses to be connected with electricity.

Having intimate knowledge of mini-grids speaks of users' associations with mini-grids through using them. Apparently, the more they consume electricity, the more they learn about different aspects of mini-grid operations, for instance, by getting to know their technician, revenue collection model, and project funder, developing closer relationships between users and the mini-grid; hence, they have a stronger sense of ownership towards the mini-grid. The more information that is derived from the mini-grid, the more attached to it they become. Mini-grid users exposed to more elements described in these routes can develop a greater sense of ownership. Figure 11 summarises the explained routes through which individuals' sense of ownership towards the mini-grid develops:

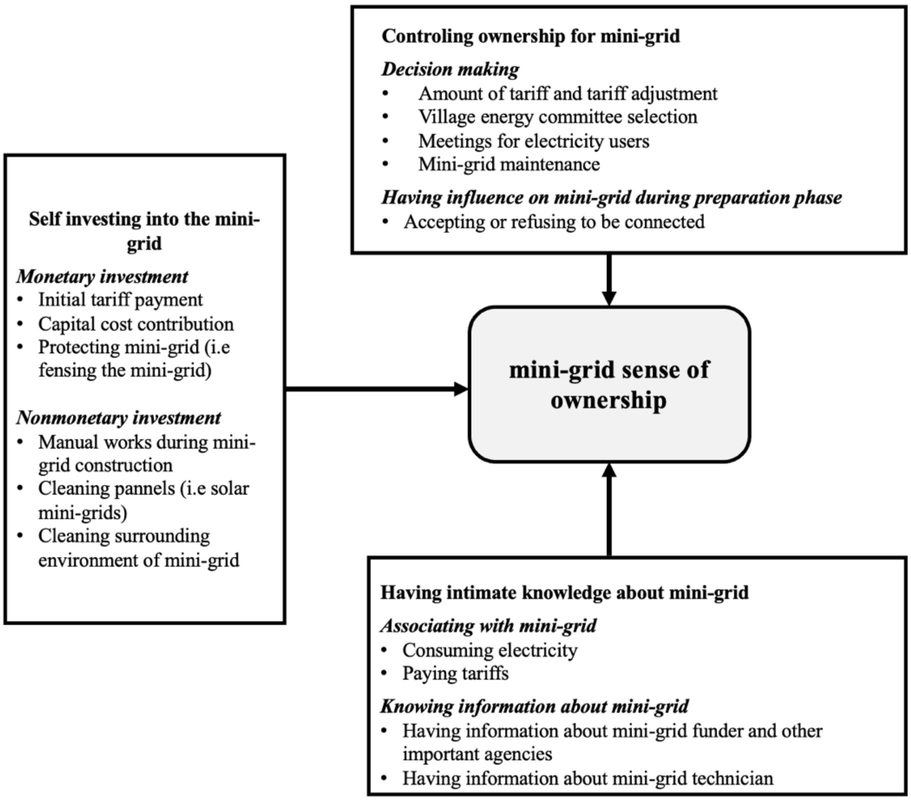

Figure 11: Analytical framework: Sense of ownership routes for rural community mini-grids.
Source: Author.

3. Methods

3.1. Research setting

Tanzania was selected as a case study for several reasons: 1) national electricity access has increased over the past decade (by 37.7% by 2020), but the gap between urban areas (73.2%) and rural areas (24.5%) has remained high; 2) over the past three years, Tanzania has attracted a large number of investors and developers to invest in private, faith-based and community-based mini-grids (CBMs); to date, however, extremely few CBMs have survived; and 3) despite the mini-grid market having taken off earlier than other East African countries, Tanzania lags behind Kenya in mini-grid deployment and has few operational CBMs relative to the latter.

In an effort to electrify rural communities, the government of Tanzania, through its Ministry of Energy and Minerals, received a soft loan from the Austrian government and constructed 14 community solar mini-grids across 10 villages in three regions: Dodoma, Katavi, and Tabora (Odarno et al., 2017). This was a pilot project that targeted unelectrified villages (selected by the Ministry of Energy and Minerals) that were unlikely to be connected to the main grid electricity in the near future and had relatively concentrated houses. A contract was signed between the Ministry of Energy and Minerals and Elektro Merl Company from Austria to install all mini-grids, connect all targeted customers, and perform maintenance services to all mini-grids. The company consulted the respective Village Energy Committees (VECs) and the village governments, which were supervisors and guardians for mini-grid projects, following guidelines developed by the Ministry of Energy and Minerals (Ngoti, 2024a). The aim of this pilot project was to attain experience from this model of operation and management and later deliver it to other unelectrified villages in other parts of Tanzania. Legal ownership of mini-grids was with the government and would be transferred to the respective villages after the contract with Elekro Merl company to oversee mini-grid maintenance expired.

Of the 14 mini-grids in 10 villages, the Silale and Leganga mini-grids located in the Dodoma region were the only surviving mini-grids when this study was conducted, both of which are included in the empirical analysis. Due to different reasons, such as battery failures and poor management by the beneficiary communities, the remaining 12 mini-grids stopped operating within the first four years of their commencement. Despite their non-operational status, mini-grid assets such as solar panels, electricity poles, wires, and production systems (inverters, batteries, and energy generation technologies inside containers) are still at the sites to date.

After the cessation of these mini-grids, some villages were connected to the main grid electricity, and others switched to alternative energy sources such as home solar systems and generators.

The two cases were selected for this study because 1) there is a limited number of operating CBMs across Tanzania and 2) operational CBMs from other energy sources are absent in addition to solar energy. Therefore, the two cases met the potential CBM criteria needed for this study (beneficiaries are solely responsible for mini-grid management). With fewer than 400 inhabitants in each village, agriculture is the primary economic activity in Silale and Leganga. Few businesses, such as shops, restaurants, and hair salons, exist in the villages. Institutions such as a dispensary in Leganga, a primary school, and a church in each village also contribute to the local landscape. The two villages benefited from the aforementioned mini-grid projects due to the absence of anticipated connections to the national grid in the foreseeable future.

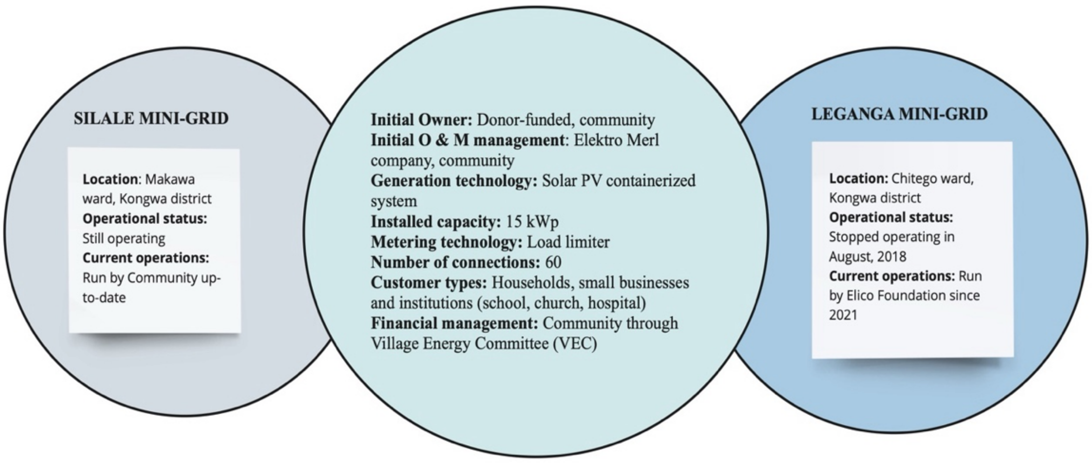

Figure 12: Key similarities and differences among mini-grid cases. Source: Author.

A total of 60 connections were made to each village. The connections included households, businesses, and institutions. Businesses with higher energy consumption, such as welding machines, were not connected. As described in Figure 12, the original setups for the two mini-grids are similar in several ways: technical setting, financial investment (funder), management arrangement, and number of connected customers; however, the operational sustainability outcomes differ. Unlike Silale, the Leganga mini-grid ceased operations three years after its commencement and remained without electricity until 2021, when another organisation revitalised it. The survey on Leganga mini-grid, therefore, is based on the period prior to its cessation. The current management of Leganga mini-grid is entirely under Elico Foundation, with no community involvement in the O&M. Despite the outlined similarities, the most interesting feature of both cases is the difference in sustainability outcomes. In the first three years, the Elektro Merl Company operated both mini-grids specifically on the maintenance side, while VEC members were responsible for collecting tariffs, conducting meetings with electricity users, managing electricity connections and disconnections, controlling illegal connections, and using banned electrical appliances (Ngoti, 2024a). After three years, the Elektro Merl Company (mini-grid operator) left, and the VEC became solely responsible for each mini-grid management, with an additional role in running mini-grid maintenance. The technician who previously served under Elektro Merl continued maintaining both mini-grids. Both communities participated in feasibility studies conducted before the construction of the mini-grids. During the construction phase, both communities provided the land on which the mini-grids were set up and provided manual labour. However, site selection for connected houses was based on prior arrangements between the Ministry of Energy and Minerals and the Elektro Merl Company, with no direct involvement of community members.

3.2. Data collection

The qualitative data were collected during field visits to the two mini-grids where 18 in-depth semistructured interviews were carried out. Study tools were developed to gather information from the following list of interviewees: 6 VECs (3 members from each mini-grid), 3 village council leaders (2 from Leganga and 1 from Silale), 8 normal electricity users (3 from Leganga and 5 from Silale) and 1 technician (maintaining both mini-grids). Gender-wise, the interviewees included 6 females (3 from each mini-grid) and 12 males (5 from Leganga, 6 from Silale and 1 technician). The diversity of participants enabled the study to collect balanced opinions on how CBM is initiated, operated, maintained, and managed.

Five days were spent on each mini-grid site between May and June 2022. All the VEC and village council leaders available during field visits were interviewed. The snowball method was applied to normal household electricity users without leadership titles in the case studies. The technician was interviewed because of his strategic position (the only technician who has served since the commencement of both mini-grids). The study included only 18 participants, mainly because of data saturation during the interviews. Moreover, some previously connected households relocated to other locations. Generally, the sample is representative for ensuring reliable results. During data collection, all the interviews were conducted in Kiswahili before the transcripts were translated into English.

3.3. Data analysis

After data collection, the audio was transcribed using the original interview language, Kiswahili. The transcriptions were performed in MAXQDA 2022, a software package for both qualitative data analysis and mixed methods research.

A preliminary codebook was then developed based on both theory-driven and data-driven codes. The sense of ownership theme that emerged during data collection was then coded using the coding framework presented in Table 10 to assess its role in rural community mini-grid management. The second round of coding was conducted to capture all aspects and mechanisms of the themes related to a sense of ownership. Finally, the third round of coding was further conducted to assess all the transcripts and ensure that they were well captured by the resulting codebook.

To analyse the research findings, the coding framework for the SO indicators presented in Table 10 was developed based on the above expressions.

Table 10: Sense of ownership coding framework. Source: Author.

Indicators	Description	Keywords	
		Kiswahili	English
Possessive expressions towards mini-grid	Use of possessive words towards mini-grid as a target and its maintenance fund that is used for mini-grid operations and maintenance	Umeme wetu	Our electricity
		Mradi wetu	Our project
		Mtambo wetu	Our plant
		Mali yao	Their asset (i.e., mini-grid)
		Akaunti/Hela yetu	Our account/money
		Mfuko wetu	Our fund
Possessive expressions towards people	Use of possessive words towards people connected to mini-grid such as VEC, users and technician(s)	Fundi/mafundi wetu	Our technician(s)
Negative possessive expressions	Demonstration of negative expressions towards ownership of mini-grid	Umeme wa bure, hatutakiwi kuulipia	It is free electricity; we do not need to pay for it
		Umeme tumeletewa na wazungu	Electricity was brought by whites/foreigners
		Hatukuomba mradi uje	We did not ask for the project to come

Positive possessive expressions	Demonstration of positive expressions towards ownership of mini-grid	Hatujakabidhiwa mradi rasmi lakini tunajua ni wa kwetu	We have not been officially handed over the project, but we know it is ours
		Tunaupenda umeme/mradi wetu	We love our electricity/project
		Lazima tuulinde mradi wetu	We must protect our project

Possessive pronouns for mini-grids were derived from (Furby, 1978; Pierce et al., 2001, 2003) by the use of 'our and their' (Pierce et al., 2001, 2003) combined with words such as projects or containers that are directly connected to mini-grids as targets. The sense of ownership indicators were further broken down into possessive expressions for people connected with mini-grids such as the VEC, technicians and electricity users. Apart from the person-object relationship as an expression of a sense of ownership, (Pierce et al., 2003) [25] acknowledged how a sense of ownership can also be expressed in connection with nonphysical entities such as people. Since feelings of possessiveness can be demonstrated either positively or negatively towards the target (Nuttin & Jozef, 1987; Pierce et al., 2001), negative and positive possessive expressions towards mini-grids were subjected to further analysis to measure the sense of ownership and make the results more robust.

Use of the words 'my, mine, our, or their' without being attached to mini-grids' elements was ignored and considered to lack a sense of ownership. In addition, words such as "mini-grid plant", "project", or "container", without the attachment of possessive expressions listed earlier, were considered to lack ownership. The third and fourth columns in Table 10 present keywords of possessive pronoun expressions indicating a sense of ownership, both in the original interview language, Kiswahili, and in the language of translation, English. The last indicator is a composite of several expressions geared towards mini-grid management and sustainability.

To determine the factors affecting electricity users' sense of ownership, this study assessed the co-occurrence and relationship between a sense of ownership and its routes (investing the self in the mini-grid, controlling ownership of the mini-grid and having intimate knowledge about the mini-grid). Visual mapping of the relationship between a sense of ownership and its routes was also performed (see Figure 13).

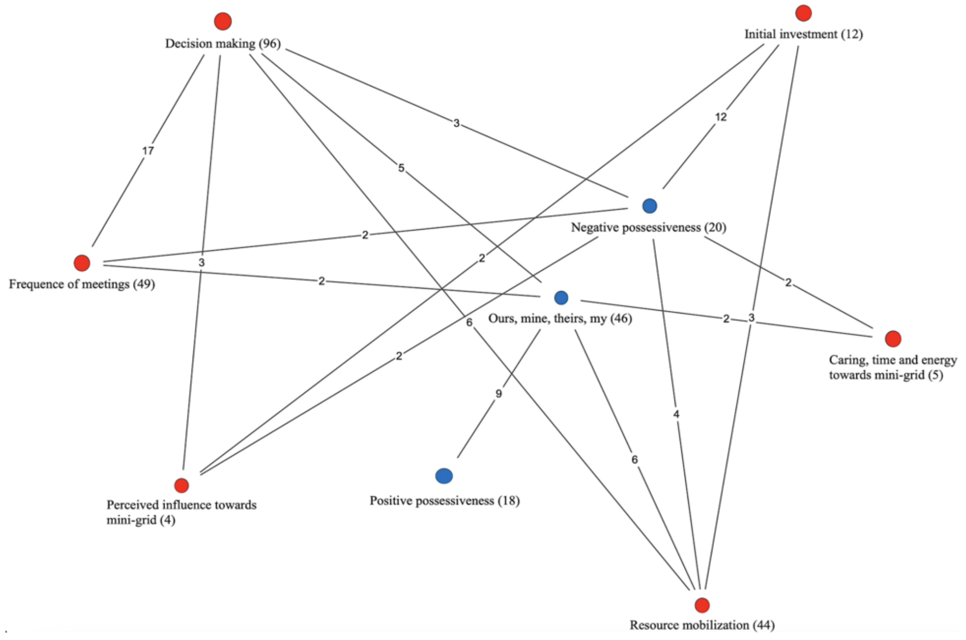

Figure 13: Relationship between sense of ownership and its routes. Source: Author. Note: The numbers next to the nodes represent frequencies for the respective codes, while the numbers next to the lines represent the number of interview documents mentioning both connected concepts. For example, 46 is the number of times "ours, mine, theirs, my" was used as an indicator for sense of ownership, while five interview documents refer to "decision-making" and "our, mine, theirs, my" together. The blue nodes represent ownership indicators, and the red nodes represent the routes.

It becomes evident that the sense of ownership is affected differently by its routes. Resource mobilisation, frequency of meetings, and decision-making appeared most frequently in connection with the sense of ownership indicated by "our, mine, theirs, my". This implies a strong relationship among these variables. A low sense of ownership indicated by "negative possessiveness" is highly related to initial investment (12 interview documents) followed by "resource mobilisation". It is also evident that "positive possessiveness" intersects with the indicator "ours, mine, theirs, my" in describing the concept of a sense of ownership.

Interview transcripts from both VECs and household users were thus thoroughly reviewed to identify any significant connections among them. The approach to measuring a sense of ownership in this study employed few of the measurement items of sense of ownership available in the literature. Nevertheless, the study managed to extract in-depth insights from the data.

4. Results

4.1. Sense of ownership for Leganga and Silale mini-grids

Given the similar setup of the Leganga and Silale mini-grids (Figure 12), the sense of ownership was first examined to determine whether the results were also similar. Surprisingly, the sense of ownership differed between the two mini-grids. According to the indicators for a sense of ownership in Table 10, Silale had a greater sense of ownership than Leganga. More interviewees at Silale demonstrated both possessive expressions and positive expressions towards mini-grids and people related to mini-grids.

Most respondents at Silale reported a strong sense of ownership towards the mini-grid project by expressing how they treat it as theirs, even without an official transfer of ownership to them by the government: "Not officially handed over. We know the project belongs to us […]" (Interviewee 4).

Through possessive expressions, a sense of ownership emerged not only for the mini-grid but also for the technicians and the tariffs collected. Some energy committee members interviewed for both mini-grids treated electricity users as 'their' customers. Participants in both Silale and Leganga shared the following views:

> "*…in case the electricity is off for 'our' customer, we call them [technicians], after calling them they would come. They would go to the customer to determine if there is any equipment damaged [...]*" (Interviewee 17).
>
> "*…therefore, as a committee, we observed and said, let us balance bills for 'our' customers so that...since problems had already begun during collection because of high tariff rates […]*" (Interviewee 5)

A low sense of ownership for the Leganga mini-grid is reflected in its users' more negative possessive expressions and less positive possessive expressions. Most respondents claimed that foreigners—donors—had introduced the project for free power distribution; hence, there was no need to pay tariffs to manage it or be disconnected from it: "… *And we were told when this project was brought, we have been told that this is a free project […]*" (Interviewee 11)

> *"...people started saying, electricity was just brought to us […]"* (Interviewee 14)
>
> *"…another person says, the whites brought me the electricity, therefore I should not be disconnected […]"* (Interviewee 12)

Such statements demonstrate a negative sense of belonging attached to the project by most of the users in Leganga. This analysis revealed that the sense of ownership for Silale mini-grid users was greater than that for Leganga mini-grid users. The analytical status of a sense of ownership between these cases is a foundation for answering the research questions raised in this study.

4.2. Factors affecting community mini-grids' sense of ownership

Given the different sense of ownership status between the two cases, this section answers research question (1) by utilising the analytical framework presented in Figure 11. The absence of initial investment through tariff payments emerged as the strongest factor causing a low sense of ownership among electricity users at Leganga. Unlike at Silale, electricity users at Leganga consumed electricity freely almost seven months after the project started. When the time came for them to start paying tariffs, a significant number declined, asserting that electricity is to be consumed without charges: *"...Technicians are disconnecting the electricity, when they tell you it is because you don't pay tariffs, the reply is I am not paying for a free electricity [...]"* (Interviewee 11).

Not paying tariffs from the beginning of the project emerged as a challenge to revenue collection later on, and users felt offended when instructed to pay for electricity: *"... the biggest challenge was in tariff collection. People used to say that the electricity was just freely brought to us [...]"* (Interviewee 14).

These statements indicate that the low sense of ownership towards the Leganga mini-grid was strongly affected by the absence of initial monetary investment in the mini-grid through tariff payments.

Perceptions of users having influence on mini-grids from the initial preparation and design phase are found to affect the sense of ownership in both cases. It is worth mentioning that households connected to both projects were already under a map designed by the Ministry of Energy and Mineral in collaboration with the Elector Merl Company. This prearrangement ignored the autonomy of selected households to accept or reject the project. These households are more likely to have a low sense of ownership towards the project because they have had little control of the mini-grid since its inception. In this regard, Interviewee 7 said:

> "*...this electricity is connected to few houses...first-of-all, the first time they came, there were other people who were connected and did not see its importance, and they are the ones who caused problems in paying tariffs. However, only if they came because they*

came with a map, which was designed to connect just a small village piece. So in that piece, there were others who were in that map who were not even in need of it, but they were connected. However, there were others who were highly in need of being connected, and they were left out of the map, you see".

This indicates the limited influence of users on mini-grids, as their consent to access electricity connections was not investigated from the beginning. It may seem an excuse to avoid paying tariffs, but it reflects users' perceptions of the project — feelings of having no influence over certain aspects of mini-grid management — which consequently affects their sense of ownership.

The ability of electricity users to influence decision-making pertaining to mini-grids also affects their sense of ownership because it makes them feel that they control the mini-grid. Mini-grid users at both Leganga and Silale participated in different decision-making processes, for instance, adjusting tariff amounts and selecting energy committee members. However, some decisions at the Silale Mini-grid were approved by all users via village quarterly meetings after proposals from the VEC and village council. Such decisions included expenditures on maintenance matters and expenditures for non-electricity village matters. The VEC and village council at Silale exhibited greater autonomy in dealing with defiant electricity users who defaulted to pay tariffs. Interviewee 5 explained:

"*Challenges were being resolved, for example, bill collection emerged to be a major challenge, so when you meet with a long-term stubborn electricity beneficiary, and you called him and you talked to him and he still seems unwilling to pay the electricity bill…therefore the challenge was normally resolved, for example you can call him, you talk to him as a committee. If you are not successful with such people, then you forwards the information to village council leaders. The village government will make a statement and talk to him on how to solve that problem and agree on the date that he will pay the debt. If he fails, the electricity will be disconnected, but he must pay the money."*

At Leganga, meetings on mini-grid matters were infrequently held, and rule breakers were rarely punished. VECs, together with village councils, were reluctant to take action against rule breakers. Generally, participation in decision-making on management and technical and financial mini-grid matters was greater at Silale than at Leganga, which contributed to the greater sense of ownership at Silale than at Leganga.

Another factor affecting the sense of ownership among mini-grid users is the knowledge they have about their technicians and donors, along with establishing connections with the project through electricity consumption and tariff payments. Users in both mini-grids clearly understood mini-grid funding sources, the existing revenue collection model, and whom to consult when the mini-grids malfunctioned. This level of knowledge and association with mini-grids fostered a sense of ownership among mini-grid users.

4.3. Mini-grid phases and sense of ownership

As previously explained, the mini-grid lifecycle undergoes different phases. To answer research question (2), this section examines the crucial phase for fostering a sense of ownership among electricity users in CBM. Most interviewees lived in the respective villages during the preparation and design phase for both mini-grids and clearly remembered what occurred at that time. As mentioned earlier, households connected to the mini-grids in both cases were already on the planned map designed by the Ministry of Energy, which collaborated with the Elektro Merl Company. In this context, users asserted that they were not engaged in the initial planning of the projects, as they were not consulted about their preference for the projects. Based on this, the obligation to pay for electricity consumed is deemed irrelevant to users:

> *"... they said they have a map, yes they said they have a map of which they came to put those electricity poles and those people to get electricity, those 64 houses. However, it is not that asked to be connected, no… Therefore, people said, since it is a trial project, let us just be connected. However, later they it came to be associated with payment […]".* (Interviewee 16)

During this phase, the sense of ownership among users was likely to decline despite their participation in other ways, such as providing their land for mini-grid construction.

In the implementation phase, electricity users at both Leganga and Silale offered their labour for construction and participated in protecting mini-grids against any jeopardising circumstances and at different levels of decision-making. (Interviewee 5):

> *"…for example, the project that we are given is a solar project, so it needs to be taken care of. We do not want to see someone, for instance, walking with a catapult, eeh shooting birds from the streets, around the mini-grid area. If we see such a person, we warn him, and if he is a troublemaker, we handle him in accordance with the rules because 'our' projects are solar power. Therefore, such solar projects need be handled with care […]".*

Such community participation during the implementation phase appears to be related to a sense of ownership, as users are directly associated with the mini-grid. In this phase, users in Leganga paid no tariff in the first seven months, which was previously found to have weakened the sense of ownership towards the project.

After the mini-grid operated for a particular period, mini-grid users tend to realise the socioeconomic impacts. For example, more children could study at night, the number of electricity-consuming businesses increased, and village dispensaries were equipped with reliable services such as vaccine storage facilities. At Leganga, for instance, the sense of ownership was already low during the first and second phases and continued to diminish during the monitoring and evaluation phase until the mini-grid ceased operation in 2018, despite harnessing mini-grid benefits. In contrast, Silale had a greater sense of ownership than Leganga did in the first and second phases; the sense of ownership even increased during the M&E phase. Some interviewees appreciated the benefits of the mini-grid and insisted they were willing to do everything in their power to make it survive even longer.

4.4. Sense of ownership and mini-grid management

A sense of ownership among VEC members of mini-grids is also found to increase the sense of ownership among other electricity users; hence, (un)sustainable mini-grid management depends on the type of effect. Participation in decision-making among normal electricity users, the VEC, and local village leaders helped promote a sense of ownership of mini-grid management. Mini-grid decision-making included VEC election, tariff adjustments, mini-grid repair and maintenance, revenue management for O&M, and disciplinary action(s) for refractory electricity users. Leganga, for instance, rarely conducted meetings, and VEC elections were based on "blood brotherhood" rather than individual leadership capability. Interviewee 11 explained this as follows:

> *"As for me, I can select the one I know is more capable, but another person may elect relatives because they are relatives. He may do that just because they are relative but not because of his capabilities".*

Moreover, the study revealed that VEC motivation to mobilise resources for O&M at Leganga was negatively affected by users' disruptive behaviours. Users used threats and rude responses when VECs were collecting tariffs to prevent them from fulfilling their obligations. However, no punitive action was taken against such disorderly energy users. Implicitly, community mini-grid management can be negatively affected by both users and leaders. As a countermeasure, strong leadership and collaboration between users and VECs can create a greater sense of ownership and, consequently, smoother mini-grid management.

In contrast, Silale had three rounds of VEC leadership, and elements of "blood brotherhood" elections (based on nepotism) were somewhat subdued. In addition to tariff adjustment and VEC elections, decision-making among users at Silale was greater in terms of overall mini-grid management than at Leganga. Indeed, the higher users' participation in decision-making was notable as a stimulus of the sense of ownership at Silale. Interviewee 4 said:

> *"…and later they realised that this project is real 'our' property because the money collected is not going to be taken by anyone, the government, or the company; they manage the revenues and expenditure by themselves; they dawned on them that it is 'their' property".*

Regarding technical management matters, the VEC at Silale, which collaborates with village councils, usually consulted technicians with queries on the mini-grid system and proceeded to solve the problem without involving the normal users. Normal users usually become involved in decision-making for monetary resource mobilisation, particularly fundraising, during an emergency amidst a mini-grid failure requiring contingency measures. Specifically, they would raise funds to help technicians reach the mini-grid site and buy the required spare parts or equipment.

The sense of ownership in mini-grid management among users in this study is also found to be connected to the sense of ownership among VEC members. The evidence shows that VEC members with strong decision-making and resource mobilisation skills in Silale exhibited a high sense of ownership. This positively affected the sense of ownership of normal users compared to their VEC counterparts at Leganga. As normal electricity users admitted, strong leadership skills among VEC members in managing the mini-grid are among the factors that contributed to mini-grid survival. One user explained,

> *"The current committee is good, as there are some die-hard defaulters who insist on using powers [from the mini-grid] but do not want to pay the tariff. The committee usually disconnects such users from the power supply. You may find that the committee is working for our development. How can you consume such service without paying for it? Who will run this project if not ourselves!"* (Interviewee 8).

Some VEC members at Silale also acquired some technical skills from the mini-grid technician who helped address user electricity needs. As Interviewee 7 noted,

> *"...in the first phase, we depended on the technician to do everything. However, now we are lucky that we have elected young people unlike at the beginning where we elected the elderly ... right now the elected VEC has been taught by the technician some stuff and they can even climb the electricity poles in case of a problem. The technician will give them instructions on what to do, but not inside the container, only outside. For instance, when there is someone with an electricity problem in his or her house, a technician can instruct the VEC to check the problem. Some other problems can be solved without the technician paying them physical visits."*

Evidently, the sense of ownership among VEC members at Silale increased the sense of ownership among normal users and made mini-grids more manageable and sustainable. In contrast, at Leganga, the VECs were on the receiving end for failing to serve as role models for normal users; instead, they failed to pay tariffs and did not punish defaulters. Consequently, there was also a low sense of ownership among normal users. One of the normal users said:

> *"At first, the committee collected tariffs without any problems. It later became a problem when tariff collectors started saying that they would not pay tariffs. Now, if the collector says that he or she is not going to pay when he or she should be leading as an example, how will I pay?"*

Overall, this incident illustrates the low sense of ownership among VECs, which further translated into poor mini-grid management at Leganga.

Generally, the relationship between a sense of ownership and CBM management is explained by the factors described in Figure 11 and analysed in the results. In turn, these factors lead to a sense of ownership among users and are also found to affect management, as Figure 14 illustrates:

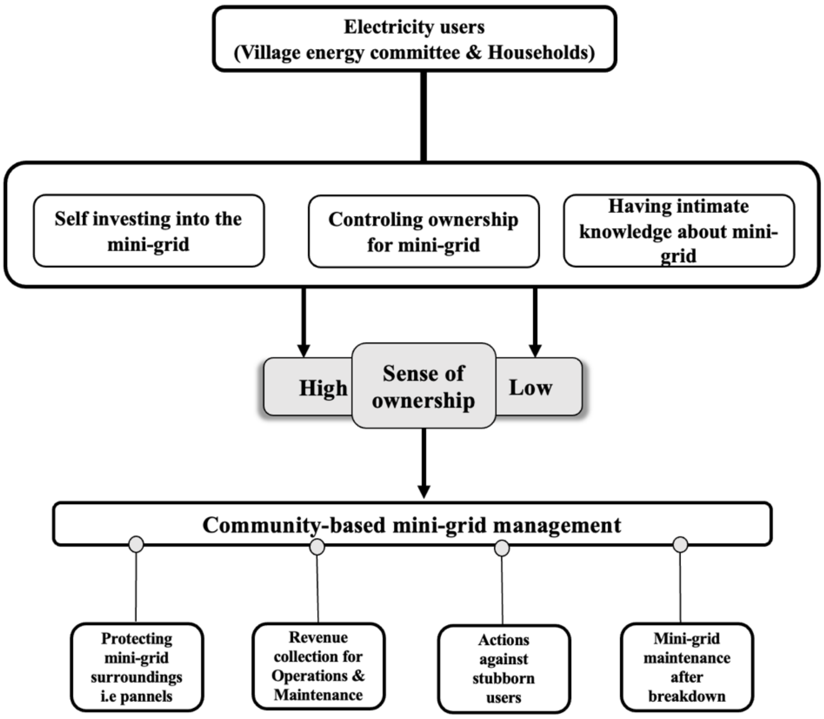

Figure 14: Relationship between SO among electricity users and rural community mini-grid management. Source: Author.

The results revealed that the more multiple factors were prevalent, the stronger the sense of ownership among users and the better the management of community-based mini-grids and vice versa. The Silale mini-grid exhibited more factors that led its users to develop a stronger sense of ownership and better management and sustainability than did the Leganga mini-grid. A greater sense of ownership positively affects overall CBM management. Thus, with good mini-grid management, the successful collection of tariffs for mini-grid operation and maintenance (O&M), the implementation of punitive actions against defaulters in accordance with the set rules, the use of mini-grids in the event of failure through repairs and maintenance, and the good protection of mini-grids by all the users.

5. Discussion

This paper explores the role of the sense of ownership in community-based mini-grid management in Dodoma, Tanzania. Understanding the factors affecting the sense of ownership among mini-grid users and mini-grid phases in which a sense of ownership arises is important for this study. The findings of this study showed that a sense of ownership exists for a mini-grid as an ownership target, for its users, and for accounting management elements such as tariffs. This finding implicitly shows that a sense of ownership is not only about feelings directly towards mini-grids (objects) but also indirectly through the people related to the mini-grids (Pierce et al., 2003). It is also evident from this study that the sense of ownership for community mini-grids soars even when the projects are not officially transferred to the community or when users are not legal owners of the mini-grid (Thema et al., 2020).

By analysing the factors affecting the sense of ownership among community mini-grid users, this study revealed that tariff payments from the beginning of community mini-grid projects are essential for stimulating a sense of ownership and for later smooth mini-grid management even in the absence of capital contributions from community members. Even though tariffs may constitute payments for a product (i.e., electricity service), they are far more a form of self-investment for electricity users (Mahsud & Jinxing Hao, 2017). Initial tariff payments further instil a greater sense of ownership by allowing users to intimately understand that tariff management matters in addition to accommodating their efforts in mini-grid survival (Mahsud & Jinxing Hao, 2017; Pierce et al., 2003). Self-investing in the target in terms of offering time, energy, and care towards the target (Pierce et al., 2003) was practised in both mini-grids, as community members freely volunteered their time by cleaning panels and areas surrounding the mini-grids, protecting panels from kids throwing stones and providing lands where mini-grids were installed. However, the initial monetary investment emerged as a fundamental factor affecting the sense of ownership of community mini-grid users in this study. Users reported their own contributions and efforts from the beginning and became easily attached to the mini-grid for a longer period; in contrast, the lack of initial monetary investment towards the mini-grid had the opposite effect.

Along with a lack of initial monetary investment in mini-grids, low participation in decision-making on managerial, financial, and technical matters among users was also found to negatively affect the sense of ownership and vice versa. This finding is supported by (Kelly et al., 2017; Maier, 2007), who also found that participatory decision-making in financial and management matters increases the sense of ownership of users of community infrastructure. Associations and sufficient knowledge of mini-grids found in both case studies also fostered a sense of ownership among users (Pierce et al., 2003). However, traveling through multiple sub-elements via multiple routes or through multiple factors by users in one mini-grid tends to affect their corresponding sense of ownership compared with that of mini-grid users with fewer factors (Pierce et al., 2003). This is observed in the analysis when SO was greater for users at the Silale mini-grid because it was more strongly affected by factors than were the users at the Leganga mini-grid.

The study findings further revealed that the sense of ownership among mini-grid users is negatively affected if community engagement in the design and preparation phase is ignored. Engaging communities by seeking their consent to be connected with projects from the early stage, for example, was found to be important in this study. Users' consent to be connected to the electricity supply creates less room for future disagreements in mini-grid management. It also stimulates a sense of ownership because users' interest in electricity connection was integral to the prerequisites and developed from the beginning. In this context, users are placed in a position to perceive ownership of the project. Shi & Yao (2019) likewise found it important for both users and development agencies to be engaged in the preparing and designing phase of different infrastructure developments, as a sense of ownership is normally created and serves as a stepping stone for smooth operations in the later phases of such projects. Community engagement during the design phase is also found to be correlated with the sustainability outcomes of projects (Isham et al., 1995).

It is further revealed that any financial commitment by users in community-managed mini-grid projects should be introduced during the preparation stage and rigorously enforced as soon as the implementation phase begins. The sense of ownership among users is also induced by their upfront payment of dues and labour and capital contributions to the project (Marks & Davis, 2012). The greater the different forms of participation (monetary and nonmonetary) among electricity users in the implementation phase, the stronger the sense of ownership towards the mini-grid.

Therefore, the sense of ownership in the preparation and design phase provides a strong foundation for a stronger sense of ownership in the later stages of the mini-grid life cycle and eventually positively impacts general mini-grid management. During the M&E phase, the sense of ownership tends to become stronger if it has already existed in the previous two phases. Users become more attached to the mini-grid, exerting efforts to ensure its effective management and sustained operations. Conversely, if the sense of ownership is initially low or absent in the first and second phases, it is also likely to remain low during the M&E phase. These results reinforce claims regarding the importance of local community involvement from the initial phase (Maier, 2007), preparation and design to the implementation phases of community mini-grids, as involvement and experience bring people together (Thema et al.,

2020) to create a strong foundation for a sense of ownership once communities are equipped with the autonomy to design their rules (Katre et al., 2019; Maier, 2007; Shi & Yao, 2019; Thema et al., 2020), which in turn facilitates sustainability (Katre et al., 2019; Thema et al., 2020).

The extant literature has associated the sense of ownership of different rural community infrastructures, such as water systems, with proper management (Ambuehl et al., 2021), user participation (Marks & Davis, 2012) and sustainability (Marks et al., 2013), and with energy systems, such as community mini-grids (Thema et al., 2020) and off-grid systems (Gill-Wiehl et al., 2022; Shi & Yao, 2019; Tran, 2013). Similarly, the current study's findings reaffirm how users' sense of ownership is related to mini-grid management through their participation in decision-making and resource mobilisation(Gill-Wiehl et al., 2022). Similarly, prior research has shown that the ability of users, VECs, and village leaders to discuss and make decisions on various matters relating to their energy systems is essential for instilling ownership among users and making the management of such projects effective and successful (Maier, 2007). The literature also shows that resource mobilisation through monetary contributions to community-based projects further enhances the sense of ownership (Kelly et al., 2017; Maier, 2007) and that strong characteristics and behaviours among VECs affect the sense of ownership of other users, which may also have an impact on the general management of different infrastructure systems (Kelly et al., 2017).

Generally, there has been limited theoretical discussion on the relationship between the sense of ownership among electricity users and rural community mini-grid management. This study highlights the factors that facilitate developing a sense of ownership among community mini-grid users that, in turn, affect the management of those projects. This study revealed that this relationship exists through all psychological ownership routes, as described by (Pierce et al., 2001, 2003). Individual self-esteem and self-characteristics among VEC members are found to affect their sense of ownership towards mini-grids and other mini-grids.

6. Conclusions

Overall, this study shows that a sense of ownership among electricity users plays a crucial role in promoting the successful management of rural community mini-grids in Tanzania. This study has developed a sense of ownership analytical framework in the community mini-grid context. This framework analyses the routes that facilitate ownership among rural mini-grid users while establishing a theoretical foundation for analysing the management of community mini-grids. The analysis shows that a sense of ownership may arise in any of the mini-grid phases; however, the earlier it develops, the better the mini-grid management in the subsequent phases. The existence of a sense of ownership in the preparation and design phase further strengthens the sense of ownership in the implementation and M&E phases. Community engagement and participation in decision-making also varyingly bolster the sense of ownership in each phase of the community mini-grid lifecycle. As such, the users' initial investment in the mini-grids by paying tariffs for O&M from the inception stage helps to develop a sense of ownership, which further engenders a sense of responsibility for mini-grid management among users. The study also shows that a high sense of ownership among VEC members has positive spillover effects on the electricity users and that strong mini-grid leadership is essential for its sustainable management. Additionally, the planning and design of community mini-grids should go hand-in-hand with obtaining user consent to connect and educate community members on selecting energy leaders who are capable of managing mini-grids.

These findings suggest that efforts to electrify rural areas in Tanzania using the CBM ownership model should focus on creating an environment that supports instilling a sense of ownership when designing and developing rural electrification programs. Policy designs should strategically include monetary contribution designs (e.g., paying tariffs), full community participation and engagement, and other drivers explored in the study to instil a sense of ownership of such projects among users, even though capital investments are commonly known to come fully from funders.

The analytical framework developed in this study stems from the qualitative exploration of two community mini-grids. Testing this analytical framework on other mini-grid ownership models and using quantitative research are important for future research. The questions for future inquiry should also comprise how different forms of community participation affect community sense of ownership for mini-grid users and analyse the drivers of sense of ownership among VEC members in managing community mini-grids. In its aim to examine the role of a sense of ownership among electricity users in rural community mini-grid management, the study was limited by the employed measurement method of sense of ownership. While the unidimensional items utilised in this study have partially captured the wide range of sense of ownership indicators, other studies suggest that sense of ownership is a multidimensional construct. Thus, research involving multidimensional measurements of a sense of ownership is essential to address this gap.

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Declarations

Ethics approval and consent to participate

The author declares that all ethical standards of the research have been met. Participation in the study was voluntary, and informed consent was obtained from all participants. No compensation was provided to the participants for their involvement; hence, there was no incentive to influence their participation.

Competing interests

The author declares the following financial interests/personal relationships that may be considered potential competing interests: The author reports that the German Federal Ministry of Education and Research provided financial support.

Availability of data and materials

Requisite data will be available upon request.

Chapter V: Exploring the causes of failure in community managed containerised solar mini-grids: A coupled infrastructure systems framework analysis

Abstract

Rural community mini-grid systems face long-term sustainability challenges that may adversely affect the livelihoods of surrounding communities. In this paper, we aim to explore the causes of failure in such systems, drawing on coupled infrastructure systems, a framework that provides an interactive perspective on the management and governance of community mini-grids. We analyse the dynamic interaction of influencing factors on four community-managed mini-grid cases in Tanzania to demonstrate how these systems are embedded in a series of complex interrelations among social, soft, hard, human infrastructure, and exogenous drivers, which often interact in reinforcing ways that threaten sustainability. Utilising causal loop diagrams, the analysis highlights feedback effects within different infrastructure systems, with reinforcing feedback loops that connect various factors, contributing to cascading failures in the mini-grid cases. Based on the empirical data, our analysis concludes that mini-grid failure is not derived from an isolated financial, technical, or social obstacle, but rather arises from complex, dynamic interactions among system components. The study commends the effective diffusion of information between central government institutions and local government bodies, which initiate such projects, to support informed decision-making, promote accountability, and strengthen local governance structures. Enhancing such coordination is essential for the long-term viability of community-managed mini-grids.

Keywords: Community mini-grids, Causal loop analysis, Coupled infrastructure systems, Mini-grids failure, Sustainability

1. Introduction

Mini-grids have become a preferred form of electricity infrastructure for addressing rural electrification challenges in Sub-Saharan Africa (Ahlborg & Hammar, 2014b; Akinbulire et al., 2014; Motjoadi et al., 2020b). Like many countries in the region, Tanzania has facilitated the deployment of solar mini-grids, along with other renewable energy sources, to underserved rural populations beyond the reach of the national grid. However, the sustainability of solar mini-grids, i.e., their long-term operation according to plans, has been of great concern. Findings show that a majority of mini-grids fail between 5 to 15 years after their commencement (Duran & Sahinyazan, 2021a; Greacen, 2004; Maier, 2007), while some others fail earlier than that (Ikejemba, Mpuan, et al., 2017), posing a threat to electricity-dependent development activities in rural areas.

Research identifies social, economic, technical, institutional, and political factors as sources of mini-grid failures. Mini-grids that are poorly or rarely maintained and repaired may result in the technical failure of the mini-grid system (Duran & Sahinyazan, 2021a; Greacen, 2004; Ikejemba, Schuur, et al., 2017). Inadequate implementation of institutional arrangements, such as poor enforcement of mini-grid rules, failure to apply graduated sanctions, and a lack of accountability among mini-grid users and their leaders, is associated with poor mini-grid maintenance(Gollwitzer et al., 2018; Ngoti, 2024a; Tang, 1991). Poorly set tariff schemes and insufficient savings for maintenance (Ngoti, 2024a; Taele et al., 2012) and a lack of trust in the mini-grid technician(s) (Ngoti, 2024b; Rawn & Louie, 2017) contribute to the collapse of communally-managed mini-grids. A significant focus on technical and economic reasons for mini-grid failure (Duran & Sahinyazan, 2021a; Dutt & MacGill, 2013; Katre et al., 2019; Numminen & Lund, 2019) can divert attention from other critical factors that cause the failure of systems that are technically and economically well-designed (Cust et al., 2007). While independent analysis of all factors, as mentioned earlier, is vital for understanding individual processes, it is challenging to attribute their interactional effects on the life cycle of the mini-grid infrastructure. This is particularly important given the interconnected nature of most factors (Hartvigsson, 2018). Considering isolated factors for mini-grid failure while ignoring their interconnectedness partially addresses the root causes for mini-grid system vulnerability. Technical failure of solar mini-grids, for instance, is not solely due to the breakdown of the batteries or panels but also arises from poor mini-grid maintenance financing, illegal connections, lack of sense of ownership, poor decision making, and others. This shows that mini-grid infrastructure is far more than hard infrastructure that is comprised of generation and distribution components, but rather it is embedded in a series of interrelated factors. Little has been done on this, and therefore, it becomes relevant to examine the mini-grids' failure from those systemic effects. Our analysis employs the Coupled Infrastructure Systems (CIS) framework (Anderies et al., 2016; Janssen & Anderies, 2023) to address this research gap in existing mini-grid infrastructure research.

Utilising this framework for our analysis illuminates the mini-grid as a complex infrastructure system composed of interlinked social, technical, political, institutional, and economic components (Ikejemba, Mpuan, et al., 2017; Künneke & Finger, 2009). We therefore apply this framework in the community-managed mini-grids infrastructure in rural Sub-Saharan African settings, where electricity access and connections in a small population stimulate economic activities that further stimulate energy demand despite standard energy use restrictions that usually come with mini-grid installations, alter energy users' behaviors, impact existing and new local governance, and even political conditions.

There are only a few studies that employ the CIS framework. (Janssen et al., 2022) have examined the unsustainability of highways from the perspective of coupled infrastructure systems. The linking between institutions and CIS by (Anderies et al., 2016) and the infrastructure for sustainability by (Janssen & Anderies, 2023) and (Homayounfar et al., 2018) provide a clear picture of what systems are and what makes them resilient. The CIS framework is not explored explicitly in rural electrification, but some scholars have employed its components partially (Liu et al., 2007; Namujju, 2024). This study thus contributes to what is missing in the literature by examining causes for mini-grids' failure as systems of interconnected infrastructure systems using the CIS framework. With this approach, we provide theoretical and practical insights into the systemic causes of failure of mini-grid systems. We use community-managed solar mini-grids for our case studies to examine how the CIS framework can help explain multifaceted dynamics that lead to their failure by using feedback loops analysis, a foundational concept of systems thinking that aids in unmasking interconnections and causal relationships within the system (Waltner-Toews et al., 2008).

2. State of the art

2.1. Governance of mini-gids in Africa, particularly in Tanzania

Rural electrification, especially of remote and poor areas, has proven challenging due to low electricity demand and therefore low returns on the one side, but high risks on the other side

(Barnes, 2007). Mini-grids are financially viable without subsidies only if the main customer is an anchor user or a group of middle- or higher-income users with substantial electricity demand. Productive use is a well-known predictor of the financial success of rural mini-grids (Cabraal et al., 2005; Lukuyu et al., 2023; World Bank, 2022). However, mini-grid designers often overestimate its potential in remote areas that lack roads and access to external markets (Ankel-Peters et al., 2025; Peters et al., 2019b). Access to finance can be another hurdle for developing productive uses, which mini-grid operators can address by either cooperating with microfinance institutions (Peters et al., 2019b) or providing financial services directly (Holstenkamp, 2019b). Van Hove et al. (2022) demonstrate that the type of productive use is essential for the economic evaluation, with uses that operate the whole year being most beneficial for mini-grids.

Poorer households usually cannot afford cost-covering, relatively high, electricity tariffs that are common in off-grid applications (Ankel-Peters et al., 2025), or they are not willing to pay cost-reflective prices. Capital grants result in lower tariffs being charged to customers. Alternatively to or in combination with capital grants, governments could subsidize tariffs for poorer households, e.g., via vouchers (Urpelainen, 2018).
Besides this financing dimension, public authorities are involved in mini-grid projects as regulators. Public regulators influence project risks in at least two ways: First, they can – and should – specify what happens if the main grid arrives in the village supplied by the mini-grid (Tenenbaum et al., 2018). Second, they may regulate tariffs that operators can charge from their retail customers (Tenenbaum et al., 2014b), either in the form of price or quality regulation (Martinot & Reiche, 2000; Reiche et al., 2006). Any of these regulations may be changed over time, so even if there is a favourable regulatory setup in a country at the time of the initial investment decision, this situation can be reversed. The Tanzanian case illustrates this quite well, leading to less growth or even the abandonment of commercial mini-grids in recent years.

In general, the public is involved in mini-grid projects through the coordination of rural electrification efforts as the owner of a national utility company, as the site selection and procuring entity, as the concession or license/permit issuer, or by devolution to the community (Barnes & Foley, 2004; Foley, 1992). Institutional setups further include modes of delivery and/or revenue collection (pre-paid, post-paid, sale to third-party retailer; fee for service, fixed charge, consumption-based tariffs, hybrid; see Williams et al., 2015) and maintenance (e.g., maintenance funds, service companies as a form of contracting out, community technicians), types and shares of customers, especially the so-called “ABC model” (Dibaba et al., 2023; Ramchandran et al., 2016), and different types of ownership of whole systems or per asset (especially split between grid infrastructure and generation assets; Dibaba et al., 2023; Mutubuki-Makuyana, 2010).

There is a growing body of literature on all these different dimensions of governance of mini-grids in Africa. Ownership of systems is a major component of these institutional arrangements. Therefore, authors commonly discuss success and failure related to different types of ownership, distinguishing four basic types of ownership: public, private, community, and non-profit organization (NGO) or faith-based organizations (FBO). Different ownership models have developed over time. The World Bank (2022) distinguishes three phases or “generations” of mini-grids globally (see Table 11). The mini-grids studied in this paper belong to the third generation. Here, solar hybrid mini-grids are developing into a new technological standard. Ownership models diversify, depending on the institutional environment in the respective countries.

Table 11: Mini-grid Generations according to the World Bank.

Phase	**First Generation**	**Second Generation**	**Third Generation**
Time	Late 19^{th} to early 20^{th} K	1980s to early 2000s	Since 2010s
Geographies	Global North, China	Low Income Countries	Global
Technologies	e.g. thermal power [hydropower, generally: local resources]	Diesel & mini hydro	Solar hybrid + PAYG, smart meters, mobile payment, real-time monitoring
Ownership	Small municipal public Rural cooperatives (both supported by public and non-profit entities, associations) Public utility companies	Local entrepreneurs Community organizations	+ international investors, large technology firms + national private companies (JV with local firms, PPP)

Abbreviations: JV = Joint Venture, PAYG = Pay As You Go, PPP = Public-Private Partnership

Source: World Bank (2022)

Some of the general developments of ownership models can be demonstrated using the case of Tanzania (see also, e.g., African Development Bank, 2015; Johnson & Muhoza, 2016). Due to favourable regulations, Tanzania has been a frontrunner in mini-grid deployment for some time. Sector regulation in Tanzania lies with the Energy and Water Utilities Regulations Authority (EWURA), an autonomous agency. The most important company is the state-owned parastatal Tanzania Electric Supply Company (TANESCO). TANESCO is a vertically integrated company, covering the full electricity supply chain. They generate electricity, operate the grid, and distribute and sell electricity to end customers. As a public utility company, it also owns and operates several mini-grids. In 2009, Tanzania launched a Small Power Producers (SPPs) Framework, including a standardised power purchase agreement and a specific tariff methodology. Due to these national policies and funding opportunities offered by the Rural Electrification Agency (REA), the number of mini-grids in general and those run by private developers in particular increased significantly after 2010, with a slowdown in recent years.

Community-managed mini-grids make up around one-sixth of the cases in a database from 2017, provided by the World Resources Institute (WRI), with a medium expansion in recent years. Most of the cases are probably led by village electricity committees (VECs), thus constituting cases of what Pedersen (2016) calls "symbolic ownership".

Long-term sustainability of community-managed mini-grids is questioned by some authors mainly due to three reasons (Fajardo et al., 2025): First, communities do not have the capacity to run and maintain mini-grids, and it may be difficult to build these locally. Second, communities in remote rural areas often highly depend on donor money. Third, there is a certain tendency in community-managed mini-grids to allocate insufficient funds for maintenance and repair (Ilskog et al., 2005; C. Kirubi et al., 2009), as well as potential expansion. So, tariffs tend to be too low. With proper support and/or some extent of formalisation and professionalisation in energy cooperatives, the community ownership model may work in the longer term, though (Fajardo et al., 2025). Moreover, Duran and Sahinyazan (2021b) suggest that community engagement is a success factor for mini-grid sustainability, and costs seem to be lower and success rates significantly higher for community-owned compared to publicly owned mini-grids.

Hence, there are different perceptions about community ownership of mini-grids in Africa. Rather than correlating type of ownership with long-term sustainability, we are interested in the concrete structures and processes, which may determine the success of community-owned mini-grids, and feedback loops between these factors.

2.2. Using the CIS framework to explain mini-grid failures and successes.

The CIS framework developed by Anderies et al. (Anderies et al., 2016) provides a sophisticated analytical tool for understanding complex, i.e., interconnected and potentially nested infrastructure systems. The framework views such systems as sets of "dynamically interacting infrastructure classes in which institutions are viewed as one particular class", and where ultimately governance is seen not as something we do, but rather as an emergent feature of a coupled infrastructure system. The framework is an interdisciplinary approach rooted in the study of the governance of shared resources (Elinor Ostrom) and systems resilience (C.S. Holling) (cf.(Janssen & Anderies, 2023)).

The framework builds on Ostrom's institutional design principles and emphasises that institutions are intimately intertwined with the human, social, and biophysical context within which they operate. It recognises five types of infrastructure: hard infrastructure, soft infrastructure, natural infrastructure, human infrastructure, and social infrastructure. *Hard infrastructure* is comprised of man-made biophysical structures like roads, irrigation systems, and nuclear power plants. Mini-grid system falls under this category, comprising infrastructure components like solar panels, distribution networks, and batteries. These infrastructures are often too large and expensive to be developed individually, making collective engagement a practical approach. *Soft infrastructure* consists of human-created rules and guidelines that govern the use of infrastructure, for instance, the institutional arrangements. In the mini-grid context, this type of infrastructure includes rules, norms, and governance mechanisms that guide users in the proper operation and management of the system. *Natural infrastructure* comprises physical structures that are not man-made. For mini-grids, this includes the land with all its physical properties where the mini-grid container and distribution components are installed. *Human infrastructure* is related to knowledge–build-up of human capacity to do a certain activity, e.g., knowledge of how a mini-grid is run and maintained. *Social infrastructure* encompasses the relationships among individuals. The social infrastructure of the mini-grid system is driven by users' behaviours, values, and beliefs. For our study, we assume that natural infrastructure (land) as fixed (Anderies et al., 2016; Janssen et al., 2022; Janssen & Anderies, 2023). We therefore focus on the mini-grid system, which is built on land as hard infrastructure, and how it interacts with other infrastructure types to influence system sustainability. When applied to electrical mini-grids in Africa, the CIS framework helps explain outcomes through several key mechanisms**:**

Infrastructure coupling dynamic: The framework reveals how mini-grid success depends on effective coupling between the different kinds of infrastructures at play (Künneke & Finger, 2009). **Hard infrastructure** components (solar panels, batteries, distribution networks), instances of soft **infrastructure** (governance structures, payment systems, maintenance protocols), s**ocial infrastructure** elements (community engagement, users' behaviours), and human **infrastructures** (local capacity, cultural practices) (Künneke & Finger, 2009).

Failure mode analysis: Mini-grid failures often occur when coupling between these infrastructure types breaks down, either through disconnection or through mutual reinforcement ("feedback loops"). For example, technical systems are often deployed without appropriate institutional frameworks for maintenance, economic models that do not align with local social structures, readily accessible knowledge, and governance arrangements that do not match community practices or external regulatory requirements, or are disconnected from them.

Sustainability pathways: The framework suggests that sustainable outcomes emerge from a robust coupling across all infrastructure types, explaining why purely technical or economic approaches to mini-grid deployment often fail when the full coupled system is not understood (Osmundson et al., 2008).

Context sensitivity (or the lack of): The framework emphasises that successful institutional arrangements must be carefully matched to the local contexts (Janssen & Anderies, 2023), which helps explain why standardized mini-grid approaches often fail when applied across diverse African settings without the necessary local adaptation.

This study uses this framework to shed light on the failures of solar mini-grids in Tanzania, based on data from four different cases.

3. Methodology

3.1. Case selection

We use a comparative case study design to investigate our research questions. The four cases selected all comprise containerised solar systems sponsored by the Austrian Development Agency (ADA) and handed over to local communities by the Tanzanian government. Overall, their technical and institutional setup is very similar, with only small variations in processes and structures. Degrees of success or failure – our dependent variable – vary (see Table 12). Thus, we follow a *most similar system design* (Anckar, 2008).

Table 12: Overview of Selected Cases.

	Leganga	Silale	Loya	Ilunde
Region	Dodoma	Dodoma	Tabora	Katavi
District	Kongwa	Kongwa	Uyui	Mlele
Size [kW]	15	15	2x 15	2x 15
Commission year	2015	2015	2015	2015
Ownership	Community VEC	Community VEC	Community VEC	Community VEC
Status as of data collection date	Stopped operating in 2018/8	Operating, though with struggles	Stopped operating in 2018	Stopped operating in 2019
Data collection date	2022/5-6	2022/5-6	2023/7	2023/7

VEC: village electricity committee.

3.2. Data collection

Data on the four cases were collected in two periods. The semi-structured interviews and focus group discussions (FGDs) were conducted with key stakeholders: village council leaders, one retired councilor, VEC, mini-grid technicians, and household users. In the first period, 18 in-depth semi-structured interviews were conducted in Leganga and Silale, between May and June 2022. A diverse setting of interviewees facilitated the collection of comprehensive insights on both successful and unsuccessful management stories of the two cases. In the second period, FGDs were conducted in Ilunde and Loya mini-grids in July 2023. Two FGDs involving local leaders and household users were undertaken separately with a focus on the inception, operational management, challenges and possible factors for failure of the two cases.

FGDs in Ilunde and Loya mini-grids were conducted to gain insights on the reasons for failure that individuals may not have expressed in isolation, considering the inception years of the projects and that the mini-grids stopped operating over three years before data collection. Apart from collected information on mini-grid institutional arrangements, maintenance management on Silale and Leganga mini-grids (Ngoti, 2024a), and the role of sense of ownership in mini-grid management (Ngoti, 2024b), additional data were therefore collected to add more sample cases and mine more information specifically on the perceived enormous failure of the solar community-managed mini-grids in Tanzania. All interviews and FGDs were conducted in Swahili by the lead author, who is a native speaker.

3.3. Data analysis

After data collection, all interviews and FGDs were transcribed and coded in Swahili using MAXQDA 2024 software. The application of systems thinking to analyse the four cases was done, firstly by identifying key contributing factors (variables) for failure under mini-grid subsystems using five types of infrastructure under the CIS framework (see Section 2.2). The qualitative data collected was then coded using these variables. Two rounds of coding were done to capture all potential variables used in the analysis. In the second stage, we used visual tools in MAXQDA to identify the connections among variables that facilitated the development of Causal Loop Diagrams (CLDs). In the third stage, the CLDs were then developed to visualise the generated interrelations, cascading effects, and potential feedback loops among variables.

CLDs aim to lay out the structure and interconnections of a system, highlighting the causal relationships and feedback loops within the system (Haraldsson, 2004). Variables in CLDs are connected by arrows that demonstrate unidirectional causal links. Arrows with a positive sign (+) show a positive link, which indicates that variables are changing in the same direction, while a negative sign (−) shows a negative link, which indicates that variables are changing in the opposite direction. The signs signify the direction of change between variables (same or opposite) and not the decreasing or increasing effects in the affected variables. Feedback loops emerge when variables affect one another in a chain-like sequence back to the previous variable (Groundstroem & Juhola, 2021). A feedback loop can be either reinforcing (R) when there are amplified changes, causing exponential growth or decline in variables, or balancing (B), if there are counteracting changes in variables that stabilise the system (Groundstroem & Juhola, 2021; Laimon et al., 2022). The interactions between variables in feedback loops were potential in the analysis to identify system performance that resulted in mini-grid failure.

In this paper, the feedback loop analysis of CLD was categorised according to the coupled infrastructure subsystem elements derived from the CIS framework*:* human infrastructure, social infrastructure, soft infrastructure, hard infrastructure & exogenous drivers. For easy follow-up in the analysis, the subsystem elements from each of these infrastructure are differentiated with colors: human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, exogenous drivers in green colour.

4. Results

4.1. Resource users' perspectives of the case studies failures

The users under the cases studied had different views regarding the causes for the failure of their mini-grid projects. Table 13 summarises the causes that are considered as main themes and direct views from the users. Some causes cut across all mini-grid cases while others do not.

Table 13: Resource users' perspectives on the reasons for failure.

Coupled infrastructure subsystem elements /Themes	Respondent perspectives	Mini-grid case
Social infrastructure system		
Poor users' behaviours	"Another person says, the whites brought me the electricity, therefore I should not be disconnected."	Leganga
	"I will know what to do. Now when someone says that and he is an elderly person, we respect them because they are old…"	
	"The biggest problem was the tariff collection. You encounter lots of challenges. You may encounter rude replies from people when you go to collect tariffs…"	Silale
	"The problem was that some of our fellow users had harsh responses. The first three months brought a few problems, with responses like, since we started using electricity, we were not paying for it."	Loya
	"People started saying that they were paying for the electricity that was rarely available. That also became a problem."	
	"But there was also electricity theft, meaning someone who was not on the official connected users' plan, was illegally connecting the electricity, and wanted to use it outside the existing plan."	Ilunde
Lack of trust	"Sometimes he would call us when he got to the container and had already been inside, the technician. The law requires him to sign first in the village office, but he didn't. He would arrive at the container, open it, do what he was doing, and leave. And that worried us that when these technicians of ours arrive, they get quietly, and we don't know what's going on in there. You know, we don't have expertise in those things."	Loya
	"Let me just tell you a secret, for example, this technician of ours, you find that he knows the starting dates for tariff collection. When the dates for collection arrive, there must be an electrical fault... and some of these committee members are friendly with them and he knows that if they collect in a month, they get a certain amount of money, he knows. So, he comes, and a problem occurs that matches the collected amount of tariff, and he takes it all…"	Silale
Exclusiveness in tariff payment among users	"We didn't really charge the elderly; we just collected tariff from working group... there were about 7 or 8 old people's homes."	Leganga
	"Institutions were not charged...Remember what they said, they said the elders are not to be charged, how many elders do we have in the village? I don't know if you understand me. This means the users who pay tariffs are just half of the whole group that are electrified. What do you think will happen!"	Ilunde
Soft infrastructure system		
Poor tariff collection model	"… Some people did not pay for 3 months, if it's five thousand, fifteen thousand, he comes and pays 5000. Others do not pay at all. The committee got tired. If I came to you, give me the money for those months that you did not pay, you say, sir, I will not give you the money. The responses here in the villages were just too inappropriate. So, you get tired, you see"	Leganga
	"The problem is the mode of payment, going physically to collect tariffs. That shouldn't exist."	Silale
	"...The collections were not as they should have been. I think they were collecting as if it was an optional matter, whether someone paid or not.	Loya
	"...We have been using electricity freely for a long time. That's the mistake, 3 years, 3 years."	Ilunde
	"Another challenge that caused the project to fail, I think the first thing is the free use	

	of electricity for a long time."	
Lack of legal ownership/Low sense of ownership	"...They should quickly hand over so that the village can now have the power to manage and even control the income. Otherwise, the village lacks power. The village has not been handed over. Even so, the village has to use force to apprehend those people who have not paid, when even the project itself has not been handed over to the village government. The village office therefore lacks power..."	Loya
	"The handover process kept on being postponed, and we did not have the authority to directly holding accountable those technicians."	Leganga
	"It has not been officially handed over. We know that the project is ours, but it is not handed over. That is why we always face challenges. If you go to the council, who will you go to! The planning officer is not aware of the project, if you go to community development officer, he is not aware either, the director himself does not know."	Silale
External use of tariffs	"When they took the money, they told us that they were borrowing this money from the electricity project and using it for school projects. They didn't return it, and now the money they borrowed hasn't been returned, that's the only easy answer."	Silale
Poor rules enforcement	"I tell you, even if someone refused to pay the tariff, no chairman could call him or do anything."	Leganga
	"The technician comes and gets in the container without VEC or chairman... so even the technician does not cooperate with them. He comes, he opens, he gets in, he leaves. That is also a challenge."	Silale
	"The law requires him to sign first in the village office, but he didn't. He would arrive at the container, open it, do what he was doing, and leave. And that worried us that when these technicians of ours arrive, they get quietly, and we don't know what's going on in there. You know, we don't have expertise in those things."	Loya
Low external support	"The one who brought the project did not get through opinion polls and left (MP). The citizens usually consider the running projects as projects brought by the ones in power even if it was brought by the government, we know at the end of the day it is the work of the same man. Now he left his position for another person. We told him there was this and that problem and he was not aware… Now where are you going to ask about this?"	Silale
Human infrastructure		
Low knowledge of the system	"...When night comes, people use all their appliances. Some use their fridge, but they don't know that what they are using is a backup, which is a battery."	Ilunde
	"….The other day, the technician said that he would call all those with refrigerators and instruct them when to use them."	Silale
Hard infrastructure system		
Low energy generation/storage capacity	"The batteries have had a lifespan because when they came to repair them, it was found that all the batteries were dead... there were about 16 batteries…"	Leganga
	"As the days go by, the batteries are running out of power... the batteries and the panels. You know, there are many cracked panels."	Silale
	"The electricity may be on from 5 p.m. and when it gets darker, it runs out of power and goes off. This caused problems since people found no reason to pay for it as it was unreliable. This also became a problem."	Loya
	"Apart from changing the batteries, sometimes you could find dead and busted batteries. We later came to realise that the batteries were worn out. That is the biggest reason why our project was stalled."	Ilunde
Exogenous drivers		
Politics	"Once a politician tells the citizens that they don't have to pay, this electricity is ours, we brought it for free, there is no way out to change the mindset of citizens."	Loya
	"We recognize that this electricity was brought to us as a help by our honourable MP, how come you guys are starting to charge money?"	
	"After the 2020 elections, this became one of the projects when the big boss questioned its existence. Now the handover period has passed, to date there has been no handover activity to the village, or the village council."	Silale

Own translation from Swahili.

4.2. Systems thinking analysis of mini-grid failures as coupled infrastructure systems

The findings about resource users' perspectives in 4.1 point out different factors contributing to the failure of case study projects, formulating key themes incorporated in the mini-grid coupled infrastructure subsystem elements.

4.2.1. The case of Leganga mini-grid

As described in Table 12, the Leganga mini-grid stopped operating three years after its commission. Based on the identified individual factors for failure derived from users' perceptions in Section 4.1, the following findings are extracted.

4.2.1.1. Human-social infrastructure loops

Loop R1 shows interactions between community awareness of the mini-grid system (human infrastructure subsystem) and social factors, including resource users' behaviour and participation across the mini-grid life cycle from the inception stage (Figure 15). User behavior in all cases is conveyed either through tariff nonpayment or how and when users use electricity. As shown in loop R1, low community involvement in the Leganga mini-grid matters created low collective awareness of the system, as they spent no money on the project commissioning and even paid tariffs in the first few months. This discouraged tariff payment behaviours in the later project phases. As a result, users' involvement in mini-grid matters was lowered further.

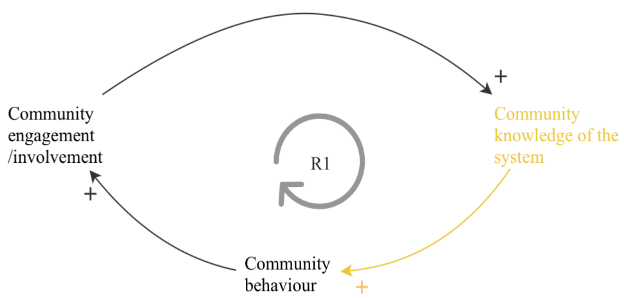

Figure 15: CLD nodes and links of subsystem interactions of human and social infrastructure in Leganga mini-grid. Human infrastructure subsystem in light brown colour, and social infrastructure in black colour.

4.2.1.2. Human-social-soft infrastructure loops

The loops in Figure 16 illustrate multiple interactions of elements among three mini-grid infrastructure subsystems. Unfulfilled directives from the government who was the initiator of these community mini-grid projects, Leganga being included, regarding the transfer of mini-grid ownership from the government through the Ministry of Energy and Mineral to the community, contributed to low attention when it came to who should own what of the mini-grid system (legal ownership). This lowered the sense of ownership among Leganga users, which weakened users' participation in mini-grid matters (loop R2). A low sense of ownership, in turn, created less trust among users towards the system.

As previously described (4.2.1.1), low community participation created low community awareness of the mini-grid system (loop R1). Low community awareness in Leganga had multiple adverse effects on other subsystem elements of soft and human infrastructure in the sense that it caused poor mini-grid rules enforcement, such as implementing sanctions on tariff non-payers, which in turn had repercussions on the maintenance fund (loop R3). It also altered compliance towards contributing to the mini-grid maintenance fund (loop R4). Maintenance fund with an insufficient balance was also caused by factors such as low users' ability and willingness to pay for electricity services, tariff exclusiveness to some resource users, e.g., elderly households, and low community participation in mini-grid matters.

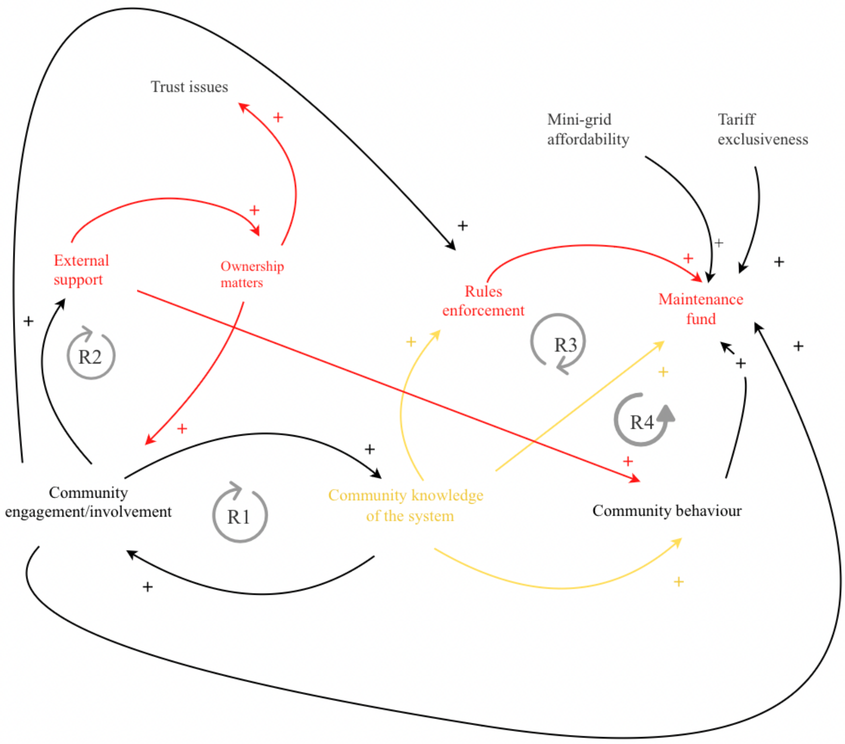

Figure 16: CLD nodes and links of subsystem interactions of human, social, and soft infrastructure in Leganga mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, and soft infrastructure in red colour.

4.2.1.3. Human-social-soft- hard infrastructure loops

In addition to the interactions among subsystem components of the mini-grid infrastructure system in 4.4.2.2, Figure 17 shows additional reinforcing loop R5, which demonstrates hard infrastructure components to be among the causes for the failure of Leganga mini-grid as CIS.

The setup of mini-grid generation and storage capacity was confined to a small group of targeted end users in Leganga (60 users). This contributed less to the mini-grid maintenance fund, as the tariff rates were also low, and the fact that some users were excluded from paying tariffs. The insufficient balance of maintenance funds further limited the purchase of battery replacement when degraded and the expansion of mini-grid generation and storage capacity (loop R5), which caused low mini-grid maintenance and upkeep

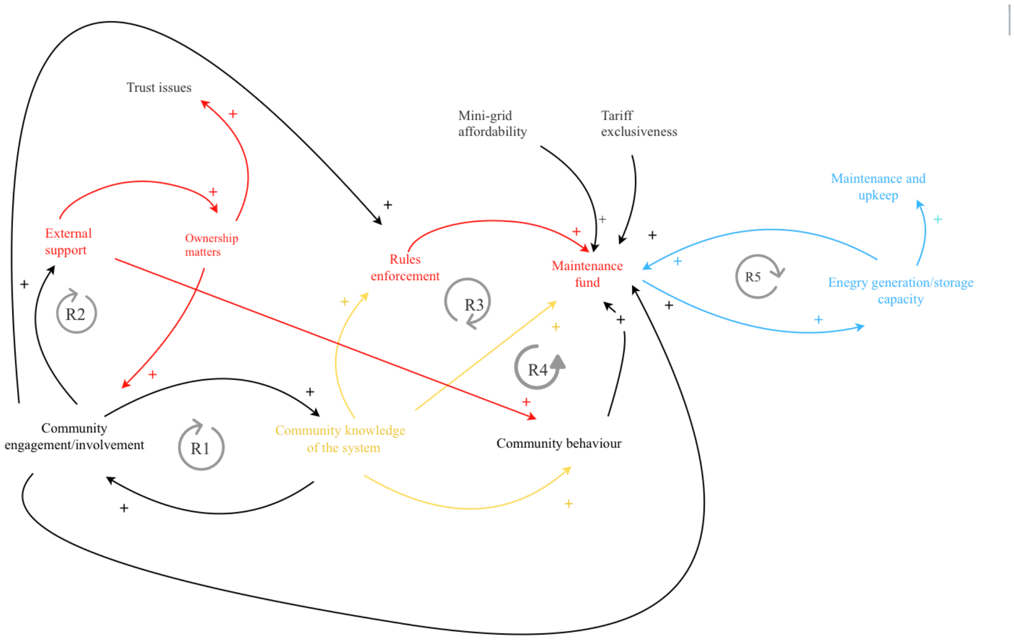

Figure 17: CLD nodes and links of subsystem interactions of human, social, soft, and hard infrastructure in Leganga mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, and hard infrastructure in blue colour.

4.2.2. The case of Silale mini-grid

The Silale mini-grid was operational from its inception in 2015 until the field visit in 2022. It is thus considered more sustainable than Leganga, Loya, and Ilunde mini-grids, despite being on the verge of death during a field visit in 2022.

4.2.2.1. Social infrastructure loop

Figure 18 summarises two feedback loops that exist within the social infrastructure subsystems in Silale. R1 describes how less affordable mini-grid services and associated costs in Silale have been encouraging bad community behaviour (i.e., untimely tariff payment), which affected mini-grid financial stability and elevated operational costs, making mini-grid even less affordable. R2 shows that less active involvement of users in mini-grid matters from both the inception and implementation phases affected tariff compliance behavior among users, lowering their involvement even more. The continuous cascading process of these factors could cause the failure of Silale mini-grid soon if there is no improvement.

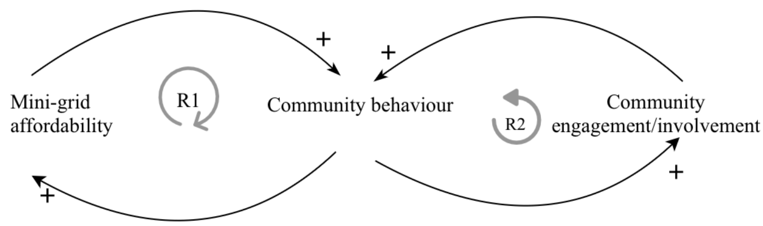

Figure 18: CLD nodes and links of subsystem interactions of social infrastructure in Silale mini-grid.

4.2.2.2. Human-social- soft infrastructure & exogenous drivers loops

Multiple reinforcing loops are displayed in Figure 19 to show causal interactions for possible mini-gid failure among different subsystems. The loops clearly show the interdependency among infrastructure components, in this case, the intersection between human-social-soft infrastructure and exogenous drivers. The explanation for social infrastructure loops (R1 and R2) is provided in 4.2.2.1. R3 describes how limited users' participation subdued a sense of ownership among resource users towards mini-grid operations, which, in turn, lowered the external support from the government. The existence of low external support lowered trust among resource users towards the system, which in turn discouraged users from contributing to the maintenance fund, weakening mini-grid sustainability. The situation in Silale mini-grid displayed poor maintenance due to inadequate maintenance funds, which had been affecting its reliability, while reinforcing inappropriate behavior among the community as users feel their contribution is futile.

In R4, the existence of unclear establishment of ownership status in Silale has been providing a bad signal to the external entities, e.g. District Council, about Silale mini-grid project and whether it is worth supporting. This created loopholes for bad politics to intervene and erase existing contracts of community mini-grids such as Silale, which may further complicate ownership status (legal and sense of ownership) as there was no official handover of the projects from the government ownership through the ministry to the respective communities. The mini-grid system's performance and output may eventually be negatively affected. R5 highlights that tariff nonpayment behaviour in Silale contributed to lower revenues for the maintenance fund as the days went by. The funds have been used for maintenance and to improve mini-grid reliability. Inadequate maintenance funds continued to reinforce nonpayment behaviour, as users saw less of what their money could do, thus negatively impacting system performance. This came after years of operations of Silale, where the mini-grid's performance kept getting lower and lower. The users got poor services, unlike at the beginning of the project, and they were discouraged from contributing tariffs as their contribution outmatched the services they received. Inadequate maintenance funds have also been negatively affected by poor rules enforcement, especially rules concerning mini-grid expenditures, such as external use of funds for non-mini-grid matters, e.g., financing primary school construction after the village pleaded with VEC, whereby the money was never refunded as promised. The actions in loop R5 continued to reduce the available balance for mini-grid maintenance and upkeep and, in turn, have been enormously affecting the system's performance.

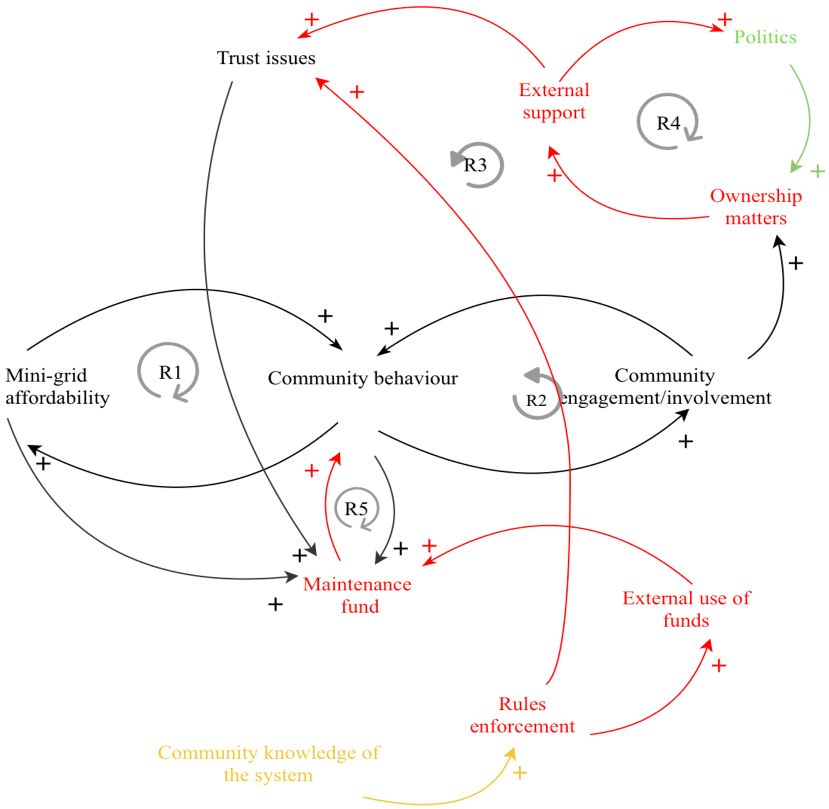

Figure 19: CLD nodes and links of subsystem interactions of human, social, soft infrastructure, and exogenous drivers in Silale mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, and exogenous drivers in green colour.

4.2.2.3. Human-social-soft- hard infrastructure & exogenous drivers loops

Hard infrastructure elements also have an interdependent relationship with other infrastructure subsystems (see 4.2.2.2) in explaining the possible failure of Silale mini-grid as CIS. Additional loop R6 indicates how the maintenance fund with insufficient balance has been an obstacle to finance needed spare parts and services from a reliable supply chain to maintain the mini-grid system. An example is when users in Silale wanted to replace the batteries but could not as they did not have enough funds for purchase. As a result, unreliable mini-grid system performance has existed due to ineffective system maintenance and upkeep, causing user dissatisfaction with the services, negatively affecting the contributions to the maintenance fund, and, eventually, the system performance.

Energy generation and storage capacity, a subsystem of hard infrastructure, is also affected by other types of mini-grid infrastructure in Silale, such as social and human infrastructure, which may further cause system failure in the near future. Bad community behaviour, such as low or no tariff payment, has been among the reasons for low maintenance funds for upgrading mini-grid capacity. The same can be said with regard to resource users' consumption of more energy during off-peak hours. Reduced tariff amounts by Silale users due to affordability complaints resulted in less revenue collected to maintain and upgrade the system, making it challenging to meet the growing energy demand. Less knowledge about the mini-grid system, including off-peak hours energy consumption, and illegal connections, has been burdening the energy generation components and affecting the mini-grid's performance. The interdependence of various factors among mini-grid subsystem elements explained here is said to be the possible cause for the failure of Silale mini-grid in the near future.

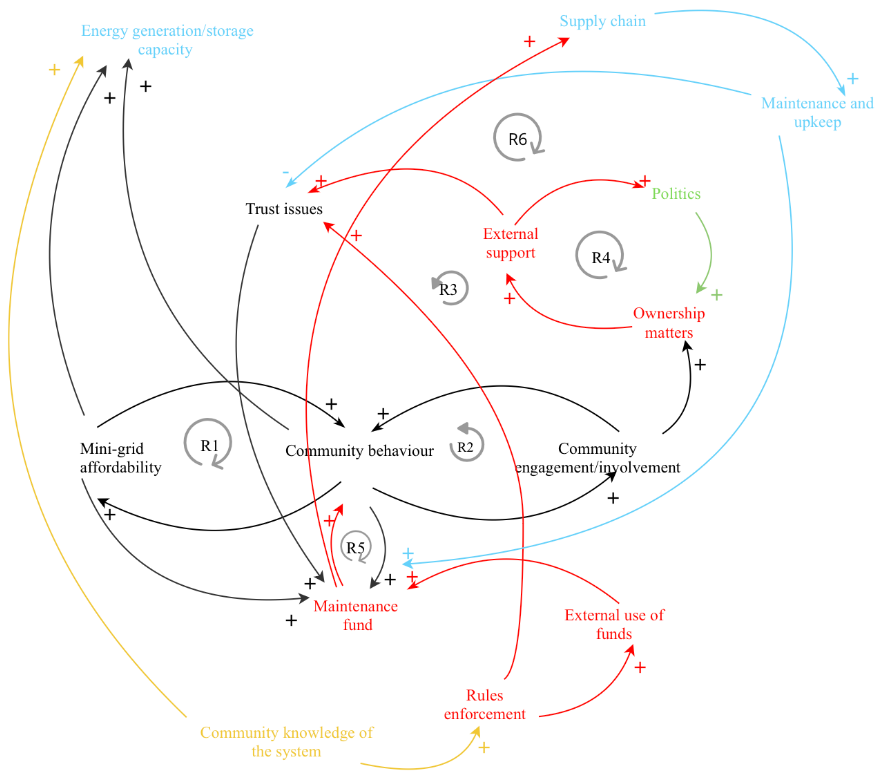

Figure 20: CLD nodes and links of subsystem interactions of human, social, soft, hard infrastructure, and exogenous drivers in Silale mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour.

4.2.3. The case of Loya mini-grid

The Loya mini-grid located in Tabora has operated for only three years since its inception. The following are the causes for the failure of this mini-grid from the interaction of subsystem elements of CIS.

4.2.3.1. Social-soft infrastructure loops

Loops R1 and R2 show the interactions between the financial status of Loya users, their behaviours, and maintenance funds. Money to finance mini-grid maintenance was affected by the nonpayment of tariffs by poor households. The maintenance fund was also affected by the lack of legal ownership of the mini-grid, as some users found no need to pay for the project that was freely given to them, and VEC and village officers could do nothing for such users because of the lack of ownership. Lack of ownership status made it hard to enforce some rules, as the users claimed that they had no control over the mini-grid. Lack of legal ownership made users trust the technician less when the mini-grid started to perform poorly because users had no control over the key to the mini-grid container, and they suspected the technician of foul play, as he could get into the container with no VEC member accompanying him.

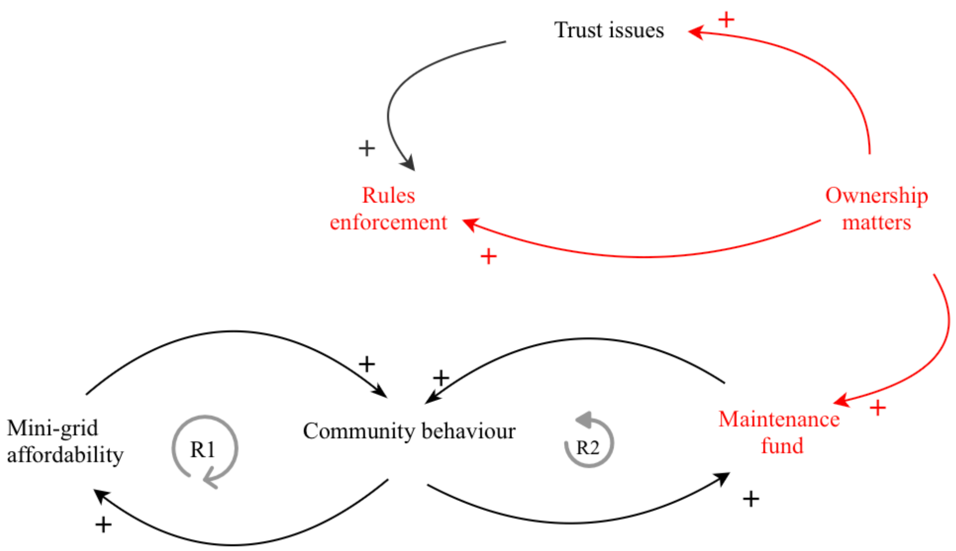

Figure 21: CLD nodes and links of subsystem interactions of social and soft infrastructure in Loya mini-grid. Social infrastructure subsystem in black colour, and soft infrastructure in red colour.

4.2.3.2. Human-social- soft infrastructure & exogenous drivers loops

In addition to interactions of social and soft subsystem infrastructure in Figure 21, politics as an exogenous factor had negative effects on multiple subsystem elements such as tariff nonpayment users' behaviour, maintenance fund, ownership status, and external support. This happened after a particular member of parliament told the users that he was personally responsible for bringing the Loya mini-grid to the community, and thus they are entitled to consume the electricity freely. Local politics further affected soft infrastructure – for example, the enforcement of rules - as VEC had less power to sanction users who failed to pay tariffs, having been told they could consume electricity without restriction. These dynamics highlight the interplay between soft and social infrastructure in shaping community governance. It is clear from Figure 22 that the failure of Loya mini-grid is not only from the three identified infrastructure subsystems but also interrelated with politics as an exogenous factor.

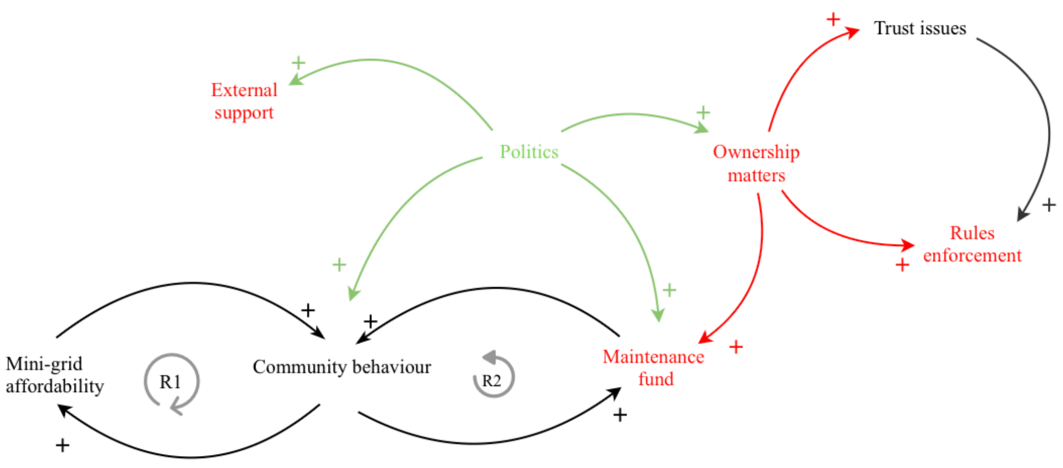

Figure 22: CLD nodes and links of subsystem interactions of human, social, soft infrastructure, and exogenous drivers in Loya mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, and exogenous drivers in green colour.

4.2.3.3. Human-social-soft- hard infrastructure & exogenous drivers loops

Politics, in addition, affected other mini-grid infrastructure, such as hard infrastructure (e.g., energy generation and maintenance upkeep) through social infrastructure (e.g., users' behaviour). Poor user behaviour, like connections and the use of banned electric appliances, degraded the system over time, which in turn increased maintenance costs. With higher maintenance costs and frequent system maintenance, users' trust was lowered as they thought there was a game being played for them to pay for maintenance, which also made them break some of the rules, like refusing to pay tariffs. The cause for failure in the Loya mini-grid is therefore due to interactions of subsystems from multiple mini-grid infrastructures.

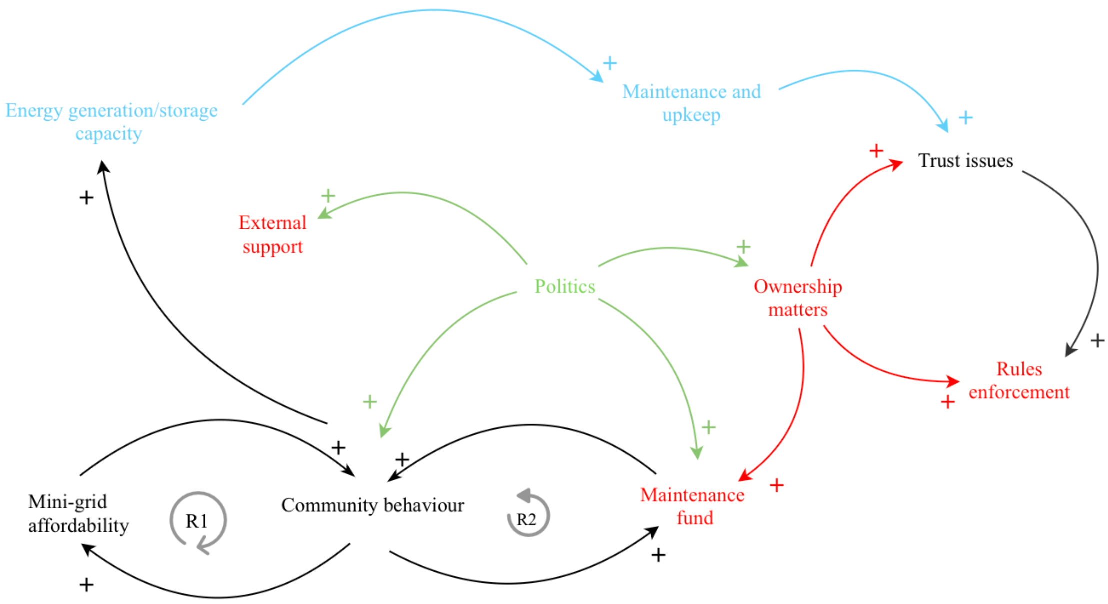

Figure 23: CLD nodes and links of subsystem interactions of human, social, soft, hard infrastructure, and exogenous drivers in Loya mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour.

4.2.4. The case of Ilunde mini-grid

The failure of the Ilunde mini-grid, one year after Loya and Leganga, was also a result of the interdependence of multiple elements across all types of infrastructure in the CIS framework. The following CLDs describe the interdependence.

4.2.4.1. Social-hard infrastructure loops

Degraded batteries in Ilunde mini-grid supplied less electricity and altered users' behaviours, such as energy overconsumption during night hours, which in turn continued to affect the batteries negatively (loop R1).

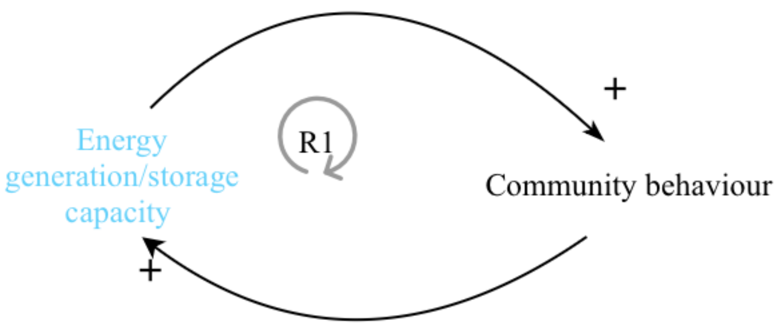

Figure 24: CLD nodes and links of subsystem interactions of social and hard infrastructure in Loya mini-grid. Social infrastructure subsystem in black colour, and hard infrastructure in blue colour.

4.2.4.2. Human-social- hard infrastructure loops

Figure 25 illustrates interactions between social, human, and hard infrastructure. R2 shows that users' tariff noncompliance behaviour depicted in Figure 24 is also affected by a lack of user knowledge on how the system functions. Some users were not aware of energy-saving practices such as switching off the refrigerators during the night.

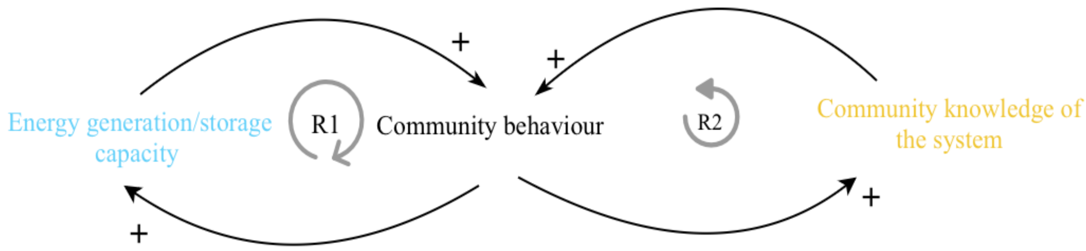

Figure 25: CLD nodes and links of subsystem interactions of human, social, and hard infrastructure in Ilunde mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, and hard infrastructure in blue colour.

4.2.4.3. Human-social-soft- hard infrastructure & exogenous drivers loops

Figure 26 summarises the feedback loops existing within the human, social, hard infrastructure, and its intersection with the *exogenous* environment. In addition to the feedback loops in Figure 25, insufficient balance in the maintenance fund (Soft infrastructure) affected mini-grid maintenance. Maintenance of the mini-grid in Ilunde was in addition affected by the exclusion of some members, such as elders, from paying tariffs, and a lack of knowledge about the function of the mini-grids (members had a notion that the electricity was for free as they did not pay tariffs almost three years of the mini-grid operation), and politics.

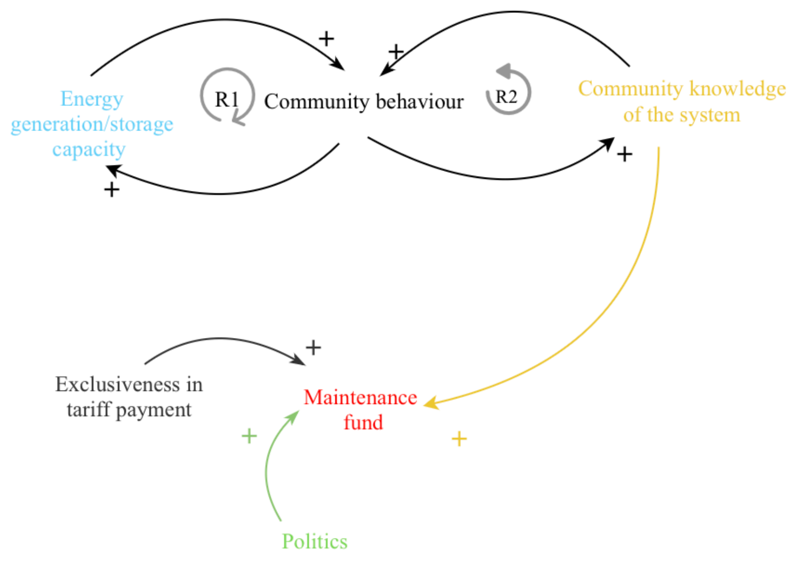

Figure 26: CLD nodes and links of subsystem interactions of human, social, soft, hard infrastructure, and exogenous drivers in Ilunde mini-grid. Human infrastructure subsystem in light brown colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour.

Generally, the failure of mini-grids as CIS is a result of interdependence among all types of infrastructure and not just single factors. In all mini-grid cases, there exists a complex linkage within subsystems of which some revealed possible cascading impacts for ongoing processes that gave rise to a failure of mini-grids.

5. Discussion

This section discusses the findings from the study, which explored reasons for the failure of Tanzania's solar community mini-grids as coupled infrastructure systems. The study shows how mini-grid as a small-scale electricity supply system is embedded in a complex and interrelated network of social, soft, hard, human subsystems and exogenous drivers, that may turn out to be cascading factors for mini-grids' sustainability. Conversely, effective coupling of these subsystems creates a mechanism for mini-grid sustainability. The feedback effects in the mini-grid system, explained by the reinforcing loops as highlighted by CLDs in the results section, show that the failure of the studied mini-grid system cases is dynamically affected by a series of interrelated factors. As described in Section 4.2, application of systems thinking using CLDs by incorporating infrastructures from the CIS framework in Section 2.2 has led to a large number of connections and causal loops that signify the value of interconnections between mini-grid subsystem elements. This gives insights that the factors for the failure of examined community-managed mini-grids systems cases are not just isolated and independent but are dynamically related (Laimon et al., 2022). This relates to the failure mode analysis and sustainability pathways–mechanisms in Section 2.2– in the sense that addressing one issue e.g., changing the revenue collection model from manual to pay as you go through smart meters, without addressing mini-grid ownership status, rules enforcement, and strengthening good electricity use practice among others, will probably result in a silent failure initially and later into a total failure of the system or a total failure from the beginning..

The factors explaining failure recur in all cases, though to different extents. There are four different groups of factors, namely, (1) users' behaviour, (2) inadequate maintenance, (3) local politics, and (4) absence of mini-grid legal ownership.

The users' behaviour (i.e., social infrastructure system) in terms of tariff nonpayment is the central factor in the reinforcing loops across all mini-grid cases. This kind of behavior has been shown to trigger other connected infrastructure subsystems (Palit & Chaurey, 2011). Tariff nonpayment behaviour in Silale and Loya was highly related to other factors compared to Leganga and Ilunde. In Silale, some users resisted paying tariffs because of financial constraints, nonpayment in the first few months of mini-grid inception, and insufficient balance in their maintenance fund (see Figure 20). In Loya, apart from insufficient balance in the maintenance fund and financial constraints of some users, local politics severely contributed to the nonpayment of tariffs among users (see Figure 23). A member of parliament in the region claimed to be the facilitator of the project and insisted that users not pay tariffs. The intensity of poor user behaviour in tariff payment was higher in Loya as it was enforced by local politics, which affected other factors like ownership matters and maintenance funds, which impacted the users' nonpayment behaviour even further. Users' behaviour in tariff payment in Leganga and Ilunde was less related to other factors. The majority of electricity users in the studied cases were new to using electricity, and there was insufficient knowledge dissemination on tariff payments for operational and maintenance purposes. While users' behaviour is unpredictable, continuous education on the importance of tariffs to sustain mini-grid systems is necessary. This can be done by either mini-grid moderators or VEC, who are considered custodians of community-managed mini-grids.

The issue of inadequate maintenance facing all studied cases is associated with poor functioning of other infrastructure subsystems. As the heart of mini-grids, sustainable financing is the potential for the sustainable performance of community mini-grids (Kapole et al., 2023). Figures. 17, 20, 23, and 26 show lots of incoming arrows from other subsystem elements towards the maintenance fund, compared to any other factor. This implies that inadequate maintenance fund is not affected by a single factor, e.g, a low amount of tariffs paid by mini-grid users. Rather, it is influenced by both independent factors and a series of factors interconnected with each other (eg., reinforcing feedback loops R4 and R6 in Figure 20, with R4 showing maintenance fund being affected by trust issues through local politics, ownership matters, and external support). However, the intensity of inadequate maintenance is described more in the Leganga mini-grid compared to the other cases. Maintenance fund in Leganga is affected by factors such as tariff payment exclusiveness among some users, low affordability, poor rules enforcement, poor tariff payment behaviour, low community involvement, low knowledge of the system, and low energy generation (coming from four types of infrastructure (see Figure 17). Among these factors, four are subsystem elements of social infrastructure, implying that, local cultural norms and behavioral factors have a large role to play in the community-managed mini-grids. Therefore, to alleviate the problem of inadequate maintenance funds, which is a common reason for failure among many rural community-managed mini-grids in developing countries, attention should also be on other mini-grid subsystem elements.

The findings in this study further found that exogenous drivers can also be a center of complexity to the mini-grid subsystems in affecting its sustainability. Local politics, for instance, is found to have interconnectedness with other factors in causing the failure of three mini-grids, except for Leganga. The degree of its effects on other factors, however, differs across mini-grids. In the Loya mini-grid, for instance, the existence of local politicians' directives directly affected mini-grid performance. Mini-grid users were directed not to pay tariffs by a certain politician (member of parliament), which negatively affected the maintenance fund and users' tariff payment behaviors when approached by VEC, who were responsible for tariff collections. There was also low external support from the district council to the village leaders concerning these projects because of a lack of legal transfer of ownership from the government to the village. This is illustrated by multiple outward arrows from politics to other subsystem elements in the Figures. 22 and 23. The intensity of local politics was highly experienced in Loya compared to the other mini-grids. Involvement of local politics in these projects, therefore, blocked the respective communities from getting external assistance from district councils regarding the transfer of ownership, as there were barely any records of such projects in the respective district councils. Nonproductive political agenda in such projects often conflicts with the intended outcomes (Ikejemba, Schuur, et al., 2017). Involvement of local politics in such projects targeting rural communities should be minimal to avoid tensions (Ogeya & Lambe, 2025), especially during the mini-grid implementation phase.

Our findings also pointed absence of legal ownership as a problem that raised a series of interrelated issues, such as noncompliance with tariff payment, poor rule enforcement, and low trust among users, which impacted the sustainability of these projects. This ownership status was also associated with low external support from the district council when village leaders approached them with ongoing challenges regarding these mini-grid projects. This factor, however, was a concern in three mini-grids, excluding Ilunde. It was more intensified in the Loya mini-grid because of the local politics, which had highly influenced users into thinking that the microgrid was a free project given by the members of the parliament. It is therefore essential to clarify the legality of microgrid ownership status from the project's inception to avoid ambiguities in later phases (Behrendt, 2023; Hirsch et al., 2018).

As our findings illustrate, the dynamics among factors from all cases are different. In Loya, bad (local) politics played a major role. Insufficient maintenance fund was a significant contributing factor to the failure of both Leganga and Ilunde, although the underlying causes differed in each case. In Ilunde, the maintenance fund was undermined by a highly exclusive approach to tariff collection. Specifically, out of 120 households, around 42 were exempted from paying electricity tariffs. In Leganga, the inadequate maintenance fund was affected by multiple factors that were mentioned earlier. Early community involvement through tariff payments in Silale, driven by strong village leadership (village council and VEC), which aligned with the Ministry of Energy and Minerals' guidelines for mini-grid management, played a significant role in promoting its sustainability, distinguishing it from the other case studies. This distinction emphasises on framework's mechanism regarding the lack of context sensitivity (see Section 2.2). The institutional arrangements in the form of standardised guideline books were supplied across all mini-grid cases to explain mini-grid rules and governance structure. However, they did not fit across all mini-grid cases, as three experienced failure and one success. This misfit occurred because local and contextual adaptations were not deliberately considered during project design. Therefore, mini-grid systems in Ilunde, Loya, and Leganga ended up with misaligned infrastructures, whereas in Silale strong leadership ensured adequate implementation of institutional arrangements (i.e., soft infrastructures).

The reinforcing feedback loops in the studied cases were found to be prolongedly unaddressed by delayed interventions, leading to unexpected outcomes, e.g., insufficient balances in the maintenance funds, low community involvement, poor rule enforcement, and users' behaviors. Hence, unaddressed feedback loops turned out to be the silent killers for these community projects. These dynamics and reinforcement mechanisms, rather than single factors, explain failures and different degrees or speed of failure in the four cases under investigation. Using the CIS framework and CLDs enables us to illustrate these dynamics.

At the same time, better performance in Silale due to higher early community involvement and, especially, better leadership points to the importance of agency that is somewhat underrepresented in the CIS framework, which has a clear focus on structures.

6. Conclusion

Application of the CIS framework on the four containerised solar community mini-grid cases in Tanzania underlines the rationale that mini-grids are a complex system with a series of interrelated social, soft, hard, and human infrastructure, as well as exogenous drivers, whose reasons for failure are not independent but systemic. Ensuring the long-term sustainability of a mini-grid system involves more than resolving isolated subsystem failures, as these are typically linked to broader, interdependent factors that shape overall system performance. Key findings from the analysis indicate that all mini-grid cases face financial difficulties that affect the maintenance fund. However, the reasons for insufficient maintenance fund balances vary across cases, with some being influenced by fewer factors and others by a more complex range of issues. The study also finds that external influences, such as local politics, have adverse effects on the sustainability of community-managed mini-grids by influencing users' behaviors, particularly regarding tariff payments, which negatively impact the maintenance funds. This issue is exacerbated when politicians seek short-term popularity for an election campaign, which misleads users into believing that electricity is free, despite the practical nonexistence basis for such claims.

The study emphasises the need for effective information diffusion about the existence and progress of community mini-grid projects between the central government institutions (e.g., the Ministry of Energy, Rural Energy Authority) and the local government bodies (e.g., districts and regional offices), who initiate such projects, to encourage and strengthen local governance for the long-term sustainability of these projects. It also demonstrates the application of the systems thinking approach of the CIS framework to analyse interactions among infrastructure systems and to uncover the underlying reasons for failure of community mini-grid systems, without explicitly using public infrastructure, public infrastructure providers, resource users, and resource, the four components of the CIS framework. This exclusion is primarily due to the absence of response from key infrastructure providers relevant to the study, including personnel from the Ministry of Energy and Elektro Merl company, who were well informed about the project. An important area for future research could be to explicitly employ the aforementioned components of the CIS framework, offering an alternative perspective for examining the failure of such mini-grid projects.

CRediT authorship contribution statement

Irene F. Ngoti: Conceptualisation, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Lars Holstenkamp:** Conceptualisation, Writing – original draft, Writing – review & editing, Supervision, Methodology. **Tobias Klaus:** Conceptualisation, Writing – original draft, Writing – review & editing.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Irene F. Ngoti reports that the German Federal Ministry of Education and Research provided financial support for data collection.

Data availability

Data will be made available on request.

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Appendix 1: Author contribution statements

(in accordance with the Guideline for cumulative Ph.D. theses enacted at the Faculty of Sustainability in January 2012)

Arti-cle No.	Bibliography	Publication status	Specific author contributions	Specific contri-bution of Ph.D. candidate	Weighing factor	Public talk / Conference presentation
I	Namujju, L. D., Acquah-Swanzy, H., & **Ngoti, I. F**. (2023). An IAD framework analysis of mini-grid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania. *Energy Policy*, *182*, 113742. https://doi.org/10.1016/j.enpol.2023.113742.	Published in *Energy Policy* (IF = 9.2)	**Lillian Donna Namujju**: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **HenriettaAcquah-Swanzy**: Methodology, Writing – original draft, Formal analysis. **Irene F. Ngoti**: Methodology, Writing – original draft, Formal analysis**.**	Co-author with important contribution	0.5	A:RT-D Grids Graduate Training for Sustainable Energy Development June 28, 2021 to July 2, 2021**,** Germany 5th to 9th September, 2022, Germany
II	**Ngoti, I. F**. (2024). Institutional arrangements and sustainable maintenance management of community-based mini-grids in Tanzania. *Energy Research & Social Science, 115, 103632*. https://doi.org/10.1016/j.erss.2024.103632.	Published in *Energy Research & Social Science* (IF = 7.4)		Single author	1.0	
III	**Ngoti, I. F**. (2024). The role of sense of ownership in rural community mini-grid management: qualitative case study from Tanzania. Energy, Sustainability and Society. *Energy, Sustainability and Society*, *14*(1), 1-16. https://doi.org/10.1186/s13705-024-00496-7.	Published in *Energy, Sustainability and Society* (IF = 4.6)		Single author	1.0	A:RT-D Grids Graduate Training for Sustainable Energy Development 7th to 11th August, 2023, Tanzania
IV	**Ngoti, I. F.,** Holstenkamp, L., & Klaus, T. Exploring the causes of failure in community managed containerised solar mini-grids: A coupled infrastructure systems framework analysis. *Submitted to Energy Research & Social Science……*	Under Review in *Energy Research & Social Science* (IF = 7.4)	**Irene F. Ngoti:** Conceptualisation, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Lars Holstenkamp**: Conceptualisation, Writing – original draft, Writing – review & editing, Supervision, Methodology. **Tobias Klaus**: Conceptualisation, Writing – original draft, Writing – review & editing.	Co-author with Predominant contribution	1.0	

Declaration (according to § 16 of the guideline for cumulative Ph.D. theses):
I avouch that all information given in this appendix is true in each instance and overall.

Iringa-Tanzania, 29 August 2025

Irene Fredolin Ngoti

Explanatory Notes:

Specific contribution of PhD candidate submitting the Ph.D. dissertation / Author status according to § 12 of the guideline for cumulative Ph.D. theses
Single author: own contribution amounts to 100%.
Co-author with predominant contribution: own contribution is greater than the individual share of all other co-authors and is at least 35%.
Co-author with equal contribution: (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.
Co-author with important contribution: own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.
Co-author with small contribution: own contribution is less than 20%.

Weighing Factor according to § 14 of the guideline for cumulative Ph.D. theses

Single author	1.0
Co-author with predominant contribution	1.0
Co-author with equal contribution	1.0
Co-author with important contribution	0.5
Co-author with small contribution	0