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

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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 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 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.

1. Introduction

Mini-grids have become a preferred form of electricity infrastructure for addressing rural electrification challenges in Sub-Saharan Africa [1–3]. 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 and 15 years after their commencement [4–6], while some others fail earlier than that [7], 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 [4,5,8]. Inadequate implementation of institutional arrangements [9–11], 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. Poorly set tariff schemes and insufficient savings for maintenance [10,12] and a lack of trust in the mini-grid technician(s) [13,14] contribute to the collapse of communally-managed mini-grids. A significant focus on technical and economic reasons for mini-grid failure [4,15–17] can divert attention from other critical factors that cause the failure of systems that are technically and economically well-designed [18]. 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 [19]. Mini-grid failure analyses that consider isolated factors while ignoring their interconnections only partially address system vulnerability. For example, technical breakdowns in solar mini-grids stem not just from failed batteries or panels, but from poor maintenance financing, illegal connections, lack of ownership, poor decision-making, and related issues. This demonstrates that mini-

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grids extend far beyond hard infrastructure (generation and distribution); they are embedded in interrelated factors. With limited prior work on these systemic effects, our analysis applies the Coupled Infrastructure Systems (CIS) framework [20,21] 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 [8,22]. We therefore apply this framework to community-managed mini-grids in rural Sub-Saharan African settings. In these areas, electricity access for small populations stimulates economic activities and energy demand, which in turn alters user behaviour and impacts local governance.

There are only a few studies that employ the CIS framework. Janssen et al. [23] have examined the lack of sustainability of highways from the perspective of coupled infrastructure systems. The linking between institutions and CIS by [20] and the infrastructure for sustainability by [21,24] 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 [25,26]. This study fills this gap by analyzing mini-grid failure as interconnected infrastructure systems through the CIS framework, providing theoretical and practical insights into systemic causes. Using community-managed solar mini-grids as cases, we apply feedback loop analysis — a core systems thinking tool — to reveal causal relationships and dynamics driving failure [27].

This study makes three main contributions. First, it applies the CIS framework to rural electrification, where explicit use has been limited. Second, it combines CIS with causal loop diagrams (CLDs) to systematically identify dynamic interactions across infrastructure types. Third, it demonstrates that mini-grid failure emerges from breakdowns in coupling between providers, users, and infrastructure — not isolated technical, financial, or social factors. By documenting recurring loops across four Tanzanian cases, the paper advances a systemic explanation beyond factor-based analyses.

2. State of the art

2.1. Governance of mini-grids 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 [28]. 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 [29–31]. However, mini-grid designers often overestimate its potential in remote areas that lack proper roads and access to external markets [32,33]. Access to finance can be another hurdle for developing productive uses, which mini-grid operators can address by either cooperating with microfinance institutions [33] or providing financial services directly [34]. Van Hove et al. [35] demonstrate that the type of productive use is essential for economic evaluation, with year-round uses being most beneficial for mini-grids.

Poorer households usually cannot afford cost-covering, relatively high, electricity tariffs that are common in off-grid applications [32], 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 [36].

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 [37]. Second, they may regulate tariffs that operators can charge from their retail customers [38], either in the form of price or quality regulation [39,40]. Any of these regulations may be changed over time, so even if there is a favorable regulatory setup in a country at the time of the initial investment decision, this situation can be reversed. The Tanzanian case illustrates this well, having led to slower growth or even the abandonment of commercial mini-grids in recent years.

In general, the public institutions are involved in mini-grid projects through coordination of rural electrification efforts as owners of utility companies, as the site selection and procuring entity, as the concession or license/permit issuer, or by devolution to the community [41,42]. 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 [43]) 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" [44,45], and different types of ownership of whole systems or per asset (especially split between grid infrastructure and generation assets; [44,46]).

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 [31] distinguishes three phases or "generations" of mini-grids globally (see Table 1). 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.

Some of the general developments of ownership models can be demonstrated using the case of Tanzania (see also, e.g., [47,48]). Tanzania has been a frontrunner in mini-grid deployment due to favorable regulations overseen by the Energy and Water Utilities Regulatory Authority (EWURA). The state-owned Tanzania Electric Supply Company (TANESCO), a vertically integrated utility, generates, operates, and distributes electricity, including several mini-grids. The 2009 Small Power Producers (SPP) Framework – supported by standardized power purchase agreements, specific tariffs, and Rural Electrification Agency (REA) funding – drove significant growth after 2010, though growth has slowed recently. Community-managed mini-grids comprise about one-sixth of cases in a 2017 World Resources Institute (WRI) database, with moderate expansion since. Most of the cases are probably led by village electricity committees (VECs), thus constituting cases of what Pedersen [49] calls "symbolic ownership".

Table 1
Mini-grid generations according to the World Bank.

Phase	First generation	Second generation	Third generation
Time	Late 19th to early 20th C.	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 [31].

Long-term sustainability of community-managed mini-grids is questioned by some authors mainly due to three reasons [50]: 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 [51,52], 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 co-operatives, the community ownership model may work in the longer term, though [50]. Moreover, Duran and Sahinyazan [53] 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. [20] 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. [21]).

The CIS framework builds on Ostrom's institutional design principles, emphasizing how institutions intertwine with human, social, and biophysical contexts. It recognizes five infrastructure types: hard (man-made physical structures like roads or mini-grid components such as solar panels, batteries, and distribution networks, which require collective engagement due to scale); soft (rules, norms, and governance mechanisms guiding system use); natural (non-man-made physical features like land); human (knowledge and capacity for operation and maintenance); and social (user relationships, behaviors, values, and beliefs). For this study, we treat natural infrastructure (land) as fixed [20,21,23]. 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.

The CIS framework distinguishes four structural components: (i) the resource (electricity generated and distributed by the mini-grid); (ii) the public infrastructure (physical system: panels, batteries, distribution network); (iii) public infrastructure providers (actors such as the Ministry of Energy and Minerals, Rural Electrification Agency, VECs, and technicians); and (iv) resource users (households consuming electricity and participating in governance). Exogenous drivers like local politics interact with all components. This study shows that disruptions in provider–user and provider–infrastructure links drive mini-grid failure across cases.

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 [22,54]: Hard infrastructure components (solar panels, batteries, distribution networks), instances of soft infrastructure (governance structures, payment systems, maintenance protocols), social infrastructure elements (community engagement, users' behaviour), and human infrastructures (local capacity, cultural practices) [54].

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, with 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 [55].

Context sensitivity (or the lack of): The framework emphasises that successful institutional arrangements must be carefully matched to the local contexts [21], 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 2). Thus, we follow a *most similar system design* [56]. In addition to the similarity of their setups, the mini-grids to be selected had to be of a certain age to ensure that any successful operation was not merely down to chance.

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. The interviewee list included 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

Table 2
Overview of selected cases.

	Leganga	Silale	Loya	Ilunde
Region	Dodoma	Dodoma	Tabora	Katavi
District	Kongwa	Kongwa	Uyui	Mlele
Size [kW]	15	15	2 × 15	2 × 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 August 2018	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.

each mini-grid) and 12 males (5 from Leganga, 6 from Silale, and 1 technician) [13].

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 [10], and the role of sense of ownership in mini-grid management [13], 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 performed by first 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 were 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 [57]. 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 [58]. 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 [58,59]. 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 infrastructures are differentiated with colours: human infrastructure subsystem in purple colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour.

4. Results

4.1. Resource users' perspectives of the case studies failures

The users in the cases studied held different views on the causes of the failure of their mini-grid projects. Table 3 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.

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

The findings about resource users' perspectives in Section 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 2, 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 (Fig. 1). Users' behaviour 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 behaviour in the later project phases. As a result, users' involvement in mini-grid matters was lowered further.

Viewed through the CIS lens, loop R1 represents a self-reinforcing failure within the resource user component: the gap in human infrastructure (low awareness) amplified a social infrastructure failure (disengagement from governance), eroding resource users' collective capacity to govern the shared public infrastructure. This reflects the CIS infrastructure coupling mechanism: the human and social infrastructure subsystems, which should reinforce each other in sustaining governance, instead became mutually degrading.

4.2.1.2. Human-social-soft infrastructure loops. The loops in Fig. 2 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 a lack of clarity regarding the legal ownership of the mini-grid system. 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 shown (Section 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

Table 3
Resource users' perspectives on the reasons for failure.

Coupled infrastructure subsystem elements/ themes	Respondent perspectives	Respondent group	Mini-grid case
Social infrastructure system			
Poor users' behaviour	"Another person says, the whites brought me the electricity, therefore I should not be disconnected."	Village council leader	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…"	Village council leader	
	"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…"	VEC	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."	Normal electricity user	Loya
	"People started saying that they were paying for the electricity that was rarely available. That also became a problem."	VEC	
	"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."	Normal electricity user	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."	Normal electricity user	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…"	Normal electricity user	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."	VEC	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!"	VEC	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"	VEC	Leganga
	"The problem is the mode of payment, going physically to collect tariffs. That shouldn't exist."	Normal electricIty user	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.	Normal electricIty user	Loya
	"…We have been using electricity freely for a long time. That's the mistake, 3 years, 3 years."	Normal electricIty user	Ilunde
	"Another challenge that caused the project to fail, I think the first thing is the free use of electricity for a long time."	Normal electricIty user	
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…"	VEC	Loya
	"The handover process kept on being postponed, and we	Village council leader	Leganga

(continued on next page)

Table 3 (*continued*)

Coupled infrastructure subsystem elements/ themes	Respondent perspectives	Respondent group	Mini-grid case
	did not have the authority to directly holding accountable those technicians."		
	"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."	Village council leader	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."	Normal electricIty user	Silale
Poor rules enforcement	"I tell you, even if someone refused to pay the tariff, no chairman could call him or do anything."	Normal electricIty user	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."	Normal electricIty user	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."	Normal electricIty user	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?"	Village council leader	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."	VEC	Ilunde
	"…The other day, the technician said that he would call all those with refrigerators and instruct them when to use them."	VEC	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…"	Village council leader	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."	Technician	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."	Normal electricIty user	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."	Technician	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."	Technician	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?"	VEC	
	"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."	Village council leader	Silale

Our own translation from Swahili.

exclusiveness to some resource users, e.g., elderly households, and low community participation in mini-grid matters.

Loops R2, R3, and R4 collectively expose a breakdown in the link between public infrastructure providers and resource users. The missing legal handover — a failure of soft infrastructure on the provider side

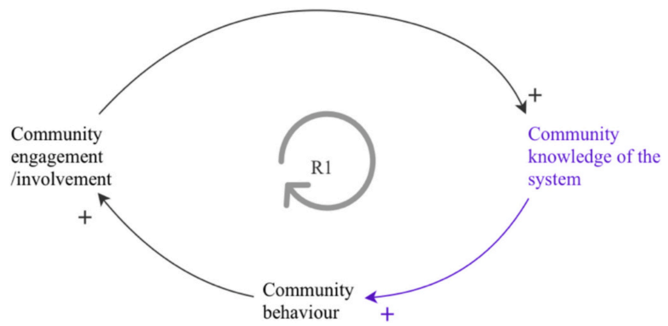

Fig. 1. CLD nodes and links of subsystem interactions of human and social infrastructure in Leganga mini-grid. Human infrastructure subsystem in purple colour, and social infrastructure in black colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

severed the governance chain: without formal ownership, VEC (providers) lacked authority to enforce rules (R3), and users lacked a sense of obligation to contribute to the maintenance fund (R4). Loop R2 specifically illustrates how the provider–user coupling was never properly established at the project's inception, leaving resource users without a legitimate governance mandate. All three loops reflect the CIS failure mode mechanism: infrastructure coupling broke down not through technical degradation but through an absent institutional link.

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 Section 4.2.1.2, Fig. 3 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

Loop R5 extends the failure into the resource and public infrastructure components: the degraded hard infrastructure (batteries) could no longer be sustained by an already depleted maintenance fund. This illustrates the CIS sustainability pathway mechanism in reverse: without robust coupling across all infrastructure types, the physical resource base deteriorated progressively, foreclosing recovery. Leganga's failure was therefore complete when all five infrastructure types were simultaneously in a degraded state, with no single component coupling able to reverse the trajectory.

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. Fig. 4 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

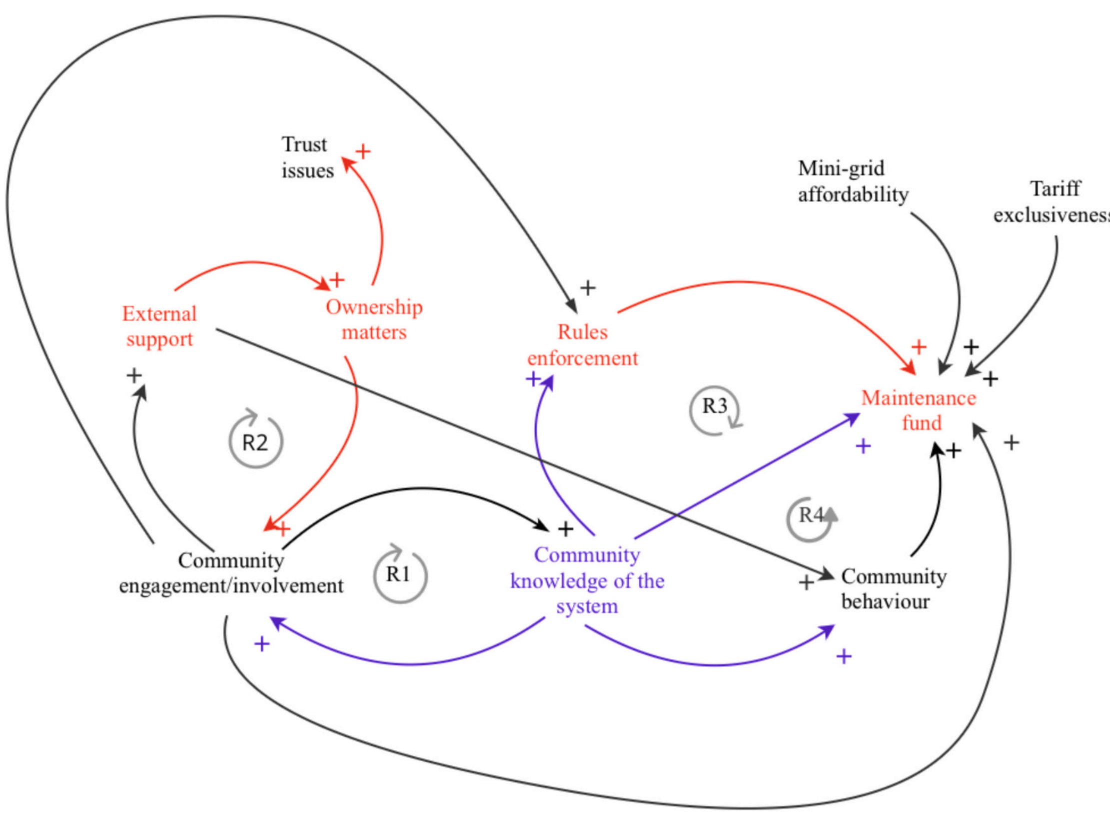

Fig. 2. CLD nodes and links of subsystem interactions of human, social, and soft infrastructure in Leganga mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, and soft infrastructure in red colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

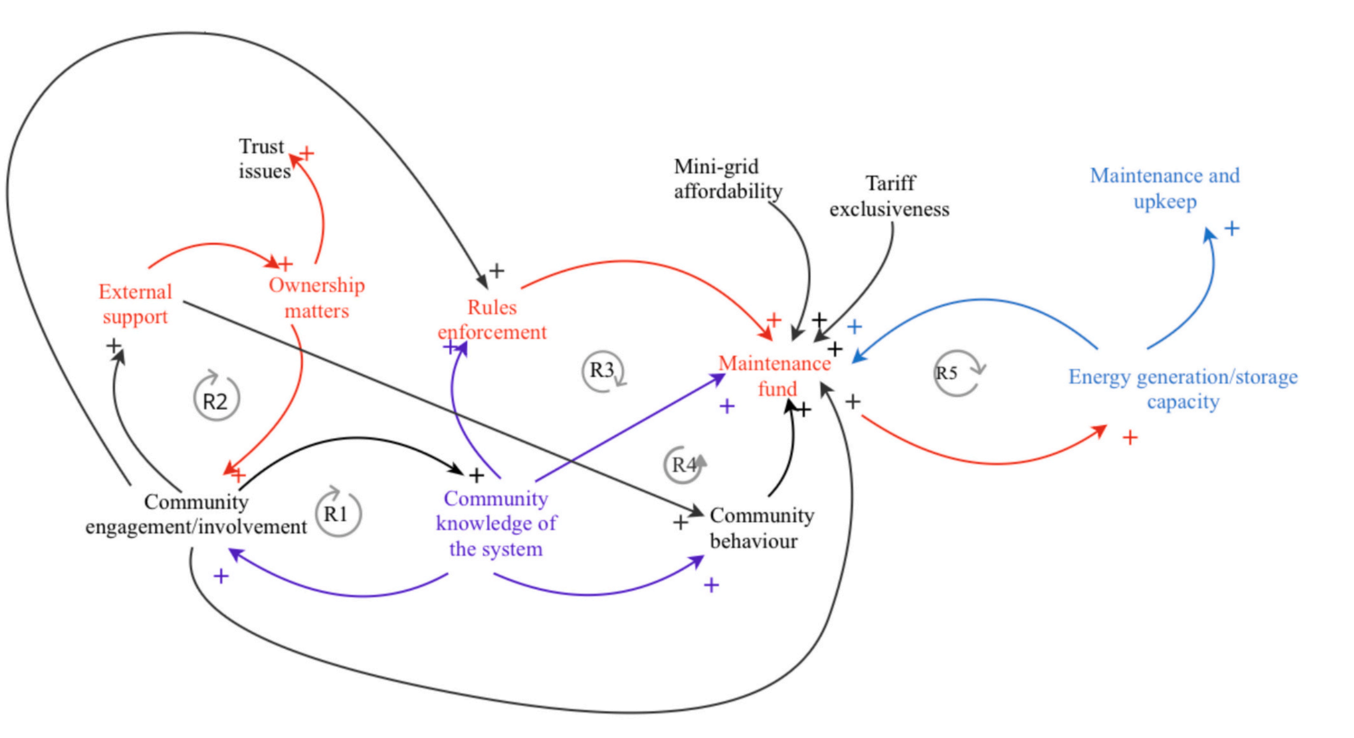

Fig. 3. CLD nodes and links of subsystem interactions of human, social, soft, and hard infrastructure in Leganga mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, soft infrastructure in red colour, and hard infrastructure in blue colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

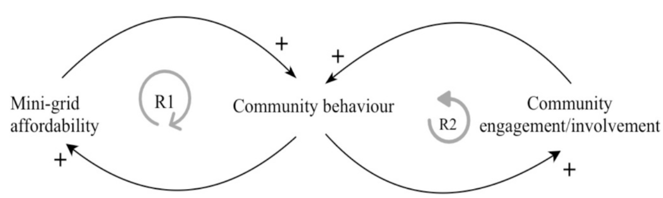

Fig. 4. CLD nodes and links of subsystem interactions of social infrastructure in Silale mini-grid.

behaviour 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.

Loops R1 and R2 represent self-reinforcing dynamics within the resource user component operating through social infrastructure. R1 captures a direct resource–user feedback loop: resource users' experience of the public infrastructure (unaffordable, unreliable service) fed back negatively into their willingness to sustain it through tariff payments. R2 shows that low user involvement at the provider–user interface weakened social norms supporting tariff compliance. Both loops reflect a failure of the infrastructure coupling mechanism at the user–governance boundary.

4.2.2.2. Human-social-soft infrastructure & exogenous drivers loops. Fig. 5 shows multiple reinforcing loops illustrating causal interactions leading to Silale mini-grid failure across human, social, soft infrastructure, and exogenous drivers. Social infrastructure loops R1–R2 are explained in Section 4.2.2.1.

Loop R3 shows how limited user participation weakened ownership, reducing government support. Low external support eroded trust, discouraging maintenance fund contributions and threatening sustainability. Poor maintenance due to inadequate funds then reinforced community disengagement, as users saw little return on contributions.

Loop R4 reveals how unclear ownership signaled project weakness to external actors (e.g., District Council), inviting political interference that further complicated legal handover and ownership status, ultimately impairing system performance.

Loop R5 demonstrates tariff nonpayment reducing maintenance funds over time. Inadequate funds – exacerbated by poor rules enforcement and external fund diversion (e.g., unreturned school construction loans) – led to declining reliability, user dissatisfaction, and further nonpayment, creating a vicious cycle of degradation.

In the CIS framework, R3 maps the provider–user–exogenous driver triangle: the soft infrastructure failure (no legal handover, a provider responsibility) progressively weakened trust between resource users and the system, ultimately starving the public infrastructure of maintenance funds. R4 illustrates how ambiguous ownership status opened a pathway for exogenous political intervention, further destabilising soft infrastructure on the provider side. R5 captures the closing of a reinforcing loop between the public infrastructure (system reliability) and resource users (willingness to pay): as performance declined, users' perceived return on tariff contributions fell, accelerating financial collapse. These three loops together exemplify the CIS failure mode mechanism: broken coupling between providers, users, and public infrastructure generates cascading deterioration.

4.2.2.3. Human-social-soft-hard infrastructure & exogenous drivers loops. Hard infrastructure interacts with other subsystems to explain Silale mini-grid failure (see Section 4.2.2.2). Loop R6 shows how insufficient maintenance funds blocked spare parts procurement, as when users could not replace batteries. This led to poor system performance, user dissatisfaction, reduced contributions, and further degradation.

Energy generation and storage capacity – a hard infrastructure subsystem – is also strained by social and human factors. Low tariff payments, off-peak overuse, affordability complaints, poor system knowledge, and illegal connections limit funds for upgrades, burden generation components, and threaten near-term failure.

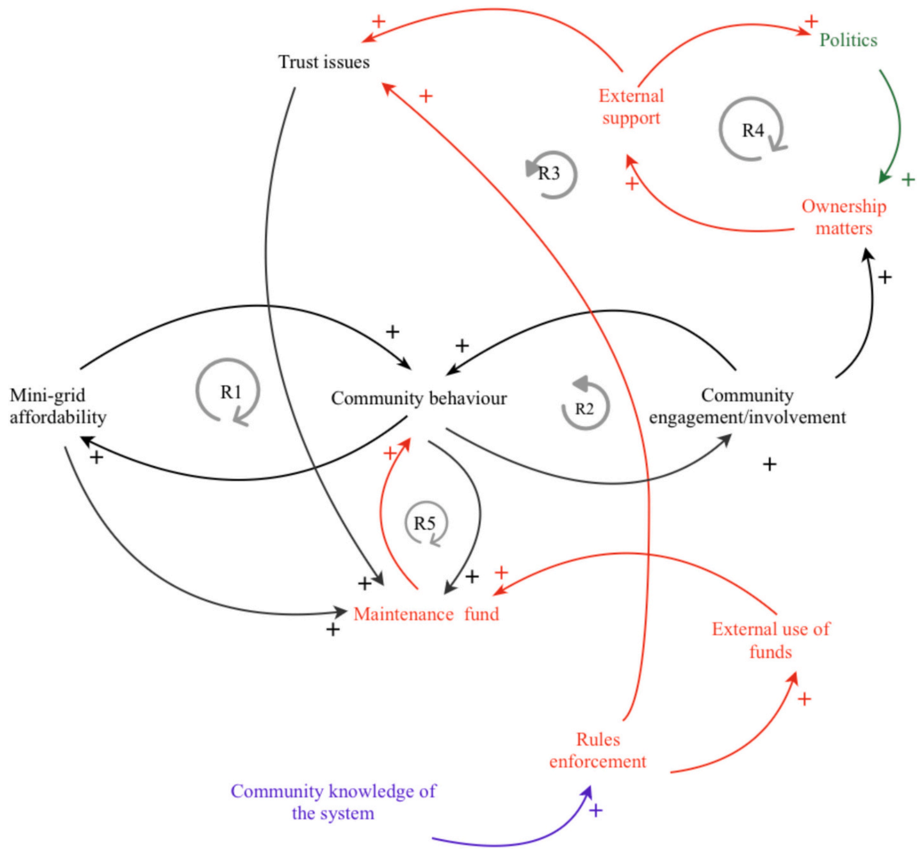

Fig. 5. CLD nodes and links of subsystem interactions of human, social, soft infrastructure, and exogenous drivers in Silale mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, soft infrastructure in red colour, and exogenous drivers in green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Loop R6 closes the CIS picture for Silale by connecting the financing collapse directly to the physical public infrastructure: the inability to procure spare parts reflects a breakdown in the provider–infrastructure maintenance link, which translated into declining system reliability. In CIS terms, this is the point at which the sustainability pathway closes: once hard infrastructure degrades beyond a maintenance threshold, coupling across all infrastructure types can no longer rescue system performance.

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 in Fig. 7 show the interactions between the financial status of Loya users, their behaviour, 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.

In CIS terms, loops R1 and R2 in Loya reveal an early collapse of the provider–user governance link, driven jointly by a social infrastructure failure (poor households unable to pay) and a soft infrastructure failure (absence of legal ownership preventing VEC from enforcing rules). The absence of formal ownership meant that the provider component (VEC) was structurally disempowered, inverting the governance relationship that the CIS framework identifies as necessary for collective infrastructure management.

4.2.3.2. *Social-soft infrastructure & exogenous drivers loops.*

Politics as an exogenous factor negatively affected multiple subsystems in Loya — tariff nonpayment, maintenance funds, ownership status, and external support (Fig. 8). A local member of parliament claimed personal responsibility for the mini-grid, telling users they could consume electricity freely. This undermined VEC authority to enforce tariff rules and weakened soft/social infrastructure coupling. Loya's failure thus arose from interactions among three infrastructure subsystems plus political interference.

These loops illustrate a distinctive CIS failure mode where exogenous political interference disrupted multiple component links simultaneously. The MP's directive undermined soft infrastructure (rules enforcement), social infrastructure (user behaviour and trust), and the provider–user governance relationship in one intervention. This reflects the CIS context sensitivity mechanism: institutional arrangements lacking protection from local political dynamics were systematically overridden, accelerating Loya's failure.

4.2.3.3. *Social-soft-hard infrastructure & exogenous drivers loops.*

Politics also affected hard infrastructure (energy generation and maintenance) through social infrastructure (user behaviour). Poor behaviour – illegal connections and banned appliances – degraded the system, raising maintenance costs. Higher costs and frequent repairs eroded user trust, with users suspecting manipulation to extract payments. This led to rule-breaking, tariff refusal, and subsystem interactions that caused Loya mini-grid failure.

Fig. 9 shows that the Loya failure ultimately involved all four CIS structural components: the resource (electricity supply), the public infrastructure (mini-grid system), the providers (VEC and government authority), and the resource users (behaviour and trust). The exogenous political driver acted as an amplifier across all component links, accelerating the collapse of the coupled infrastructure system.

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' behaviour, such as energy overconsumption during night hours, which in turn continued to affect the batteries negatively (loop R1).

In CIS terms, loop R1 represents a direct feedback between the public infrastructure (hard: batteries) and resource users (social: behaviour), operating within the resource itself. Degraded batteries altered how users consumed electricity, which in turn accelerated battery degradation further. This loop demonstrates a failure of infrastructure coupling at the resource–user interface, where the absence of effective human infrastructure (user knowledge) allowed physical degradation to become self-reinforcing.

4.2.4.2. Human-social-hard infrastructure loops. Fig. 11 illustrates interactions between social, human, and hard infrastructure. R2 shows that users' tariff non-compliance behaviour depicted in Fig. 10 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.

Loop R2 adds the human infrastructure dimension: the gap in users' knowledge of system operation a provider responsibility that was never fulfilled created the conditions for the social behaviour driving loop R1. In CIS terms, this implicates the provider–user link: public infrastructure providers (Ministry, external technicians) never equipped resource users with the knowledge needed to manage the public infrastructure responsibly, leaving the resource vulnerable to user-driven degradation.

4.2.4.3. Human-social-soft-hard infrastructure & exogenous drivers loops. Fig. 12 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 Fig. 11, 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.

Fig. 12 shows Ilunde failure – like the other cases – required simultaneous breakdown across all five CIS infrastructure types and multiple structural links. Tariff exclusivity (soft infrastructure failure) combined with missing user education (human infrastructure failure), depriving the system of revenue and operational knowledge needed for hard infrastructure maintenance. No single intervention could reverse failure once coupling across infrastructure types collapsed.

Mini-grid failure emerges from interdependencies among infrastructure types, not isolated factors. Across cases, the most damaging loops crossed structural boundaries — provider–user governance, provider–infrastructure maintenance, and user–infrastructure funding–performance links. Failed legal ownership handover consistently impaired provider–user coupling, cascading through soft, social, and human subsystems into hard infrastructure degradation. These loops represent emergent properties of coupled systems where key structural links were never established.

4.3. Cross-case synthesis of failure dynamics

Across the four cases, feedback loop analysis reveals four recurring failure mechanisms in community-managed mini-grids as coupled infrastructure systems — generalizable beyond individual contexts.

Governance breakdown: Weak provider–user coupling from incomplete ownership transfer undermined VEC authority, limiting rule enforcement, tariff collection, user participation, and governance capacity in self-reinforcing loops.

Trust erosion: Low transparency and accountability in technician/committee roles eroded social–soft infrastructure trust, reducing tariff willingness and collective management, further weakening institutions.

Financing–performance: Insufficient tariffs depleted maintenance funds, degrading system reliability. Deteriorating service then reduced payments, accelerating financial instability and infrastructure decline.

Political interference: Exogenous actors framed electricity as free, disrupting governance, amplifying non-payment, and cascading across subsystems.

These interacting loops across infrastructure types and components create progressive decoupling between users, providers, and infrastructure. We term this the coupled failure dynamics model of community-managed mini-grids.

5. Discussion

Building on the cross-case synthesis, mini-grid failure emerges from four recurring systemic mechanisms – governance breakdown, trust erosion, financing–performance, and political interference – rather than unstructured individual factors. These loop types capture core pathways of self-reinforcing decline across infrastructure interactions, enabling generalizable insights beyond case-specific explanations.

The study demonstrates how mini-grids, as small-scale electricity systems, are embedded in interrelated social, soft, hard, human subsystems, and exogenous drivers that cascade towards failure. Conversely, effective coupling creates sustainability mechanisms. As shown in Section 4.2, systems thinking via CLDs incorporating CIS infrastructure types reveals extensive causal connections, confirming that failure factors are dynamically interrelated rather than isolated. [59]. 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 behaviour has been shown to trigger other connected infrastructure subsystems [60]. Tariff nonpayment was more interconnected with other factors in Silale and Loya than in Leganga and Ilunde. In Silale, resistance stemmed from financial constraints, early nonpayment, and insufficient maintenance funds (Fig. 6). In Loya, these factors plus local politics – where an MP claimed project ownership and banned tariffs – intensified nonpayment, further affecting ownership and funding (Fig. 9).

Most users were new to electricity and lacked education on tariffs for

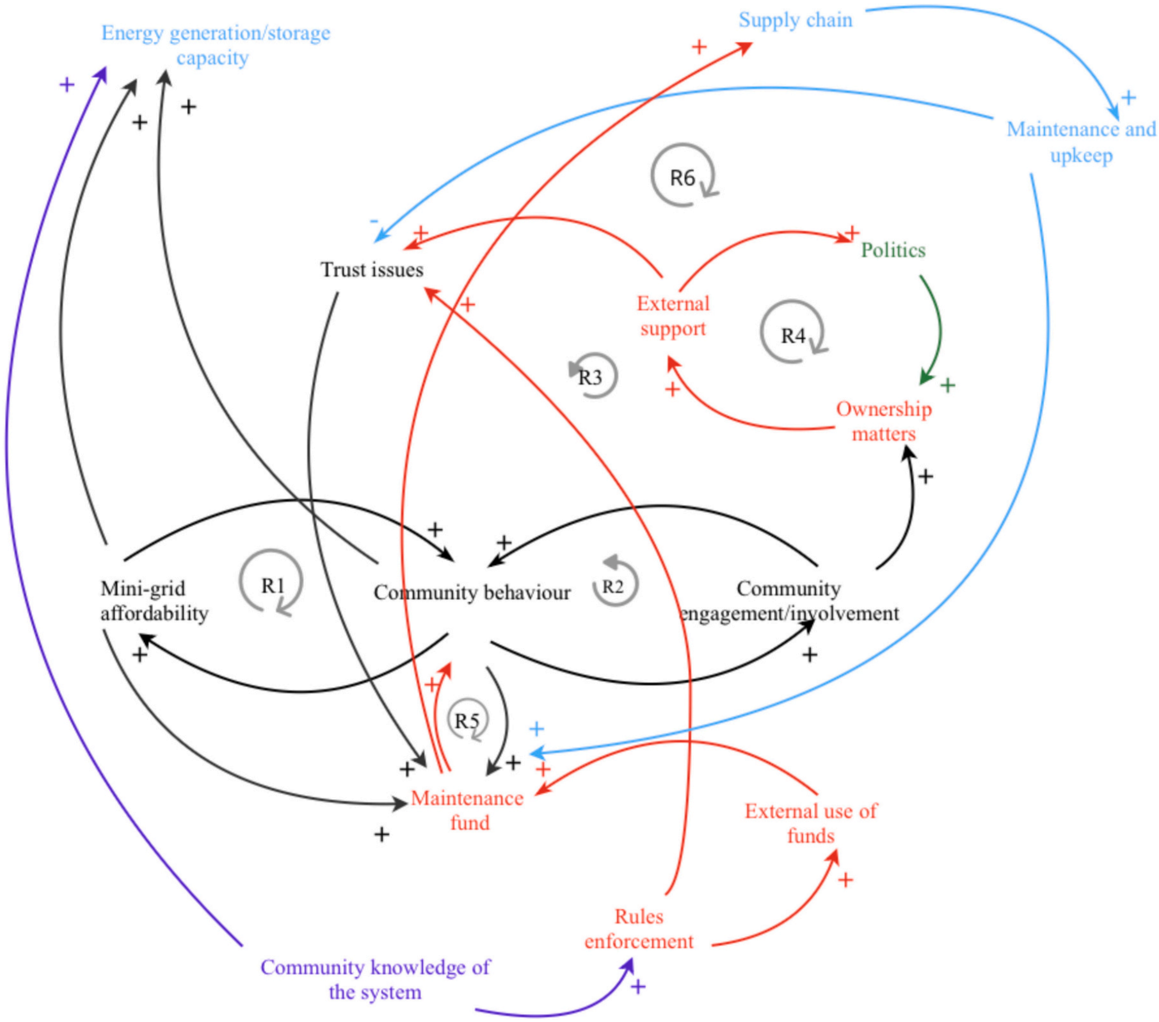

Fig. 6. CLD nodes and links of subsystem interactions of human, social, soft, hard infrastructure, and exogenous drivers in Silale mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

operations and maintenance. Continuous education by VECs or moderators is essential, despite unpredictable user behaviour.

Inadequate maintenance across cases stemmed from poor subsystem interactions. Sustainable financing – as the heart of mini-grids – is

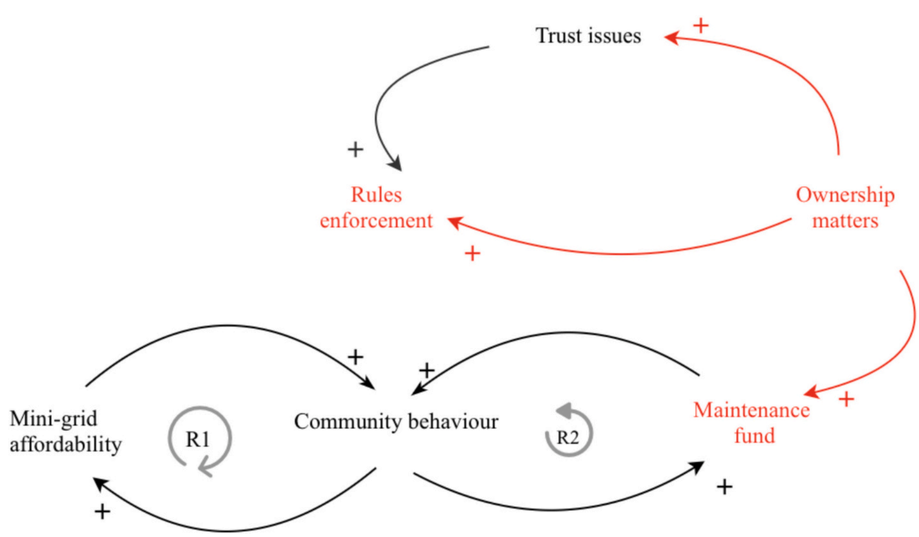

Fig. 7. CLD nodes and links of subsystem interactions of social and soft infrastructure in Loya mini-grid. Social infrastructure subsystem in black colour, and soft infrastructure in red colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

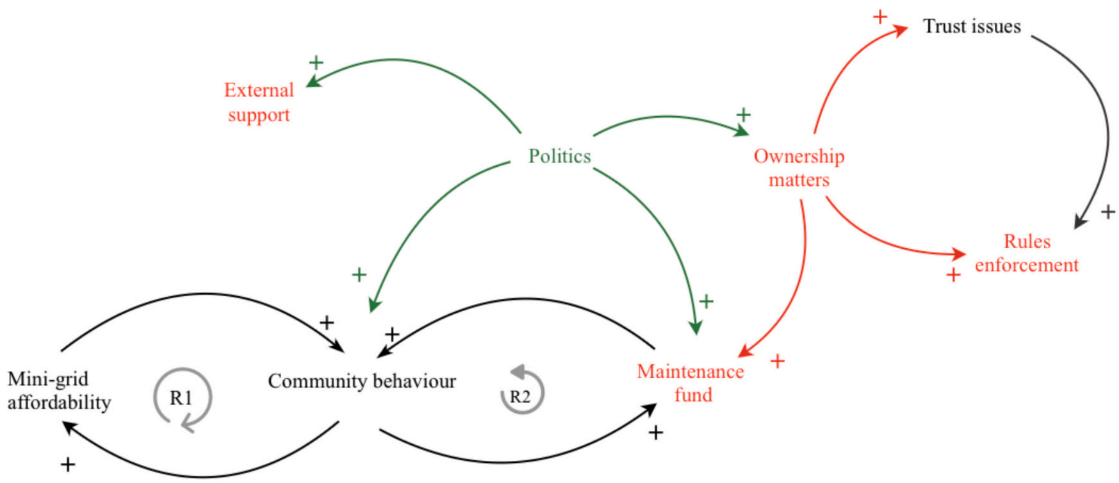

Fig. 8. CLD nodes and links of subsystem interactions of social, soft infrastructure, and exogenous drivers in Loya mini-grid. Social infrastructure subsytem in black colour, soft infrastructure in red colour, and exogenous drivers in green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

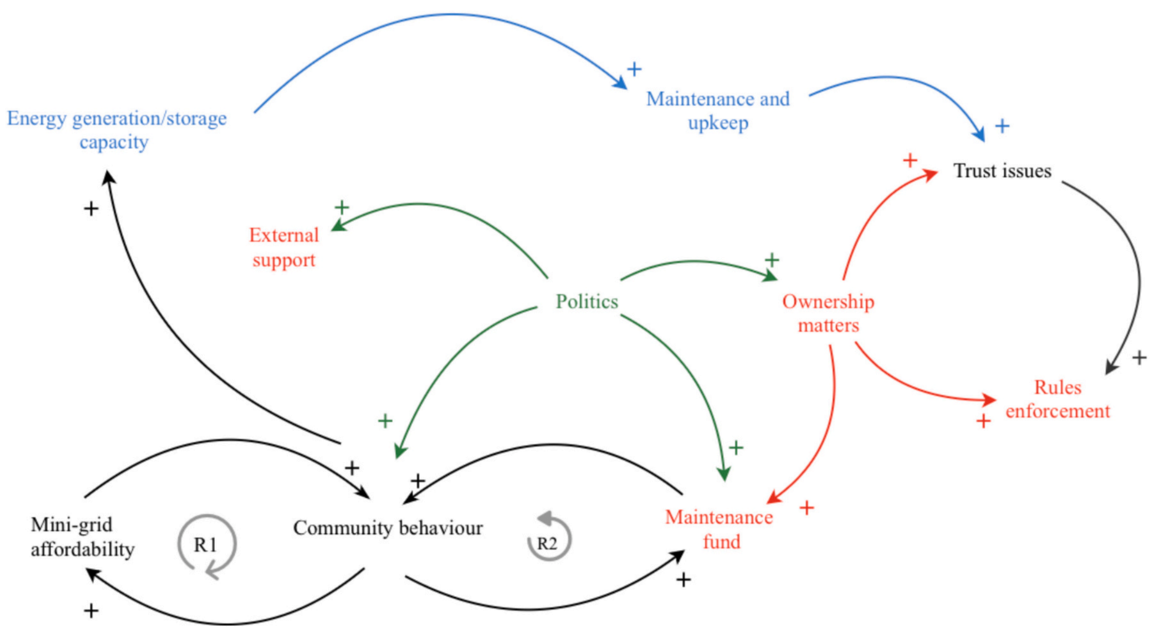

Fig. 9. CLD nodes and links of subsystem interactions of social, soft, hard infrastructure, and exogenous drivers in Loya mini-grid. Social infrastructure subsystem in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

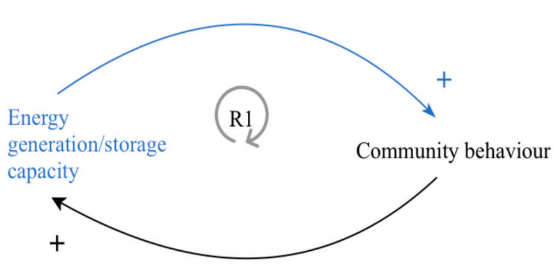

Fig. 10. CLD nodes and links of subsystem interactions of social and hard infrastructure in Loya mini-grid. — Social infrastructure subsystem in black colour, and hard infrastructure in blue colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

essential for community mini-grid performance [61]. Figs. 3, 6, 9, and 12 show multiple incoming arrows to the maintenance fund from other subsystems, indicating it results from interconnected factors (e.g., reinforcing loops R4 and R6 in Fig. 6, where trust issues via politics, ownership, and external support deplete funds) rather than isolated causes like low tariffs alone. Leganga shows the highest intensity, affected by tariff exclusivity, low affordability, poor rule enforcement, bad payment behaviour, low community involvement, poor system knowledge, and low generation capacity — four from social infrastructure, highlighting cultural and behavioral influences. Addressing inadequate maintenance thus requires targeting interconnected subsystems.

Exogenous drivers like local politics also complicate sustainability, affecting three cases (not Leganga) to varying degrees. In Loya, an MP's directive against tariffs directly impaired performance, maintenance funds, and VEC collection efforts, while absent ownership records blocked district council support (Figs. 8–9). Political interference thus

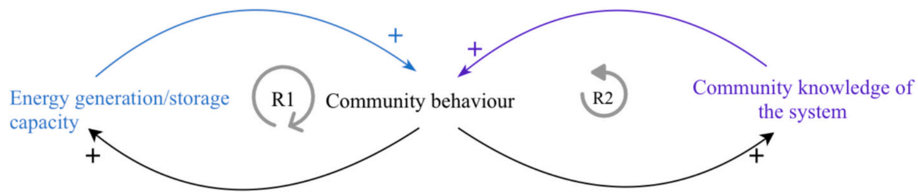

Fig. 11. CLD nodes and links of subsystem interactions of human, social, and hard infrastructure in Ilunde mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, and hard infrastructure in blue colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

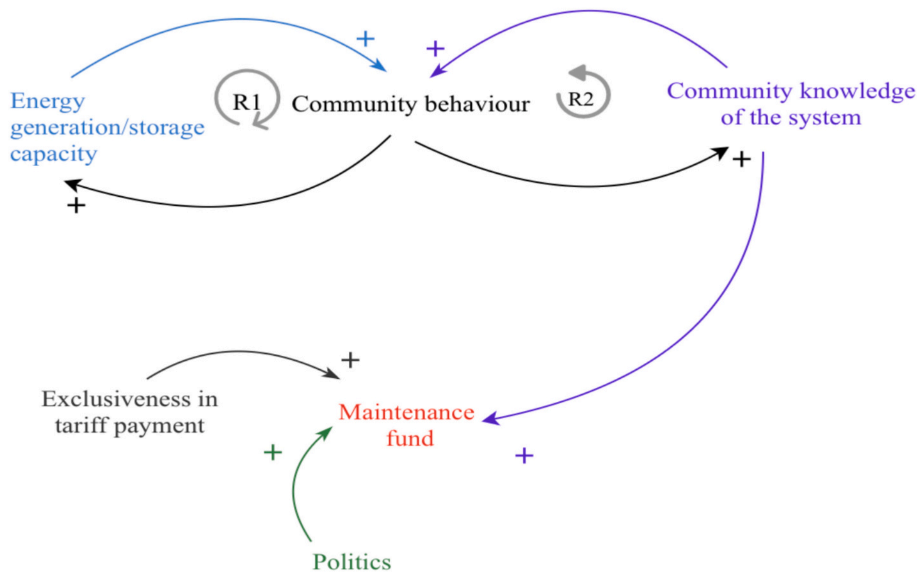

Fig. 12. CLD nodes and links of subsystem interactions of human, social, soft, hard infrastructure, and exogenous drivers in Ilunde mini-grid. Human infrastructure subsystem in purple colour, social infrastructure in black colour, soft infrastructure in red colour, hard infrastructure in blue colour, and exogenous drivers in green colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prevented external assistance and conflicted with project goals [8]. Involvement of local politics in such projects targeting rural communities should be minimal to avoid tensions [62], 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 [63,64].

The literature [65,66] provides well-known lists of factors or conditions under which collective action (including cooperative/community ownership) works. This study, however, adopts a complex systems perspective that stresses interactions of these factors and dynamics rather than just correlating isolated factors with success. We use a specific case (small mini-grid = electricity systems in Tanzania) to investigate this but assume that these or similar dynamics (causal loops) can be observed elsewhere in the world and in relation to other technical infrastructures.

Case dynamics varied. Politics dominated Loya's failure. Insufficient maintenance funds drove Leganga and Ilunde failures, but through different pathways: Ilunde's highly exclusive tariff collection exempted ~42 of 120 households; Leganga's stemmed from multiple interconnected factors. Silale's relative success came from early tariff payments driven by strong village leadership (council and VEC) aligned with Ministry guidelines, highlighting CIS context sensitivity (Section 2.2). Standardized guideline books supplied across cases failed to adapt locally, causing misalignment in three cases, while Silale's leadership ensured effective soft infrastructure implementation.

Prolonged unaddressed feedback loops – insufficient funds, low involvement, poor enforcement, bad behaviour – acted as "silent killers," explaining varying failure speeds rather than isolated factors. CIS and CLDs reveal these dynamics. Silale's better performance also underscores agency (leadership), somewhat underrepresented in structure-focused CIS.

6. Conclusions

Mini-grid failure in the four Tanzanian cases – as complex coupled infrastructure systems – arises from interrelated social, soft, hard, human, and exogenous factors rather than isolated causes. Long-term sustainability requires addressing interdependent subsystem failures affecting maintenance funds, which vary across cases from simple to complex influences. Local politics exacerbated issues by promoting free electricity for electoral gain, undermining tariff payments and user behaviour.

The study highlights the need for better information sharing between central (Ministry of Energy, REA) and local (district/regional) authorities to strengthen governance. It demonstrates CIS systems thinking via

CLDs to reveal infrastructure interactions and structural failures (e.g., provider–user gaps), though future work should incorporate provider perspectives and participatory validation of diagrams.

Ultimately, failure reflects progressive decoupling of governance (providers–users), financing/use (users–infrastructure), and maintenance (providers–infrastructure) links, driving mutually reinforcing degradation.

CRediT authorship contribution statement

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

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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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