UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft

Minigrid Organisation Design & Governance

Essays on Design of Sustainable Minigrid Institutions in a Developing Country Context

Der Fakultät für Wirtschaftswissenschaften der

Universität Paderborn

zur Erlangung des akademischen Grades

Doktor der Wirtschaftswissenschaften

- Doctor rerum politicarum -

vorgelegte Dissertation

von

Lillian Donna Namujju, M.Sc.

geboren am 18.02.1981

in Kampala

October 2024

Table of Contents

Acknowledgements

This PhD thesis marks the culmination of a journey that has been both challenging and deeply rewarding. Along the way, I have been supported, inspired, and guided by many incredible individuals and groups, without whom this milestone would not have been possible.

First and foremost, I extend my deepest gratitude to **Prof. Dr. Burkhard Hehenkamp**, my doctoral supervisor, for his invaluable support throughout this journey. Your insightful reviews, patient guidance, and scholarly contributions shaped my research and sharpened my analytical lens. Thank you for believing in my work and for your unwavering encouragement every step of the way.

To my colleagues in the **Chair of Institutional Economics & Economic Policy**—**Dr. Angelika Endres-Frölich, Dr. Britta Hoyer, Tahmina Faizi, Amirhossein Kiannik, Alexander Koch, and Niklas Otto**—thank you for the countless hours you spent listening to my raw ideas, reading the earliest drafts of my manuscripts, and providing candid yet kind feedback. You created a warm and supportive family that enriched my time at the Chair immeasurably.

A heartfelt thank you goes to **Christiane Borghoff**, who was my solid backup and unwavering support throughout my PhD program. There was no challenge too big to overcome as long as I had you in my corner. Thank you for your care, your tireless support, and for fighting—and winning—many battles on my behalf. I am forever grateful.

To my rock, my lover, my husband, and the father of our children—**Martin Kaddumukasa (MD, PhD)**—thank you for holding down the fort at home and being the anchor of our family during these four years. Your love, sacrifice, and steadfast support made it possible for me to pursue and complete this PhD. This achievement is as much yours as it is mine.

To my **ART-D Grids project colleagues**—**Dr. Teddy Mangeni, Dr. Godiana Philipo Hagile, Dr. Henry Asiimwe, Dr. Ibrahim Mwammenywa, and Drs.-to-be Josephine Kakande, Mark Kagarura, Paul Bogere, Henrietta Acquah-Swanzy, and Irene Ngoti**—your presence and camaraderie provided an invaluable piece of home that kept me going through the tough German winters and those *lööööng* Deutsch classes. I cherish the friendships and shared experiences we built along the way.

This work would not have been possible without the generous support of **Paderborn University**, the **ART-D Grids Project**, and the **German Federal Ministry of Education and Research (BMBF)** under award grant number **03SF0607B**. I am profoundly grateful for the financial and institutional backing that allowed me to pursue this research and achieve my academic goals.

I am equally indebted to my **Doctoral Supervisory Committee**, who graciously gave their time and expertise to be part of the PhD evaluation process. Your insightful comments and alternate research perspectives provided me with a fresh lens through which to view and refine my work. I am honored by the grace and trust you showed, and I am forever grateful for your valuable contributions to this research.

Finally, I dedicate this thesis to my father, **Samuel Senabulya Mugalasi (RIP)**. Your love of books ignited my passion for academia and set me on this path. Pursuing this PhD was my way of honoring your legacy, and I hope that, wherever you are, you feel pride in the academic legacy you helped to create.

To all of you—thank you. This achievement would not have been possible without your support, love, and encouragement.

Thesis Abstract

The contents of this thesis are focused on minigrid organisation design, governance and sustainable functioning in a developing country context. The research covers the analysis and design of minigrid organizational frameworks in the region, as well as, analysis and design of governance mechanisms to oversee their operations, and ensure their long-term viability and sustainability within the broader economic and institutional context. It involves considerations of regulatory and policy frameworks, minigrid ownership, decision-making processes, and the alignment of incentives to promote efficient and sustainable energy delivery to communities. The research contributes to enhancing our understanding of how institutional frameworks impact the performance and longevity of energy projects. It further advances scholarly discourse on energy governance institutions and how their structure(s) link to energy sector outcomes offering insights that can inform policy-making, investment decisions, and community engagement strategies.

.

1 Introduction

This thesis is organized in a series of four conceptually related but independent research studies focused on minigrid organization design, governance and sustainable functioning. Minigrids by definition are localized electricity generation and distribution systems that serve a small geographic area, typically used to electrify remote communities where extending the main grid is not feasible or cost-effective (Pedersen, 2016). Rapid technology advancements coupled with reducing hardware costs have made mini-grids an increasingly viable option for driving electricity access in rural marginalized communities. They play a crucial role in increasing access to electricity, especially in rural and underserved areas, and can contribute to sustainable development by fostering economic growth, improving living standards, and supporting various social services (Dal Maso et al., 2020). The four research studies incorporate desk research via literature reviews, utilize institutional economics frameworks, apply network theoretic and systems dynamics modelling, and incorporate case studies and empirical survey findings. They are set within the context of East Africa - a developing region characterized by some of the world's lowest electrification rates (IEA, 2022). In a developing country context, structural externalities such as limited infrastructure, socio-economic disparities, and weak governance systems, are critical considerations in institutional economics research (Helmsing, 2003). These factors have significant impact on the functioning of institutions, the behavior of economic agents, and the overall performance of markets and systems. In the different research studies, we attempt to understand, address and account for these structural externalities.

A substantial body of literature within economics and political science underscores the crucial role of institutions in shaping outcomes, and development trajectories (Casson et al., 2010; Matthews, 1986; Nelson and Sampat, 2001; North, 1990b). This discourse has extended into the area of sustainable development, with emphasis on the role of institutions in governing markets, natural resource management, climate change mitigation, and socio-economic progress

(Acemoglu and Robinson, 2008; Cleaver, 2002; Hermann, 2008; Leach et al., 1999). Moreover, research on institutions in the energy sector has been robust and evolving, reflecting the growing recognition of the criticality of institutional factors in shaping energy policies, regulations, and outcomes. It has been applied to analysis of the design and effectiveness of energy policies and regulations (Seungtaek Lee et al., 2015); investigation of institutional structures and governance mechanisms within energy markets (Erdogdu, 2013); examination of the role of local communities, NGOs, and other stakeholders in energy decision-making processes (Sanne Hettinga et al., 2018); etc. In this thesis, we employ an interdisciplinary perspective in application of these different discourses combining contributions from institutional economics with those from development economics, network institutionalism and social network theory, behavioral economics and psychological theories, to shed light on sustainability of institutions, the link between network structure and performance, market imperfections and failures, and how these factors influence consumer choices and behaviors.

Over time, the concept of institutions has evolved from its initial definition as formal organizations like governments and corporations to later encompassing informal institutions such as customs, traditions, and social norms shaping behavior and outcomes (Hodgson, 2006). For this thesis, institutions are defined as human-made constraints or rules that govern and shape human interactions (North, 1990a). Knight (1992b) describes them as established systems of social norms, rules, and shared strategies that organize and guide human behavior. The rules in this case are central as they set the groundwork for actor engagement, providing a degree of predictability regarding others' actions in a given context. This predictability facilitates individual decision-making and multi-party negotiations, allowing them to progress with a measure of certainty (Nelson and Sampat, 2001). These rules can range from formal laws, policies, and regulations to informal cultural norms or standard operating procedures. They establish incentives for desired behaviour in recurring situations (Crawford and Ostrom, 1995) and are crucial for managing situations that necessitate coordination among large groups of people (Hurwicz, 1994).

This thesis bridges both *old institutionalism* and *new institutionalism* in its analysis of institutions. Old institutionalism, exemplified by scholars like Thorstein Veblen and John R. Commons, emerged in the late 19th and early 20th centuries within economics and sociology (Hodgson, 1998). It focused on the role of institutions, including laws, customs, and traditions, in facilitating or hindering efficient resource allocation, economic growth, and development; and it tended to view institutions as relatively stable and slow to change (Chavance, 2008; Hodgson, 1998). In this context, Chapter 2 of the thesis applies Ostrom's Institutional Analysis and Development (IAD) framework to analyze what are fairly stable and established regulatory and policy frameworks of minigrids. It investigates minigrid systems and their service provision as a collective action problem requiring interorganizational coordination; whose institutional arrangements must maximize incentives to cooperate if the systems are to be sustained over the longer term (Imperial, 1999). The IAD framework is a tool or structured approach within the broader field of institutional economics that has been applied to the understanding of institutional arrangements that facilitate or hinder effective resource management and collective action (Ostrom, 1999a, 1990a, 1986). It emphasizes the importance of context-specific analysis, collective decision-making, and the roles of different actors within institutional settings (Polski and Ostrom, 1999).

As part of this study, we explore the questions: ***What institutional factors are pivotal in determining sustainability outcomes in minigrid systems? What are the essential decisions and actors' patterns of interaction contributing to or in the way of desired sector outcomes?*** This IAD study conducts a comparative institutional analysis of the minigrid sectors in Uganda and Tanzania, examining outcomes and developing a diagnostic framework to understand the causal interactions between actors and the external contexts that impede the sustainability of the sector. The study reveals notable institutional inefficiencies in the sectors examined, leading us to recommend a flexible solution strategy. This strategy involves strategically modifying the adaptable elements of the IAD framework, focusing on addressing the root causes rather than merely the surface problems. This approach enables targeted interventions by making precise adjustments to directly and effectively tackle the underlying issues.

Moving from old, to new, the emergence of ‘new institutionalism’, attributed to scholars like Douglass North (North, 1995), Paul DiMaggio (DiMaggio, 1998) and John Meyer (Meyer, 2010) expanded the scope of institutional analysis to include informal institutions such as norms, culture, and beliefs. New institutionalism explores how institutions evolve, how they influence behavior and outcomes, and how they are influenced by broader social, economic, and political forces (March and Olsen, 1983). The approach aimed to shed light on the interaction between formal and informal institutions and how they shape behavior and influence outcomes. Within this framework, a specific focus emerged on institutional analyses related to collective decision-making structures exploring how individuals self-organize to create systems of rules and governing structures to address common challenges without relying on external institutions (Hall and Taylor, 1994; Ostrom, 2020). Notably, Elinor Ostrom's pioneering work on common pool resources and the design of sustainable institutional arrangements has been instrumental in advancing this discourse on new institutionalism (Ostrom, 2005, 1999a, 1999b, 1990a).

Similarly, as prominent under the realm of new institutionalism, is Ostrom’s contribution in form of design principles – essentially prescriptive guidelines for designing effective governance institutions. Ostrom Design Principles (ODPs) are based on empirical observations across diverse settings contributing valuable insights by demonstrating how institutional arrangements can foster sustainable governance and address collective action problems within specific contexts (McGinnis and Ostrom, 1996; Ostrom, 1992). They assume a relatively stable and predictable environment and emphasize local-level management of common-pool resources. They represent what are generally accepted as standard features of successful governance systems of common pool resources such as clearly defined boundaries, collective choice arrangements, monitoring mechanisms, graduated sanctions, etc. Chapter 3 of this thesis explores how these principles apply to a minigrid system – a complex adaptive socio-technical system characterized by emergent behavior, deep uncertainty, and intricate interaction between physical, technical and social subsystems (Anderies et al., 2003). Further, drawing from development economics literature, which posits that institutional quality may account for the continued poverty among poor countries (Pande and Udry, 2005), the study examines the salient dynamics when quality institutions as defined by ODPs confront structural externalities in a remote rural developing country context. It specifically answers the research questions: ***What are the choice set constraints actors face in these contexts? What causes suboptimal decision-making and behavior in this developing context? How resilient are generally accepted institutions and design principles in the face of emergent effects arising from a minigrid system set in this study context?***

This study specifically explores the resilience of ODPs in the face of emergent effects arising from rural community minigrids as complex adaptive socio-technical systems. It seeks understanding on how institutions can bolster the resilience of energy systems in these contexts, promote equitable energy access and meet the energy needs of these marginalized communities. The study employs Systems Thinking and feedback loop analysis to explore how interactions between institutional and physical infrastructures, socio-cultural factors, and the external environment impact the design, organization, and functioning of minigrid systems. The findings highlight the urgent requirement for adaptive governance strategies in rural contexts, especially in light of structural externalities beyond community control.

The thesis further extends *new institutionalism* to the realm of organizational analysis whose focus is on examining the relationships among formal rules, informal norms, social networks, and purposive action (Brinton and Nee, 1998). The emphasis here is on how institutions and networks combine to determine economic and organisational performance. The social mechanisms through which institutions shape the parameters of choice are actually built into ongoing social relationships - network ties structuring a wide array of economic phenomena (Nee and Ingram, 1996). Network institutionalism, a branch of institutional theory, underscores the embeddedness of organizations and individuals within social networks (Ansell, 2008; Ohanyan, 2012). It emphasizes that social networks play a crucial role in shaping and spreading institutional norms, practices, and arrangements across organizations and societies. This approach integrates insights from social network theory into institutional theory to explore how network structures influence institutional stability, change, and innovation (Owen-Smith and Powell, 2008). It examines factors such as the patterns of relationships, the centrality of key individuals or organizations within networks, and the density of connections, all of which affect the adoption and diffusion of institutional practices (Clemens and Cook, 1999). Network institutionalism also considers how power and influence are distributed within networks, and how influential actors can drive institutional change or reinforce stability (Ibid). By highlighting the role of social networks as conduits for transmitting institutional norms and practices, this perspective enriches our understanding of how networks shape organizational behaviors, collective actions, and societal outcomes. Utilizing network institutionalism and social network theory Chapter 4 in this thesis quantifies the influence and constraints imposed by the network's structure, emphasizing their effects on agents' identities and possible strategic interactions within the energy sector. It specifically answers the research question: ***How do these structural characteristics define node-level influence and value in the network?***

This study examines the link between network structure and performance for the case of a minigrid financing and investment network in Uganda. It dissects the power-political consequences of network positions across three crucial dimensions: accessibility to other actors and the advantages therein, the role of brokerage and the influence derived from connecting disparate network nodes, and the efficiency of resource diffusion as shaped by the strategic positioning of actors. Through Principal Component Analysis (PCA), the study integrates essential centrality metrics to construct comprehensive influence scores that capture these multifaceted aspects of power within the network. The study reveals that access power benefits more from influential and non-redundant connections than from merely having a high quantity of connections. It also finds that a node's brokerage power is more significantly impacted by the interconnections among its neighbors than by its strategic placement on the shortest paths between nodes. Additionally, resource diffusion is determined not by proximity to neighbors but by a node's strategic location along essential communication pathways and its critical role in overall network connectivity.

Ultimately institutions play a critical role in shaping individual behavior and decision-making processes. Formal rules establish default options and incentives that guide decisions, while informal norms influence social preferences and behaviors (Sunstein, 2015). Behavioral economics enriches our understanding by exploring how cognitive biases and psychological factors influence decision-making, deviating from traditional economic models (Reisch and Zhao, 2017). Institutionalism incorporates these behavioral insights to examine how institutions adapt to or resist behavioral changes. It investigates how institutions can be designed or reformed to better align with behavioral realities and achieve desired outcomes.

Chapter 5, the final research study in the thesis relies on choice architecture - a concept within behavioral economics with a focus on designing decision environments to encourage specific behaviors (Thaler et al., 2013). Institutions set the framework for choice architecture by establishing rules, incentives, and constraints. Understanding behavioral tendencies helps institutional designers develop more effective policies and governance structures. The study sets out to answer the research question: **'*What is the impact of key rationing choice architecture strategies on power consumption behaviors and overall minigrid system and market stability?*** This thesis sub-study is rooted in fundamental theories of choice architecture and behavioral economics applied to energy management. Choice architecture theory investigates how decision-making environments influence individual choices and behaviors. The research aims to advance understanding of how institutional designs and decision-making frameworks can foster sustainable energy practices in resource-limited environments. The study utilizes a Traffic Light System (TLS) with visual and accoustic queues to regulate power consumption choices, aiming to guide consumers towards more sustainable energy use patterns. The system adopts a tiered strategy, starting with gentle nudges using visual color and acoustic cues and progressing to harder choice architecture culminating in automatic power disconnection. The implementation of this system resulted in a 47.4% reduction in peak energy demand, alongside a significant change in power consumption patterns of the community underscoring the efficacy of nuanced behavioral nudges in combination with goal setting in achieving significant and enduring changes in energy use behaviors.

In sum, these different strands of institutional research, here applied to the analysis of energy sector minigrid institutions, collectively form the foundation of this thesis. The thesis assesses the effectiveness of minigrid institutions, investigates the institutional complexities and prospects associated with integration of minigrids as complex socio-technical systems into rural communities, examines how network positions within energy policy networks influence relative power of stakeholders, and evaluates the effects of various choice architecture strategies on power consumption behaviors. The thesis findings make significant contribution to the institutional economics literature by demonstrating a systematic application of the IAD framework to the diagnosis and treatment of institutional inefficiencies in minigrid sectors in a developing country context. Moreover, researchers get an enhanced understanding of the intricate socio-technical dynamics of minigrid systems, illuminating the interactions between institutional arrangements and the physical and social subsystems. Additionally, the ODP study offers empirical insights into the resilience of ODPs amidst emergent effects from minigrid socio-technical systems in a rural developing country context. The findings provide practical guidance for designing effective institutional arrangements that promote sustainability and resilience in energy access initiatives. Furthermore, the Social Network Analysis (SNA) study makes a substantial contribution to academic literature by providing insights into the structural dynamics of energy policy networks.

The development of influence scores for access power, brokerage, and resource diffusion introduces crucial new quantitative measures that contribute to empirical research on network dynamics, providing guidance on optimizing network structures for effective policy formulation. Lastly, the choice architecture study enriches academic discourse by demonstrating a novel application of behavioral economics principles within the context of energy management. The Traffic Light System (TLS) exemplifies an innovative approach that integrates real-time energy monitoring with intuitive, color-coded signals to effectively influence consumer behavior. This application expands the theoretical framework of choice architecture by showcasing how non-financial nudges can significantly impact energy consumption patterns.

The rest of this document details the motivations, methodology, results, discussions and policy implications of the four research studies comprising this thesis. Chapter 2 covers the IAD framework study, Chapter 3 discusses the ODP study, Chapter 4 presents the SNA study, and Chapter 5 explores the choice architecture study.

2 Governance Institutions Galvanizing Minigrid Performance

An IAD Framework Analysis of Minigrid Institutions for Sustainable Rural Electrification in East Africa: A Comparative Study of Uganda and Tanzania[1][2]

Lillian D Namujju[3], Henrietta Acquah-Swanzy[3], Irene F Ngoti[4]

Abstract

Minigrids 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 minigrids across their development stages. We map sector actors and their respective roles in the minigrid sector providing a framework for their interactions and choices towards sustainable outcomes. We further present a comparative institutional assessment of Uganda and Tanzania's minigrid 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 minigrid sector and its relationship with adjacent sectors. It further uncovers significant institutional inefficiencies in the minigrid 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.

JEL Codes**:** D02, D04, E02, Q48

Keywords*:* Minigrid sustainability, Institutional analysis, IAD framework, Energy policy, Regulatory framework, Sub-Saharan Africa.

---

[1] This research has been published: *Namujju, L.D., Acquah-Swanzy, H., Ngoti, I.F., 2023. An IAD framework analysis of minigrid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania. Energy Policy 182, 113742*

[2] The research has been submitted as part of PhD theses for co-authors Henrietta Acquah-Swanzy and Irene F Ngoti

[3] Faculty of Economics, Chair of Institutional Economics & Economic Policy, Paderborn University

[4] Faculty of Sustainability, Leuphana University, Universitätsallee 1, Lüneburg

2.1 Introduction

Minigrids have been posited as economically viable options for driving electricity access in underserved areas beyond the reach of main grids (Ahlborg and Hammar, 2014; Motjoadi et al., 2020). In Sub-Saharan Africa, with some of the lowest electrification rates in the world (IEA, 2022), the viability and sustainability of minigrids is central to the achievement of SDG7 - sustainable energy for all by 2030. While technical and financing factors in the study of minigrid sustainability are important (Katre et al., 2019; Peters et al., 2019; Poudel et al., 2022; Zebra et al., 2021), the institutional framework within which minigrids operate is just as important (Palit and 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 behavior and social interactions (Knight, 1992a). 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 behavior in repetitive situations (Crawford and 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 and Ostrom, 2000; Ostrom, 1999a; Ostrom et al., 1994; Ostrom et al., 1993; Ostrom, 1990a, 1986) to analyze the institutions governing minigrid implementation and operation. The IAD framework has been valuable in analysing and designing policy and institutional interventions in a wide range of political-economic situations (Polski and Ostrom, 1999). It has been utilized to analyze minigrids as common pool resources (Gollwitzer et al., 2018; Gollwitzer and Cloke, 2018; Greacen, 2004; Kirubi, 2009; Maarten Wolsink, 2012; Maier, 2007). The Social-Ecological Systems (SES) framework (extended IAD) has also been used to explain community minigrids (Holstenkamp, 2019; Sanchez and Tozicka, 2013; Yadoo and Cruickshank, 2010). In this paper, we apply the IAD framework as a tool for analysing institutions and evaluating policy effectiveness in the minigrid context.

Previous works on minigrid 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 minigrid implementation (Duran and Sahinyazan, 2021a; Duran and Sahinyazan, 2021b). Several have referenced the regulatory environment to point to challenges facing the roll-out of minigrids (Mondal et al., 2010; Ohunakin et al., 2014; Peters et al., 2019; Shyu, 2012) without necessarily going in depth into particular regulations and their implications. In contrast, our study goes beyond surface-level analysis, undertaking a causal and interactions analysis to establish the underlying rationale behind local actor choices and patterns of interaction alongside a rigorous structural analysis of minigrid sector policies in a bid to explain sector outcomes.

Uganda and Tanzania, two of the least electrified countries in the world (IEA, 2022), have adopted off-grid electrification in a bid to achieve a leapfrog on their rural electricity access targets (Brenda Banura, 2022; Odarno et al., 2017). We use these two countries as case studies in our analysis of minigrid sectors in East-Africa, addressing three research questions: (1) What are the key institutional and socio-cultural considerations driving sustainability outcomes in minigrid 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 minigrid sector policies?

The rest of the paper is organized as follows: In section 2.2 we present an overview of the IAD framework and how it is uniquely applied in answering our research questions. In section 2.3 we apply the IAD framework to the general minigrid context to establish the institutions and socio-cultural factors driving minigrid sector outcomes and go on to map the actors, their roles, positions, and choices across the minigrid development phases of financing, planning, and implementation. In section 2.4, we present a comparative and diagnostic institutional assessment of Uganda and Tanzania's minigrid energy sectors and in section 2.5, policy implications and conclusion.

2.2 Methodology

2.2.1 The IAD Framework

The IAD framework is quite versatile and applicable to a variety of research questions about human decision making (Hess and 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 1 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.

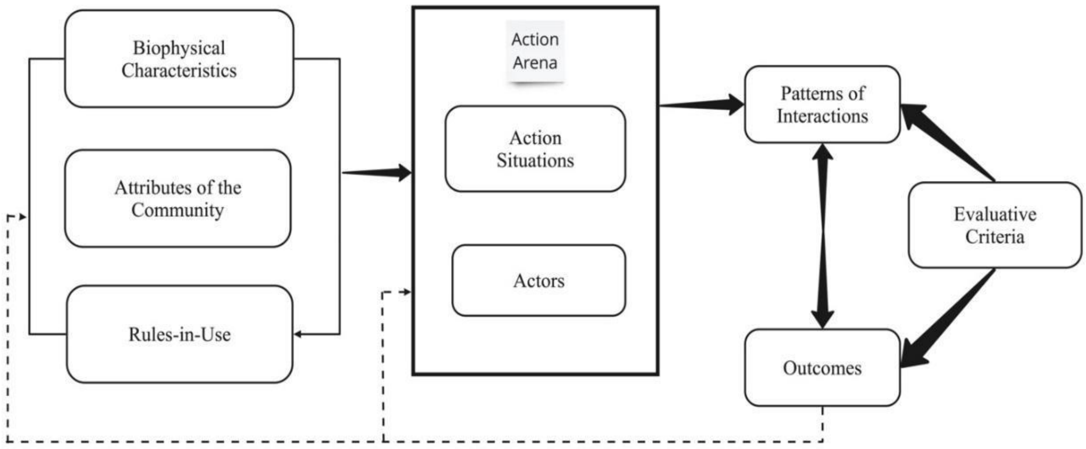


Figure 1: IAD Framework. Source: Kiser and Ostrom, 1982

The action arena is the core of the IAD Framework useful in analysing dilemmas in processes of institutional change (Hess and 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).

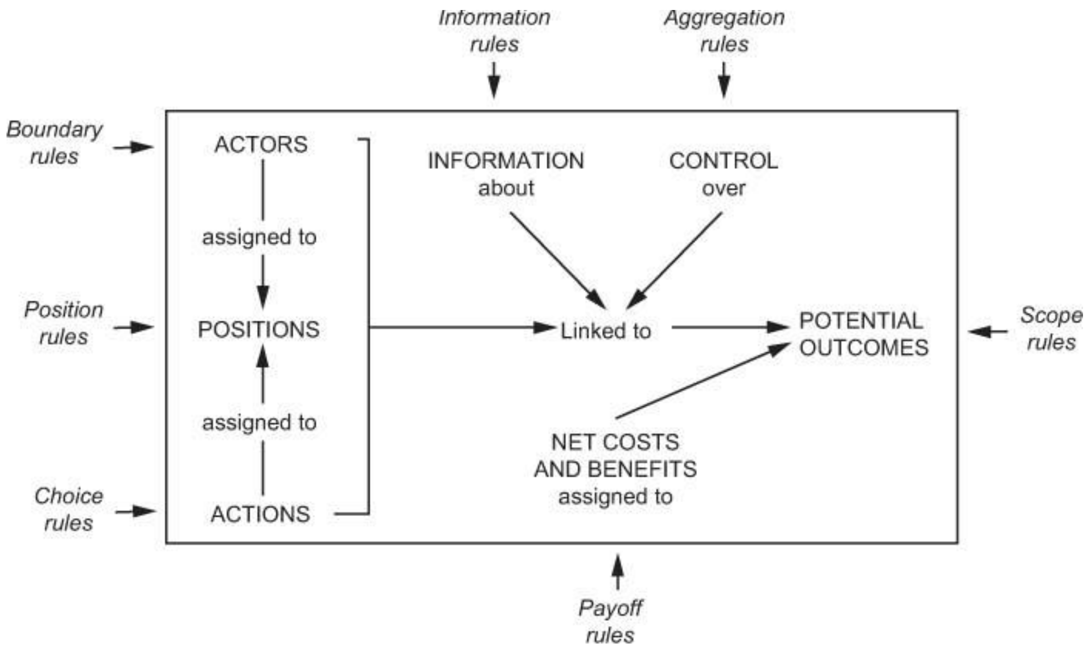


Figure 2: Rules-in-use in the exogenous context directly affecting the action arena (Source: Ostrom 2005)

The action situation, contained within the action arena, is detailed in Figure 2. It specifies the nature of relevant actors, the resources, and choices at their disposal and essentially approximates the "rules of the game" (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 analyzing 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 and 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 and 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).

2.2.2 IAD Framework Materialization

We performed a *literature review* related to the sustainability of minigrid 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, policy documents, international energy agency databases, and regional minigrid development agency reports. Included were those studies and reports providing insights into the regulatory frameworks, policies, and institutional arrangements enabling or hindering minigrid sustainability in the region. 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 minigrid 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 and Guinto; Lestari et al., 2018; Nigussie et al., 2018; Oh and Hettiarachchi, 2020) or for the analysis of existing policies (Imperial and Yandle, 2005; Shah and Niles, 2016). In the former, the analysis is focused on identifying the institutional factors that contribute to the problem or issue (Ostrom, 1990a). 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 effectiveness of the policies and identifying opportunities for improvement (Polski and Ostrom, 1999). Here, the 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 analyze the institutional and socio-cultural considerations at work in the minigrid sector. Starting with the specific political-economic context - minigrid sustainability, we work forwards through the framework in Figure 1; 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 backward through Figure 1 to reaffirm or revise policies, evaluate policy outcomes, and understand the information and incentive structures of different policies. The steps are summarized in Figure 3. Applying both approaches to the problem adds robustness to the methodology - providing a comprehensive understanding of the institutional context, allowing for anticipation of unintended consequences and the design of context-relevant policies.

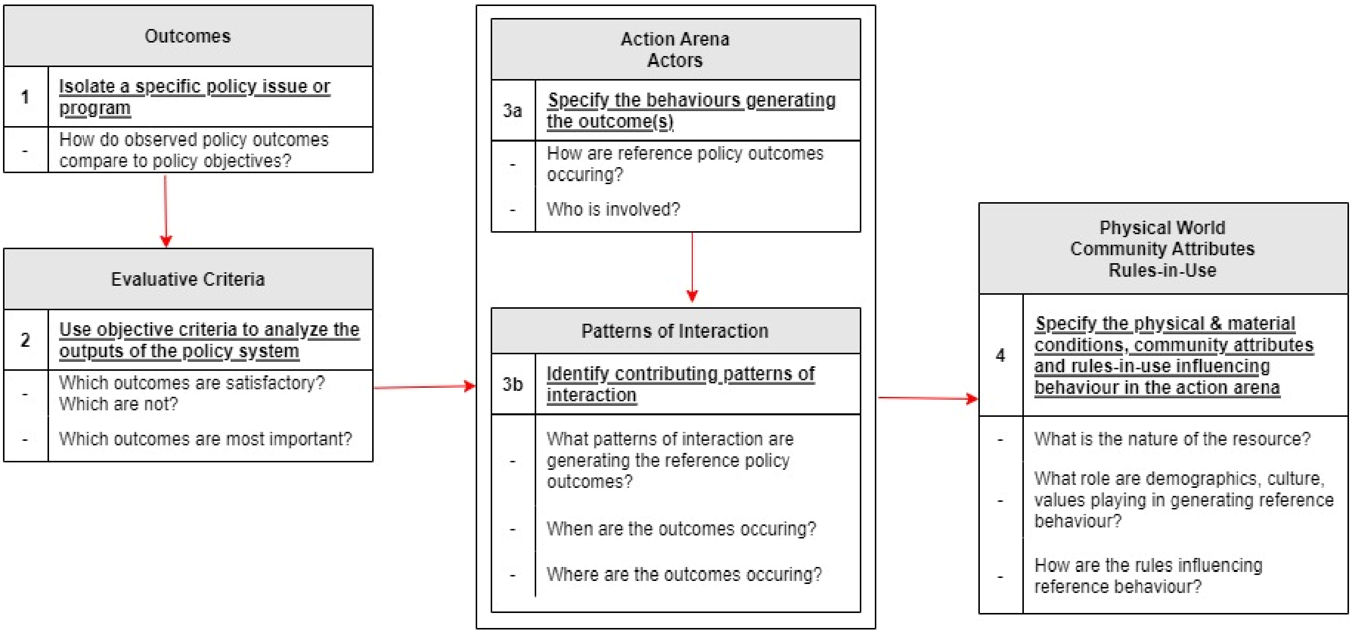


Figure 3: Diagnostic application of IAD framework. Source: Authors. Abstracted from (Polski and Ostrom, 1999)

2.3 IAD Framework Analysis of the Minigrid Sector

2.3.1 Institutional and Socio-Cultural Analysis of the Minigrid Context

We use the IAD framework to decompose the minigrid institutional context into its component parts to understand how actors against a backdrop of technical, social, and economic constraints interact together to produce desired outcomes. Figure 4 shows core minigrid variables structured into a relational schema that is the IAD framework.

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 minigrid resource; *community attributes* are defining characteristics of the community that pertain to using and managing the minigrid resource (Gollwitzer et al., 2018).

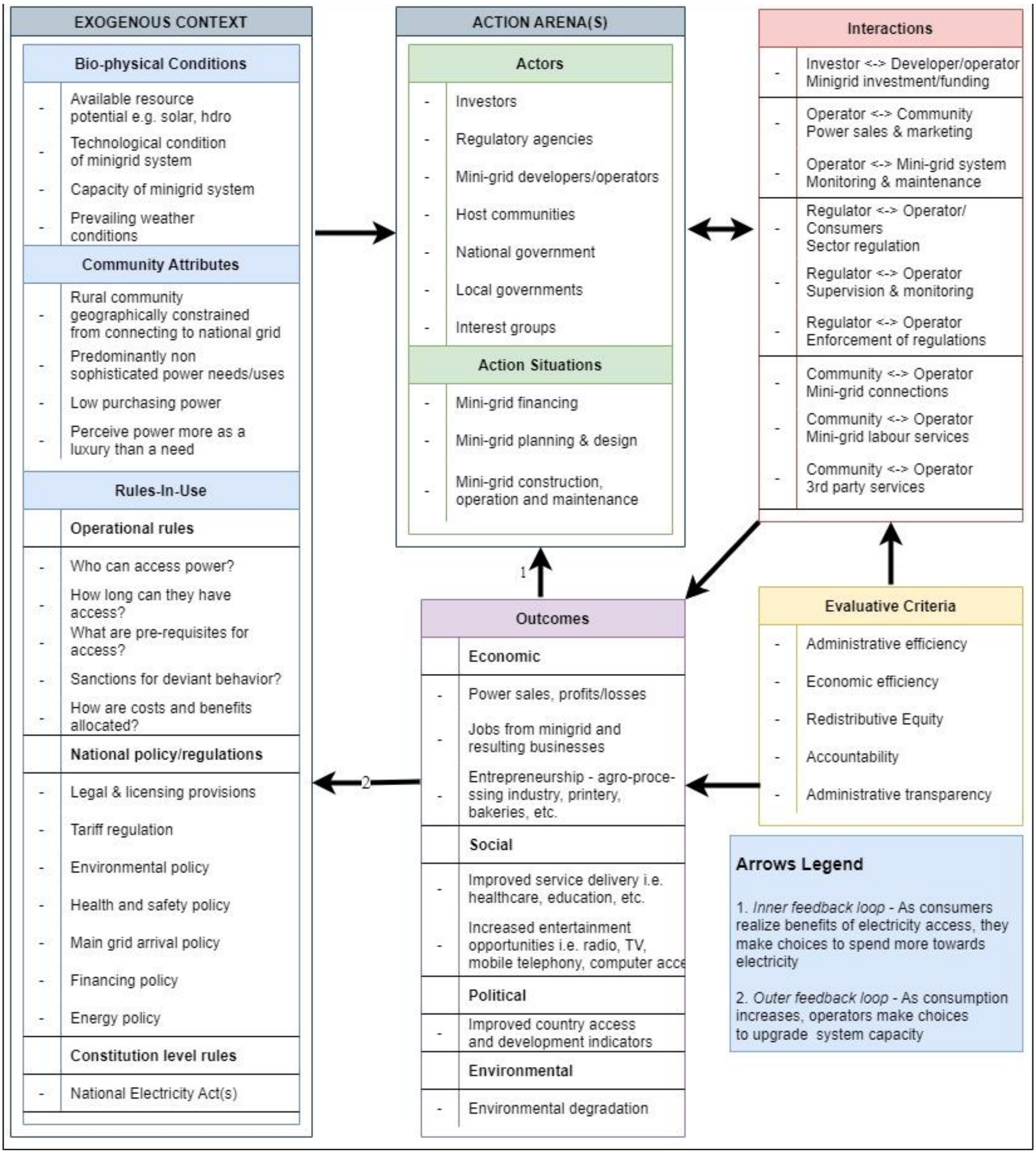


Figure 4: IAD framework structure of core minigrid institutions. Source: Authors

The Rules-in-use in Figure 2 are at three levels (Cole, 2017): At operational level, individuals interact with each other and the minigrid 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., 2015). At the policy level, regulators craft regulations for the operators and consumers while the minigrid operator sets the rules of service for consumers. At the constitutional level are position rules that establish who can issue minigrid licenses and craft governing policy for the sector.

At its centre, Figure 4 lists the central actors: Investors are private, local governments, donor/development partner agencies, or host communities funding minigrid 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 and Oladokun, 2021). Local governments provide permitting and local approvals for minigrid operations. Host communities are target consumers of power and resource partners in minigrid implementation. Interest groups including Non-Governmental Organisations (NGOs), donors, and 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, minigrid resource appropriation involves interactions of consumers with the minigrid resource in the sale and purchase of power and interactions of the minigrid resource system with the biophysical context in terms of resource generation. Second, the rule-making arena is where different rule-making agencies interact to draft governing rules for the sector. Third, the resource maintenance arena involves interactions on the part of the operator, consumers, and the resource system on maintenance, and lastly, the monitoring and supervision arena in which the operator, consumers, and regulator interact to ensure compliance with established rules.

Outcomes are generated at the juncture of action situation outcomes, actors' choices and interactions, and exogenous impacts. There are a number of minigrid 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. Minigrid 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 minigrid context, applicable criteria may include economic efficiency, administrative efficiency, distributional equity, and administrative transparency.

2.3.2 Action Arenas in the Minigrid Implementation Context

Building on the minigrid institutions and social-cultural context presented in section 2.3.1, we now explore the action arenas that make up the three main stages of the minigrid implementation cycle – *Minigrid Financing*, *Planning and Design*, and *Implementation*. For each stage of minigrid 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).

2.3.2.1 Minigrid Financing

In this arena, minigrid investments are motivated and funded. Information on business plans, grid ownership models, and risk assessments are prepared as inputs into investment decisions. Investments come from private investors, donor organizations, governments, direct from the target minigrid communities, or a hybrid combination of 2 or 3 sources. The source of investment determines the minigrid ownership model, the payback, and Return on Investment (RoI) requirements.

Table 1: Analysis of Minigrid 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 minigrid 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 minigrid asset	Private/public /community investment	**Boundary rules** -> Minigrid 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 Terms & Conditions, 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 minigrid 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	- Minigrid operation licenses - Minigrid concessions, subsidies (if any)	
Minigrid 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	- Minigrid funding - Business profit share	- Minigrid funding - Investment partnerships - Profit share and payback agreements	

In Table 1 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-in-use, and the resulting net costs and benefits. The rules referenced in Table 1 are the policies and guidelines in place to guide actors' choices and behaviors. They govern who investors can be and the roles of the different actors (position rules). They set the terms of actor interactions (choice rules). They structure the minigrid market via minigrid tariff policies and government concessions/subsidies (pay-off rules).

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 (USAID, 2018a, 2018c). In the community-based model, local communities own, operate and maintain the minigrids, 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 minigrid 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, and local tax rates (Bhattacharyya and Palit, 2016; USAID, 2018a). These are external to the minigrid 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 behavior, respect for the rule of law, and consumer preferences, which inform future minigrid market prospects (Bhattacharyya, 2018; Madriz-Vargas et al; 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.

2.3.2.2 Minigrid Planning & Design

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

Another key planning role is that of local governments - intermediaries between host communities and minigrid developers, responsible for community mobilization of needed resources e.g. land, local labor, coordinating engagement efforts between the community and developers, and mediation in case of disputes. The existence of regulations that are necessary, efficient, and effective is fundamental in easing the complexity of interactions between all actors in the planning and design stages as many projects are abandoned here (Bhattacharyya and Palit, 2016; USAID, 2018b). Regulations inform land procurement and settlement processes, choice of service territories, tariff regimes, minigrid concessions, etc.

Table 2 brings to light the multiple policy arenas at play in the minigrid 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 minigrid implementation (Deshmukh, 2013). These agencies are autonomous but interdependent, sharing information at different stages of the minigrid 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 minigrid license (ERA, 2020).

Table 2: Analysis of Minigrid 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 - Achieving projected electricity access outcomes	- Minigrid 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,
Community (Target consumers/ Host community/ Landlord) - Community leaders - Local	- Clear resettlement & compensation plans (if any) - Planned product and service portfolio	- Support or sabotage minigrid plans	- Improved social & economic prospects - Improved job prospects	- Local project acceptanc e	

government representatives - Local community					impact assessments to regulator for approvals
Minigrid 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 minigrid plans	

2.3.2.3 Minigrid Implementation - Construction, Operation & Maintenance (O&M)

The implementation phase covers the actual execution in terms of minigrid 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 minigrid site set-up making local labor, 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 minigrid operators, technical staff, marketing and sales, customer support as well as the host community. Table 3 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, and 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, and service and environmental standards.

Table 3: Analysis of Minigrid Construction, Operation and Maintenance Action Arena

Actors (Roles)	Information requirements	Choices	Net Costs & Benefits	Outcomes	Rules
Minigrid operator (System installers/ Monitoring agents/ Maintenance agents/ Sales& marketing agents)	- Technical installation standards - System performance reports - Power sales reports - Financial reports - Customer complaints reports	- Choice of local capacity building or external expert hires - Choice to subcontract operations or use in-house team - Choice of power tariffs	- Cost of local training & capacity building - Cost of sales	- Return on investment - Local support capacity - Sustainable operations	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
Regulator (Regulator/ Supervisor/ Monitor/ Enforcer)	- Sale prices/tariffs - Customer complaints and resolution procedures - Technical system design(s) - Minigrid performance reports	- Choice to penalize operator breaches or not - When and how much to inspect - Choice to review obsolete policies	- Direct costs of monitoring & supervision - Standard system installations	- Consumer protections - Environmental protections - Up to date sector policies	
Community (Consumers/ Customers/ Labour/ Business partners)	- Sale prices/tariffs - Operator service level agreements - Service complaints handling procedures - Minigrid jobs on offer - Available partnership opportunities	- Choice to take up jobs on minigrid - Choice of business partnerships with operator - Choice to connect to minigrid - When and how much to consume	- Direct electricity costs - Added jobs - Added business opportunities	- Electricity access for the community - Improved social, economic prospects	

2.3.3 Synthesis of Findings from the Minigrid Action Arenas

The following themes emerge from the minigrid action arenas described in sections 2.3.2.1-2.3.2.3: 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 minigrid sector.

2.3.3.1 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 minigrid ownership/management models – private, government, community, hybrid; the full scope of internal minigrid actors – developers, operators, financiers, suppliers, service providers; and a plurality of regulatory/policy arenas at play – energy/electricity, environment, financial, labor, 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 centers of decision making and a complex mash-up of rules governing all the interactions. Figure 5 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 interconnectedness.

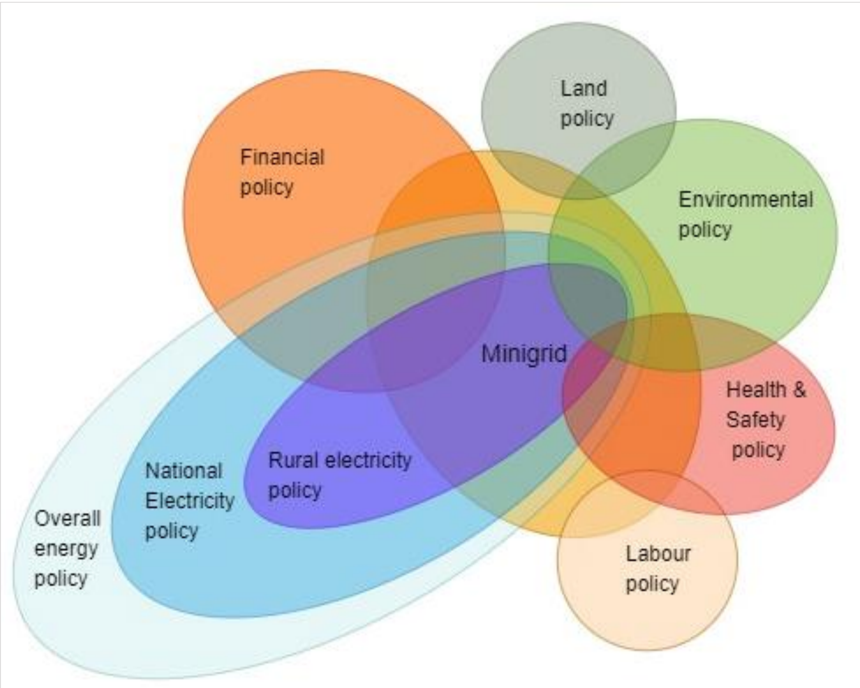


Figure 5: Nested, inter-dependent minigrid policy arenas. Source: Authors

2.3.3.2 Regulation in the Minigrid Sector

An analysis of all action arenas highlights the enormous role of the regulator across all 3 stages of minigrid implementation – regulating, licensing, monitoring, and supervising. Minigrids 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 1) 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 using penalties, to alter the economic behavior of actors.

The fast pace of scientific innovation, social change, environmental challenges and the impetus for rural economic development in the minigrid 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 and Palit, 2016).

2.3.3.3 Minigrid Adjacent Situations/Arenas of Influence

Each action situation in the minigrid 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 minigrid 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 minigrid sector (IRENA, 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 and Ducroux, 2003). Renewable energy minigrids have become a strategic focus for sector actors; reflected in increased technological innovation budgets at the international and national levels, and more investor friendly minigrid policies and regulations. The main-grid is another influential arena with direct influence not only on the prioritization of minigrid related resources, choice of minigrid technology, siting/location, minigrid tariff, but also specific policies like main-grid arrival policy (Nkiriki and Ustun).

Minigrid action arena(s) are nested within the local and national political action arena(s). Minigrid 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).

2.4 Comparative Institutional Analysis of Uganda and Tanzania's Minigrid Sectors

In this section we undertake a systematic, comparative institutional assessment of Uganda and Tanzania's minigrid energy sectors. We describe their minigrid 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 minigrid institutions.

2.4.1 Overview of Uganda and Tanzania's Minigrid Regulatory Context

Key in the countries' minigrid sectors is government's central role in the determination of minigrid 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))[5] 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

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

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 minigrid 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 minigrid numbers and made her a regional leader in mini-grid development (Ibid). Prior to 2013 when REA(U) was established (Mini-Grids Partnership, 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 minigrid 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 minigrid regulatory frameworks is presented in Table 4.

Table 4: A comparative assessment of Uganda & Tanzania's regulatory frameworks

A.	**Minigrid Financing**	
1.	Minigrid investment laws and policies	Uganda's Rural Electrification Strategy and Plan specifies Government's energy investment plans plus the areas earmarked for minigrid 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 minigrids investors	To drive sector growth, in **both countries**, Rural Energy Agencies 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	Minigrid 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 minigrid sites	**In both countries**, operators 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 minigrid commencement (GoU, 2020) (Tenenbaum et al., 2014).
B.	**Minigrid Planning and Implementation**	
1.	Minigrid 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** (Mini-Grids Partnership, 2020)
2.	Technical standards and designs for minigrids	**Both countries** have specific regulations on minigrids technology, technical standards and codes relevant for design, construction, operation and maintenance of minigrids.
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** minigrid 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 minigrid licensing and operations.
7.	Decommissioning of minigrid	**Uganda** issues specific guidelines on minigrid decommissioning. See Appendix 1 **Tanzania** however, lacks specific regulations on minigrid decommissioning.

2.4.2 Uganda and Tanzania's Minigrid Sector Outcomes

We examine minigrid sector outcomes in the two countries with a focus on current numbers of minigrid connections, growth rates and minigrid survival rates, comparing them against the policy objectives in the respective policy frameworks. Table 5 summarizes latest available[6] minigrid data for Uganda and Tanzania.

Table 5: Uganda & Tanzania cumulative annual minigrid numbers, connections and growth rates

Minigrid types	Uganda			Tanzania					
	2020[1]	2021[2]	2022[3]	< 2016[4]	2016/17[5]	2017/18[6]	2018/19[7]	2019/20[8]	2020/21[9]
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	**16***	**19***	**48***	**109****	**112**	**116**	**136**	**159**	**175**
Connections	**4,000**		**>20,000**	**184,000**			**187,298**	**193,955**	**199,951**

[1](UOMA 2020); [2](UOMA 2021); [3](UOMA 2022); [4](Odarno et al. 2017); [5](EWURA 2018); [6](EWURA 2019); [7](UWURA 2020); [8](EWURA 2021); [9](EWURA 2022)

** Only includes minigrids with confirmed operational ststus ~18 minigrids have unknown operational status*
*** Number includes 14 non-operational minigrids and 18 minigrids of unknown status*

Missing fields – Unable to find information in that category
The grand total for minigrids and connections in Tanzania, are authors' compilation from the cited sources

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% (IEA, 2020). From Table 5, Uganda's minigrid 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 minigrids between 2020 and 2022 (UOMA, 2022). There has been an improvement in the minigrid 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

[6] Current country specific minigrid data for both Uganda and Tanzania from government agencies and established sources are limited and incomplete which restrains precise triangulation of minigrids numbers.

(RESP) of 2013-2022. In addition, the survival of existing minigrids is a concern. As of 2020, out of 34 minigrids, only 16 were confirmed as operational and 18 had unknown status; a survival rate of ≈47% (UOMA, 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; UOMA, 2022, 2021, 2020, 2019).

As of early 2016, Tanzania had 109 minigrids, of which only 77 were confirmed to be operational, 14 non-operational and 18 with unknown status; a minigrid survival rate of ≈71% (AMDA, 2018; Odarno et al., 2017). A total of 66 minigrids were subsequently registered between 2017 and 2021 (EWURA, 2022, 2021, 2020, 2019, 2018), which makes a total of 175 registered minigrids in Tanzania (See Table 5). While Tanzania posts much better numbers than Uganda, her minigrid 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 (ESMAP, 2022; Mini-Grids Partnership, 2020).

2.4.3 Key Action Arenas, Causal Patterns of Interactions and Exogenous Context

The outcomes presented in section 2.4.2 reveal low minigrid numbers, poor rates of minigrid survival and sector growth rates that lag set government targets. The outcomes are generated out of actor interactions in the minigrid market, permitting and administration, and minigrid 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.

2.4.3.1 Minigrid Market

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

Minigrid financing. Uganda's Rural Energy Fund (REF) was established in 2007 to fund electricity access projects to rural communities through the development of minigrids. The program, funded by the World Bank and the government of Uganda, offers financial incentives to private minigrid 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 and 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 minigrid sector. Additionally, Tanzania's program is managed by a single agency, REA(T) (Willcox and 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.

Minigrid 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 minigrid tariff (Mini-Grids Partnership, 2020; UOMA, 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 (ERA, 2006). ERA, however, imposed a minigrid 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). Tanzania's

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 (Mini-Grids Partnership, 2020). TANESCO-run rural minigrid 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 minigrids.

2.4.3.2 Minigrid Licensing and Supervision Regimes

Sector reforms. Both Uganda and Tanzania's energy sectors experienced a devolution of functional and fiscal responsibilities transferring authority 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 2.3.4.1, 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 6) causing a level of incoherence and overlaps (Wabukala et al., 2022). Each has its own requirements and they do not coordinate on delivery timelines (Mini-Grids Partnership, 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) .

Administrative efficiency. Regulatory processes in the two countries, of minigrid license application, tariff approvals, environmental impact assessment approvals, etc. are characterized as cumbersome, expensive and time consuming (Mini-Grids Partnership, 2020) revealing a level of institutional inefficiency. Table 6 summarizes the different levels of approvals required for minigrids development in Uganda and Tanzania. With more than ten approvals to obtain, minigrid 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).

Table 6: Required approvals and responsible authorities involved in minigrid licensing

Required Approvals	**Responsible Authority**	
	Uganda	**Tanzania**
Minigrid operation		
Registering Minigrid	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 Minigrid 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

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 (UOMA, 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 that mandates prior social and environmental impact assessment approvals and takes a minimum of 180 days (ERA, 2020; Kapika and 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 the requirement is simply registration with the regulator. Registration, unlike licensing, is for information purposes only and does not require regulatory approval (Tenenbaum et al., 2014). This concept of light-handed regulation for SPPs may account for higher investment attraction in Tanzania.

2.4.3.3 Minigrid Policy-Making

Minigrid sector complexity. The complexity of the energy sector discussed in section 2.3.3.1 directly impacts the processes and outcomes of policy-making. There are various levels of government involved in minigrid 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 and 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 play 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 that support the deployment of minigrids. 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 the mini-grid policy in Tanzania over the last decade, with fewer significant changes or revisions. The higher level of certainty in Tanzania's minigrid sector could account for its relatively higher private minigrid investments.

2.4.4 Sustainability Implications of Uganda and Tanzania's Minigrid 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 2.4.2 and 2.4.3 has established that the current minigrid institutions in the two countries are not producing the desired sector outcomes. Figure 6 highlights the logical links from our IAD framework analysis of Uganda and Tanzania's energy sectors

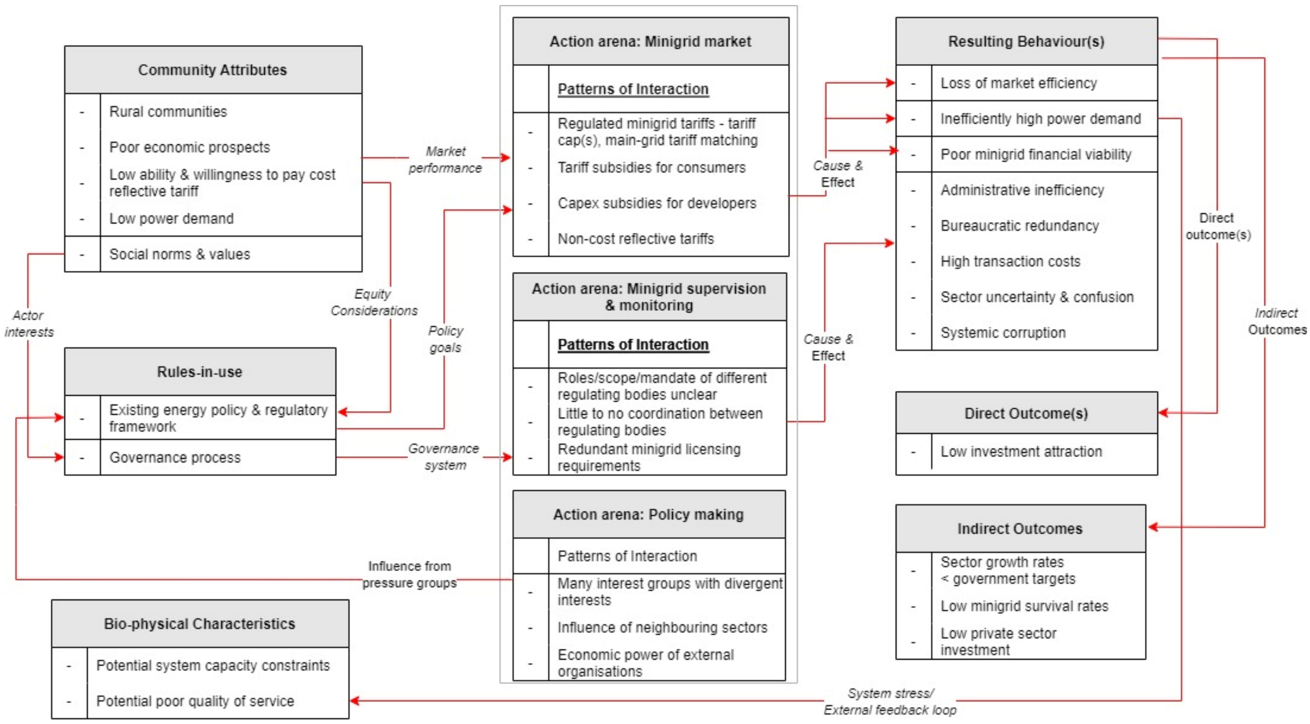


Figure 6: Logical links from IAD framework analysis of Uganda & Tanzania energy sectors. Source: Authors

2.4.4.1 *Institutional Efficiency*

The inefficiencies in the minigrid 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 2.4.3.2 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 minigrid regulatory framework (Wabukala et al., 2022).

2.4.4.2 Minigrid Market Design

With inflexible non-cost reflective tariffs and insufficient support financing, minigrid 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 minigrid 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 minigrid tariffs were not capped, there is a risk that electricity prices offered by minigrid operators may be unaffordable for many rural households. This could limit power demand potentially leading to the failure of minigrid projects.

2.4.4.3 Integrated Policy-Making

Described in sections 2.3.3.1, 3.3.3 and 2.4.3.3, 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 centers (see section 2.4.3.2). 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 and Biesbroek, 2016). It transcends the boundaries of established policy fields and individual departments (Meijers and 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, acknowledging a broader range of policy consequences concerning time, space, actors and issues, and consistent –applicable at all policy levels and government agencies (Meijers and Stead, 2004).

2.4.4.4 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 minigrid institutions. 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 (Ostrom, 1993a). Negative consequences are bound to arise when external rules that don't match the local context are imposed (Cox et al., 2010). In the minigrid case, the actors most affected, operators and consumers, should contribute in the formation and modification of minigrid 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.

2.4.4.5 Alignment of Social Norms and Cultural Values

In the socio-cultural context, human behavior 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 behavior 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, policies 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 minigrid 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, and maximize their interests at the expense of a thriving minigrid sector, the result is corrupt institutions characterized by unnecessary bureaucracy and unending gridlock.

2.5 Conclusion and Policy Implications

We set out to find the key institutional and socio-cultural considerations driving (un)sustainable outcomes in minigrid systems; the driving actors' choices and patterns of interaction and the sustainability implications of Uganda and Tanzania's minigrid policies. Our findings on minigrid institutions highlight two main considerations for sustainability: First, the challenge posed by the complexity and inter-connectedness of the minigrid sector and adjacent sectors. Second, the potential positive and/or negative impact(s) from adjacent sector arenas on the focal minigrid action arenas. In addition, we found the ability of Uganda and Tanzania's minigrid institutions to coordinate key actor interactions in the long term for the 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.

2.5.1 Policy Insights and Recommendations

2.5.1.1 Reshape Patterns of Interaction; Transform Outcomes

Section 2.4.3.2 highlights problematic patterns of interaction in the administration of Uganda and Tanzania's minigrid sectors. Poor inter-agency coordination, redundant-highly bureaucratic processes, and corrupt actor behaviors 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/behaviors 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 *standardization* of processes to reduce complexity.

(2) Change of actor incentives: *Digitalization* 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 the 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 the 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.

2.5.1.2 Integration in Policy-Making and Implementation

Section 2.4.3.1 reveals a distorted minigrid market that is reliant on unsustainable government subsidies, a result of ‘fixed’ community attributes and external environment in the low economic prospects of minigrid communities and consumers’ low ability to pay. In 3.3.1 and 3.3.3, we describe minigrid 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, labor, etc. Adjacent sector impacts will either combine with focal sector dynamics to reinforce 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 the growth of viable and sustainable minigrid energy markets independent of long-term government stabilization programs.

2.5.1.3 Structures for Participatory Policy-making

Given the diversity and heterogeneity of policy actors, the formulation and adoption of minigrid 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.

2.5.1.4 Values Adoption to Drive Institutional Change

Section 2.4.4.5 discusses the impact of a potential mismatch between host community core values and the values informing minigrid 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, policymakers can drive values adoption; positively altering expected patterns of behavior and consequently outcomes. To achieve this, policymakers must strengthen the feedback mechanism with the 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.

2.5.2 IAD Framework Contribution

The minigrid institutional context is a complex system of divergent actor interests from multiple interdependent 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 minigrid 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 minigrid institution sustainability.

2.5.3 Study Limitations and Future Research

It is worth noting that the study is limited by the paucity of verified minigrid numbers data for triangulation purposes 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 minigrid 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.

2.6 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.

Funding: This work was supported by Africa: Research and Teaching Platform for Development - Sustainable Modular Grids Project (A: RT-D Grids) funded by the German Federal Ministry of Education and Research (BMBF) under the Client II program – funding ref 03SF0607A.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful for the support of Prof. Dr. Burkhard Hehenkamp for the valuable discussions and insights that led to the direction of this paper. A special thank you to Angelika Endres-Fröhlich for her detailed manuscript review and feedback.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

3 Design of Sustainable Minigrid Governance Institutions

Navigating Emergent Effects in Off-grid Systems: Ostrom's Design Principles and Rural Energy Policy Implications[7]

Lillian D. Namujju[8,9]

Abstract

The study explores the resilience of Ostrom Design Principles (ODPs) in the governance of rural community off-grid systems as complex adaptive socio-technical systems displaying emergent behavior, and whose environment is constantly changing and unpredictable. Applying Systems thinking and feedback loop analysis, this study utilizes Gwere-Luzira, a rural Sub-Saharan African community off-grid project, as a case study to investigate the complexity of interactions between the institutional and physical infrastructures of off-grid systems, their external environment, the influence of people-culture on their design and functioning, and the resulting emergent effects stemming from these interactions. It identifies emergent effects, such as poor infrastructure access, limited local economic prospects, and community disengagement, as challenges to the robustness of the ODP framework, hindering off-grid system sustainability. The analysis maps out reinforcing feedback loops to trace perceived governance failures from their root causes to cascading impacts across subsystems, while proposing balancing loops to counteract negative spirals and enhance project sustainability. The study recommends integrating ODPs with broader strategies to address external challenges outside of host community control and ensure the long-term viability of community-owned off-grid systems.

JEL Classification: D02, D04, P28, Q48

Keywords: Ostrom Design Principles, Socio-technical Systems, Systems thinking, Causal loop analysis, Community minigrids, Energy policy.

[7] The research paper has been accepted for publication with the *Journal of Energy Research & Social Science*

[8] Chair of Institutional Economics & Economic Policy, Department of Economics, Paderborn University, Warburger Str. 100, 33098, Paderborn, Germany

[9] Department of Electrical & Computer Engineering, College of Engineering, Design, Art & Technology, Makerere University, Kampala, Uganda

3.1 Introduction

Off-grid systems are energy solutions that operate independently of the main electrical grid (Mandelli et al., 2016), essential for remote and rural areas where extending the central grid is impractical or too costly. These systems, such as mini-grids and pico-grids, typically range from a few kilowatts (kW) to several hundred kilowatts tailored to smaller electricity demands and community sizes. They offer cost-effective solutions for rural electrification in Sub-Saharan Africa. This study utilizes Ostrom Design Principles (ODPs) to assess the resilience and sustainability of such small-scale off-grid systems, focusing on their formation, organization and governance. The case study of Gwere-Luzira (Gwere) pico-hydro system, a community-owned project in rural Northern Uganda, illustrates these dynamics.

There is a large body of literature about the organization of collective action in common pool resource (CPR) management featuring ODPs for sustainable community-governed commons (McGinnis and Ostrom, 1996; Ostrom, 1992). ODPs have been widely applied to analyze the management of natural common-pool resources such as forests (Ostrom, 1999c; Saeed et al., 2017), fisheries (Trimble and Berkes, 2015), and water resources within local communities (Dell’Angelo et al., 2016; Ostrom, 1993b). They have also been extended to urban contexts, including the management of public spaces, urban forests, and community gardens (Foster and Iaione, 2019). The principles have been adapted to fit specific resources, user communities, and ecological contexts, avoiding a one-size-fits-all approach (Hanna et al., 1995; Ostrom, 1990b; Pinkerton and Weinstein, 1995; Wade, 1988; White and Runge, 1995). However, a significant gap exists in the literature regarding the governance of socio-technical CPRs, particularly when these resources are foreign-installed infrastructures within local communities.

ODPs assume a relatively stable and predictable CPR environment and focus primarily on local/micro-level governance of CPRs. By contrast, socio-technical systems (STS) are large-complex systems with a multiplicity of links, un-predictable non-linear dynamic behavior, limited ability of actors to influence the overall conditions of the system, the success of which depends on coordinated interaction and co-dependence between technical and social subsystems (Johannes M. Bauer and Paulien M. Herder, 2009; Taysom and Crilly, 2017). They are complex infrastructures where technological, economic, political, and social features interact through various mechanisms and feedback loops (Künneke and Finger). Off-grid energy systems are one such system and the focus of this study. This study explores the robustness of ODPs within the context of an off-grid socio-technical system in a rural Sub-Saharan setting, where emergent behaviors—such as unexpected operational challenges and shifting community dynamics—arise due to deep uncertainties in factors like infrastructure and resource availability. It also examines the strong interactions between physical subsystems, like energy infrastructure, and social subsystems, such as community engagement and economic participation, which together shape the overall performance and sustainability of the off-grid project. Understanding the dynamics and complexities of STS, their formation, and governance is crucial for ensuring their sustainability, resilience, and impact on local communities.

Studies on STS are not new. A number have focused on STS institutional design and governance (Koppenjan and Groenewegen, 2005; Pitt et al., 2017; Pitt and Diaconescu, 2016), while others have examined the complexity of STS design and its impact on social integration of technological systems (de-Bruijn and Herder, 2009; Righi and Saurin, 2015). A few have applied the ODPs to the analysis of rural electrification initiatives (C.G. Monyei et al., 2018; Moran et al., 2022; Schnitzer et al., 2014; Stephanie Hirmer and Heather Cruickshank, 2014). This study, by contrast, adopts a longitudinal approach in applying the ODPs to the understanding of socio-technical energy systems governance. It employs a holistic system thinking analysis of the emergent effects arising between the different parts of a community off-grid system and how they affect the robustness of its governance system.

Emergent effects are an integral part of STS and, in this study, serve as independent variables in evaluating ODP robustness. They are those outcomes or phenomena that arise from the interaction of different parts of a complex system, rather than the result of any one individual part, and as such, are not predictable from the properties or behavior of individual system components in isolation (John S. Osmundson et al., 2008). The systems thinking approach recognizes the interconnected and complex nature of community off-grid systems and the need for a holistic understanding of their dynamics; enabling a comprehensive examination of the interactions and interdependencies. Significantly, feedback loop analysis, a key component of systems thinking, plays a crucial role in uncovering the causal relationships and feedback dynamics within the system (Kay, 2008).

The remainder of this paper is structured as follows: Section 3.2 lays out the theoretical foundation of systems thinking, emergent effects, and ODPs in the context of off-grid STS sustainability. Section 3.3 details the study methodology. Section 3.4 examines the emergent effects in the Gwere case study. Section 3.5 analyzes how the emergent effects arise and evaluates the effectiveness of the ODPs in addressing these emergent effects. Finally, Section 3.6 concludes.

3.2 Socio-technical Systems: Concepts, ODP robustness & Off-Grid Analysis

The literature on systems thinking and feedback loop analysis is extensive and spans various fields, including environmental sustainability, telecommunications, organization management, and energy systems (Hossain et al., 2020; Rachel Freeman et al., 2013). Systems thinking emphasizes viewing the system as a whole and recognizing interdependencies between social, technical, economic, and environmental factors (Groundstroem and Juhola, 2021; Laimon et al., 2022). It helps researchers understand interconnections, feedback loops, and emergent properties, identifying potential leverage points for intervention (Jenny Tejeda and Susan Ferreira, 2014; Laimon et al., 2022). Feedback loop analysis is valuable for identifying reinforcing and balancing loops, showing how changes in one component affect the entire system and where design principles can be adjusted to promote sustainable outcomes (Laimon et al., 2022).

This study uses systems thinking principles, specifically feedback loop analysis, to examine the emergent effects of the Gwere Community minigrid and assess the robustness of ODPs in addressing these effects and their impact on minigrid sustainability. Systems thinking is employed to capture the complex interdependencies within socio-technical systems, which include physical infrastructure, institutional arrangements, and socio-cultural factors. By recognizing these interconnections, this approach helps policymakers anticipate unintended consequences, develop robust strategies, and design adaptive management practices.

3.2.1 ODPs and Robustness Mechanisms

The strength of the ODPs in governing socio-technical systems is rooted in their capacity to address the inherent complexities, dynamics, and uncertainties that these systems entail (Anderies et al., 2003). The robustness of a governance framework lies in its ability to maintain its performance and effective function when subjected to external, unpredictable perturbations in a wide range of conditions and scenarios (Anderies et al., 2003). Such a framework is effective, scalable, and can withstand changes in the environment, economy, and society (Nelson et al., 2007). In essence, a robust application of Ostrom's Design Principles implies that they are not overly rigid or prescriptive but can be customized, remaining effective in promoting sustainable resource management and governance even when faced with changing environmental, social, or economic circumstances (Ingram and Hong, 2009; Ostrom, 2008).

ODPs incorporate mechanisms for monitoring and adaptive responses to address uncertainties and risks in STS (Haryanto et al., 2022). Figure 7 summarizes the ODPs as they pertain to the governance of highly complex and uncertain socio-technical systems. They promote the establishment of conflict resolution mechanisms, emphasize the importance of local autonomy, empowering communities to take ownership for the management of their systems. However, ODPs are limited in handling non-linear system dynamics and feedback loops, where small changes can cause disproportionate and unpredictable effects (Haryanto et al., 2022; Singleton, 2017). Operating within a linear cause-and-effect framework, ODPs work well for traditional resource management where outcomes are predictable—clear rules and governance structures directly translate into expected outcomes (Anderies et al., 2003). However, in complex socio-technical systems like community-owned off-grid systems, multiple interconnected subsystems interact, and a small technical failure, coupled with a community’s limited economic resources, can cascade into financial instability, reduced community participation, and ultimately impact the system's sustainability.

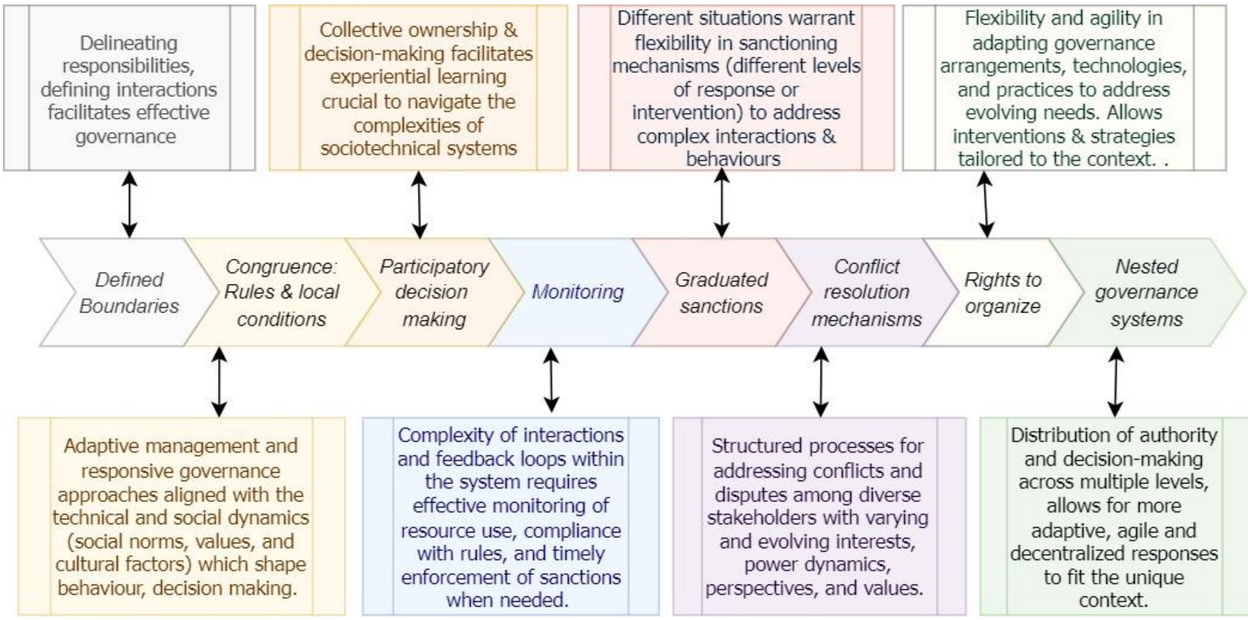


Figure 7: ODPs applied to navigating the complexity, dynamism, and uncertainty of Sociotechnical Systems. Source: Author

3.2.2 A Longitudinal Approach to ODP Implementation

The ODP framework has typically been applied in the context of governance of socio-ecological systems, where multiple individuals or communities have shared interests and responsibilities in managing a resource. The principles provide guidance for establishing effective governance mechanisms that promote sustainable and equitable outcomes. They provide a comprehensive framework for effective governance that emphasizes collective choice arrangements, monitoring regimes, graduated sanctions, conflict resolution mechanisms, and the alignment of rules with local conditions (McGinnis and Ostrom, 1996). In this study, the ODPs are applied longitudinally across the formation, organization, and governance stages of the off-grid STS lifecycle, facilitating a comprehensive examination of their relevance and applicability at different developmental phases. This approach not only assesses current governance practices but also highlights trends and changes over time. STSs demand adaptable governance approaches that can evolve with the unique challenges posed at each stage of their development. When applied flexibly and adaptively, ODPs in an off-grid setting can ensure that governance structures are congruent with changing local conditions, addressing the dynamic nature of energy access in remote areas.

3.2.3 *The Off-grid Socio-technical System*

The study conceptualizes the socio-technical off-grid system as comprising six interconnected subsystems, as adapted from (Anderies et al., 2004). Figure 8 illustrates their different interaction interfaces. In an off-grid system, electricity forms the resource subsystem, classified as a rival good due to its finite and subtractable nature, yet renewable as it is hydro-powered.

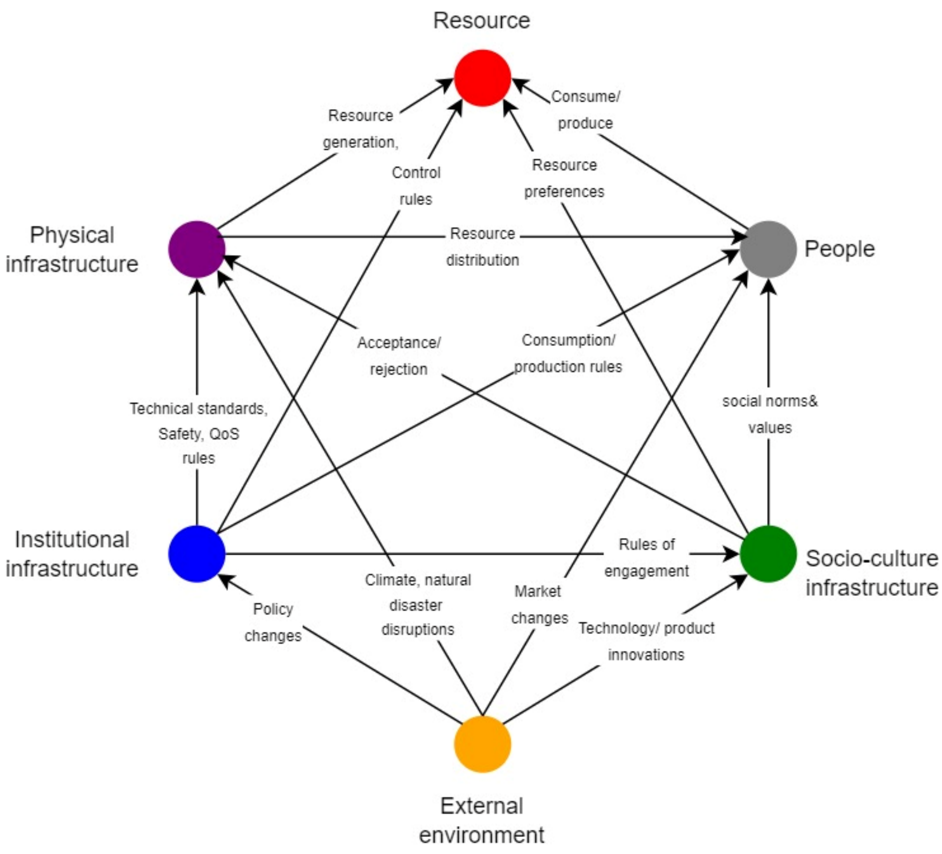


Figure 8: A socio-technical systems thinking perspective of the off-grid system following (Anderies et al., 2004). Source: Author

3.2.3.1 *Off-grid Physical Infrastructure, External Environment Subsystems*

The physical infrastructure consists, a complex, evolving system characterized by dynamic, non-linear interactions and emergent effects. The physical infrastructure of a minigrid STS is a complex network of components, interconnected and interdependent, that interact in uncertain, indeterminate ways leading to non-linear emergent effects that are difficult to predict (Polojärvi et al., 2023; Ronan Bolton and Timothy J. Foxon, 2015). This uncertainty can be driven by technological advancements, evolving user requirements, or external factors such as regulatory changes. The physical infrastructure consists of the power grid, including hardware components, software systems, communication networks, etc., each with their own specializations and roles.

The physical infrastructure is embedded within a broader context, the external environment dimension, encompassing all the external factors and conditions that can influence the operation, sustainability, and performance of the minigrid system including uncertainties from natural, social, regulatory, and technical disruptions. Navigating these elements is essential for ensuring the resilience and success of the off-grid system.

3.2.3.2 Off-grid Institutional Subsystem

Institutional infrastructure of an STS comprises the formal and informal rules, norms, and governance mechanisms that guide the behavior of individuals and organizations within the system (North, 1993; Powell and DiMaggio, 2012). It includes formal mechanisms like laws, regulations, policies, standards, as well as informal norms, beliefs, and values that shape the behavior of individuals and groups within the system (Ostrom, 1990b). A strong and effective institutional infrastructure can help to ensure that the benefits of the system are shared equitably and sustainably, and that the system functions effectively over the long-term (Ostrom, 1990b). To describe the minigrid institutional infrastructure, I adopt Treib et al. (2007) (Treib et al., 2007) governance dimensions: the politics dimension which is focused on the actors involved and the power relations between them including negotiations, and decision-making processes; the polity dimension which is about the formal rules governing interactions between the actors as well as the unwritten rules that form the framework for the political culture of a community (Caiani and Graziano, 2022; Sager and Gofen, 2022); and the policy dimension pertaining to the instruments, both formal and informal, that are used in enforcing the rules that guide the establishment, operation, and management of the minigrid (Treib et al., 2007).

Based on the context of a small community-owned off-grid system, this study categorizes the policy dimension into subsystems including the regulatory framework, policies (such as energy and environment), and incentive schemes. The polity dimension encompasses local governance structures, stakeholder committees, local system operation and management rules, community engagement mechanisms, collective action, and community ownership. The politics dimension includes power dynamics, political will and support, advocacy and lobbying, resource allocation, community buy-in, and compliance. These subsystems interact through various causal and reinforcing feedback loops, ultimately impacting the energy delivery subsystem, which is part of the physical infrastructure.

3.2.3.3 Off-grid People-Culture Subsystems

The "people-culture" subsystems in a community minigrid encompass the social and cultural dimensions that influence and are influenced by the minigrid's design, implementation, and operation (A. Gill-Wiehl et al., 2022). The *People* subsystem involves service providers and resource users, reflecting diverse interests, shifting demands, and preferences shaped by the community's social and technological norms, ethics, and values. Understanding this interplay ensures that minigrids are not only technically robust but also socially and culturally sustainable, integrating seamlessly into the community's fabric (Venkata Bandi et al., 2022). The *Socio-culture* infrastructure of a socio-technical system, driven by its members' beliefs, values, and behaviors, significantly impacts its functioning and performance. Norms and values influence communication, collaboration, and innovation within the system. Cultures promoting open communication and collaboration foster innovation and effectiveness, while those resistant to change might hinder adaptability and resilience (Coiera, 2007) (Ropohl, 1999). Additionally, cultural norms around authority and decision-making affect how decisions are made and how individuals behave within the system (Namujju et al., 2023a). These cultural factors also shape attitudes towards risk and uncertainty, impacting risk tolerance, uncertainty acceptance, and the balance between short-term and long-term objectives.

3.3 Research Design and Methodology

This study employs a case study approach to analyze the Gwere off-grid hydro project, focusing on emergent effects within the socio-technical system and evaluating the robustness of ODPs. The analysis covers the minigrid project's design, formation, and governance, providing a comprehensive understanding of factors influencing off-grid system sustainability across its lifecycle.

3.3.1 Data Collection

Data collection comprised both primary and secondary sources. Primary data was obtained through semi-structured interviews and focus group discussions (FGDs) with key stakeholders in the Gwere hydro project community, including local leaders, community members, and representatives from the donor agency (GIZ), using purposive and convenience sampling. A total of 19 one-on-one interviews and 3 FGDs were conducted. Secondary data was gathered from project reports, governance documents, and relevant literature, enabling triangulation and cross-verification of findings.

The interviews and FGDs were designed to capture a broad range of perspectives on the formation, governance, and operation of the community minigrid system, particularly focusing on the perceived challenges and factors contributing to the project's failure. The interviews explored the participants' understanding of the project's technical aspects, community participation, governance structures, and socio-cultural influences. Topics included community ownership, maintenance issues, resource allocation, institutional support, and external economic factors. The focus group discussions provided a platform for group reflection on the collective experience of the project, particularly regarding stakeholder collaboration, conflict resolution mechanisms, and the broader socio-economic impact of the minigrid system.

3.3.2 Data Analysis

Interview data was transcribed and coded using MaxQDA software, with qualitative data analysis (QDA) focusing on identifying, examining, and attributing meaning to evident patterns or themes in the qualitative data. To analyze the Gwere off-grid system using systems thinking, the study first defines system boundaries and identifies key components and subsystems that influence each other. Causal relationships between these variables are then mapped based on qualitative data from interviews and focus group discussions, using Causal Loop Diagrams (CLDs). In these diagrams, a (+) arrow indicates variables changing in the same direction, while a (-) arrow shows variables moving in opposite directions. By tracing the arrows, feedback loops emerge: Reinforcing loops (R) amplify changes, driving exponential growth or decline, while Balancing loops (B) stabilize the system by counteracting change (Groundstroem and Juhola, 2021; Hossain et al., 2020; Laimon et al., 2022). Feedback loop analysis is further applied to examine these interactions to determine their impact on system performance and sustainability.

The study also maps ODPs to different stages of the minigrid lifecycle (formation, organization, and governance) to evaluate their effectiveness and identify gaps. This approach provides insights into current governance practices' strengths and weaknesses and offers recommendations for enhancing the resilience and sustainability of community-owned minigrid systems in rural contexts. By integrating systems thinking and feedback loop analysis, the methodology provides a holistic examination of the Gwere pico-hydro project's governance and operational dynamics.

3.4 The Case of Gwere-Luzira Minigrid Project

This section presents the results of a methodical case study evaluation of the Gwere community off-grid project. This examination encompasses the project's inception, establishment, governance, and ultimate decline, viewed through the perspective of Ostrom's design principles.

3.4.1 Gwere Project Description, Formation, Organisation & Governance

The Gwere Power Station, situated along the River Amoa in Northern Uganda's Moyo District, was a community-owned pico-hydroelectric project possessing a generation capacity of 0.5 kW, serving ~80 households within the village of Gwere.

3.4.1.1 Project formation

The project's inception was driven by a community member inspired by a similar project in Swaziland. The Gwere community raised initial funds by having each able male contribute UGX 20,000 (~$10 then) and each female UGX 10,000, plus a UGX 2,000 membership fee, totaling UGX 6 million. However, they needed an additional UGX 5 million for a turbine and cabling.

They sought support from the Promotion of Renewable Energy and Energy Efficiency Programme (PREEP) affiliated with the German Corporation for International Cooperation (GIZ). The villagers built the dam with GIZ's technical guidance, using locally sourced stones and sand. They constructed a 100-meter-long canal and a brick structure housing the control point including switch room and battery backup system. GIZ provided financial support for generation and transmission equipment and technical oversight, along with basic training for two technicians.

3.4.1.2 Project organization and governance

This section analyzes the core governance aspects of the Gwere off-grid project. Table 7 highlights the key areas of alignment between the Gwere project governance framework and the ODPs as applied over the different phases of its lifecycle.

Table 7: Mapping Gwere Project Governance with ODPs

ODPs	Context of application in Gwere
(1) Clearly defined boundaries†	• *Physical boundaries* technically defined by wired electrical connections connecting consumers to grid power. They delineate the physical reach and extent of the electrical grid. • *Social boundaries* determined by membership status and participation in the project restricting access to only those residents who held registered membership in the pico-hydro project • *Economic boundaries* associated with the villagers' capability to pay the fees set by the CBO. Inability-to-pay meant exclusion from access
(2a) Proportional equivalence of costs and benefits‡	• Without exception, all connected households received a single 5W bulb, and switches were only installed at a communal control point to support phone charging, communal radio, television facilities. • All households were obligated to partake in critical maintenance tasks, which included the clearance of the dam canals. Any instances of default were subject to fines as a form of penalty. • Project contributions from the community were levied based on gender with males required to pay twice as much as females • Due to lack of power metering, a flat maintenance fee of 1,000UGX was charged per month for all consumers irrespective of their consumption
(2b) Rules should fit local circumstances‡	• Subscription fees, project fees, cash fines set within the group constitution were proposed and agreed by members in line with what the average household could afford • Manual labor contributions for maintenance were demanded per household to compensate for the low power tariffs, which were insufficient to cover the costs of professional maintenance services

	• Central power point and communal switches were strategically located at the customary gathering spot where adult men would meet every evening to drink and socialize aligning with community's socio-cultural structure
(3) Participatory decision-making†‡§	• Group constitution was proposed and adopted in a meeting of all members • Group meeting resolutions are generated by majority vote • According to the constitution, attendance of group meetings was obligatory, and there were penalties in place for individuals who did not attend these meetings.
(4a) Commons must be monitored‡§	• Monitoring the physical conditions of the pico hydro dam was an integral part of the daily operations conducted by the operations committee. • This included overseeing member households' compliance with scheduled maintenance activities to ensure the proper functioning and upkeep of the hydro-dam.
(4b) Monitors accountable to the user community‡§	• Elected monitors on the operations committee were registered members of the group having close ties with the resource user community, including neighbors, relatives, and friends.
(5) Graduated sanctions for deviant behavior‡§	The group constitution strucures the sanctions as follows: • *Instant Cash Fines*: Smaller offenses, such as missing a meeting or defaulting on maintenance work, incur instant cash fines of UGX 3,000. • *Bigger Offenses*: including failure to pay the fine or repeated failure to participate in scheduled work, are handled by a select disciplinary committee with the authority to impose larger fines as necessary. • *Sub-County Court (LCIII)*: Cases that are not resolved by the disciplinary committee are escalated to the sub-county court of LCIII – a local government office. • *Property Seizure:* Group's constitution allows the operations committee to seize the property of members who do not pay the fines as specified, equal to the fine amount.
(6) Conflict resolution easily accessible‡§	Conflict resolution arenas include: • Group meetings: Resolutions are made by majority vote • Disciplinary committee: For resolving cases of repeat offenders or those contesting awarded fines • Any conflicts beyond the scope of the group meeting or disciplinary committee are fowarded to the sub-county LCIII court for resolution
(7) Commons need the right to organise†§	• The community officially registered a Community Based Organisation (CBO) - Gwere-Luzira Self Help Pico-Hydro Electricity Project. • Its constitution is legally recognized and acts as a governing document that outlines the rules, rights, and responsibilities of the cooperative and its members • Provisions within the cooperative's constitution are generally legally enforceable, both by the cooperative itself and by its members.
(8) Commons work best when nested within larger networks†§	• Group by-laws are binding on members but are subordinate to the general country laws, particularly as specified by the Cooperative Societies Act of 1991. • Conflict resolution structure involves various organizations within the group framework including internal disciplinary committee and external local government structures

† At the *project formation* stage, the primary focus is on defining the scope, ensuring inclusive decision-making, and securing the right to organize and integrate into larger networks (ODP 1, 3, 7 & 8).

‡ At the *project organisation* stage, focus is on setting rules that ensure fair distribution of costs and benefits, operationalizing mechanisms for inclusive decision-making, setup of monitoring processes, defining sanctions for rule violations, and establishing mechanisms for resolving disputes (ODP 2-6).

§ At the *project governance* stage, focus is on the continuous application and adaptation of these principles, ongoing participatory decision-making, continuous monitoring, application and adjustment of sanctions, support for the community's self-organization efforts, and calling on larger networks for broader support (ODP 3-8).

3.4.2 Stakeholder Perspectives of Gwere Minigrid Project

3.4.2.1 Community benefits vs expectations from minigrid project

In spite of the small size of the system, the community still reported a number of benefits achieved from the minigrid project including lighting, phone charging, communal radio, television and refrigeration facilities. For the different groups, differences in focal functional interests emerged.

Table 8 summarizes the main themes and specific stakeholder perspectives pertaining to the benefits of the project to the community.

Table 8: Perceived community benefits from the project

Theme	Main respondent category	Respondent perspectives
Lighting	Women	"That project was very good. When it was working, we had lights, children could read in the evening." "They (students) used to help out more at home because they had the extra time at night to finish their school work"
	Local teacher	"The extra reading time at night, allowed them (students) time in the afternoon to play more sports at school."
	Men	"With lighting at the central power point in the evenings, men could stay longer - drinking and socializing without worrying about increasing their kerosene costs"
Phone charging	All	"We were able to charge our phones without going long distances like before."
Income	Community leadership	"It was a source of income. People came from surrounding villages to charge their phones here."
Jobs	Community leadership	"Project employed 3 workers; 2 technicians and another worker in charge of central power point tasks e.g., charging cell phones."
Entertain-ment	Men	"There was a radio at the central point so we could listen to some news and football."
Community prestige	Community leadership	"We used to walk tall among our neighbors. They used to envy us a lot!" "Everyone knew our village. Reporters came all the way from Kampala (capital city) just to interview us."

Overall, the project, though small, had positive social and economic impacts and was a source of pride for Gwere village. In addition to benefits, respondents were questioned about their initial expectations for the project. The community held certain expectations at the project's outset, but some of these hopes remained unfulfilled, leading to a degree of disappointment. Table 9 summarizes the main expectations for key stakeholder groups. The expectations illustrate a mix of optimism, misconceptions, and a possible dependency mindset in terms of over-reliance on external actors outside the community.

Table 9: Stakeholder expectations of the project

Theme(s)	**Sub-theme**	**Respondent group, No./Total (%)**	**Respondent perspectives**
Free electricity	Expected free power in the face of free streaming water	CBO members, 6/17 (35.3%)	*"I thought that we would not have to pay for power since it was being generated from the stream, and the stream is free for all of us.*"
Unfulfilled expectations	Disappointed by unfulfilled system functionality	CBO members, 13/17 (76.5%)	*"We looked forward to using radios and maybe TV at home but it was disappointing that they (installers) did not install switches in our houses."*
Unexpected maintenance burdens	Did not expect the household maintenance burden for the system to be so big	CBO members, 8/17 (47.1%)	*"Many times, you had something else to do, but the leaders were strict and work had to be done.*"
Community ability to pay	Expected community contributions to fully support system maintenance	Local leadership, 3/4 (75.0%)	*"The income from the control point together with the monthly collections was expected to cover the maintenance but it was too little." "We had no choice but to set lower tariffs; that is what most households could afford*'.
Community dependency mindset	Over reliance on external actors for support i.e., Donor agency	Local leadership, 4/4 (100.0%)	*"We thought that in case the system failed, the donor would step in to support us "*
	Over reliance on external actors for support i.e., Government	Local leadership, 2/4 (50.0%)	*"Even the government was another channel we thought would come to our aid in case the system failed"*

3.4.2.2 Local technical capacity

Interviews with the local project leadership revealed challenges in retaining the two GIZ-trained technicians due to low remuneration. One member of the former operations committee explained, "*The GIZ training made them very valuable…. They got marketable skills that could export them out of Gwere. They got work outside.*" Another member recalled, "*It was a real problem supervising them. They looked for greener pastures. Sometimes the system would be off for days waiting for them to come back to support us.*" The financial viability of the CBO and the economic prospects in Gwere were insufficient to retain the skilled resources needed for the sustainable operation of the off-grid project.

3.4.2.3 Gwere project failure

Hydro-turbine failure. The hydroelectric system in Gwere-Luzira operated for about a year before the turbine failed. Previous failures, including lubrication needs and blockages from silt and debris, had been resolved by the community despite procurement challenges from Kampala, a 6-8-hour bus ride away. However, the latest turbine failure was more severe, and past solutions were ineffective, prompting the project leadership to seek assistance from the donor agency.

Donor agency engagements. The donor agency took the failed turbine to Kampala for repairs in 2011 but never returned it. Despite efforts by the Gwere project leadership to follow up, they were unsuccessful. Respondents noted, "*We had accumulated some savings with the village SACCO which we deployed so that the Village Committee chairman could go to Kampala to meet GIZ people. We heard that the problem required a new turbine to be imported from Germany. We got updates until the GIZ project coordinator left the country. After that, he (chairman) went about three times to Kampala but failed to meet anyone and the effort was abandoned.*" Additionally, there were no formal agreements outlining the responsibilities within the project, leading to information asymmetry and a lack of clarity for the community on the terms of engagement. When the project was handed over to the community, residents and local leaders recalled, *"… a big* *ceremony with many politicians from Kampala. Even the Minister of Energy, Madam Muloni came. …. there were many speeches and photographs, but no formal MoU or project handover document was signed with us".*

Community ownership and responsibility. The community set up a group savings fund via the local savings and credit cooperative organization (SACCO) from monthly tariff collections, which also served as a project maintenance fund. This fund allowed them to independently support multiple system repairs, showcasing community ownership and responsibility. However, as highlighted in section 3.4.2.2, the collections were insufficient to adequately pay and retain local technicians or support major repairs and turbine imports from Germany. Efforts to engage with minigrid sector governance agencies, such as the Electricity Regulatory Authority (ERA) and Rural Electrification Agency (REA), were unsuccessful, with the leadership noting, *"They did not give our request much priority; our project was too small."*. Consequently, the community's hopes for assistance were pinned on the donor agency. One member noted, *"We felt that as our partners, they would come to our aid when we needed them."* The community expressed a sense of powerlessness regarding the project failure, with the committee chairman stating, *"There was nothing we could do. They are the ones who paid for the turbine in the first place. What options did we have if they refused to return it?"* He added, *"The morale of the community was obviously not good after it failed. As chairman, I still feel embarrassed going back to re-engage the community for other projects."* The community exhibited some ownership and accountability for the system's sustainability; however, this was insufficient as they relied on external entities like the donor agency or the government and lacked a concrete long-term strategic plan to ensure its enduring viability.

Donor perspective. Interviews with two GIZ representatives, although not specific to the Gwere project due to faded institutional memory, provided valuable insights. They noted a shift in the PREEP program's funding strategy from hydro to solar minigrids, discontinuing investments in hydro projects like Gwere's. This shift was driven by ongoing innovations in solar technology, reducing costs over time. Further, GIZ's role in international development covering project management, financial oversight, procurement, and logistical coordination, as well as knowledge transfer, extends only until project completion. Typically, as a donor agency, GIZ collaborates with an implementing entity responsible for local execution and post-project support. In Gwere's unique case, the community acted as the implementation partner, responsible for both project execution and continuous maintenance.

3.5 Analysis of Gwere's Emergent Challenges & ODP Mitigation Strategies

Based on the findings in Section 3.4.2 regarding community perceptions of the Gwere project's failure, this study applies the systems thinking framework for community off-grid systems, outlined in Section 3.2.3, to conduct causal analysis and develop causal loop diagrams across the six subsystems. This holistic approach identifies the driving mechanisms behind dominant emergent effects, focusing on key reinforcing and balancing feedback loops, and assesses the extent of impacted subsystems. By doing so, the study evaluates the effectiveness of the governance system in addressing these issues and explores potential Ostrom Design Principle (ODP) strategies for mitigation.

3.5.1 Systems Thinking Analysis of Gwere Off-grid System

From the results in section 3.4 the study extracts key thematic subsystem elements constituted within the different subsystems of the Gwere off-grid STS, and these then form the interfaces of interaction that are the basis for the causal loop analysis.

The dominant themes in the physical infrastructure relate to the generation system, access roads, repairs and maintenance, and spare parts and inventory. The external environment features the local economy, off-grid regulatory framework, and the employment and labour context. The institutional infrastructure features the regulatory framework and off-grid policies and incentive schemes in the policy dimension, power dynamics, political will & support, advocacy & lobbying and resource allocation processes, as well as compliance and community buy-in in the politics dimension. The Polity dimension features the local governance structures, stakeholder committees, local rules and community engagement processes and the resulting community sentiment in terms of collective action and project ownership. Within the People-culture infrastructure are the social norms & values, the social-economic impacts from the project, community participation & ownership, stakeholder collaboration, education & capacity building, conflict resolution & grievance mechanisms and gender & social inclusion.

3.5.1.1 Off-grid Physical Infrastructure, External Environment Interactions

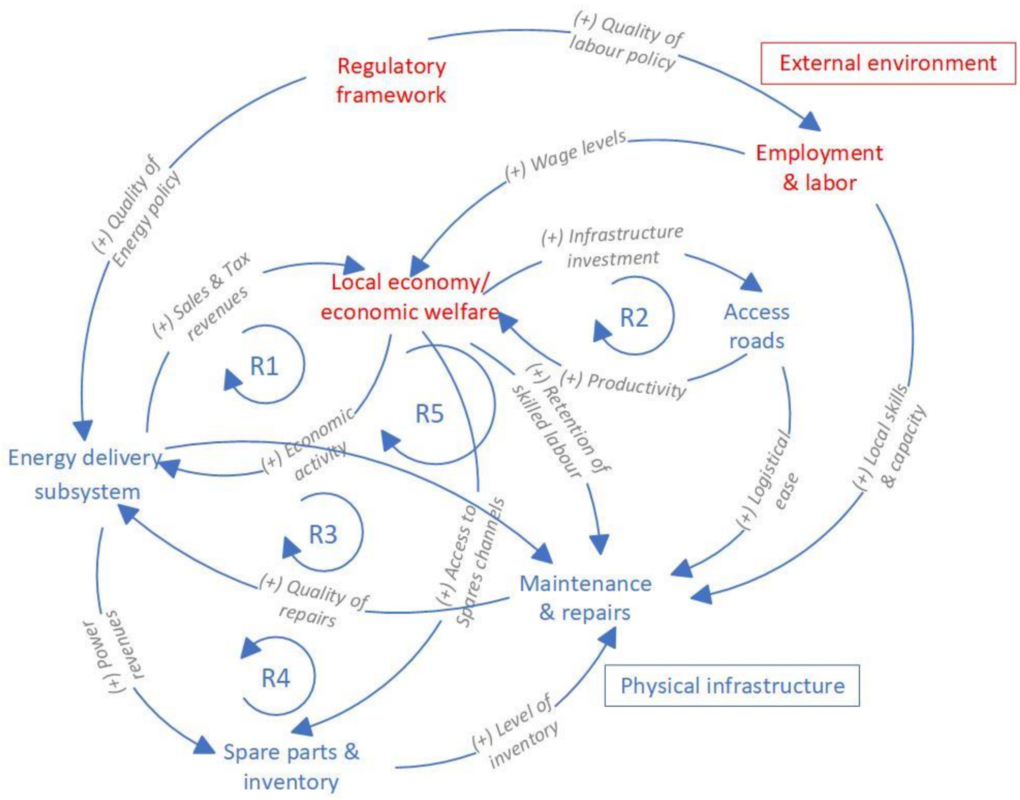


Figure 9: Causal loops and feedback mechanisms within the physical infrastructure and external environment. Source: Author

Figure 9 summarizes the multiple feedback loops that exist within the physical infrastructure ecosystem and its intersection with the external environment. The off-grid physical infrastructure interacts with the external environment through various causal and reinforcing feedback loops (R). R1 describes how improved energy system performance boosts sales and tax revenues, enhancing the local economy, which in turn increases productivity and power consumption. R2 shows that better transport infrastructure boosts productivity and strengthens the local economy, allowing for more infrastructure investment. R3 highlights that increased revenue from the energy system funds maintenance, improving system uptime and sales. In R4, a high-performing energy system generates revenue to stock up on spare parts, enhancing maintenance and ultimately system performance. R5 combines all these loops, showing that a high-performing energy system boosts the local economy, drives infrastructure investments, and facilitates maintenance logistics, further enhancing system performance and outputs.

3.5.1.2 Minigrid Institutional Subsystem Interactions

Figure 10 illustrates the causal loops within the institutional infrastructure. Within the policy dimension, fair regulatory frameworks mitigate negative power dynamics, preventing monopolization and ensuring equitable access and participation in the off-grid system. These frameworks also strengthen local governance structures, ensuring compliance and operational efficiency. Incentive schemes enhance community engagement and investment, fostering a sense of ownership and better maintenance of the microgrid. Additionally, strong advocacy efforts influence political will, leading to policy changes and resource allocation that support the microgrid's sustainability. In the polity dimension, local governance structures establish and empower stakeholder committees to represent community interests. These committees act as intermediaries, ensuring community voices and concerns are addressed. Community engagement fosters buy-in and ownership by involving members in the planning, decision-making, and implementation of the off-grid system. High levels of engagement and buy-in promote collective action, encouraging community collaboration towards common minigrid goals. In the politics dimension, power dynamics shape resource allocation within the community, allowing those with greater influence to steer decisions to their benefit. They also affect the level of political will and support a project receives, with powerful stakeholders able to mobilize political backing. Strong political support, in turn, leads to better funding and resource distribution. Advocacy and lobbying efforts influence policymakers, shaping political will and support. Those with more power can enhance their lobbying efforts through greater resources and networks. Effective advocacy can convince decision-makers to allocate more resources to the off-grid project.

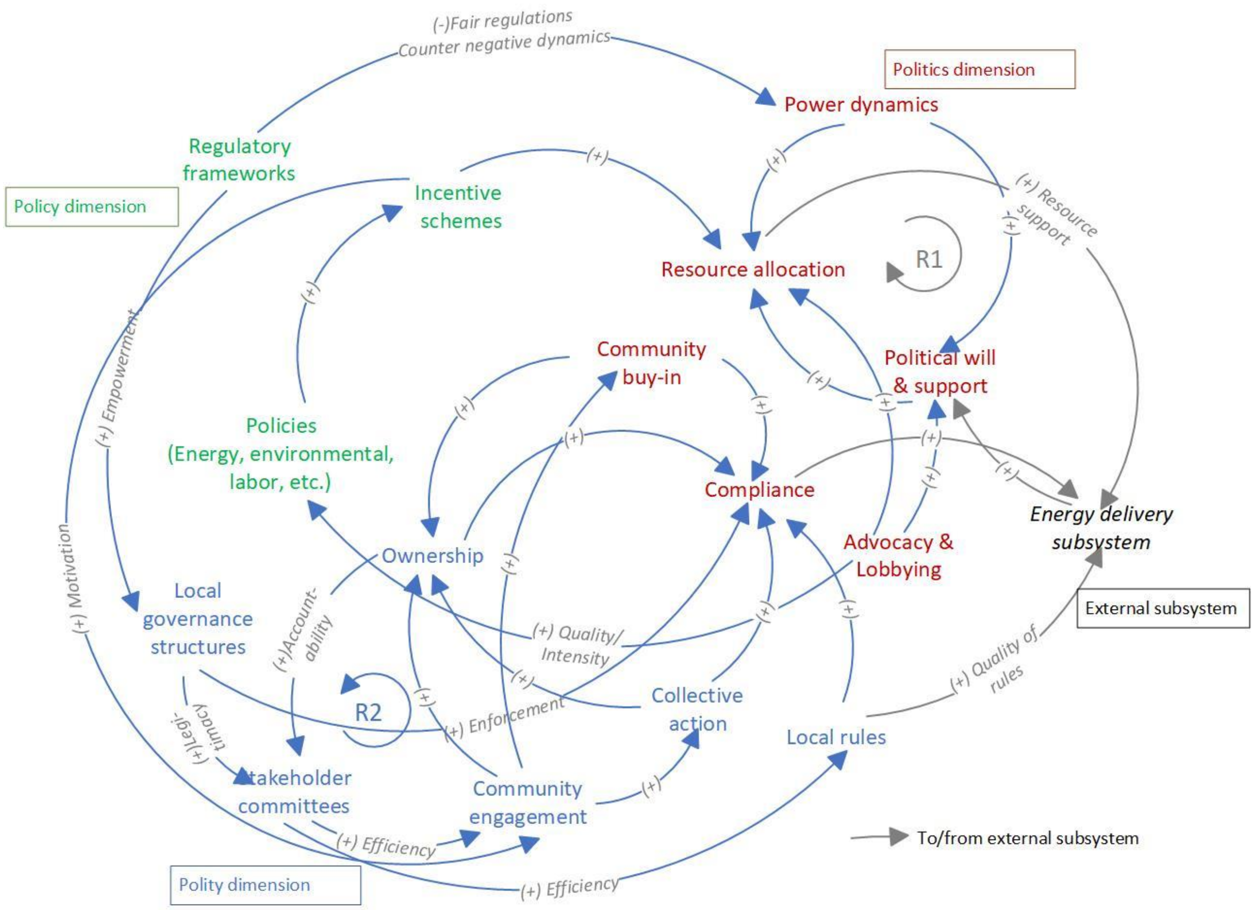


Figure 10: Causal loops and feedback mechanisms within the institutional infrastructure. Source: Author

The institutional infrastructure is influenced by two reinforcing feedback loops. In R1, effective resource allocation improves the energy delivery subsystem, leading to reliable electricity and community satisfaction. This success garners political will and support, resulting in more resources being directed to the subsystem, enhancing its performance further. In R2, stakeholder committees drive community engagement, fostering collective action and a strong sense of ownership among community members. This heightened ownership reinforces the effectiveness of stakeholder committees, perpetuating active community participation and support.

3.5.1.3 Minigrid People-Culture Subsystem Interactions

The interaction map in Figure 11 presents an analysis of the main interacting sub-systems and the nature of interactions within the people-culture components of the off-grid STS.

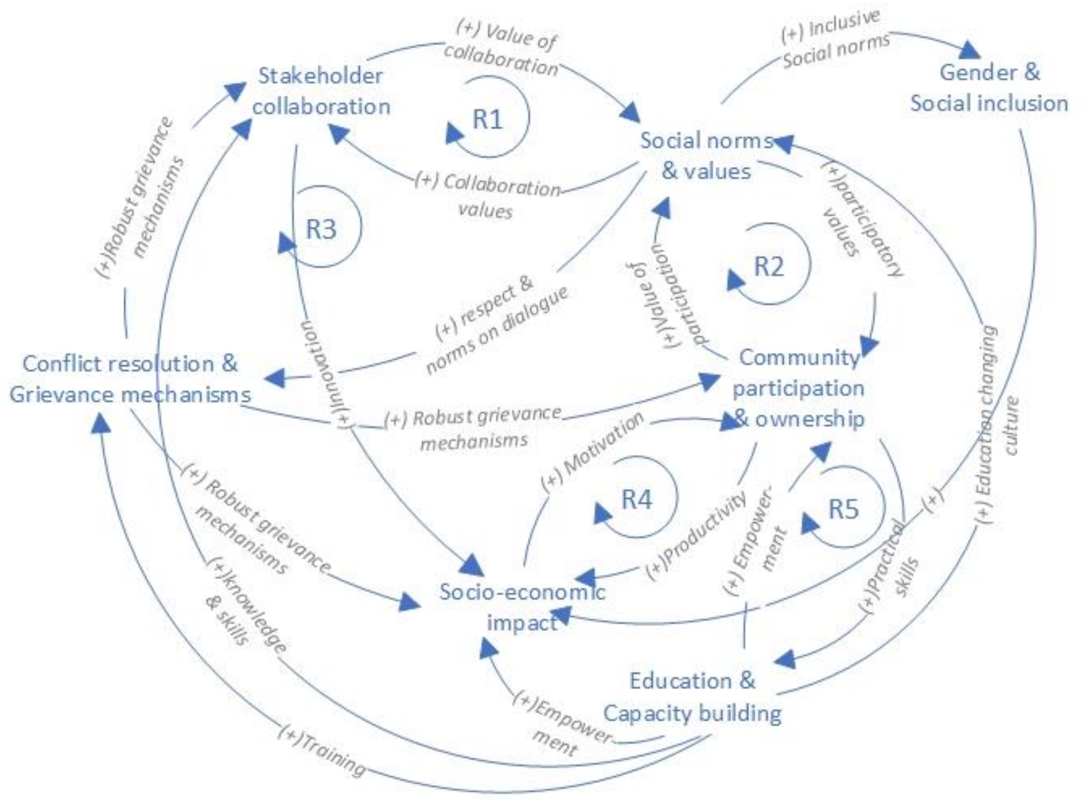


Figure 11: Causal loops and feedback mechanisms within the People-cultural sub-system. Source: Author

In R1 and R2, positive social norms and values drive higher stakeholder collaboration and community participation, respectively. As these virtues grow and yield tangible benefits, social norms and values are further strengthened, perpetuating the cycle. In R3, positive social norms and values lead to effective conflict resolution mechanisms and stakeholder collaboration, which in turn reinforce these norms, creating a continuous improvement cycle. In R4, increased community participation boosts overall productivity, leading to positive socio-economic impacts that motivate continued participation and ownership, reinforcing the cycle. Finally, in R5, education and capacity-building efforts empower the community to participate in the project, with practical skills enhancing their knowledge and capacity through active involvement.

3.5.2 *Emergent Effects & ODP Mitigation Strategies in the Gwere Failure*

From section 3.4.2, a number of key issues arise with a direct contribution to the failure of the project. They are here categorized within the STS framework of Figure 8. In the physical infrastructure domain, the study found a weak or near-non-existent physical support infrastructure for the community off-grid system. Within the institutional infrastructure, three main issues were found: (1) low political will and support for the project, (2) insufficient project ownership and accountability, and (3) information asymmetry. The People-Culture dimension was influenced by the absence of specific conflict resolution and grievance mechanisms for the project. Lastly, within the External Environment, emergent effects arising from the economic prospects of Gwere, were found to have compounded the problems.

3.5.2.1 *Physical infrastructure & External Environment - Dominant Effects & Mitigating ODPs*

Section 3.4.2.3 describes Gwere's rural East African context, highlighting a big problem on inadequate physical support infrastructure including, no spares access channels, a limited transport and logistical support network, and costly import requirements for replacement components. Additionally, there is a failure to retain skilled technical capacity for system maintenance. These issues create significant emergent effects impacting off-grid sustainability.

Figure 9 emphasizes the dominant reinforcing loop R5, involving the *'Energy delivery subsystem,' 'Local economy,' 'Access roads,'* and *'Maintenance & repairs.'* Key components of physical infrastructure, especially those related to maintenance, are tightly linked with the local economy in the external environment. Poor road networks, long travel distances for spare parts, and the lack of accessible spare parts channels, stemming from the local economy, result in extended operational downtimes, disrupting the continuous supply of electricity. High costs for spare parts and repairs strain project finances, affecting affordability and financial sustainability. Dependence on costly imports makes the system vulnerable to global supply chain disruptions, in addition to diverting resources from other project aspects. These effects underscore the importance of resilient and locally accessible physical infrastructure for the sustainability of community off-grid projects. Furthermore, feedback loop R1 between the energy delivery subsystem and the local economy creates financial sustainability challenges. Gwere's limited economic prospects make it difficult for residents to afford cost-reflective electricity tariffs, hindering revenue generation for maintenance costs. This results in difficulties retaining skilled technicians, causing operational disruptions and increased reliance on external experts. The community's limited economic opportunities increase dependence on external support, diminishing ownership and self-reliance, negatively affecting the institutional infrastructure.

To counteract the negative spiral from reinforcing loops R5 and R1, balancing loops that stabilize the system by addressing the root causes of decline are essential. Introducing a *Community Engagement-Local Mobilization* balancing loop, based on ODP (7) and ODP (3), is crucial. These principles emphasize the community's right to organize and participate in decision-making. Enhancing community engagement in the maintenance and operation of the off-grid system fosters a sense of ownership and responsibility, making members more likely to support and participate in maintenance activities. This approach facilitates local resource mobilization strategies, reducing dependency on external sources.

A dedicated maintenance and repair fund, sourced from community contributions, local businesses, and potential partnerships with local government, ensures timely maintenance and procurement of spare parts. Encouraging community contributions through local initiatives leverages the community's strengths and resources. As community engagement and local resource mobilization improve maintenance activities, the energy system's reliability and performance should increase, supporting local economic activities and generating more revenue. This, in turn, provides more funds for infrastructure investments, creating a positive feedback loop that stabilizes and enhances system performance. However, these principles alone may not address all challenges stemming from broader regional or economic factors, necessitating collaboration with external stakeholders. Thus, while ODPs enhance resilience, broader strategies are needed for comprehensive infrastructure solutions.

3.5.2.2 Gwere – Institutional infrastructure - Dominant Effects & Mitigating ODPs

Figure 10 shows two dominant reinforcing loops within the institutional infrastructure. Loop R1 highlights the relationship between *political will and support*, *resource allocation*, and the *energy delivery subsystem*. Low political will and associated inadequate resource allocation leads to the underperformance of the energy delivery subsystem. This underperformance further diminishes political will, creating a negative feedback loop that exacerbates sustainability issues. The lack of political backing results in insufficient funding, hampering efficient operation and reducing overall support and confidence in the project's viability. In loop R2 poor community engagement efforts frustrate collective action and diminish community sense of ownership of the project. As a result, the community does not feel accountable for the project's success, leading to neglect in maintenance and operation, ultimately harming the project's sustainability. Similarly, poor or lack of community engagement closes channels for communication of project details, roles, responsibilities which are essential for managing community expectations. The resulting lack of collective action and ownership further exacerbates the information gap, creating a disconnect between the community and the project and negatively impacting the project's sustainability.

To stabilize the system in the R1 context, a balancing loop that boosts political will and resource allocation through enhanced community advocacy and stakeholder engagement is proposed. This loop focuses on showcasing the community's commitment and the benefits of the off-grid project to gain increased political support and resources. A *Community Advocacy and Engagement* balancing loop, based on ODP (7), which emphasizes the community's right to organize, would encourage the community to actively advocate for their needs and the project's benefits to local and national government representatives. Effective advocacy would raise political leaders' awareness of the project's significance, leading to increased political support and improved resource allocation. This support ensures adequate funding for maintenance and operations, enhancing the energy delivery subsystem's performance. Successful project outcomes would further bolster political will, creating a positive cycle of advocacy, resource allocation, and system performance, thereby stabilizing the system and ensuring the off-grid project's sustainability and success.

To close the information gap and enhance community engagement in loop R2, a *Community Information and Involvement* balancing loop based on ODP (3) - Participatory decision-making and ODP (6) - Easily accessible conflict resolution, can be implemented. This loop would ensure that community members are well-informed about project details, roles, and responsibilities, thereby fostering collective action and ownership. Establishing clear communication channels through regular community meetings and digital platforms would disseminate essential project information effectively. Engaging community members in decision-making processes ensures their voices are heard and they have a stake in the project's success. Education and training sessions would empower the community to actively participate in project maintenance and operations. Implementing easily accessible conflict resolution mechanisms to address disputes promptly would build trust in the project. Establishing feedback mechanisms for community concerns, suggestions, and experiences is crucial for continuous improvement and strategy adjustment. This balancing loop would enhance ownership and accountability, close the information gap, and support the project's sustainability by ensuring full community engagement and informed participation.

3.5.2.3 Gwere – People-Culture - Dominant Effects & Mitigating ODPs

The People-Culture dimension was significantly impacted by the absence of specific conflict resolution and grievance mechanisms for the project. Loop R3 in Figure 11 highlights the interaction between *social norms and values*, *conflict resolution and grievance mechanisms*, and *stakeholder collaboration*. The community's social norms and values, characterized by high power distance, contributed to unequal power dynamics in negotiations and conflicts with the donor agency. This imbalance made it difficult for the community to effectively address the turbine failure and the resulting stakeholder disagreements. Without established mechanisms for resolving disputes and grievances, the community's social norms reinforced behaviors detrimental to successful collaborations. This included a lack of clear specification of each party's interests and insufficient accountability for partners' obligations.

To address the negative dynamics in loop R3, a *Social Empowerment and Collaboration* balancing loop can be implemented. This loop focuses on leveling power dynamics by fostering a culture of equality and collaboration within the community and with external stakeholders. Key actions include capacity building and education to advise the community about their rights and responsibilities, empowering them with negotiation and conflict resolution skills, establishing structured and impartial conflict resolution mechanisms (ODP 6), enhancing stakeholder collaboration through structured platforms for regular dialogue and inclusive decision-making (ODP 3), and strengthening community leadership and advocacy capacity (ODP 7). With these measures, the community would build internal strength, they would ensure fair conflict resolution, better collaboration, and mitigate the negative impacts of their high power-distance, thereby supporting the sustainability of the off-grid project.

3.6 Conclusion & Policy Implications

The Systems thinking perspective on Gwere's minigrid project governance and failure presented in this paper underscores the significance of ODPs as a strong foundational framework for governance in community-owned off-grid systems. While ODPs empower communities to take ownership and responsibility for their projects, their limitations become evident when faced with external challenges that spill into the local context—issues beyond the community's control. Ensuring long-term sustainability requires not only the flexible application of ODPs but also adaptive management strategies that address external challenges and foster stronger collaboration with external stakeholders and governing bodies. Establishing multi-tiered alliances with similar projects across regions could provide shared technical expertise, financial resources, and collective bargaining power for critical resources like spare parts. Such a network would facilitate knowledge exchange and preemptively address challenges, as seen in Gwere. Potential partnerships in the region include Uganda's Nyamwamba, Rwimi, Buseruka, and Nkusi mini/pico-hydro power projects, alongside Rwanda's Rubagabaga and Kenya's Tungu Kabiri projects. Additionally, pooling resources to establish a common insurance fund would provide financial security in the event of technical failures or emergencies, enhancing the overall resilience of these initiatives.

This case study of Gwere provides valuable insights into the complexities of community off-grid projects in rural developing contexts, offering detailed data for analyzing physical infrastructure, institutional arrangements, socio-cultural factors, and external influences. The study emphasizes the need for adaptable governance approaches, strategies to address external challenges, and collective collaboration for resource and risk sharing. It also demonstrates the use of systems thinking methodology integrated with socio-technical systems analysis to analyze the interactions between infrastructure, institutions, and socio-cultural factors, identifying emergent effects that impact the sustainability of similar off-grid systems. However, its context-specific nature may limit its generalizability to other regions or projects. Additionally, the qualitative nature of the research introduces the possibility for bias in data collection or analysis. To mitigate these biases, the study utilized multiple data sources (semi-structured interviews, focus group discussions, and secondary data from reports and governance documents) to ensure that the findings were corroborated across different types of data. By comparing and cross-verifying information from these diverse sources, the study minimized the risk of relying on any single biased source of data. In addition, the study employed purposive sampling to assure the representation of diverse voices within the Gwere project.

Future research could expand on these findings by exploring similar projects in different contexts, examining the long-term sustainability of the proposed governance strategies, and integrating more detailed technical and aesthetic considerations to provide a more comprehensive understanding of the socio-cultural-economic impacts and benefits of community off-grid projects.

3.7 Declarations

Acknowledgement: The study acknowledges the support of Mr. Cyril Dracho, the local technical advisor for the project, Mr. Ivan Kisembo, the GIZ project coordinator (2009-2010) and the Gwere community for their invaluable contributions during the data collection process.

Funding: This work was supported by the Africa: Research and Teaching platform for Development - Sustainable Modular Grids Project (A:RT-D Grids) funded by the German Federal Ministry of Education and Research (BMBF) under the Client II programme – funding ref 03SF0607A.

Data Availability Statement: The datasets analysed for this study are available from the author upon reasonable request.

Conflicts of Interest: The author declares no conflict of interest.

4 Linking Structure of Governance Networks to Performance

Linking Network Structure & Performance: Influence in an Off-grid Financing Policy Network

Lillian Donna Namujju[10,11]

Abstract

This study employs Social Network Analysis to scrutinize the structure and dynamics within Uganda's off-grid financing and investment network, demonstrating how network structure configurations influence power and capacity of network agents. By integrating Principal Component Analysis with traditional centrality metrics, the research constructs detailed influence scores, revealing a network characterized by significant disparities in power and connectivity. It pinpoints international development banks and partners as pivotal influencers, who dominate network operations through their extensive access, brokerage capabilities, and diffusion capacities. Moreover, the study highlights strategic opportunities to strengthen the network by enhancing the connectivity of peripheral nodes and amplifying the roles of the most central nodes to improve overall network robustness and cohesion. These findings have broader relevance, providing key insights for optimizing network governance in similar off-grid energy systems worldwide, ensuring a more integrated and effective network structure.

JEL Codes: *L14, O33, Q42, Q48, O55*

Keywords: *Social network analysis, Policy networks, Off-grid financing, Network structure, Network influence*

---

[10] Chair of Institutional Economics & Economic Policy, Department of Economics, Paderborn University, Warburger Str. 100, 33098, Paderborn, Germany

[11] Department of Electrical & Computer Engineering, College of Engineering, Design, Art & Technology, Makerere University, Kampala, Uganda

4.1 Introduction

Rural electrification efforts involve a diverse array of participants including federal, state, and local governments, alongside non-state actors from both for-profit and non-profit sectors, development partners, and international agencies, calling for a non-traditional governance network. This relational complexity, the base for productive collaborations among multiple actors from different sectors, is a fundamental characteristic of policy networks (Kapucu, 2015).

Different from the top-down approach to policy in traditional main grid initiatives, off-grid systems, which are small-scale generation systems operating independently from traditional energy grids (Mandelli et al., 2016), are set in rural hard to reach areas, inaccessible to the main grid, giving them differing geographic, economic and social scales for consideration (Namujju et al., 2023b). Koliba et al. (2017) defines such networks as consistent patterns of coordinated actions and resource exchanges among policy actors from various sectors—public, private, and nonprofit, interacting through diverse arrangements, including competitive, command and control, cooperative, or negotiated frameworks, all aimed at achieving a shared objective. They tend to emerge around specific policy issues with agent relationships and contacts structured around shared, albeit, continuously negotiated beliefs and interests (Heard-Laureote, 2018).

Off-grid policies are shaped by a range of factors, including technical, economic, social, and environmental considerations (Nkiriki and Ustun; Tenenbaum et al., 2018). This study utilizes Uganda's Off-grid Financing and Investment (OFI) policy network as a case study to examine the link between policy network structure and performance. Within this network, coordinated actions and resource exchanges among actors—supported by incentive policies, financial instruments, and partnership models—are aimed at mobilizing public and private investments to develop and implement sustainable energy solutions in underserved areas (Bhattacharyya, 2013; Glemarec, 2012; Shi et al., 2016). Effective governance of this network calls for fast and efficient share of information and key resources, as well as effective administrative hierachies, all of which derive from the structure of the network.

Policy network analysis has been extensively utilized to investigate network structures, emphasizing the connections and interdependencies between policymakers and societal actors. Numerous studies have explored factors contributing to enhanced effectiveness in network governance across various fields, including health systems (Provan and Milward, 1995), public management (Meier and O'Toole, 2007), clean energy governance (Yi, 2017), and environmental project networks (Klijn et al., 2010). Many have examined network performance across different geographic regions (Kelman et al., 2016; Klijn et al., 2016; Lee and Rethemeyer, 2013). However, a notable research gap remains in the space of energy financing and investment policy networks. This network's structural topology and diverse value flows—including financial, technical, and information resources, along with policy and advocacy support—have received limited attention. This research is crucial for optimizing these value flows, promoting collaboration, and ultimately bolstering the effectiveness and impact of OFI initiatives.

This study enhances the field of Social Network Analysis (SNA) (Berkowitz and Donnerstein, 1982; Burt, 1980; Freeman, 2004; Holland and Leinhardt, 1977; Marsden, Peter V., Lin, Nan, 1982) by integrating multiple centrality measures to assess node influence within network structures. It transcends traditional SNA approaches that focus on singular metrics, allowing a nuanced examination of how actors access, facilitate or hinder resource and information flow. The study investigates three key aspects: (1) the defining structural characteristics of agent/node groups and linkages within the network, (2) how these characteristics influence node-level power, and (3) the implications of node positions on policy and political dynamics, including access, brokerage, and resource diffusion. It also assesses how network structure affects policy coordination, collaboration, and resource flow for Uganda's off-grid projects, providing critical insights into network governance.

The remainder of the paper is organized as follows: Section 4.2 presents a theoretical framework relating network position, centrality, and the various dimensions of network power. Section 4.3 describes the study methodology and case study network context. Section 4.4 presents the network centrality results. Section 4.5 Section 6 discusses the conclusion and policy implications of the network structure.

4.2 Theoretical Framework

The existing literature has predominantly focused on the performance of managed networks - typically characterized by centralized control and coordination (Gillett and Kapor, 1997; Osman, 2018), with limited attention directed towards the examination of self-organizing networks. The latter rely on decentralized decision-making and emergent order, where interactions among network participants drive the organization and functioning of the network (Berardo and Scholz, 2010; Di Serugendo et al., 2006). The OFI policy network embodies the characteristics of a self-organizing network. Decision-making authority is distributed among various stakeholders (government agencies, donors, financial institutions, and private sector entities) so that each participant holds a level of autonomy and agency, allowing them to make decisions aligned with their interests, objectives, and limitations (Pryke et al., 2018). The study utilizes SNA methodology to investigate how structural network characteristics drive performance within self-organizing off-grid policy networks. The central hypothesis underpining structural analysis is that actors' performance is an outcome of their structural position in the network. Similarly, any structural opportunities that actors can enjoy derive from possible relations mobilized from specific positions (Carlsson and Sandström, 2008; Chiesi, 2006).

4.2.1 *Effect of Network Position on Power & Influence*

A positional analysis of a social network operates under the assumption that the group's role hierarchy and individuals' positions within it are discernible through the observed relationships within the network dataset (Wasserman and Faust, 1994). Through persistent patterns of association among actors, structures are created that can define, enable, or restrict the node behavior (Banzhaf, 2009; Glisic, 2016). The paper uses SNA to measure these potential sources of actor influence and constraint. It examines the strategic consequences of network positions, with a particular emphasis on centrality — a measure of actors' importance in a network. An actor is considered central if they are closely connected to all other actors in the network (Bonacich, 1987; Burt, 1976; Friedkin, 1991; Mark S. Mizruchi and Blyden B. Potts, 1998; Mintz, 1985). This notion is motivated by the belief that individuals who maintain close ties with others tend to have access to more information (Leavitt, 1951; Stephenson and Zelen, 1989), higher status (Hubbell, 1965), more power (Bonacich, 1987; Mintz, 1985; Yamaguchi, 1996) and greater influence (Friedkin, 1991) than others. Another aspect of centrality discussed in SNA literature relates to positional advantage. This concept suggests that actors are central insofar as they occupy positions that lie between other actors on the paths of communication (Freeman et al., 1991; Freeman et al., 1979; Freeman, 1977; Friedkin, 1991). Such individuals can facilitate or inhibit the communication of others, thereby influencing the access of other actors to information, power, or influence. Occupying a central position within a network grants an actor greater potential power to exert influence, shape agendas, and manipulate interests compared to being in an isolated position. Based on this, the study defines network power as the capacity of an actor to generate effects through social relations, thereby shaping their ability to influence their circumstances and outcomes (Barnett and Duvall, (2005).

4.2.2 Network Power

Power in social networks is not a fixed attribute of an individual but arises from the relationships and connections between actors (Hafner-Burton et al., 2009; Hafner-Burton and Montgomery, 2010). Established sources of power in SNA literature including resource control, influence, network position, value offered, etc., are leveraged by actors to exert influence and navigate the network landscape. An actor's access to others in the network , their brokerage capacity and their resource diffusion abilities are all crucial elements of relational power that actors use to leverage their connections to influence others (Bassoli et al., 2014; Burt, 2018; Jason M. Smith et al., 2014).

In our examination of the OFI network, the study assesses power across these three fundamental dimensions: (1) the accessibility to other actors and the corresponding advantages gained by those who access them – *access power*, (2) the role of brokerage in connecting indirectly linked actors or groups, and the influence that stems from this intermediary position – *brokerage power*, and (3) the efficiency of resource propagation through the network and the relative advantages accrued to each actor – *resource diffusion power*.

While previous research has relied on established centrality measures (in-degree, out-degree, betweenness, closeness, eigenvector) to identify powerful actors in social networks (Gómez et al., 2003; Hanneman and Riddle, 2005b; Raffaele Vignola et al., 2013; Samaneh Ghafoori Kharanagh et al., 2020), this study takes a significant step forward. It advances traditional SNA by integrating unconventional metrics such as Local Network Efficiency (LNE), effective size, constraint, power centrality, and information centrality (*centrality metrics in Appendix A*). By doing so, it offers a richer, more comprehensive view of network power dynamics. Traditional analyses often assess centrality metrics in isolation, potentially overlooking how these metrics interact to influence a node's strategic role within the network. To address this, the study employs Principal Component Analysis (PCA) to synthesize these diverse metrics into composite scores, effectively capturing both the direct and indirect dimensions of node influence across access, brokerage, and diffusion capabilities. This approach not only provides a deeper understanding of the multifaceted roles nodes play in network functionality and resilience but also enhances the statistical reliability of the results (Lieftucht et al., 2006).

4.2.2.1 Access power

The study defines *Access power* within a network as an actor's ability to reach and leverage resources through their direct connections and interactions with other network participants. Most studies quantifying the concept of power-as-access have traditionally relied on degree centrality, which directly counts an actor’s connections and serves as an indicator of their connectivity (Jason M. Smith et al., 2014). This study expands upon this by incorporating eigenvector centrality, an indirect measure of access power that considers the influence and reach of an actor's connections (Wasserman and Faust, 1994). Alongside these, the study uses effective size, a less conventional metric that accounts for the redundancy within these direct connections (Burt, 2018; Burt, 2012; Hanneman and Riddle, 2005a). It highlights how well-connected an actor is to distinct parts of the network, not just a high number of connections to the same group, allowing for multiple, independent channels for acquiring resources, information, and opportunities. By combining degree centrality, eigenvector centrality, and effective size, this study provides a more comprehensive understanding of power-as-access within networks, going beyond simply counting connections but also accounting for connection quality and diversity.

4.2.2.2 Brokerage power

Brokerage power refers to the ability of a node to facilitate or control the flow of information or resources between other nodes that are not directly connected (Burt, 2007; Stovel and Shaw, 2012); derived from its strategic position connecting otherwise isolated parts of the network (Kwon et al., 2020). *Betweenness centrality* has served as a fundamental metric for evaluating brokerage power in most SNA literature (Everett and Valente, 2016; Hanneman and Riddle, 2005b). Nodes with high betweenness centrality hold significant control over the flow of information, resources, and influence, positioning them as strategic but vulnerable points within the network (Mark S. Mizruchi and Blyden B. Potts, 1998). Their centrality provides strategic advantages but also makes them critical points of failure, as their removal can disrupt the network (Holme et al., 2002).

This study expands the analysis of brokerage power by incorporating two less commonly used metrics alongside betweenness centrality: *Constraint* and *Power centrality*. Constraint complements betweenness centrality by capturing the limitations an actor faces due to the structure of their connections (Martin G. Everett and Stephen P. Borgatti, 2020). It effectively quantifies how much a node’s network contacts are interconnected, thereby constraining the node's autonomy and limiting its opportunities to broker information and control resources among distinct groups

(Lin et al., 2021). With lower constraint, a node links groups or nodes that do not have other direct pathways to connect and as such has higher brokerage power because it can control unique information or resource flows between these groups. Power centrality, in contrast, assesses a node's ability to amplify its influence through its connections. It is defined recursively so that a node's power increases with the power of its neighbors in cooperative relationships but decreases as its neighbors grow stronger in competitive settings (Bonacich, 1987). In the case of Uganda's OFI network, the study assumes cooperative relations among actors so that power comes from being connected to those who are powerful. This metric is particularly relevant in the OFI network as it highlights nodes that, through their strategic connections, can influence decision-making processes and resource allocations within the network.

4.2.2.3 Resource diffusion power

Resource diffusion in a network refers to the process by which resources—be it information, financial capital, goods, or services—spread across the various nodes within the network. The speed and extent of resource diffusion within a network can be influenced by the network structure in terms of the pattern of connections (e.g., density, centrality, and clustering), the characteristics of individual nodes such as their strategic position within the network, as well as the nature of the resources themselves (whether they are tangible or intangible) (Sun et al., 2022). Resource diffusion power measures how swiftly and efficiently resources move through the network to various nodes (Centola, 2015; Gould, 1969).

This study broadens the evaluation of resource diffusion by incorporating two less commonly used metrics - Information Centrality and LNE alongside closeness centrality. Information Centrality assesses a node's impact on network communication efficiency, revealing its critical role in sustaining network integrity (Stephenson and Zelen, 1989). High scores indicate that removing the node would significantly disrupt network flow. Conversely, LNE focuses on a node's impact within its immediate subgroup, evaluating the effectiveness of communication when the node is removed, and identifying key actors in localized network segments (Crucitti et al., 2003). These metrics together provide a nuanced understanding of each actor's influence on both broad and localized network dynamics.

4.2.3 Exploring Group-Level Network Structure

SNA offers group-level metrics that reveal a network's overall robustness. These measures go beyond individual nodes and capture the cohesion, structure, and interactions between groups (Gesell et al., 2013). Their importance lies in uncovering macro-level patterns that influence how well the network functions, adapts, and withstands disruptions. This study assesses the connectivity of Uganda's OFI network using standard and advanced SNA metrics. Network density reflects the overall connectedness, indicating potential pathways for information flow (Peter V. Marsden, 1993; Wasserman and Faust, 1994). Average path length measures the steps required to travel between actors, providing insight into the speed of information transfer (Bloch et al., 2023; Mao and Zhang, 2013; Pan and Saramäki, 2011). Global network efficiency builds on this by evaluating the effectiveness of these paths, highlighting how efficiently information navigates the network (Aytac and Atay, 2015). Together, these metrics offer a detailed view of the network's capacity to effectively disseminate information.

4.3 Methodology & Study Context

This study defines performance as the influence and opportunities actors derive from their network positions in Uganda's OFI sector. Employing a mixed-methods approach, it integrates qualitative data from literature reviews—including research articles and policy documents—with quantitative SNA using R. This approach facilitates a comprehensive examination of the network's structure and relationships, where qualitative insights provide context and augment the quantitative findings derived from network visualization and analysis. The research process includes data collection, preparation, analysis, visualization, and interpretation, ensuring a thorough understanding of network value-flows.

4.3.1 Data Collection & Validation

An iGraph map of Uganda’s OFI network was developed using a dual data collection approach. Initially, internet crawling techniques were used to analyze legislation, policies, and sector reports to identify organizations linked to off-grid financing. This list was expanded using data from Uganda's off-grid energy market reports by UOMA (UOMA, 2023), which provided information on minigrids and their funding sources, and a dynamic stakeholder map from FHI360 under a USAID partnership (FHI360, 2017a, 2017b), which detailed different financing and policy-related stakeholder interactions within the sector. These sources were cross-validated to ensure the accuracy and reliability of the network map, providing a robust basis for analyzing the structure and dynamics of Uganda’s OFI network.

4.3.2 Network Analysis & Visualization

The study utilized iGraph in R to construct and analyze a network of Uganda's OFI landscape, comprising 174 nodes and 447 edges, available in Appendix B. Using the #SNA and #VISNET libraries, the analysis included generating node and graph-level indices, structural distance and covariance calculations, detecting structural equivalence, and visualizing the network in 2D and 3D. Nodes were categorized into 12 groups including government agencies, international development partners, development banks, and NGOs, among others. Edges were classified into hierarchical administrative, financing, and policy-related links, detailing the nature of interactions such as formal reporting, funding, and policy advisory within the network. The network structure analysis was conducted at two distinct levels: (1) Node-Level Analysis focussed on the relative position of each actor within the network, utilizing centrality measures discussed in section 4.2.2 to evaluate node influence and its strategic implications within the overall network. (2) Group level analysis related to overall network efficiency utilizing centrality measures discusssed in section 4.2.3.

4.3.3 Aggregate Network Influence Scores

The study seeks to calculate aggregated influence scores by combining essential centrality metrics using Principal Component Analysis (PCA). This method allows for the integration of these metrics into unified scores that reflect various dimensions of network power. As explained in section 4.2.2, PCA condenses Degree Centrality, Eigenvector Centrality, and Effective Size into an *Access Power score*, emphasizing the relative contribution of each measure based on its variance and correlation with others. Similarly, PCA combines Betweenness Centrality, Bonacich’s Power Centrality, and Constraint into a unified *Brokerage Power score*, which quantifies each node's capacity to act as a broker within the network. Additionally, a *Resource Diffusion Power* score is calculated by synthesizing Closeness Centrality, Local Efficiency, and Information Centrality, thereby highlighting nodes' roles in disseminating resources and information.

PCA is applied to reduce the dimensionality of these centrality metrics while preserving the variations most representative of each dimension of power (Andrzej Maćkiewicz and Waldemar

Ratajczak, 1993). By calculating eigenvectors and eigenvalues from the correlation matrix of these metrics, principal components that explain the majority of the variance are selected. Influence scores are then derived as weighted sums of centrality metrics, with weights based on the principal components' loadings. This method effectively integrates various centrality measures into comprehensive scores that capture not just the obvious (direct) connections and influences of nodes, but also their more subtle (indirect) impacts within the network (Janžekovič and Novak, 2012).

4.3.4 Context of Uganda's OFI Network

In the context of Uganda's OFI network, a diverse array of actors plays crucial roles in shaping the landscape illustrated in Figure 12. Figure 13 further outlines the various value-flows and interactions among the actors in the network (FHI360, 2017a, 2017b; UOMA, 2023). The detailed information on all 174 nodes, including their categories and the derived iGraph metrics is available in Appendix C.

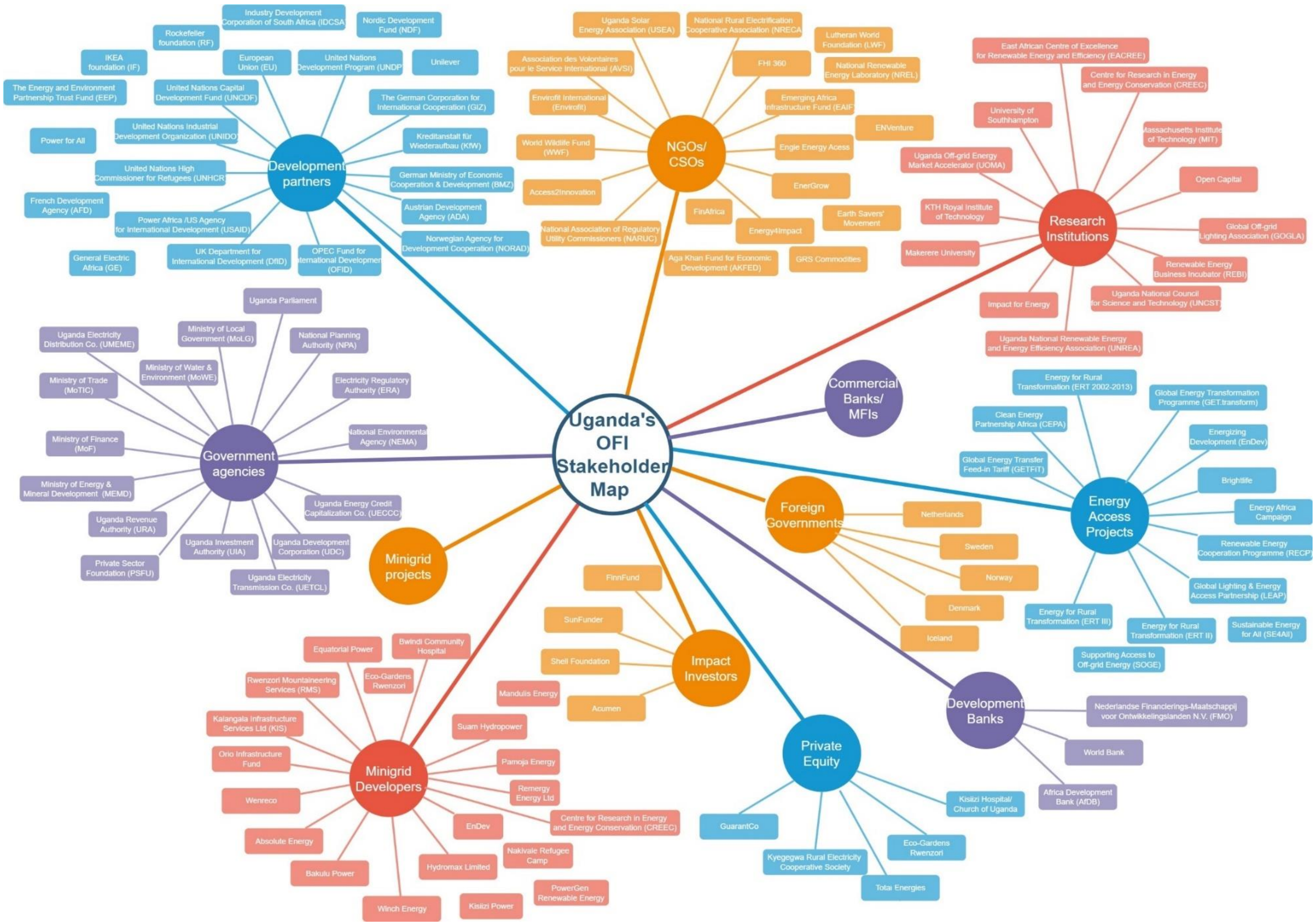


Figure 12: Uganda's OFI stakeholder map[12]

4.3.4.1 Actor Interfaces

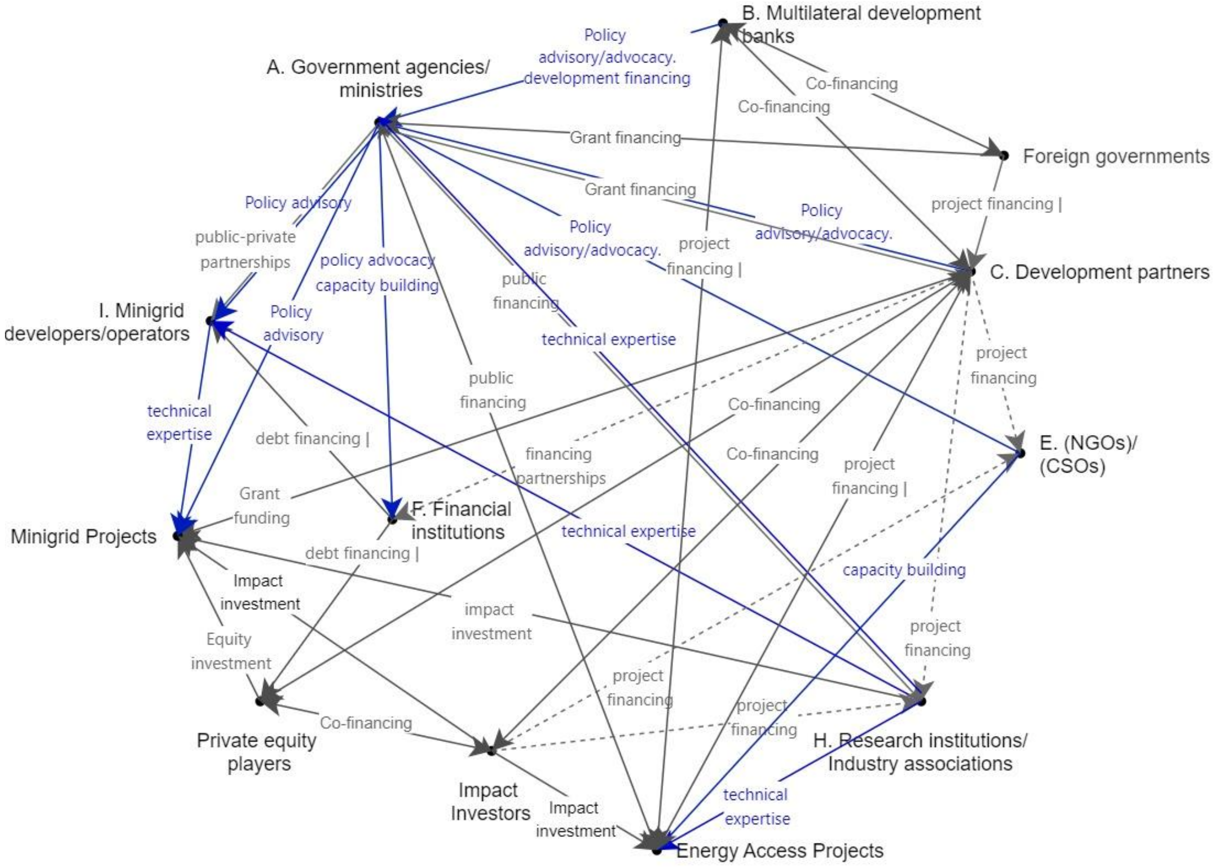


Figure 13: Overview of actors in Uganda's OFI and their actor interfaces. Source: Author

The interactions between government agencies, regulatory bodies, and various stakeholders in Uganda's OFI network form a complex and multifaceted ecosystem centered on policy implementation, funding, and project execution. Development partners and multilateral banks collaborate to finance large-scale energy projects, aligning funding mechanisms and sharing risks (KfW and Multiconsult, 2022). Strategic alliances are formed between development partners and foreign governments to influence local and international development policies. Commercial banks, microfinance institutions, and private equity funders often join forces in investment syndicates to finance energy projects through a mix of lending and equity investments (Cartland et al; Kabuta et al., 2007). Additionally, research institutions collaborate with energy access projects to provide essential technical expertise and conduct pilot testing, ensuring the applicability and effectiveness of new technologies.

NGOs and CSOs collaborate with government agencies to advocate for energy policies that integrate sustainable solutions and community input (FHI360, 2017a). They also partner with minigrid and energy access projects to support implementation and ensure projects are sustainable and locally relevant. Additionally, impact investors work with minigrid developers to fund projects that combine financial returns with sustainable impacts, supporting the scalability and effectiveness of off-grid solutions (UOMA, 2023). This intricate web of stakeholder interactions is analyzed and visualized using iGraph in the following section of the paper.

4.4 Unpacking Uganda's OFI Network Structure

This section of the study examines Uganda's OFI network structure, leveraging established SNA literature to interpret the implications of iGraph metric results. It presents a centrality analysis of the OFI network, detailing the positions of various actors within the network and discussing the resulting capabilities, opportunities, and risks that emerge from these positions.

4.4.1 Network Centrality and Implications on Stakeholder Power

This section analyzes key centrality measures to illustrate the roles and influence of various nodes within Uganda's OFI network. It identifies which actors are pivotal in managing the flow of resources, information, and influence throughout the network. Table 10 presents the average centrality values for different node groups, identifying the primary connectors, influencers, power players, gatekeepers, cross-pollinators, and information hubs within the network. Appendix A contains the full nodelist and corresponding centrality measures.

Table 10: Actor centrality in Uganda's OFI network

Node Type	Eigen Cent.	Degree Cent.	Effective Size	Power Cent.	Constraint	Between-ness	Closeness	Info Cent.	LNE
Development Partners	0.20	0.07	0.17	0.46	0.42	0.09	0.0017	0.60	0.29
Development Banks	0.15	0.05	0.14	0.68	0.53	0.03	0.0016	0.50	0.04
Government Agencies	0.13	0.04	0.12	0.49	0.40	0.12	0.0017	0.59	0.14
Energy Access Projects	0.10	0.02	0.05	0.48	0.46	0.01	0.0017	0.61	0.35
Minigrid Projects	0.11	0.02	0.04	0.48	0.40	0.00	0.0017	0.60	0.37
Impact Investors	0.08	0.02	0.07	0.47	0.79	0.01	0.0013	0.30	0.05
Research Institutions	0.05	0.02	0.06	0.48	0.49	0.06	0.0016	0.55	0.24
Minigrid Developers	0.05	0.03	0.06	0.49	0.48	0.01	0.0015	0.45	0.17
Commercial Banks/MFI	0.05	0.01	0.03	0.48	0.66	0.00	0.0014	0.43	0.22
NGOs	0.05	0.02	0.04	0.48	0.62	0.02	0.0015	0.44	0.24
Foreign Governments	0.04	0.02	0.04	0.50	0.76	0.01	0.0014	0.37	0.15
Private Equity	0.01	0.01	0.02	0.48	0.81	0.00	0.0012	0.20	0.20

4.4.1.1 Centrality Correlations & Implications on Power Dynamics

Table 11 provides a heatmap visualization of the p-values for the correlation analysis between various centrality and efficiency metrics used in studying the network's structure. This table helps identify statistically significant relationships ($p<0.005$) between the applied metrics. This visualization is crucial for assessing the interdependencies and unique contributions of different centrality and efficiency measures in understanding the power dynamics in the network.

The dominant trends from Table 11 underscore that eigenvector and degree centrality—measures of a node's connectivity and its links to other well-connected nodes—significantly correlate with nearly all other metrics, except for power centrality and LNE. This observation reinforces the classic network theory that centrality equates to power. Nodes with high eigenvector and degree centrality demonstrate strong network integration and are likely strategic for the access of information and resources. They act as vital connectors and influencers within the network, commanding access to information and control over resources due to their pivotal positions. Additionally, the strong correlation with effective size indicates that these central actors are not merely connected but also maintain a variety of links across diverse network sections. Furthermore, their significant correlation with betweenness centrality implies that these actors occupy crucial positions on the shortest paths between other nodes, enhancing their capacity to mediate and impact the flow of communication and resources within the network.

Table 11: Heatmap of p-values for metric correlations

	Eigen Cent.	Degree Cent.	Effective Size	Power Cent.	Constraint	Betweenness	Closeness	Info Cent.	LNE
EigenCent.		0.000	0.000	0.371	0.019	0.048	0.019	0.012	0.873
DegreeCent.	0.000		0.000	0.401	0.039	0.006	0.045	0.045	0.717
EffectiveSize	0.000	0.000		0.230	0.105	0.007	0.104	0.106	0.401
PowerCent.	0.371	0.401	0.230		0.905	0.960	0.746	0.883	0.068
Constraint	0.019	0.039	0.105	0.905		0.086	0.000	0.000	0.143
Betweenness	0.048	0.006	0.007	0.960	0.086		0.071	0.090	0.695
Closeness	0.019	0.045	0.104	0.746	0.000	0.071		0.000	0.199
InfoCent.	0.012	0.045	0.106	0.883	0.000	0.090	0.000		0.114
LNE	0.873	0.717	0.401	0.068	0.143	0.695	0.199	0.114	

The lack of significant correlations between power centrality, LNE, and traditional centrality metrics like degree, betweenness, and closeness, indicates unique structural and power dynamics within the network. Nodes with high power centrality may wield influence not through numerous connections but through strategically important ones, highlighting a network where control is exerted via pivotal yet potentially limited links. This suggests a complex influence landscape where some nodes command resources or information flow through subtle, perhaps less visible connections.

For LNE, its independence from other centrality measures suggests that local efficiencies are not tied to a node's global network position. This means sub-networks can be efficient even without direct ties to central nodes, enhancing resilience by ensuring parts of the network remain functional independently. This feature indicates a robust network design, potentially decentralized, where different nodes or clusters maintain functionality autonomously, bolstering the network's resilience against disruptions.

4.4.1.2 Uganda's OFI network: Connectors & Influencers

This analysis identifies key actors in Uganda's OFI network, highlighting those with significant connectivity and network integration. By evaluating eigenvector centrality, degree centrality, and effective size, the study distinguishes the primary connectors and influencers within the network. These metrics provide insights into which nodes are integral for information access and resource mobilization.

The study reveals a power-law degree distribution in the network, marked by a few highly connected nodes against a backdrop of many with few connections, as evidenced by extreme right skewness (729.5) and high kurtosis (21.9). This indicates a concentration of connectivity within certain influential nodes, particularly among development partners, development banks, and government agencies, which have the highest average degree values – 11.36, 8.00, and 7.65 respectively. Notably, government agencies are the principal connectors, accounting for 20.9% of the network's connections. International aid players, including development partners and development banks, collectively hold a substantial 20% share of connections, underscoring their significant role alongside government agencies in shaping the network's structure and dynamics.

This concentrated connectivity among a few nodes highlights the central role these actors play in maintaining network functionality and influence.

Figure 14 shows the results of a centrality analysis of the different stakeholder groups. The study finds that the three centrality measures are strongly correlated, suggesting they are closely aligned in evaluating nodes' positions within the network. Development partners, development banks, and government agencies emerge as key connectors and influencers, with the highest eigenvector centrality scores demonstrating their central roles in the network. Conversely, private equity players and foreign donor governments exhibit much lower centrality scores, indicating their peripheral influence and fewer direct connections within the network. This pattern highlights a clear hierarchy of influence and connectivity among different actors in the network.

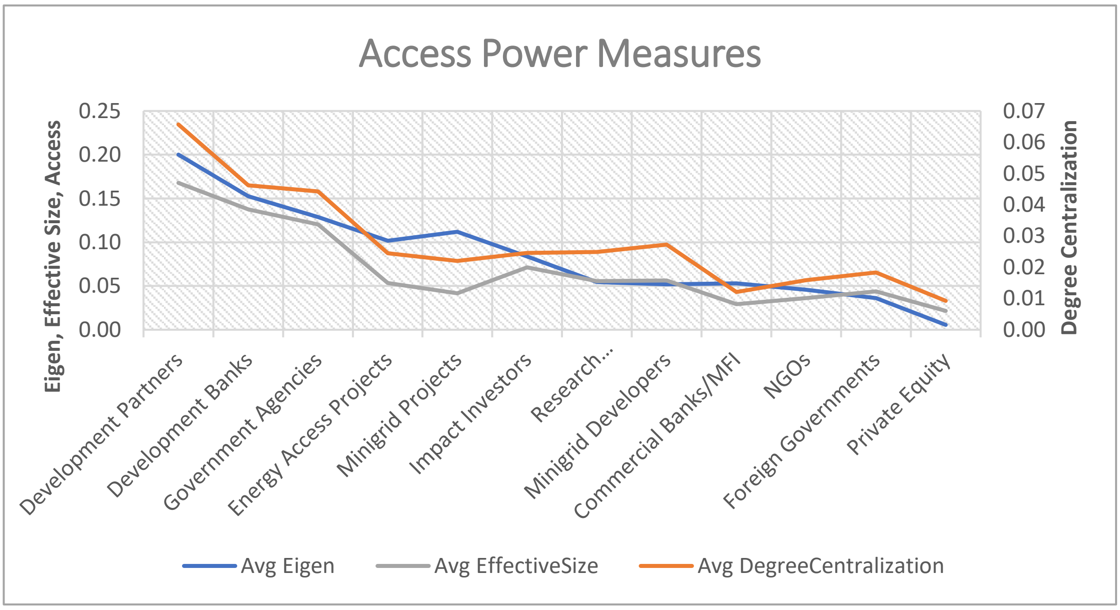


Figure 14: Access power centrality measures

4.4.1.3 Beyond Connections: Power Players & Network Gatekeepers

This section zeroes in on actors who exercise influence through more subtle mechanisms. It examines the metrics of betweenness centrality, constraint[13], and power centrality to identify key

[13] Constraint values in Figure 4 have been normalized

power players and gatekeepers within Uganda's OFI network. These measures help identify those who control critical junctures for information and resource flow, revealing the intricate dynamics of power distribution across the network. Figure 15 shows the trend for the three measures.

Figure 15 illustrates that development banks, foreign governments, and minigrid developers are the primary power players within the network, occupying the most strategic positions with power centrality scores of 0.68, 0.50, and 0.49, respectively. This means they're not only well-connected but also connected to other influential nodes within the network. Interestingly, development partners and government agencies, despite their high centrality in Figure 14, have a lower power centrality (0.46 and 0.49 respectively) in Figure 15. This suggests a curious situation. While they are well-connected (high centrality), their connections might not be to the most influential players within the network. This raises questions about the nature of their influence and their potential for driving change. Further, Figure 15 highlights the trend for betweenness centrality in the network. With the highest betweenness centrality scores, government agencies (0.13), development partners (0.09), and research institutions (0.06) emerge as key network gatekeepers, acting as essential intermediaries facilitating information flow across the network.

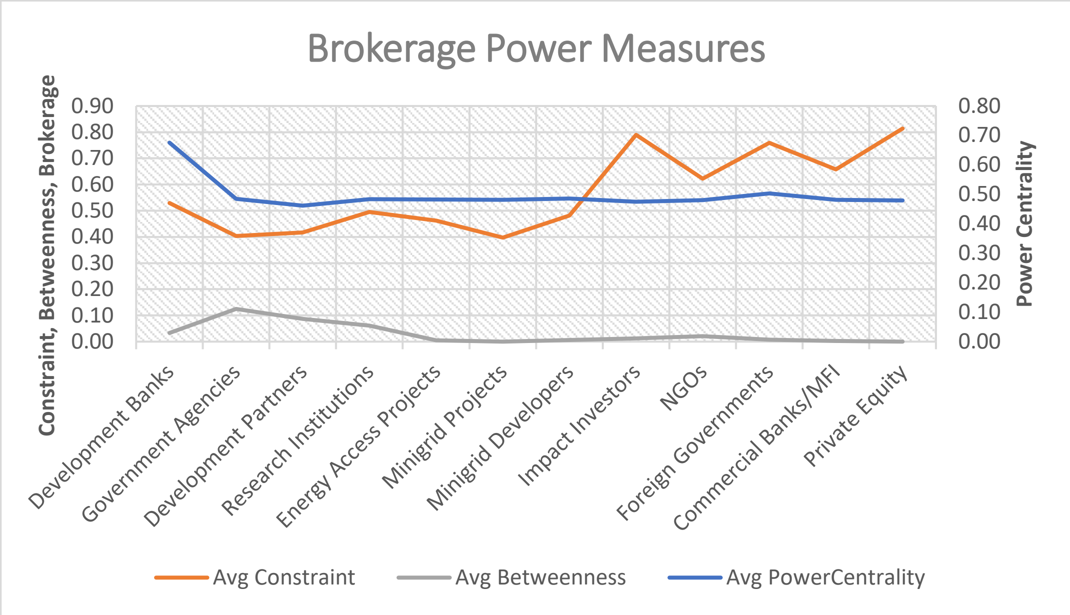


Figure 15: Brokereage power measures

4.4.1.4 Shaping Information Flow: Information Hubs & Sub-Network Efficiency

This assessment utilizes three key metrics: closeness centrality, information centrality, and local efficiency. Figure 16 shows the results of a centrality analysis of key resource diffusion metrics for different stakeholder groups.

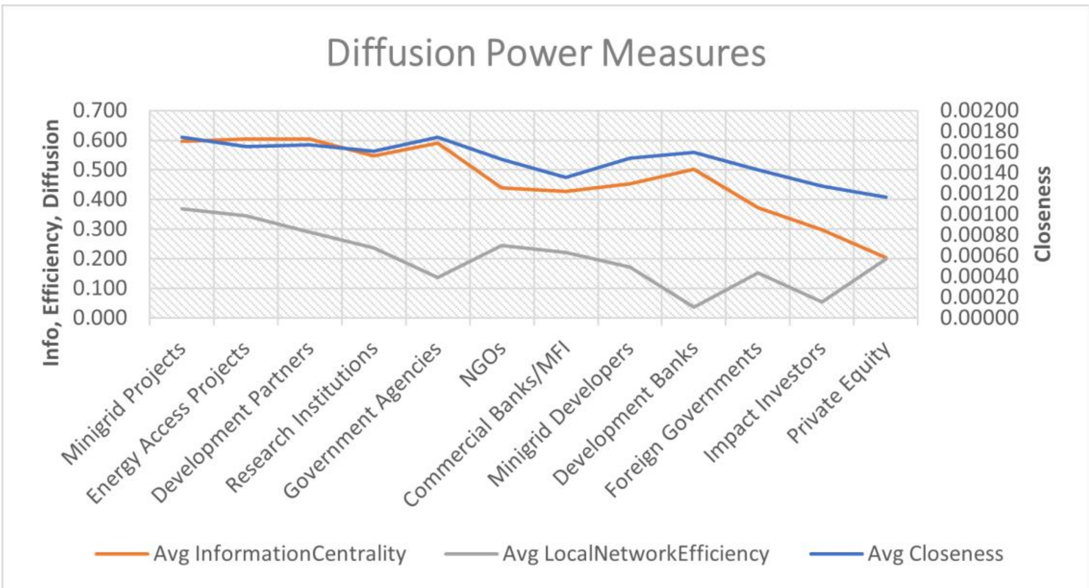


Figure 16: Diffusion power centrality measures

In Figure 16, Development Partners (0.604) serve as principal information hubs within the network, playing pivotal roles in disseminating information. They are followed closely by

Minigrid Projects and Government Agencies, which also demonstrate high information centrality scores (approximately 0.59). In contrast, Private Equity Players and Impact Investors display the lowest scores (around 0.20-0.30), suggesting less strategic positioning for optimal information flow. Additionally, Minigrid Projects, Energy Access Projects, and Development Partners exhibit the highest LNE scores (around 0.35-0.37), indicating the effectiveness and connectedness of their local subnetworks. This connectivity enables efficient information exchange and collaboration within their local sub-groups. Conversely, Impact Investors, Development Banks, and Government Agencies have the lowest LNE scores (approximately 0.04-0.14), pointing to potential inefficiencies in information flow within their immediate clusters.

4.4.2 Quantifying Influence: Access, Brokerage, and Diffusion

Table 12 displays the Principal Component Coefficients (Loadings) for each metric across the principal components (PCs) for the different dimensions of access, brokerage and diffusion and details the percentage of variance each component explains.

Table 12: PCA loading contributions

Dimension	Variable	PC1	PC2	PC3
Access power	Degree Centrality	0.2198	0.2083	0.9531
	Eigenvector Centrality	0.7353	-0.6774	-0.0215
	Effective Size	0.6411	0.7055	-0.302
	% of Variance Explained	94.98%	4.93%	0.09%
Brokerage	Power Centrality	0.065	0.929	0.364
	Inverse Constraint	0.851	0.139	-0.51
	Betweenness Centrality	0.521	-0.34	0.782
	% of Variance Explained	78.33%	13.60%	8.07%
Diffusion	Closeness	0.0010	-0.0007	1.0000
	InformationCentrality	0.8575	-0.5145	-0.0012
	LocalNetworkEfficiency	0.5145	0.8575	0.0001
	% of Variance Explained	64.24%	35.76%	00.00%

Overall Influence	Brokerage Score	0.55698	0.28648	0.77956
	Access Score	0.67989	-0.3818	-0.62608
	Diffusion Score	0.477	0.87872	-0.01788
	% of Variance Explained	77.83%	17.83%	4.34%

4.4.2.1 *Access Power Influence Score*

PC1 for the access power dimension in Table 12, which emphasizes Eigenvector Centrality (0.7353) and Effective Size (0.6411), captures 94.98% of the variance, indicating its dominant role in reflecting the nodes' capabilities to access and influence the network. In contrast, PC2 and PC3 contribute minimally, explaining only 4.93% and 0.09% of the variance, respectively. This analysis shows that influential connections and non-redundant connections (captured by Eigenvector and Effective Size) are more crucial for node influence than merely numerous connections (Degree Centrality). Utilizing PC1 for deriving the Access Power influence score thus offers a robust measure of nodes' networking effectiveness within the system. Access Power Score is modelled as,

$$AP_{score} = 0.2198 * C_D(i) + 0.7353 * C_E(i) + 0.6411 * C_{ES}(i)$$

Where $C_D(i)$ is degree centrality of node i, $C_E(i)$ is eigenvector centrality of node i, and $C_{ES}(i)$ is the effective network size for node i.

The study finds that development partners, development banks, and government agencies, with the highest Access power influence scores of 0.27, 0.21, and 0.18 respectively, are central to the network. Their high centrality metrics—degree, eigenvector, and effective size—position them as crucial nodes facilitating substantial interaction and resource flow, thus influencing the network's dynamics significantly. Conversely, entities like private equity players, commercial banks/microfinance institutions, and NGOs have the lowest Access power scores (0.02, 0.06, and

0.06, respectively), indicating their peripheral roles within the network, which impacts their efficiency and capability to distribute resources effectively.

4.4.2.2 Brokerage Power Influence Score

The PCA analysis of Uganda's OFI network brokerage power metrics—power centrality, inverse-constraint, and betweenness centrality—shows weak correlations among these metrics, suggesting they each provide unique insights into the network's structure. PC1 for the brokerage power dimension in Table 12 , explaining 78.33% of the variance, is heavily influenced by inverse-constraint, indicating it as a key factor in understanding brokerage dynamics. Power centrality and betweenness centrality, which contribute to PC2 and PC3, weighted at 13.60% and 8.07% respectively, also offer critical but more nuanced insights into the network's brokerage roles, collectively informing a composite Brokerage Power score. This metric combines influences from all three components, weighted according to their explanatory significance and individual contributions, thereby capturing a comprehensive view of nodes' brokerage abilities within the network. Brokerage Power score is modelled as,

$$BP_{score} = 0.206 * C_P(i) + 0.645 * \left({}^{1}\!/_{C_{CO}(i)} \right) + 0.424 * C_B(i)$$

Where $C_B(i)$ is betweenness centrality of node i, $C_P(i)$ is power centrality of node i, and $C_{CO}(i)$ is constraint of node i.

Development banks, government agencies, development partners, and research institutions emerge as the most influential in brokerage roles, primarily due to their high scores in inverse constraint and betweenness centrality. These components are heavily weighted in the Brokerage Power Score calculation, reflecting their critical roles in determining brokerage power.

Government agencies and development partners, in particular, exhibit high betweenness and inverse constraint scores, aligning with their significant network influence. Power centrality also contributes to the brokerage score, but its impact is less significant given its lower weight in the scoring equation. This alignment of high centrality scores with the weighted components underlines the strategic importance of these nodes in facilitating resource and information flow across the network.

4.4.2.3 Diffusion Power Influence Score

The PCA correlation matrix reveals a strong link between closeness and information centrality within the network, indicating that nodes central to network connectivity also significantly influence information flow. However, LNE displays weak correlations with both closeness and information centrality, suggesting it operates independently of a node’s central position or informational influence. This indicates a complex network dynamic where different nodes or clusters may have specialized roles—some optimizing for information transmission, others for network cohesion, and yet others for local resilience. The varying degrees of correlation among these variables suggest that the network's variance is spread across multiple principal components, highlighting the multifaceted interactions and diverse functions within the network.

The PCA results indicate that the primary component (PC1 for the diffusion dimension in Table 12), accounting for 64.244% of the variance, significantly captures the roles of Information Centrality and LNE within diffusion in the network, with minimal input from Closeness. This suggests that the main variations in the network are driven by how nodes handle information and manage local connections. PC2, explaining 35.756% of the variance, highlights the contrasting roles between LNE and Information Centrality, indicating a nuanced interplay between these metrics in the network's structure. PC3, focused almost solely on Closeness and contributing negligibly to variance, underscores that while Closeness is a clear characteristic, it does not influence node differentiation in this context. Collectively, these components suggest a complex network dynamic where the key differentiators are the effectiveness of information dissemination and local operational efficiency, rather than mere proximity or closeness among nodes. Diffusion Power Score is modelled as, $DP_{score} = 0.6424 * 0.8575 * C_{IC}(i) + 0.3576 * 0.8575 * E_{loc}(i)$

Where $C_{IC}(i)$ is the information centrality of node i, and $E_{loc}(i)$ is the local efficiency of node i.

It aggregates information centrality and LNE to measure each node's capacity for spreading resources and information. Minigrid projects, with the highest scores, are notable for their top closeness centrality and LNE (see Figure 16), facilitating effective resource and information flow within their local contexts. Their substantial information centrality further enhances their role as central information conduits across the network. Development partners also show strong diffusion capabilities, driven by high information centrality and good LNE, reflecting their key role in funding and influencing network activities. Similarly, energy access projects stand out with high LNE and significant diffusion scores, underscoring their effectiveness in project implementation and resource distribution within the network.

4.4.2.4 Concentration of Network Influence

In examining the overall structure of Uganda's OFI network, it is critical to consider the varied roles and impacts of different stakeholders as indicated by their performance across three key metrics: Access Power Score, Brokerage Power Score, and Diffusion Power Score. These metrics collectively provide a comprehensive picture of how effectively resources, information, and influence are potentially managed and propagated within the network. Figure 17 shows a star burst comparison of power scores for the different stakeholder groups.

The maximum scores recorded for access, brokerage, and diffusion are 0.27, 0.32, and 0.44 respectively, indicating a predominant concentration of lower scores across the network, as detailed in Figure 17. This distribution is characterized by a pronounced right skew, with individual nodes scoring as high as 1.45 for access and 1.19 for brokerage, far surpassing average group scores. The significant range in scores, particularly for access (1.4354) and brokerage (1.0953), highlights the variability in network roles, with a few nodes displaying exceptional capabilities. Skewness values for access (4.1551) and brokerage (3.1105) further emphasize the concentration of lower scores across most nodes but with a few outliers possessing high values. This pattern, supported by very high kurtosis values for access (23.1677) and brokerage (13.3251), indicates a network where a small number of nodes hold disproportionate influence and power, centralizing critical network functions within these few actors. This creates vulnerabilities where the network's resilience may be compromised if these critical nodes fail. In contrast, diffusion scores paint a somewhat different picture, with a mild negative skewness (-0.4469) suggesting a slightly left-skewed but more balanced distribution, though still with room for improvement. These patterns underline the need for strategic network restructuring or policy interventions aimed at enhancing connectivity and reducing the reliance on a few dominant nodes, thereby promoting a more resilient and equitable network structure.

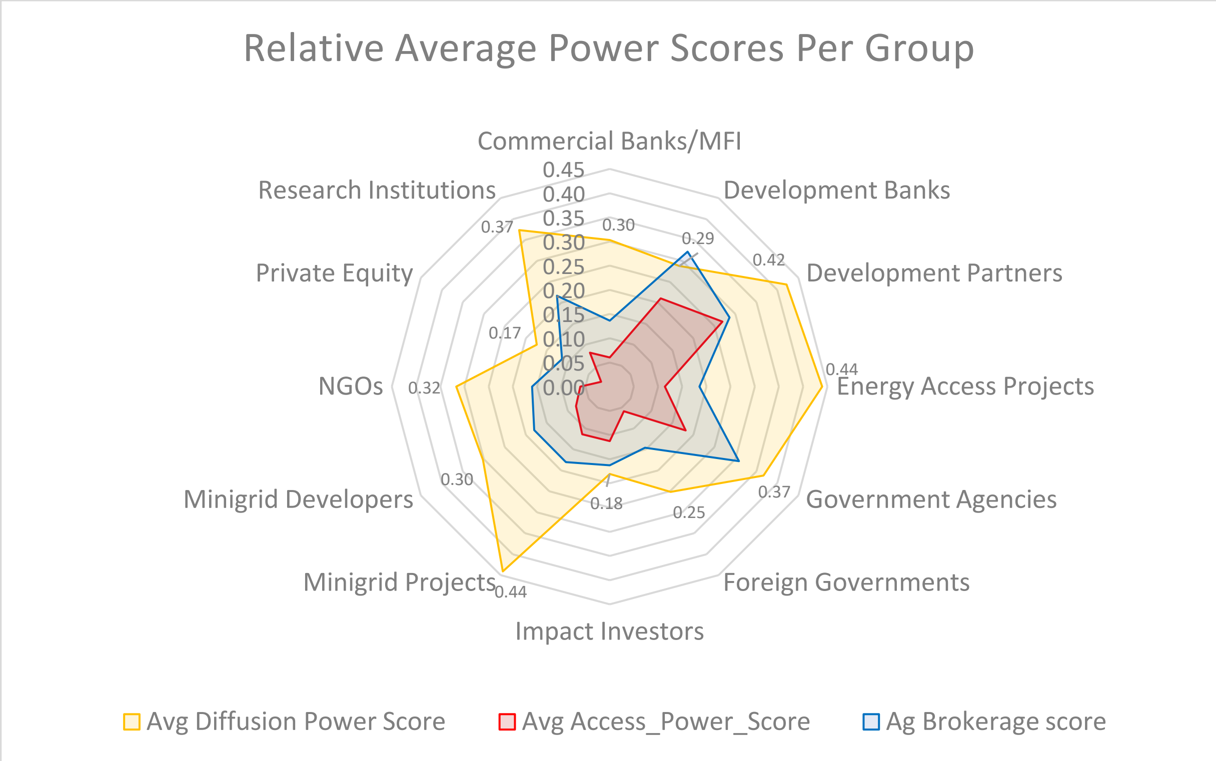


Figure 17: Power scores & relative stakeholder ranking

4.4.2.5 Network Outliers

The PCA analysis on derived influence scores for access, brokerage, and diffusion, summarized in Table 12, underscores the interconnectedness of these network roles. Strong correlations between access and brokerage (0.86872) indicate that nodes central in resource access also play key roles in connecting different network segments. However, only moderate correlations with diffusion (about 0.54) suggest that while these nodes are strategically placed, they may face inefficiencies or structural barriers that prevent them from fully maximizing resource dissemination across the network. This points to a potential area for improvement, where enhancing the capability of these nodes to distribute resources could significantly increase network efficiency.

From Table 12, PC1 capturing 77.83% of the variance, integrates access, brokerage, and diffusion capabilities with the highest influence on access, indicating nodes with a balanced mix of these capabilities are the most influential. PC2, with strong influence on Diffusion and a negative impact on Access, suggests that some nodes specialize more in spreading resources than in accessing them, illustrating the network's diverse functional roles.

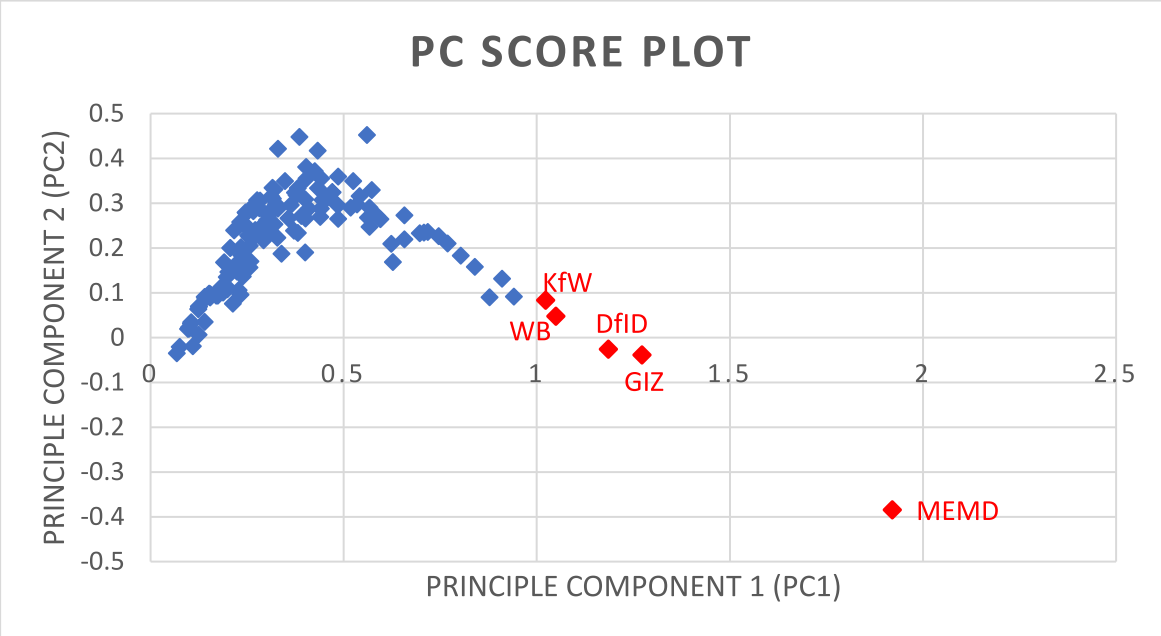


Figure 18: PC score plot of overall network influence

Figure 18 displays the distribution of nodes on the first two principal components, PC1 and PC2, showcasing notable nodes based on their distinct scores. The figure also points out outliers, significant for their extraordinary influence or unique network roles, which can inform structural insights and guide strategic enhancements within the network. The analysis identifies several key players (GIZ, DfID, Ministry of Energy (MEMD), KfW, World Bank) as influential based on their high PC1 scores (>1), indicating their central role and exceptional access to information within the network. Despite their strong network positions, these nodes exhibit limited effectiveness in information diffusion, as reflected in their low PC2 scores. Specifically, DfID, GIZ, and MEMD show negative PC2 scores, suggesting below-average capabilities in disseminating information, despite their positive influence and connectivity. MEMD's scenario is particularly notable, with a high PC1 score illustrating its significant access to vital network resources, yet a highly negative

PC2 score indicating a deficiency in information sharing. This might stem from an inward focus on information processing and policy formation, or possible communication barriers that prevent effective outward dissemination. These limitations can impede MEMD's ability to effectively influence OFI initiatives. To enhance its role in the network, MEMD could develop targeted communication strategies and strengthen collaborations with other network entities to improve information flow and jointly advance sector initiatives. This approach would leverage MEMD's central position to not only gather but also effectively distribute essential information, thus enhancing the overall network dynamics.

4.4.3 Network Robustness & Resilience

The study explores the robustness and resilience of Uganda's OFI network using metrics like degree distribution, network density, and average path length. It identifies a power-law degree distribution, with significant right skewness value of 729.5 indicating a highly asymmetric distribution that is heavily weighted towards nodes with exceptionally high degrees. This case of a few highly connected nodes amidst many with lower degrees, makes the network resilient to random failures but vulnerable to targeted attacks (Estrada, 2006). The presence of the few highly connected nodes indicates critical points of vulnerability in the network, as their removal could significantly disrupt connectivity. That a large majority of nodes possesses relatively lower degrees offers a degree of redundancy and alternative pathways, enhancing the network's resilience against random failures or disruptions.

A *normalized* network density of 0.015 points to low connectivity, potentially limiting resource flow and reducing redundancy (Hua et al., 2022; Yi, 2017) and undermining the system's robustness (Carlsson and Sandström, 2008; Sandström and Carlsson, 2008). However, within an energy network, this could suggest a strategic decentralization that distributes control and enhances system robustness (Dekker and Colbert; Mookherjee, 2006; Yamaguchi, 1996).

An average path length of 3.272 suggests moderate efficiency in information and resource transmission, balancing between centralization and decentralization to safeguard against the severe impacts of single-node failures while potentially slowing down rapid network responses (Dekker and Colbert; Pan and Saramäki, 2011). Further, an average normalized node constraint of 0.502, points to a balanced structure where nodes maintain a mix of dependency and autonomy, avoiding extremes of centralization or fragmentation. This balance supports network resilience by mitigating the risks associated with failures of central nodes and enhances robustness through diverse interconnections that provide multiple pathways for communication and resource flow. Such a setup ensures that the network can remain operational despite disruptions, with sufficient flexibility in connections to adapt and recover without excessive reliance on any single node.

The results highlight a balanced network structure characterized by low density, moderate average path length, and moderate node constraint. This balance indicates strategic planning to maintain efficiency while ensuring resilience against disruptions. The low density suggests limited connectivity, reducing the risk of widespread impacts from disruptions but potentially hindering quick information and resource flow. The moderate path length facilitates sufficient communication efficiency without overly tight connections, and the average constraint level indicates a healthy balance of node interdependence and independence, safeguarding the network against the failure of individual nodes. To further enhance the network's robustness and responsiveness, strategies could include bolstering node connections and creating more direct links to improve operational efficiency and responsiveness.

4.4.4 Node-Level Performance of Uganda’s OFI Network

The study explores how well-positioned key stakeholders are in terms of access, brokerage, and diffusion shedding light on the current effectiveness of the network highlighting strengths and pinpointing strategic opportunities for enhancing connectivity, resource allocation, and overall network resilience. Figure 17 identifies key stakeholder groups — Development Partners, Development Banks, and Government Agencies — as pivotal in both stabilizing and advancing Uganda’s OFI network. As deduced from the analysis in sections 4.4.1 and 4.4.2, *development partners* in Uganda's OFI network seem to occupy a strategic and influential position having the best access, high diffusion, and good brokerage influence. By leveraging their strengths and strategic network position, they can act as knowledge brokers, collaboration catalysts, information hubs, and advocates for positive change. *Development banks* are revealed as strategic players with a unique network position having good network access, best in brokerage influence and good diffusion in the network. They have the potential to significantly impact Uganda's OFI network by acting as brokers, knowledge hubs, and facilitators of innovation. Their ability to connect different actors and information flows can be instrumental in driving progress. *Government agencies* are found to be central players within the Ugandan OFI network having good access and diffusion and good brokerage influence in the network. By effectively disseminating information, promoting supportive policies, and fostering collaboration, they can play a crucial role in achieving Uganda's OFI goals.

These potential associations draw upon insights from SNA literature which has established key associations with network closure, where densely connected groups often form information hubs (Ehrlichman, 2021; Reagans and McEvily, 2008). These tightly-knit networks and their linkages with other subnetworks play a critical role in driving diffusion and establishing resource (information, innovations, and ideas) and contagion spreaders (Centola, 2015; Cheng, 2021; Geier et al., 2019; Rose, 2005). Moreover, SNA research underscores the importance of brokerage in innovation (Ehrlichman, 2021; Fleming et al., 2007; Reagans and McEvily, 2008; Tortoriello et al., 2015). By linking disconnected groups, brokers enhance the exchange of diverse knowledge and ideas, which can spur innovative collaborations and solutions.

On the flip side, Figure 17 identifies Impact Investors, Private Equity players and NGOs/CSOs as stakeholders with significant untapped potential within Uganda's OFI network, which, with targeted support and strategic development, could play transformative roles in enhancing the network's overall effectiveness and reach. Currently, these groups show comparatively low access and brokerage abilities and varying levels of diffusion effectiveness, indicating a peripheral network position with implications for the network efficiency and resource distribution. Specifically, Impact Investors are not fully integrated, limiting their ability to leverage their funding capabilities efficiently due to weak connections and restricted information flow. Conversely, Private Equity players, although capable of effective information dissemination within their circles, face challenges in accessing critical OFI information and in connecting with key network stakeholders, which inhibits their potential as network bridges. NGOs, in particular, may struggle to influence policy and the network's strategic direction due to their lower centrality. The conclusions are supported in SNA literature that suggests that actors outside of central network positions tend to have limited access to resources, and are hindered pertaining to their network reach, influence or information access (Gulati, 1999; Huggins and Johnston, 2010; Koka and Prescott, 2008).

4.5 Conclusion & Policy Implications

This research has methodically analyzed the structure of Uganda's OFI network and using SNA, revealing complex connectivity and power dynamics applicable to any off-grid policy network. The findings demonstrate that access power is more effectively gained through influential and non-redundant connections rather than sheer quantity. Brokerage power significantly depends on the interconnections among a node's neighbors, while resource diffusion is influenced, not by closeness, but by the node's strategic position on critical communication pathways. The findings also reveal a low network density and a skewed power distribution, indicating a need for strategies to improve connectivity and achieve a more equitable resource and influence distribution.

4.5.1 Policy Insights & Recommendations

4.5.1.1 Catalysts in Uganda's OFI Network

Development banks and development partners, with their strong connectivity and strategic placement, act as vital catalysts within the network. Equipped with high access and brokerage capabilities, they mobilize critical resources—financial, technological, and intellectual—that support substantial development projects. Their effective diffusion of resources ensures extensive distribution of benefits, enhancing equity across the network. Similarly, government agencies, demonstrate robust access, diffusion, and brokerage capabilities critical in effective resource mobilization and distribution across the network. This central role enhances the adoption of policies and support for diverse projects, while their ability to connect various stakeholders fosters collaboration and ensures alignment within the network.

4.5.1.2 Untapped Potential in Uganda's OFI Network

Section 4.4.4 highlights the peripheral positioning of Impact Investors, Private Equity players, and NGOs/CSOs in Uganda's OFI network, noting their low Access Power scores which limit their connectivity and access to critical resources. This positioning hinders their effectiveness in project implementation and crisis response. To enhance their network roles, strategic initiatives are necessary to improve their integration and connectivity. For NGOs, better network positioning could significantly boost their resource access and community service impact. Collaborations with well-connected entities like Development Banks or Partners could broaden the network reach of all three and improve information access. Impact Investors and Private Equity players could benefit from government-led matchmaking programs or specialized workshops to deepen their network integration, enabling them to leverage network resources more effectively and contribute more significantly to the network’s goals. These measures would not only bolster the effectiveness of the OFI network but also maximize the contributions of these critical yet underutilized groups.

4.5.1.3 Network dominance of international development partners

The high centrality of development banks and partners, in section 4.4.4, as key international players in Uganda's OFI sector significantly enhances network stability and sustainability due to their superior levels of access, brokerage and resource diffusion within the network. The same characteristics may foster a reliance on these external entities possibly weakening local capabilities and ownership by concentrating decision-making and resource allocation with foreign organizations. Such a dynamic risks fragmenting the sector, as the varied priorities and strategies of these international actors may clash, leading to disjointed efforts and inefficiencies. Moreover, the substantial influence these partners wield over policy directions could overshadow local needs and restrict the participation of local stakeholders, making it challenging for domestic actors to assert their interests and contribute effectively to the sector's development. Furthermore, should these international players withdraw or shift their strategies, the network could face significant instability and disruption, highlighting the need for building stronger local systems and reducing dependency on external influences.

4.5.1.4 Global Network Design & Policy Strategy Implications

Two key findings—the correlation data from Table 11 and the distinct relationship between access power and brokerage power shown in Figure 17, compared to their weak correlation with diffusion power— highlight complex dynamics across broader networks. These findings indicate that nodes with high eigenvector and betweenness centrality, essential for accessing and brokering resources effectively, are critical leverage points for enhancing the performance of any network. By boosting the capacity of these select nodes—through increased resources, enhanced decision-making authority, or improved operational capabilities—the overall functionality of the network can be significantly enhanced. Furthermore, in a bid to boost resource diffusion, increasing connections to nodes with high local efficiency but lower overall centrality can improve the network's resilience and effectiveness in spreading resources. This strategy ensures that even nodes on the periphery significantly bolster the network's robustness, leading to a more cohesive and durable network structure.

The case study reveals global policy implications useful for similar initiatives worldwide. To counteract the dominance of foreign interests in energy networks, network policies should prioritize strengthening local capacity—enhancing the connectivity of local nodes, increasing their direct links to essential network hubs, and fostering partnerships with key stakeholders. This could involve creating more partnership opportunities with key players or improving the infrastructure that supports communications and data exchange.

Moreover, harnessing the untapped brokerage potential of research institutions by fostering strategic partnerships among universities, private sector, and government entities at both local and international levels can catalyze innovation and cross-sector collaboration, ultimately boosting network efficiency and sustainability. Additionally, leveraging technology e.g. digital engagement platforms that involve all stakeholders in policymaking to transform previously marginal actors into central figures by facilitating seamless and cost-effective connections and engagements within the network.

4.5.2 Study Limitations & Future Research

This study provides significant insights into network structures and dynamics, but it's important to note that correlation does not equate to causation and general insights in existing literature may not fully apply to the unique aspects of Uganda's OFI network, as specific local challenges and opportunities can differ significantly from those studied globally. Future research should include actual performance data and longitudinal analyses to deepen understanding of the causal relationships within network configurations.

4.6 Declarations

Funding: This work was supported by the Africa: Research and Teaching platform for Development - Sustainable Modular Grids Project (A:RT-D Grids) funded by the German Federal Ministry of Education and Research (BMBF) under the Client II programme – funding ref 03SF0607A.

Data Availability Statement: The datasets analysed for this study are available from the author on reasonable request.

Conflicts of Interest: The author declares no conflict of interest.

5 Institutional Market Design in Energy Constrained Settings

Smart Metering and Choice Architecture in Demand-Side Management: A Power Resource-Constrained Perspective[14,15]

Lillian Donna Namujju[a], Ibrahim Mwammenywa[b], Geoffrey Mark Kagarura[b], Ulrich Hilleringmann[b], Burkhard Hehenkamp[a]

[a] *Chair of Institutional Economics & Economic Policy, Faculty of Economics, Paderborn University, Paderborn, Germany*

[b] *Sensor Technology Group, Paderborn University, Paderborn, Germany*

Abstract

This research explores the design and implementation of a groundbreaking smart meter for energy demand-side management (DSM) in Silale, a rural community in Tanzania, addressing challenges posed by the limited capacity and unregulated consumption off the local minigrid system. The research focuses on the meter's innovative design and its successful rollout within the community, highlighting the novelty of behavioral interventions in DSM strategies. The system adopts a tiered strategy, starting with gentle nudges using visual color and acoustic cues and progressing to harder choice architecture culminating in automatic power disconnection. The implementation of this system resulted in a 47.4% reduction in peak energy demand, alongside a significant change in power consumption patterns among Silale residents. These findings underscore the efficacy of nuanced behavioral nudges in combination with goal setting in achieving significant and enduring changes in energy use behaviors.

Keywords—Demand-Side Management, Behavioral Economics, Choice Architecture, Nudging, Traffic Light System

---

[14] Research was published: L. D. Namujju, I. Mwammenywa, G. M. Kagarura, U. Hilleringmann and B. Hehenkamp. Smart Metering and Choice Architecture in Demand-Side Management: A Power Resource-Constrained Perspective, 2024 IEEE 8th Energy Conference (ENERGYCON), Doha, Qatar, 2024, pp. 1-6, doi: 10.1109/ENERGYCON58629.2024.10488738

[15] This work was supported by the Africa: Research and Teaching platform for Development - Sustainable Modular Grids Project (A:RT-D Grids) funded by the German Federal Ministry of Education and Research (BMBF) under the Client II programme – funding ref 03SF0607A.

5.1 Introduction

Traditional DSM in developed countries is predominantly centred on conserving energy and cost reduction, emphasizing energy efficiency and minimizing waste. Conversely, in Sub-Saharan Africa, the DSM context begins with the challenge of scarce energy resources, often insufficient to meet the region's energy needs. Consequently, the focus shifts from energy conservation to maximizing the utility of the available limited energy supply - stretching the limited capacity to fulfil the essential energy requirements of the population. In Silale, a rural community in Tanzania, this challenge is acutely felt. The community's minigrid, the main source of power, grapples with the critical issue of unreliable electricity supply. This unreliability stems from a confluence of factors, most notably the constrained capacity of the minigrid, which is frequently overwhelmed by the available demand. Compounding these issues were unregulated consumption patterns during the day, constraining sufficient charging of the batteries, placing a strain on the limited battery reserves, and resulting in insufficient capacity to support even the most basic lighting services in the evening when they were most needed. As a result, residents often faced power black-outs during evening hours. This situation not only disrupted daily life but also undermined the community’s confidence and willingness to invest further in the mini-grid system.

This study seeks to explore how behavioral interventions, framed within the concept of choice architecture, can positively influence energy consumption patterns. By implementing 'nudges', subtle changes in the way choices are presented, we aim to shift consumption behaviors in a way that aligns with the mini-grid’s capacity, thereby enhancing the reliability of power supply. This approach represents a novel fusion of behavioral economics and DSM, a strategy for managing electricity demand by incentivizing customers to modify their energy consumption.

5.2 Theoretical Framework

5.2.1 Overview of Behavioral Economics in DSM

Behavioral economics explores the effects of psychological, cognitive, emotional, cultural, and social factors on the economic decisions of individuals and institutions (Reisch and Zhao, 2017). It challenges the notion of humans being purely rational actors, introducing concepts like bounded rationality and systematic biases. In the realm of energy, behavioral economics helps explain why consumers often make decisions that appear irrational, such as not investing in energy-saving measures despite apparent long-term financial benefits. Understanding these nuances is crucial for designing effective energy policies and interventions.

Typical energy consumption decisions are influenced by factors beyond cost and utility. Common mental shortcuts and biases, habitual behaviors, misconceptions about energy use, and the influence of immediate conveniences play a significant role in energy-related decisions (Ekholm et al., 2010). Energy behavior is also shaped by social norms and the actions of peers. Visibility of energy-saving behaviors in a community can set new standards, prompting others to follow (Gołębiowska et al., 2021). The behaviors underscore the importance of behavioral economics in influencing consumer choices and energy consumption patterns.

Choice architecture, a concept rooted in behavioral economics, plays a pivotal role in DSM. The concept focuses on shaping or organizing the context in which people make decisions (Thaler et al., 2013). It is about framing choices for consumers in a manner that guides their decisions and actions, without removing options or drastically changing incentives (Thaler and Sunstein, 2008). By strategically organizing how choices are laid out, it aims to subtly steer consumer behavior. In the context of DSM, this means creating a setting or presenting options in a way that nudges consumers toward more energy-efficient behaviors. Examples of this include redesigned energy bills that highlight energy-saving opportunities, or rewards for reduced consumption. This behavioral economics concept plays a crucial role in shaping DSM strategies driving energy usage patterns (EIA, 2014; Good, 2019). Many DSM strategies focus on promoting energy efficiency through consumer education and awareness campaigns often leveraging behavioral insights to encourage the adoption of energy-saving habits and technologies (Khan, 2019). Others rely on regular feedback to consumers about their energy usage, coupled with social comparison tools that show their consumption relative to neighbors (Gołębiowska et al., 2021). Others still, rely on economic incentives to influence behavior. In this category, dynamic pricing models .e.g. time-of-use pricing is used to incentivize consumers to shift their energy usage to off-peak times (Pollitt and Shaorshadze, 2011). Also in this category are gamification and reward systems for energy saving behaviors utilizing positive reinforcement and the desire for achievement and recognition (Gnauk et al., 2012).

5.2.2 Traffic Light System as a Behavioral Intervention

In this study, we employ choice architecture as a foundational strategy and the traffic light system (TLS), central to our study, exemplifies this approach. It is designed to provide clear, color coded visual cues that advise and guide residents towards more efficient energy choices. Studies in behavioral science show that humans have a strong response to visual stimuli (Morris et al., 1997). The distinct colors of the TLS serve as clear, immediate visual cues that can effectively attract attention and trigger behavioral responses without the need for complex interpretation. The choice of red, yellow, and green colors in the TLS is grounded in color psychology (Kubo et al., 2021). Red typically signifies danger or caution, prompting users to reduce consumption; yellow indicates a need for caution, and green denotes safety or optimal conditions. This color coding aligns with universal traffic signal interpretations, making it intuitive and easily understood by consumers. Furthermore, the system is designed to be salient, meaning it stands out and captures attention. The red signal is accompanied by a beeping sound to capture the consumer's attention. The integration of both visual and audio signals for the red alert, designed as a call to action, serves to engage both visual and auditory senses, maximizing the likelihood of signal recognition and response. The dual-sensory approach is particularly advantageous in scenarios where consumers might be preoccupied, lack direct line of sight to the smart meter, or face visual impairments.

Salient cues are more likely to be noticed and acted upon (Ibid), making the TLS an effective tool for influencing energy consumption behavior.

5.3 Methodology

5.3.1 Study Setting

This study was conducted at Silale community microgrid which is located at -5.8217, 36.5526, Kongwa district in Tanzania. It comprises a rural, low-income population, that is predominantly subsistence farmers. Silale’s minigrid, originally rated at 15 kWp, has experienced significant performance degradation since inception in 2015. This decline can be attributed to the damage of over 25% of its solar panels and the deterioration of its battery system, a consequence of inadequate cooling and maintenance, among others. As a result, the current average peak PV generation has been reduced to as low as 4kW.

The smart meter TLS was implemented across all 60 households connected to the Silale community mini-grid. The traffic light functionality was designed as part of smart meter infrastructure, allowing for an efficient and cost-effective deployment. The smart meter roll-out was endorsed by the minigrid village committee making it a standard component of all connected households. Because of this, consumers were not given the chance to opt in or opt out of the implementation. A usage breakdown of energy-consuming appliances across households indicated 57% have radios, 37% own TVs, 9% use refrigerators, and 2% possess laptops. Additionally, there is an average of 3 lights and 3 mobile phones per household.

The community was trained prior to the installation of the smart meters at the households. 46 out of 60 households were represented by at least 1 member in this training. The training included interactive sessions that explained how the system works, the significance of the color-coded signals, and the implications of the automatic disconnection feature as well as the associated delays prior to- and after disconnection. Special emphasis was placed on demonstrating the benefits of regulated energy consumption, both for individual households and the community's overall grid stability. Additionally, the training provided a platform for community members to share their perceptions and concerns with the technology, ask questions and receive clarifications. Local leaders and influencers were also involved, enhancing the training's reach and effectiveness.

5.3.2 Study Aims

The primary aim of this study was to investigate the effectiveness of the TLS, as a behavioral intervention tool for managing energy consumption in the rural community of Silale, Tanzania. The study focuses on assessing how this innovative approach, rooted in the principles of choice architecture and nudging theory, can influence and potentially transform consumer energy usage patterns in a setting where mini-grid capacity is limited and consumption patterns are traditionally unregulated. Specifically, we test the hypothesis: The introduction of the TLS system will alter energy consumption patterns in Silale.

5.3.3 Design of Smart Meter Traffic Light System

The system is designed to facilitate three key benefits in behavioral intervention science: (1) Immediate feedback, (2) cognitive ease, and (3) consumer conditioning. It provides instant feedback on energy usage. Immediate feedback is a powerful motivator in behavior change, as it creates a direct link between action (energy usage) and response (color change), enhancing the learning process (Froehlich). In addition, the simplicity of the TLS plays into the concept of cognitive ease, where simpler and more familiar formats lead to quicker and more confident decision-making. By reducing the cognitive load, the system makes it easier for consumers to process information and make energy-related decisions (Novemsky et al., 2007). Importantly, the system incorporates elements of consumer conditioning, a learning process where behaviors are influenced by the consequences that follow (Stuart et al., 1987). The positive reinforcement (green light) and negative reinforcement (red light) aspects of the system are designed to encourage or discourage certain energy consumption behaviors.

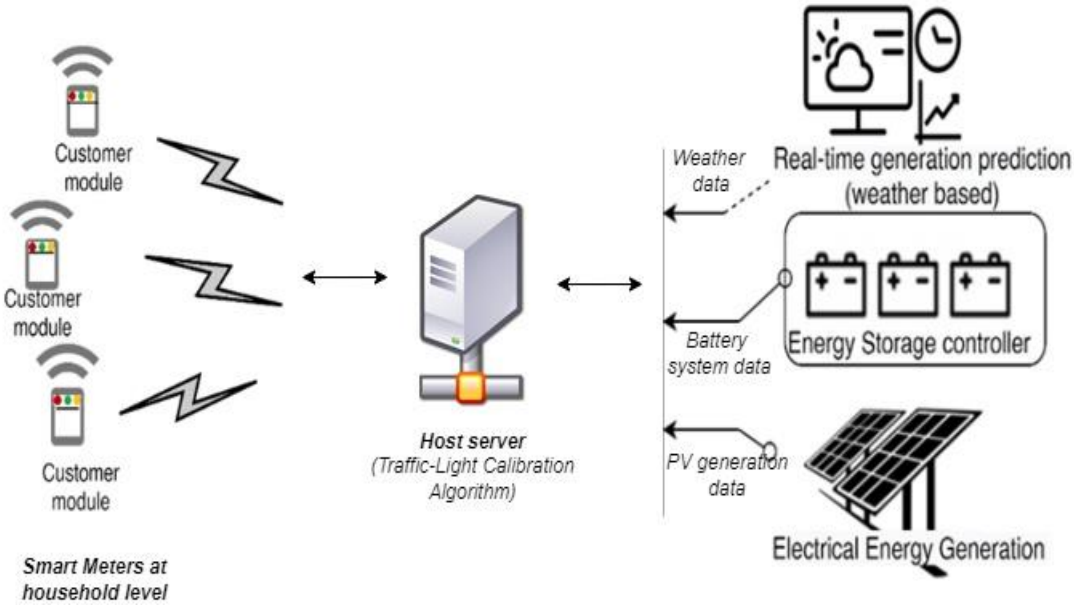


Figure 19: TLS architecture[16] (Mwammenywa et al.)

Figure 20: Installed TLS. © Josephine Kakande

Figure 19 and Figure 20 illustrate the TLS implemented in this study. At its core is the Traffic-Light Calibration Algorithm (TCA) located on the host server. This algorithm processes inputs from the photovoltaic (PV) generation system and the battery storage system, alongside the energy usage data from the smart meters at individual households. By analyzing this comprehensive dataset, the TCA, powered by an intelligent algorithm, establishes optimal

[16] The link to *Weather data* highlights an aspect of the system design that is yet to be operational - a weather-based power generation prediction module.

consumption thresholds for each household. It achieves this by comparing the real-time energy consumption data from the smart meters with the current energy availability as calculated from the storage and generation systems while ensuring battery reserves are maintained. Based on this analysis, the algorithm issues a calculated load limit signal. This signal is then wirelessly transmitted to the smart meters across the communication network (Mwammenywa et al.). A simplified mathematical model of the TCA is summarized below.

$$P_{Total} = \begin{cases} P_{gen} + max\left((P_{stor} - P_{reserve}), 0\right) & if\ P_{gen} > 0 \\ P_{stor} & if\ P_{gen} = 0 \end{cases} \quad (1)$$

$$L_{limit} = \frac{P_{Total}}{N} \quad (2)$$

Where, P_{gen} denotes power currently being generated by solar panels; P_{stor} the total power available from storage (batteries); $P_{reserve}$ the reserve capacity that we want to maintain in storage, not to be used unless $P_{gen}=0$; P_{Total} the total power available for distribution; N the number of households; and L_{limit} the power consumption limit per household. Equation 1 ensures that P_{stor} is used only if P_{gen} is unable to meet demand and $P_{reserve}$ is maintained. When $P_{gen}=0$ system relies on storage power including the reserve if necessary. This model ensures that the microgrid utilizes its generated and stored power intelligently, maintaining a reserve for emergencies or periods of no generation, and dynamically adjusting the consumption limit per household to promote efficient and sustainable energy use.

A smart meter at the household receives the load limit signal from the TCA, and compares it with the instant load of the user. Thresholds for each color indicator are customized based on the mini-grid's overall capacity and typical household consumption patterns. If the household load value is greater that the limit, the smart meter indicates a red light warning of high energy use exceeding the mini-grid's capacity. If load value ranges between 80%-100% of the limit, meter shows a yellow light signalling moderate use approaching high consumption; and if load value falls below 80%, then the meter will light green indicating low energy use within optimal limits (Hilleringmann et al; Mwammenywa et al.). The TLS employs a tiered approach to influence consumer behavior. It starts with a nudge in form of green and yellow lights before escalating to more forceful interventions. In the latter stage, the red light is accompanied by a beeping sound and ultimately a tripping of the circuit breaker after a configurable time interval (15minutes). The power is then only reinstated after another configurable duration (set to 30 minutes). This provides a structured yet flexible framework for influencing behavior.

5.3.4 Data Collection & Analysis Methods

The system was setup to collect power usage data from each household's smart meter and transmit it to a central server in near real-time. In addition to monitoring energy usage, the study conducted a survey among the connected households to gauge their reactions and attitudes towards the newly installed TLS. We adopted a cross-sectional study design to analyze and compare energy consumption data before and after the implementation of the TLS. The pre-implementation data was drawn from power load consumption records in July 2023. Post-implementation data was gathered over two distinct observation periods - August and September 2023. The three observation months all fell within Silale's dry season, eliminating seasonal variations as a factor in influencing the study's outcomes. Qualitative data on consumer reactions and attitudes to TLS was collected 1month after TLS rollout from a convenience sample of 25 one-on-one semi-structured interviews. The survey aimed to gather insights into consumers' views on the impact and benefits of the smart meters installed in their homes and to understand how they were adjusting to the restrictions imposed by the TLS.

5.4 Study results and discussion

5.4.1 Impact on Energy Consumption Patterns in Silale

Figure 21 shows that the TLS achieved changes in energy consumption patterns over the 3 observation periods. It shows a load shift as well as load peak shaving post TLS implementation pointing to a transformation in energy usage behavior among the consumers.

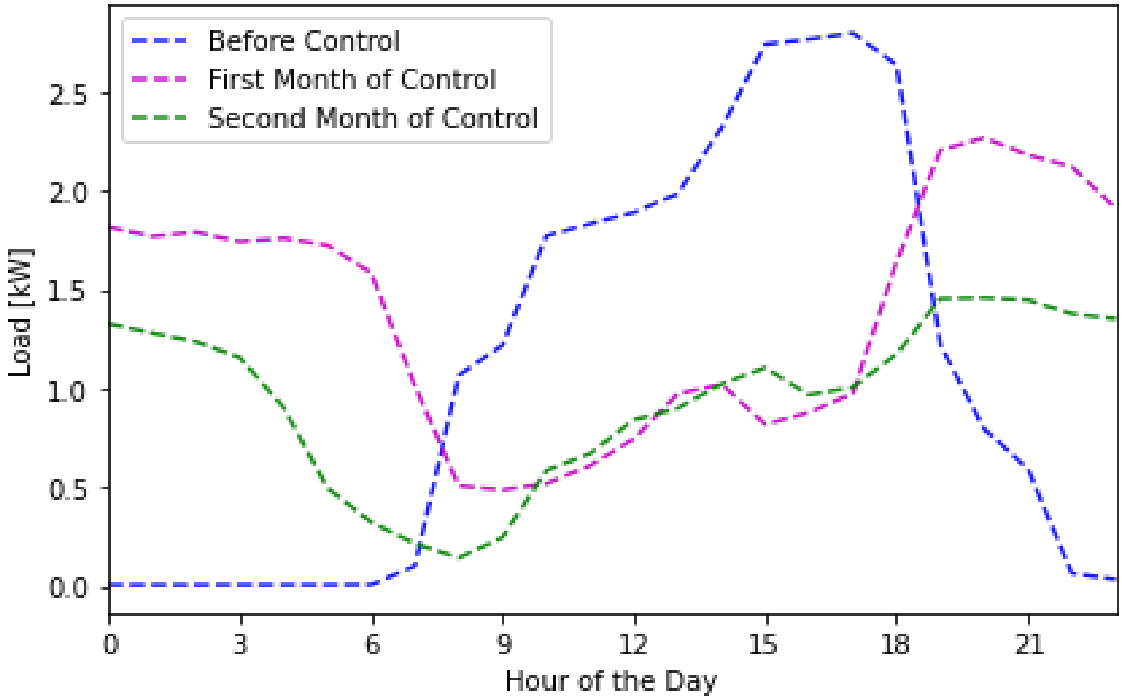


Figure 21: Mean daily load profiles before and after implementation of TLS

Before the system implementation, peak energy demand was concentrated in a single spike between 15:00 and 17:00 hours. Post-implementation, there was a noticeable shift to two distributed peak periods - early morning (00:00 - 05:00 hours) and late evening (19:00 - 21:00 hours) indicating an adaptation in consumer habits in response to the TLS cues. Another key finding was the reduction in peak demand values from approximately 2.85kW prior to implementation to progressively lower values in the subsequent months following the implementation; 2.25kW in 1st month of control (21.1% reduction) and further down to 1.45kW in 2nd month of control (33.3% reduction month-on-month). The cumulative reduction in peak demand over the 2 observation months came to 47.4%. Additionally, the consumption trends observed during these two months exhibited stable characteristics, suggesting that the behavioral shift among consumers was likely not a temporary response but a more enduring adjustment in their energy usage habits.

Research indicates that behavioral interventions aimed at reducing peak energy demand have the potential to lead to reductions in overall consumer energy use ranging between 2% and 20% in different contexts (Cornago, 2021; Pratt and Erickson, 2020). Interventions utilizing real-time feedback have tended to yield the highest energy savings (Cornago, 2021). When combined with goal setting, continuous individual feedbacks have proved to be even more effective (Lweka et al., 2019). The design of the TLS integrates real-time feedback to consumers through visual and acoustic cues alongside predefined consumption thresholds, which serve as benchmarks or objectives for energy users. This combination achieved an even greater reduction in peak demand of 47.4%.

Table 13 gives a summary of the Mann-Whitney U Test findings for month-on-month comparisons of power consumption patterns between the 3 observation periods.

TABLE 13 RESULTS OF MANN-WHITNEY U TEST

Comparison	***U statistic***	***P-Value***
July & August	110.5	0.1645
August & September	202.5	**0.0475**

The findings suggest that while consumption behaviors prior to control are statistically similar to those observed in the 1st month of control, there is a significant change between the 1st and 2nd month of control. This could indicate that the TLS strategy took time to become effective due to a more gradual adoption and adaptation by consumers or that its initial impact was not strong enough on account of initial challenges in implementation effectiveness. The significant difference observed between the two post-implementation periods suggests that the TLS strategy can be effective in influencing consumption patterns, but its impact might not be immediate and could require time, adjustments, and optimizations to achieve desired outcomes. Notably, the observed changes in consumption patterns, alongside the reduction in peak demand values, directly tackle the issue of insufficient battery charging during daytime in Silale, which previously resulted in insufficient capacity to support evening hours. This adjustment allows sufficient charging of the batteries, and has effectively minimized the strain on system, especially during periods of historically excessive energy use, ensuring the battery's availability during critical times when it is most needed.

The change in power consumption patterns across the three periods provides valuable insights into the pace of consumer learning and behavior adaptation in Silale as a response to the TLS restrictions. That consumption distributions for the two months following implementation exhibit similar characteristics implies that the behavioral adjustments made during the first month of enforcement have been solidified and carried into the second month. Barring any system changes, the reduction in peak values between the two periods suggests that these behaviors are now more deeply ingrained, leading to even more efficient energy use. Utilizing the Mann-Whitney U test to assess night-time power usage (from 6:00 PM to 7:00 AM) across the 2 months of control post-TLS implementation revealed a notable variance. With a U statistic of 64 and a p-value of 0.001, the analysis indicated a significant reduction in power consumption during the 2nd month compared to the 1st, highlighting a distinct shift in consumption patterns between the two evaluation periods. If the reduction in power consumption observed in the 2nd month is a result of behavioral adaptation by consumers, this suggests that the capacity of the battery reserved for night-time use is larger than necessary given the newly adapted power demand levels. $P_{reserve}$ is at that point in time set too high relative to the actual reduced consumption patterns of the community, indicating a potential for optimization based on these behavioral changes. A more dynamic setting for $P_{reserve}$ that tracks against average power consumption levels in the night would reduce this system inefficiency. By lowering the $P_{reserve}$ value based on the reduced night-time consumption, more power could be made available during daytime hours, thereby increasing the load limit per household. This adjustment would effectively relax consumption constraints during daylight, allowing for a more flexible energy usage policy.

5.4.2 Consumer Response to Implemented TLS

The introduction of the TLS yielded a complex and varied response from Silale's community, highlighting the challenges of implementing behavioral interventions in energy management. Out of 25 respondents, 20 (80%) reported being inconvenienced by the TLS, 9 (36%) expressed a perception of decreased reliability in the power supply following the TLS implementation. A prevalent sentiment of frustration among this group is encapsulated in this statement: "Even when power is on, we cannot use it as we wish. It is always red light. At least before, we could use what we wanted for the short time it was available." Further, from the power consumption records off the host server, a small section of the connected households (12 out of 60) was discovered to have bypassed or illegally disconnected from the TLS.

Survey responses on adherence however, indicated a fairly high level of compliance to the system's guidance by a big part of the community. Although all 25 (100%) respondents admitted having experienced the red signal, 19 (76%) still rated themselves as strictly complying with the guidance provided by the TLS. Notably, 17 (68%) indicated that they had never encountered an automatic shutdown of their power supply, a consequence of not heeding the red signal. This high percentage highlights either consumers' dedication to keeping their energy usage within the prescribed limits or their fear of the automatic switch off feature. Reflecting the evolution of consumer behaviors over time, 18 respondents (72%) admitted that they now take longer to turn off bigger power load(s) in response to a red-light signal than they did immediately following the system's initial rollout indicating that their level of urgency has dropped with time. Additionally, the survey did reveal a degree of negative sentiment towards the TLS among a minority of respondents. 6 (24%) acknowledged they would remove the smart meters in their home if they had that choice. Among the reasons for discomfort with the TLS, 3 (12%) raised fears linking the blinking lights of the system to 5G network conspiracy theories, with extreme fears that the signals could be harmful or even fatal. Additionally, 9 (36%) expressed fear that the blinking lights of the TLS were consuming so much power and reducing the already limited capacity available for share among consumers. These perceptions added a layer of resistance to the system, as it was seen not only as controlling but also as hazardous and a possible rival for already scarce resources.

The study benefitted from a generally high community acceptance of the TLS to achieve significant impact on consumption behaviors in Silale. The endorsement of the influential village leadership committee may have contributed to this, given the respect they wield in the community. The survey's findings, albeit representing a small fraction of the community's feedback, signal concerning issues for the sustainability and operational future of the TLS. That some consumers went ahead to bypass the system points to a resistance to what was perceived as overly restrictive control or a total loss of control over their choices, reflecting a gap between the intervention design and consumer acceptance. On the flip side, the community’s level of trust in- and understanding of the technology could have influenced this system response. Misunderstandings or lack of clarity about how the system works could lead to mistrust and lower compliance. This situation underscores the challenges in achieving widespread behavioral change through technological interventions in community energy management. Furthermore, learning and adaptation outcomes indicated a trend of compliance fatigue among consumers, with 72% showing a slower response to the red-light signal over time. This suggests a diminished sense of urgency towards the signal and a potential plateau in behavioral changes after an initial phase of rapid adaptation. The observed growing delay in response might also reflect habituation, where continuous exposure to the red-light signal results in weaker behavioral reactions.

The set duration of predefined waiting periods for power disconnection and restoration within the TLS acts as a key mechanism for influencing consumer response and enhancing adherence to DSM goals. Setting shorter periods between red light and disconnection allows for a quicker response to fluctuating power availability, potentially enabling more dynamic and responsive DSM. On the other hand, longer periods of disconnection should lead to greater inconvenience, driving stronger consumer compliance. However, such could also lead to frustration among consumers, possibly eroding support for the system. Selecting the optimal durations is a delicate balance between the need for effective demand management and consumer satisfaction.

5.4.3 Strength of the Traffic Light System as a DSM Strategy

The unique contribution of the TLS in Silale lies in its innovative integration of behavioral economics principles with real-time energy monitoring technology that ensures both immediate and durable impacts on energy consumption behaviors. In contrast to traditional DSM strategies that rely on financial incentives or penalties, it uses intuitive, color-coded signals to nudge consumers towards more efficient energy usage making it a more psychologically effective tool. The automatic disconnection feature ensures that the system not only advises but also enforces energy conservation. In addition, by making energy consumption patterns visible and easy to understand, the system fosters greater consumer engagement and awareness about energy conservation increasing energy literacy among the community. Furthermore, the real-time consumer feedback that is facilitated by the system allows consumers to adjust their behavior in the moment, enhancing the effectiveness of energy conservation efforts. Crucially, the system is designed with customizable thresholds to suit the specific energy needs and consumption habits of the Silale mini-grid. This context-sensitive design makes it more effective and adaptable to similar energy resource constrained settings.

5.4.4 Design and Policy Implications

This study of Silale's TLS design and implementation offers key design and policy implications, emphasizing the potential of integrating behavioral interventions in energy policies and the necessity of customizing these strategies to local contexts. It highlights the critical importance of effective consumer engagement and education to ensure successful implementation and acceptance of new energy technologies and highlights the importance of considering social, and psychological factors in designing and implementing technological solutions for community challenges.

Addressing consumer dissatisfaction with the TLS, particularly the hard choice architecture of automatic disconnection, is crucial for the system's long-term value. Growing dissatisfaction could lead to an increased number of consumers attempting to bypass the TLS, undermining its effectiveness. To address these issues, we propose integrating softer, more flexible options into the system's design. Dynamic pricing that adjusts electricity prices in real-time based on demand would work in Silale's context to drive shifts in energy-intensive activities to off-peak hours. Further, rather than complete disconnection, an automatic throttling of a household's power quota reducing supply to non-essential loads and prioritizing essential needs like lighting would prevent total disruption and the associated inconvenience to consumers.

The study raises ethical considerations, particularly concerning automated control measures like the system's automatic disconnection feature. Robust monitoring and evaluation frameworks as well as controls are necessary to govern its use and to address any potential abuse or misuse of the technology. Flashing lights have been known to induce stress and anxiety in some individuals. Smart meter designs should therefore consider the psychological impact on users. Policies might encourage designs that are less likely to induce stress or anxiety, such as using less intrusive alerts or providing users options to customize alert settings. Longitudinal studies are recommended to fully assess the long-term impact of these interventions and to explore the potential for similar approaches in different contexts. These insights are crucial for policymakers aiming to enhance energy efficiency and grid stability through consumer behavior modifications.

5.5 Conclusions

The implementation of the TLS in Silale, Tanzania, represents a significant advancement in tackling limited mini-grid capacity and unregulated energy use. The consumption distributions reveal a progressive shift towards more efficient energy use, with noticeable reductions in peak consumption values over time highlighting the effectiveness of behavioral interventions in energy management. Crucially, the TLS has effectively reduced peak demand and achieved a more balanced consumption distribution throughout the day, allowing sufficient charging of the batteries, reducing the previous strain on the microgrid and improving grid stability. The success of Silale's traffic light system offers a scalable and replicable solution for similar energy challenges in other communities, merging technological innovation with behavioral insights to promote sustainable and efficient energy use.

This study, while insightful, faces several limitations. Conducted within a specific geographic and cultural setting, its findings may not be universally applicable. The two-month observation period raises questions about the permanence of observed behavioral changes, as this duration may not suffice for lasting habit formation and could include a novelty effect influencing short-term behavior. To mitigate these constraints, the study combined quantitative data with detailed surveys and interviews, offering a richer perspective on behavioral changes and community perceptions. However, longer-term research in varied contexts is essential to validate and broaden these findings.

6 References

A. Gill-Wiehl, S. Miles, J. Wu, D.M. Kammen, 2022. Beyond customer acquisition: A comprehensive review of community participation in mini grid projects. Renewable and Sustainable Energy Reviews 153, 111778. https://doi.org/10.1016/j.rser.2021.111778.

Acemoglu, D., Robinson, J., 2008. The role of institutions in growth and development. World Bank Washington, DC.

Adamopoulou, E., Pilco, A., Chahenza, J., Stephens, J., 2022. Benchmarking Africa's Minigrids Report. Africa Minigrid Developers Association. https://africamda.org/wp-content/uploads/2022/06/Benchmarking-Africa-Minigrids-Report-2022-Key-Findings.pdf (accessed 20 February 2023).

Ahlborg, H., Hammar, L., 2014. Drivers and barriers to rural electrification in Tanzania and Mozambique – Grid-extension, off-grid, and renewable energy technologies. Renewable Energy 61, 117–124. https://doi.org/10.1016/j.renene.2012.09.057.

Akinlabi, A.K., Oladokun, V.O., 2021. A Review of Interconnected Minigrid Solution for Underserved Distribution Network in Nigeria. Technol Econ Smart Grids Sustain Energy 6, 1–10. https://doi.org/10.1007/s40866-021-00108-9.

Altomonte, J.C., Guinto, H.S. How can microgrids help the Philippines' energy transition? Adapting the Institutional Analysis and Development (IAD) framework for microgrid development, in: IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 12012.

Aly, A., Moner-Girona, M., Szabó, S., Pedersen, A.B., Jensen, S.S., 2019. Barriers to Large-scale Solar Power in Tanzania. Energy for Sustainable Development 48, 43–58. https://doi.org/10.1016/j.esd.2018.10.009.

AMDA, 2018. Mini-Grids on the Trajectory of Rural Electrification in Africa: An AMDA Position Paper. Africa Mini-grid Developers Association. https://africamda.org/AMDA/wp-content/uploads/2020/07/WHITE-PAPER-Mini-Grids-on-the-Trajectory-of-Rural-Electrification-in-Africa.pdf (accessed 9 May 2023).

Anderies, J.M., Janssen, M.A., Ostrom, E., 2003. Design principles for robustness of institutions in social-ecological systems. Joining the Northern Commons: Lessons for the World, Lessons from the World, 17–21.

Anderies, J.M., Janssen, M.A., Ostrom, E., 2004. A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. E&S 9. https://doi.org/10.5751/es-00610-090118.

Andreoni, A., Tasciotti, L., Tayari, E., 2022. Feasible Pathways for Energy Transition in Tanzania: Shifting Unproductive Subsidies Towards Targeted Green Rents. Anti-Corruption Evidence. https://eprints.soas.ac.uk/38575/1/ACE-WorkingPaper039-Tz-energy-transition-Proof02.pdf (accessed 20 February 2023).

Andrzej Maćkiewicz, Waldemar Ratajczak, 1993. Principal components analysis (PCA). Computers & Geosciences 19, 303–342. https://doi.org/10.1016/0098-3004(93)90090-R.

Ansell, C., 2008. Network institutionalism.

Aytac, A., Atay, B., 2015. MEASURE OF GLOBAL EFFICIENCY IN NETWORKS. International Journal of Pure and Applied Mathematics 103. https://doi.org/10.12732/ijpam.v103i1.5.

Banzhaf, W., 2009. Self-organizing Systems. Encyclopedia of complexity and systems science 14, 589.

Barnett, M., Duvall, R., 2005. Power in International Politics. International organization 59, 39–75. https://doi.org/10.1017/S0020818305050010.

Bassoli, M., Cinalli, M., Giugni, M., 2014. Who Are the Powerful Actors? An Analysis of Brokerage in the Networks of Organizations Dealing with Unemployment and Precarity, in: Baglioni, S., Giugni, M. (Eds.), Civil Society Organizations, Unemployment, and Precarity in Europe: Between Service and Policy. Palgrave Macmillan UK, London, pp. 157–174.

Berardo, R., Scholz, J.T., 2010. Self-organizing policy networks: Risk, partner selection, and cooperation in estuaries. American Journal of Political Science 54, 632–649.

Berkowitz, L., Donnerstein, E., 1982. External validity is more than skin deep: Some answers to criticisms of laboratory experiments. American Psychologist 37, 245–257. https://doi.org/10.1037//0003-066x.37.3.245.

Bhattacharyya, S.C., 2013. Financing energy access and off-grid electrification: A review of status, options and challenges. Renewable and Sustainable Energy Reviews 20, 462–472.

Bhattacharyya, S.C., 2018. Mini-Grids for the Base of the Pyramid Market: A Critical Review. Energies 11, 813. https://doi.org/10.3390/en11040813.

Bhattacharyya, S.C., Palit, D., 2016. Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? Energy policy 94, 166–178.

Bloch, F., Jackson, M.O., Tebaldi, P., 2023. Centrality measures in networks. Social Choice and Welfare 61, 413–453.

Bonacich, P., 1987. Power and centrality: A family of measures. American journal of sociology 92, 1170–1182.

Brenda Banura, 2022. Promotion of Mini Grids for Rural Electrification (Pro Mini Grids): Improving framework conditions for scaling up private sector investment in renewable energy mini grid electricity distribution. GIZ, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. https://www.giz.de/en/downloads/giz2022-en-mini-solar-grids.pdf (accessed 19 February 2023).

Brinton, M.C., Nee, V., 1998. The new institutionalism in sociology. Russell Sage Foundation.

Burt, R., 2012. Structural holes [1992]. Contemporary Sociological Theory 204, 9780429494468-63.

Burt, R.S., 1976. Positions in networks. Social forces 55, 93–122.

Burt, R.S., 1980. Models of Network Structure. Annu. Rev. Sociol. 6, 79–141. https://doi.org/10.1146/annurev.so.06.080180.000455.

Burt, R.S., 2007. Brokerage and closure: An introduction to social capital. OUP Oxford.

Burt, R.S., 2018. Structural holes, in: Social stratification. Routledge, pp. 659–663.

C.G. Monyei, A.O. Adewumi, K.E.H. Jenkins, 2018. Energy (in)justice in off-grid rural electrification policy: South Africa in focus. Energy Research & Social Science 44, 152–171. https://doi.org/10.1016/j.erss.2018.05.002.

Caiani, M., Graziano, P., 2022. The three faces of populism in power: Polity, policies and politics. Government and Opposition 57, 569–588.

Candel, J.J.L., Biesbroek, R., 2016. Toward a processual understanding of policy integration. Policy Sciences 49, 211–231. https://doi.org/10.1007/s11077-016-9248-y.

Carlsson, L., Sandström, A., 2008. Network governance of the commons. International Journal of the Commons 2, 33–54.

Cartland, R., Sendegeya, A.-M., Hakizimana, Jean de Dieu Khan. Analysis of the development and installations of renewable energy-based mini-grids: case study Uganda, in: 2020 IEEE PES/IAS PowerAfrica. IEEE, pp. 1–5.

Casson, M.C., Giusta, M.D., Kambhampati, U.S., 2010. Formal and Informal Institutions and Development. World Development 38, 137–141. https://doi.org/10.1016/j.worlddev.2009.10.008.

Centola, D., 2015. The social origins of networks and diffusion. American journal of sociology 120, 1295–1338.

Chavance, B., 2008. Institutional economics. Routledge.

Cheng, H.W.J., 2021. Factors Affecting Technological Diffusion Through Social Networks: A Review of the Empirical Evidence. The World Bank Research Observer 37, 137–170. https://doi.org/10.1093/wbro/lkab010.

Chiesi, A.M., 2006. Perspectives of network analysis applied to social sciences. SIS, Atti della XLIII Riunione Scientifica, CLEUP, Torino.

Cleaver, F., 2002. Reinventing Institutions: Bricolage and the Social Embeddedness of Natural Resource Management. The European Journal of Development Research 14, 11–30. https://doi.org/10.1080/714000425.

Clemens, E.S., Cook, J.M., 1999. Politics and institutionalism: Explaining durability and change. Annual review of sociology 25, 441–466.

Coiera, E., 2007. Putting the technical back into socio-technical systems research. International journal of medical informatics 76, S98-S103.

Cole, D.H., 2017. Laws, norms, and the Institutional Analysis and Development framework. Journal of Institutional Economics, 1–19.

Cornago, E., 2021. The Potential of Behavioural Interventions for Optimising Energy Use at Home. International Energy Agency 4.

Cox, M., Arnold, G., Tomás, S.V., 2010. A review of design principles for community-based natural resource management. Ecology and Society 15.

Crawford, S.E.S., Ostrom, E., 1995. A grammar of institutions. American political science review 89, 582–600.

Crucitti, P., Latora, V., Marchiori, M., Rapisarda, A., 2003. Efficiency of scale-free networks: error and attack tolerance. Physica A: Statistical Mechanics and its Applications 320, 622–642.

Curristine, T., Lonti, Z., Joumard, I., 2007. Improving Public Sector Efficiency: Challenges and Opportunities. OECD Journal on Budgeting 7, 1.

Dal Maso, M., Olsen, K.H., Dong, Y., Pedersen, M.B., Hauschild, M.Z., 2020. Sustainable development impacts of nationally determined contributions: assessing the case of mini-grids in Kenya. Climate policy 20, 815–831.

de-Bruijn, H., Herder, P.M., 2009. System and Actor Perspectives on Sociotechnical Systems. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans 39, 981–992. https://doi.org/10.1109/TSMCA.2009.2025452.

Dekker, A.H., Colbert, B.D. Network robustness and graph topology, in: ACSC, pp. 359–368.

Dell'Angelo, J., McCord, P.F., Gower, D., Carpenter, S., Caylor, K.K., Evans, T.P., 2016. Community water governance on Mount Kenya: an assessment based on Ostrom's design principles of natural resource management. Mountain Research and Development 36, 102–115.

Deshmukh, R., 2013. Sustainable development of renewable energy mini-grids for energy access: A framework for policy design.

Di Serugendo, G.M., Irit, M.-P., Karageorgos, A., 2006. Self-organisation and emergence in MAS: An overview. Informatica 30.

DiMaggio, P., 1998. The New Institutionalisms : Avenues of Collaboration. Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift Für Die Gesamte Staatswissenschaft 154, 696–705.

Duran, A.S., Sahinyazan, F.G., 2021a. An analysis of renewable mini-grid projects for rural electrification. Socio-Economic Planning Sciences 77, 100999.

Duran, A.S., Sahinyazan, F.G., 2021b. Meta-analysis data of 104 renewable mini-grid projects for rural electrification. Data in Brief 34, 106739.

EEP Africa, 2018. Opportunities and Challenges in the Mini-Grid Sector in Africa: Lessons learned from the EEP Portfolio. Energy and Environment Partnership Trust Fund, https://eepafrica.org/wp-content/uploads/2019/11/EEP_MiniGrids_Study_DigitalVersion.pdf.

Ehrlichman, D., 2021. Impact networks: Create connection, spark collaboration, and catalyze systemic change. Berrett-Koehler Publishers.

EIA, 2014. Behavioral Economics Applied to Energy Demand Analysis: A foundation. U.S. Energy Information Administration.

https://www.eia.gov/analysis/studies/demand/economicbehavior/pdf/behavioraleconomics.pdf (accessed 16 November 2023).

Ekholm, T., Krey, V., Pachauri, S., Riahi, K., 2010. Determinants of household energy consumption in India. Energy policy 38, 5696–5707. https://doi.org/10.1016/j.enpol.2010.05.017.

ERA, 2006. Tariff Determination in the Uganda Electricity Sector, https://rise.esmap.org/data/files/library/uganda/Cross-cutting/CC%2023.1,%20Tariff%20Setting%20Guide.pdf.

ERA, 2020. Licensing Procedure. Electricity Regulatory Authority, Uganda. https://www.era.go.ug/index.php/licensing/licensing/licensing-procedure (accessed 26 February 2023).

ERA, Electricity Regulatory Authority, 2013. Electricity Investment Approval and Verification Guidelines.

Erdogdu, E., 2013. A cross-country analysis of electricity market reforms: Potential contribution of New Institutional Economics. Energy Economics 39, 239–251.

ESMAP, 2022. 2022 Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. ESMAP papers. Energy Sector Management Assistance Program (ESMAP), World Bank, Washington, DC. http://hdl.handle.net/10986/38082 (accessed 11 May 2023).

Estrada, E., 2006. Network robustness to targeted attacks. The interplay of expansibility and degree distribution. The European Physical Journal B-Condensed Matter and Complex Systems 52, 563–574.

Everett, M.G., Valente, T.W., 2016. Bridging, brokerage and betweenness. Social Networks 44, 202–208.

EWURA, 2018. Regulatory Performance Report on Electricity Sub-sector for the Year Ended 30th June 2017. Energy and Water Utilities Regulatory Authority. https://www.ewura.go.tz/wp-content/uploads/2020/03/Performance-Report-on-Electricity-Sub-sector-June-2017.pdf (accessed 9 May 2023).

EWURA, 2019. Regulatory Performance Report on Electricity Sub-sector for the Year Ended 30th June 2018. Energy and Water Utilities Regulatory Authority. https://www.ewura.go.tz/wp-content/uploads/2019/07/Electricity-Performance-Report.pdf (accessed 9 May 2023).

EWURA, 2020. The Electricity Sub-sector Regulatory Performance Report for the Financial Year 2018/2019. Energy and Water Utilities Regulatory Authority. https://www.ewura.go.tz/wp-content/uploads/2020/07/Regulatory-Performance-Report-on-Electricity-Sub-sector-for-the-Year-2019.pdf (accessed 9 May 2023).

EWURA, 2021. The Electricity Sub-sector Regulatory Performance Report for the Financial Year 2019/2020. Energy and Water Utilities Regulatory Authority. https://www.ewura.go.tz/wp-content/uploads/2021/07/Electricity-Sub-Sector-Regulatory-Performance-Report-for-the-Financial-Year-2019-2020.pdf (accessed 9 May 2023).

EWURA, 2022. The Electricity Sub-sector Regulatory Performance Report for the Financial Year 2020/2021. Energy and Water Utilities Regulatory Authority. https://www.ewura.go.tz/wp-content/uploads/2022/07/Electricity-Sub-Sector-Regulatory-Performance-Report-for-FY-2020-21.pdf (accessed 9 May 2023).

Fazekas, M., Adam, I., Nikulina, O., 2021. Study on the Cost of Corruption in Uganda. Uganda Inspectorate of Government, Governance Transparency Institute (Hungary). https://www.govtransparency.eu/wp-content/uploads/2022/07/Fazekas-et-al_Cost-of-corruption-in-Uganda_published_2022.pdf (accessed 20 February 2023).

FHI360, 2017a. Scaling Off-Grid Energy Access in Uganda: A Mid-Level Landscape Analysis of Issues and Stakeholders. FHI360; USAID; UKAID; Shell Foundation; Power Africa. https://pdf.usaid.gov/pdf_docs/PA00W5JT.pdf (accessed 15 June 2024).

FHI360, 2017b. Supporting Off-Grid Energy Access in Uganda: Mid-Level Landscape Analysis: Stakeholder Map. FHI360; USAID; Shell Foundation; Power Africa. https://embed.kumu.io/88b637dce3e57622632f7844416a125c#soge (accessed 15 June 2024).

Fleming, L., Mingo, S., Chen, D., 2007. Collaborative brokerage, generative creativity, and creative success. Administrative Science Quarterly 52, 443–475.

Foster, S.R., Iaione, C., 2019. Ostrom in the city: Design principles and practices for the urban commons, in: Routledge Handbook of the Study of the Commons. Routledge, pp. 235–255.

Franz, M., Hayek, N., Peterschmidt, N., Rohrer, M., Kondev, B., Adib, R., Cader, C., Carter, A., George, P., Gichungi, H., 2014. Mini-grid Policy Tool-kit. Policy and business frameworks for successful mini-grid roll-outs.

Freeman, L., 2004. The development of social network analysis. A Study in the Sociology of Science 1, 159–167.

Freeman, L.C., 1977. A set of measures of centrality based on betweenness. Sociometry, 35–41.

Freeman, L.C., Borgatti, S.P., White, D.R., 1991. Centrality in valued graphs: A measure of betweenness based on network flow. Social Networks 13, 141–154.

Freeman, L.C., Roeder, D., Mulholland, R.R., 1979. Centrality in social networks: II. Experimental results. Social Networks 2, 119–141.

Friedkin, N.E., 1991. Theoretical foundations for centrality measures. American journal of sociology 96, 1478–1504.

Froehlich, J. Promoting energy efficient behaviors in the home through feedback: The role of human-computer interaction, in: Proc. HCIC Workshop, pp. 1–11.

Geier, F., Barfuss, W., Wiedermann, M., Kurths, J., Donges, J.F., 2019. The physics of governance networks: critical transitions in contagion dynamics on multilayer adaptive networks with application to the sustainable use of renewable resources. The European Physical Journal Special Topics 228, 2357–2369.

Gesell, S.B., Barkin, S.L., Valente, T.W., 2013. Social network diagnostics: a tool for monitoring group interventions. Implementation Science 8, 1–12.

Gillett, S.E., Kapor, M., 1997. The self-governing Internet: coordination by design.

Glemarec, Y., 2012. Financing off-grid sustainable energy access for the poor. Energy policy 47, 87–93.

Glisic, S.G., 2016. Self-Organizing Networks, in: Advanced Wireless Networks: Technology and Business Models, pp. 478–485.

Gnauk, B., Dannecker, L., Hahmann, M., 2012. Leveraging gamification in demand dispatch systems, in: Proceedings of the 2012 Joint EDBT/ICDT Workshops, New York, NY, USA. ACM, New York, NY, USA.

Gołębiowska, B., Bartczak, A., Budziński, W., 2021. Impact of social comparison on preferences for Demand Side Management in Poland. Energy policy 149, 112024. https://doi.org/10.1016/j.enpol.2020.112024.

Gollwitzer, L., Cloke, J., 2018. Lessons from collective action for the local governance of mini-grids for pro-poor electricity access. Low carbon energy for development network, Leicestershire.

Gollwitzer, L., Ockwell, D., Ely, A., 2015. Institutional Innovation in the Management of Pro-Poor Energy Access in East Africa. University of Sussex.

Gollwitzer, L., Ockwell, D., Muok, B., Ely, A., Ahlborg, H., 2018. Rethinking the sustainability and institutional governance of electricity access and mini-grids: Electricity as a common pool resource. Energy Research & Social Science 39, 152–161. https://doi.org/10.1016/j.erss.2017.10.033.

Gómez, D., González-Arangüena, E., Manuel, C., Owen, G., del Pozo, M., Tejada, J., 2003. Centrality and power in social networks: a game theoretic approach. Mathematical Social Sciences 46, 27–54.

Good, N., 2019. Using behavioural economic theory in modelling of demand response. Applied Energy 239, 107–116. https://doi.org/10.1016/j.apenergy.2019.01.158.

GoU, 2014. The Electricity (License Fees) (Amendment) (No. 3) Regulations, 2014.

GoU, 2018. The Electricity Connections Policy (2018 – 2027).

GoU, 2020. The Electricity (Isolated Grid Systems) Regulations, 2020.

Gould, P.R., 1969. Spatial Diffusion, Resource Paper No. 4.

Greacen, C.E., 2004. The marginalization of "small is beautiful": Micro-hydroelectricity, common property, and the politics of rural electricity provision in Thailand. PhD Thesis. Berkeley.

Groundstroem, F., Juhola, S., 2021. Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. Mitigation and Adaptation Strategies for Global Change 26, 29. https://doi.org/10.1007/s11027-021-09967-0.

Gulati, R., 1999. Network location and learning: The influence of network resources and firm capabilities on alliance formation. Strategic management journal 20, 397–420.

Guma, P.K., 2017. Civic governance, engagement, and protest in quest of democracy in Uganda, in: Democratizing Public Governance in Developing Nations. Routledge, pp. 185–200.

Hafner-Burton, E.M., Kahler, M., Montgomery, A.H., 2009. Network analysis for international relations. International organization 63, 559–592.

Hafner-Burton, E.M., Montgomery, A.H., 2010. Centrality in politics: How networks confer power.

Hall, P., Taylor, R. (Eds.), 1994. Political science and the four new institutionalisms.

Hanna, S., Folke, C., Mäler, K.-G., 1995. Property rights and environmental resources. Property rights and the environment: Social and ecological issues, 15–29.

Hanneman, R.A., Riddle, M., 2005a. Introduction to social network methods. University of California Riverside.

Hanneman, R.A., Riddle, M., 2005b. Introduction to social network methods: Chapter 10. Centrality and power. University of California Riverside, CA.

Haryanto, T., van Zeben, J., Purnhagen, K., 2022. Ostrom’s Design Principles as Steering Principles for Contractual Governance in “Hotbeds”. FS 6, 175–201. https://doi.org/10.24259/fs.v6i1.17993.

Heard-Laureote, K., 2018. Governance and network formation triggers, in: Global Encyclopedia of Public Administration, Public Policy, and Governance. Springer.

Hechter, M., 1993. Values research in the social and behavioral sciences. The origin of values, 1–28.

Helmsing, A.H.J., 2003. Local economic development: new generations of actors, policies and instruments for Africa. Public Administration and Development 23, 67–76. https://doi.org/10.1002/pad.260.

Hermann, A., 2008. The institutional analysis of the market. International Journal of Green Economics 2, 379–391. https://doi.org/10.1504/IJGE.2008.022448.

Hess, C., Ostrom, E., 2005. A Framework for Analyzing the Knowledge Commons : a chapter from Understanding Knowledge as a Commons: from Theory to Practice. Syracuse University Library.

Hilleringmann, U., Petrov, D., Mwammenywa, I., Kagarura, G.M. Local Power Control using Wireless Sensor System for Microgrids in Africa, in: 2021 IEEE AFRICON. IEEE, pp. 1–5.

Hodgson, G.M., 1998. The approach of institutional economics. Journal of economic literature 36, 166–192.

Hodgson, G.M., 2006. What Are Institutions? Journal of Economic Issues 40, 1–25. https://doi.org/10.1080/00213624.2006.11506879.

Hoeck, I., Steurer, E., Dolunay, Ö., Ileka, H., 2022. Challenges for off-grid electrification in rural areas. Assessment of the situation in Namibia using the examples of Gam and Tsumkwe. Energy, Ecology and Environment 7, 508–522. https://doi.org/10.1007/s40974-021-00214-5.

Holland, P.W., Leinhardt, S., 1977. A Method for Detecting Structure in Sociometric Data. Social Networks, 411–432. https://doi.org/10.1016/B978-0-12-442450-0.50028-6.

Holme, P., Kim, B.J., Yoon, C.N., Han, S.K., 2002. Attack vulnerability of complex networks. Physical review E 65, 56109.

Holstenkamp, L., 2019. What do we know about cooperative sustainable electrification in the global South? A synthesis of the literature and refined social-ecological systems framework. Renewable and Sustainable Energy Reviews 109, 307–320.

Hossain, N.U.I., Dayarathna, V.L., Nagahi, M., Jaradat, R., 2020. Systems Thinking: A Review and Bibliometric Analysis. Systems 8. https://doi.org/10.3390/systems8030023.

Hua, L., Yang, Z., Shao, J., 2022. Impact of network density on the efficiency of innovation networks: An agent-based simulation study. PloS one 17, e0270087.

Hubbell, C.H., 1965. An input-output approach to clique identification. Sociometry, 377–399.

Huggins, R., Johnston, A., 2010. Knowledge flow and inter-firm networks: The influence of network resources, spatial proximity and firm size. Entrepreneurship & regional development 22, 457–484.

Hurwicz, L., 1994. Institutional change and the theory of mechanism design. Academia Economic Review 22, 1–26.

IEA, 2020. Global Energy Review 2020: Access to Electricity. SDG7: Data and Projections. International Energy Agency. https://www.iea.org/reports/global-energy-review-2020 (accessed 12 March 2021).

IEA, 2022. SDG7: Data and Projections. International Energy Agency, Paris. https://www.iea.org/reports/sdg7-data-and-projections (accessed 1 May 2023).

Imperial, M., Yandle, T., 2005. Taking Institutions Seriously: Using the IAD Framework to Analyze Fisheries Policy. Society and Natural Resources 18, 493–509. https://doi.org/10.1080/08941920590947922.

Imperial, M.T., 1999. Institutional analysis and ecosystem-based management: the institutional analysis and development framework. Environmental management 24, 449–465.

Ingram, G.K., Hong, Y.-H., 2009. Property rights and land policies. Lincoln Institute of Land Policy.

IRENA, 2017. Renewable Energy Innovation: Accelerating Research For a Low-Carbon Future. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Nov/IRENA_Accelerating_research_2017.pdf?la=en&hash=2A53295A57DD87A0A451E68A2CE7EA020729871F.

Janžekovič, F., Novak, T., 2012. PCA–a powerful method for analyze ecological niches. Principal component analysis–multidisciplinary applications, 127–142.

Jason M. Smith, Daniel S. Halgin, Virginie Kidwell-Lopez, Giuseppe Labianca, Daniel J. Brass, Stephen P. Borgatti, 2014. Power in politically charged networks. Social Networks 36, 162–176. https://doi.org/10.1016/j.socnet.2013.04.007.

Jean-Baptiste, P., Ducroux, R., 2003. Energy policy and climate change. Energy policy 31, 155–166. https://doi.org/10.1016/S0301-4215(02)00020-4.

Jenny Tejeda, Susan Ferreira, 2014. Applying Systems Thinking to Analyze Wind Energy Sustainability. Procedia Computer Science 28, 213–220. https://doi.org/10.1016/j.procs.2014.03.027.

Johannes M. Bauer, Paulien M. Herder, 2009. Designing Socio-Technical Systems, in: Anthonie Meijers (Ed.), Philosophy of Technology and Engineering Sciences. North-Holland, Amsterdam, pp. 601–630.

John S. Osmundson, Thomas V. Huynh, Gary O. Langford, 2008. KR14 Emergent Behavior in Systems of Systems. INCOSE International Symposium 18, 1557–1568. https://doi.org/10.1002/j.2334-5837.2008.tb00900.x.

Kabuta, J., Sengendo, M., Winiecki, J., Morris, E., 2007. Using Microfinance to Expand Access to Energy Services. The SEEP Network, Washington, DC, USA.

Kapika, J., Eberhard, A., 2013. Power Sector Reform and Regulation in Africa: Lessons from Kenya, Tanzania, Uganda, Zambia, Namibia and Ghana. HSRC Press.

Kapucu, N., 2015. Introduction: Social Network Analysis Applications in Complex Governance Networks. Complexity, Governance & Networks 2, 1. https://doi.org/10.7564/15-CGN29.

Katre, A., Tozzi, A., Bhattacharyya, S., 2019. Sustainability of community-owned mini-grids: evidence from India. Energy, Sustainability and Society 9, 1–17.

Kay, J.J., 2008. An introduction to systems thinking. The ecosystem approach: Complexity, uncertainty, and managing for sustainability, 3–13.

Kelman, I., Luthe, T., Wyss, R., Tørnblad, S.H., Evers, Y., Curran, M.M., Williams, R.J., Berlow, E.L., 2016. Social network analysis and qualitative interviews for assessing geographic characteristics of tourism business networks. PloS one 11, e0156028.

KfW, Multiconsult, 2022. GET FIT UGANDA: Annual Report 2022. KfW. https://www.getfit-uganda.org/annual-reports/annual-report-2022/ (accessed 18 June 2024).

Khan, I., 2019. Energy-saving behaviour as a demand-side management strategy in the developing world: the case of Bangladesh. International Journal of Energy and Environmental Engineering 10, 493–510. https://doi.org/10.1007/s40095-019-0302-3.

Kirubi, C.G., 2009. Expanding access to off-grid rural electrification in Africa: An analysis of community-based micro-grids in Kenya.

Kiser, L.L., Ostrom, E., 2000. Synthesis of Institutional Approaches: Polycentric games and institutions: Readings from the workshop in political theory and policy analysis. University of Michigan Press.

Klijn, E.H., Edelenbos, J., Steijn, B., 2010. Trust in Governance Networks: Its Impacts on Outcomes. Administration & Society - ADMIN SOC 42, 193–221. https://doi.org/10.1177/0095399710362716.

Klijn, E.H., Sierra, V., Ysa, T., Berman, E., Edelenbos, J., Chen, D.Y., 2016. The influence of trust on network performance in Taiwan, Spain, and the Netherlands: A cross-country comparison. International public management journal 19, 111–139.

Knight, J., 1992a. Institutions and social conflict. Cambridge University Press, Cambridge England, New York N.Y., xiii, 234 ;

Knight, J., 1992b. Institutions and Social Conflict. Cambridge University Press.

Koka, B.R., Prescott, J.E., 2008. Designing alliance networks: the influence of network position, environmental change, and strategy on firm performance. Strategic management journal 29, 639–661.

Koliba, C., Meek, J.W., Zia, A., 2017. Governance networks in public administration and public policy. Routledge.

Koppenjan, J., Groenewegen, J., 2005. Institutional design for complex technological systems. IJTPM 5, 8406, 240. https://doi.org/10.1504/IJTPM.2005.008406.

Kubo, N., Watanabe, T., Chen, X., Matsumoto, T., Yunoki, K., Kuwabara, T., Kirimoto, H., 2021. The Effect of Prior Knowledge of Color on Behavioral Responses and Event-Related Potentials During Go/No-go Task. Frontiers in human neuroscience 15, 674964. https://doi.org/10.3389/fnhum.2021.674964.

Künneke, R., Finger, M. The governance of infrastructures as common pool resources, in: Workshop on the Workshop (WOW4), June 2–7, 2009, pp. 3–6.

Kwon, S.-W., Rondi, E., Levin, D.Z., Massis, A. de, Brass, D.J., 2020. Network brokerage: An integrative review and future research agenda. Journal of Management 46, 1092–1120.

Laimon, M., Yusaf, T., Mai, T., Goh, S., Alrefae, W., 2022. A systems thinking approach to address sustainability challenges to the energy sector. International Journal of Thermofluids 15, 100161.

Lane, J., Hudson, W., Gous, A., Kuteesa, R., 2018. Mini-Grid Market Opportunity Assessment: Uganda: Green Mini-Grid Market Development Programme: SEforALL Africa Hub & African Development Bank. Sustainable Energy for All.

Leach, M., Mearns, R., Scoones, I., 1999. Environmental Entitlements: Dynamics and Institutions in Community-Based Natural Resource Management. World Development 27, 225–247. https://doi.org/10.1016/S0305-750X(98)00141-7.

Leavitt, H.J., 1951. Some effects of certain communication patterns on group performance. The journal of abnormal and social psychology 46, 38.

Lee, J., Rethemeyer, R.K., 2013. Same differences: comparing social service policy networks in the US and Korea. Journal of comparative policy analysis: research and practice 15, 452–474.

Lestari, H., Arentsen, M., Bressers, H., Gunawan, B., Iskandar, J., 2018. Sustainability of renewable off-grid technology for rural electrification: A comparative study using the IAD framework. Sustainability 10, 4512.

Lieftucht, D., Kruger, U., Irwin, G.W., 2006. Improved reliability in diagnosing faults using multivariate statistics. Computers & chemical engineering 30, 901–912.

Lin, Z., Zhang, Y., Gong, Q., Chen, Y., Oksanen, A., Ding, A.Y., 2021. Structural hole theory in social network analysis: a review. IEEE transactions on computational social systems 9, 724–739.

Lweka, O., Liu, S., Shukla, A., Yan, D., 2019. Energy and behaviour at home: A review of intervention methods and practices. Energy Research & Social Science 57, 101238. https://doi.org/10.1016/j.erss.2019.101238.

Maarten Wolsink, 2012. The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources. Renewable and Sustainable Energy Reviews 16, 822–835. https://doi.org/10.1016/j.rser.2011.09.006.

Madriz-Vargas, R., Bruce, A., Watt, M. A Review of factors influencing the success of community renewable energy minigrids in developing countries, in: Proceedings of the 2015 Asia-Pacific Solar Research Conference, Brisbane, Australia. 2015, pp. 8–9.

Maier, C., 2007. Decentralised rural electrification by means of collective action: The Sustainability of Community-Managed Micro Hydels in Chitral, Pakistan. Occasional Working Papers Geographie No 33. Institute for Geographical Sciences, Free University of Berlin. https://refubium.fu-berlin.de/bitstream/fub188/18198/1/OccPapers33_Maier.pdf (accessed 12 March 2021).

Mallon, K., 2006. Renewable energy policy and politics: A handbook for decision-making. Earthscan.

Mandelli, S., Barbieri, J., Mereu, R., Colombo, E., 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renewable and Sustainable Energy Reviews 58, 1621–1646.

Mao, G., Zhang, N., 2013. Analysis of average shortest-path length of scale-free network. Journal of Applied Mathematics 2013, 865643.

March, J.G., Olsen, J.P., 1983. The new institutionalism: Organizational factors in political life. American political science review 78, 734–749.

Mark S. Mizruchi, Blyden B. Potts, 1998. Centrality and power revisited: actor success in group decision making. Social Networks 20, 353–387. https://doi.org/10.1016/S0378-8733(98)00009-4.

Marsden, Peter V., Lin, Nan, 1982. Social structure and network analysis.

Martin G. Everett, Stephen P. Borgatti, 2020. Unpacking Burt’s constraint measure. Social Networks 62, 50–57. https://doi.org/10.1016/j.socnet.2020.02.001.

Matthews, R.C.O., 1986. The Economics of Institutions and the Sources of Growth. Econ J 96, 903–918. https://doi.org/10.2307/2233164.

McGinnis, M., Ostrom, E., 1996. Design principles for local and global commons. The international political economy and international institutions 2, 465–493.

McGinnis, M.D., 2011a. An introduction to IAD and the language of the Ostrom workshop: a simple guide to a complex framework. Policy Studies Journal 39, 169–183.

McGinnis, M.D., 2011b. Networks of adjacent action situations in polycentric governance. Policy Studies Journal 39, 51–78.

Meier, K.J., O'Toole, L.J., 2007. Modeling public management. Public Management Review 9, 503–527. https://doi.org/10.1080/14719030701726630.

Meijers, E., Stead, D. (Eds.), 2004. Policy integration: what does it mean and how can it be achieved? A multi-disciplinary review.

Melnyk, M., Kelly, A., 2019. Smart Incentives for Mini-Grids through Retail Tariff and Subsidy Design: A Guide for Policymakers. Electric Capital Management, Electric Capital Management. https://southsouthnorth.org/wp-content/uploads/2019/04/Smart-Incentives-for-Mini-grids-through-Retail-Tariff-and-Subsidy-Design_-A-Guide-for-Policymakers_LEDS-GP-FWG-1.pdf (accessed 24 February 2022).

Meyer, J.W., 2010. World society, institutional theories, and the actor. Annual review of sociology 36, 1–20.

Mini-Grids Partnership, 2020. State of the Global Mini-grids Market Report 2020: Trends of renewable energy hybrid mini-grids in Sub-Saharan Africa, Asia and island nations. Energising Finance Report Series. Mini-Grids Partnership (MGP), BloombergNEF, Sustainable Energy for All. https://www.seforall.org/system/files/2020-06/MGP-2020-SEforALL.pdf (accessed 14 February 2022).

Mintz, B.A., 1985. and Michael Schwartz. The Power Structure of American Business.

Mondal, M.A.H., Kamp, L.M., Pachova, N.I., 2010. Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh—An innovation system analysis. Energy policy 38, 4626–4634.

Moner-Girona, M., Solano-Peralta, M., Lazopoulou, M., Ackom, E.K., Vallve, X., Szabó, S., 2018. Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience. Renewable and Sustainable Energy Reviews 91, 1148–1161.

Mookherjee, D., 2006. Decentralization, hierarchies, and incentives: A mechanism design perspective. Journal of economic literature 44, 367–390.

Moran, E.F., Lopez, M.C., Mourão, R., Brown, E., McCright, A.M., Walgren, J., Bortoleto, A.P., Mayer, A., Johansen, I.C., Ramos, K.N., Castro-Diaz, L., Garcia, M.A., Lembi, R.C., Mueller, N., 2022. Advancing convergence research: Renewable energy solutions for off-grid communities. Proceedings of the National Academy of Sciences of the United States of America 119, e2207754119. https://doi.org/10.1073/pnas.2207754119.

Morris, J.S., Friston, K.J., Dolan, R.J., 1997. Neural responses to salient visual stimuli. Proceedings of the Royal Society of London. Series B: Biological Sciences 264, 769–775. https://doi.org/10.1098/rspb.1997.0109.

Motjoadi, V., Bokoro, P.N., Onibonoje, M.O., 2020. A review of microgrid-based approach to rural electrification in South Africa: Architecture and policy framework. Energies 13, 2193.

Mottram, H., 2022. Injustices in rural electrification: Exploring equity concerns in privately owned minigrids in Tanzania. Energy Research & Social Science 93, 102829.

Muers, S., 2018. Culture, Values and Public Policy: IPR Report. Institute for Policy Research, University of Bath. https://www.bath.ac.uk/publications/culture-values-and-public-policy/attachments/CultureValuesandPublicPolicy.pdf (accessed 27 June 2022).

Mwammenywa, I., Kagarura, G.M., Petrov, D., Holle, P., Hilleringmann, U. LoRa-based Demand-side Load Monitoring and Management System for Microgrids in Africa, in: 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET). IEEE, pp. 1–5.

Namujju, L.D., Acquah-Swanzy, H., Ngoti, I.F., 2023a. An IAD framework analysis of minigrid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania. Energy policy 182, 113742.

Namujju, L.D., Acquah-Swanzy, H., Ngoti, I.F., 2023b. An IAD framework analysis of minigrid institutions for sustainable rural electrification in East Africa: A comparative study of Uganda and Tanzania. Energy policy 182, 113742.

Nee, V., Ingram, P., 1996. Embeddedness and beyond: Institutions, exchange and social structure. Mario Einaudi Center for International Studies, Cornell University.

Nelson, D.R., Adger, W.N., Brown, K., 2007. Adaptation to Environmental Change: Contributions of a Resilience Framework. Annu. Rev. Environ. Resour. 32, 395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348.

Nelson, R.R., Sampat, B.N., 2001. Making sense of institutions as a factor shaping economic performance. Journal of Economic Behavior & Organization 44, 31–54. https://doi.org/10.1016/S0167-2681(00)00152-9.

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Cochrane, L., Floquet, A., Abele, S., 2018. Applying Ostrom’s institutional analysis and development framework to soil and water conservation activities in north-western Ethiopia. Land use policy 71, 1–10.

Nkiriki, J., Ustun, T.S. Mini-grid policy directions for decentralized smart energy models in Sub-Saharan Africa, in: 2017 IEEE PES innovative smart grid technologies conference europe (ISGT-Europe). IEEE, pp. 1–6.

Nkiriki, J., Ustun, T.S. Mini-grid policy directions for decentralized smart energy models in Sub-Saharan Africa, in: 2017 IEEE PES innovative smart grid technologies conference europe (ISGT-Europe). IEEE, pp. 1–6.

North, D., 1990a. Institutions and their consequences for economic performance: The limits of rationality.

North, D., 1990b. Institutions, institutional change and economic performance.

North, D.C., 1993. Toward a theory of institutional change. Political economy: Institutions, competition, and representation 31, 61–69.

North, D.C., 1995. The new institutional economics and third world development. The new institutional economics and third world development 21, 31–40.

Novemsky, N., Dhar, R., Schwarz, N., Simonson, I., 2007. Preference Fluency in Choice. Journal of Marketing Research 44, 347–356. https://doi.org/10.1509/jmkr.44.3.347.

Oakerson, R.J., 1992. Analyzing the commons: A framework. Making the commons work: Theory, practice and policy, 41–59.

Odarno, L., Sawe, E., Swai, M., Katyega, M.J., Lee, A., 2017. Accelerating Mini-grid Deployment in Sub Saharan Africa: Lessons from Tanzania. Tanzania Traditional Energy Development Organisation; World Resources Institute. https://files.wri.org/d8/s3fs-public/accelerating-mini-grid-deployment-sub-saharan-africa_1.pdf (accessed 19 February 2023).

Ogeya, M., Muhoza, C., Johnson, O.W., 2021. Integrating user experiences into mini-grid business model design in rural Tanzania. Energy for Sustainable Development 62, 101–112. https://doi.org/10.1016/j.esd.2021.03.011.

Oh, J., Hettiarachchi, H., 2020. Collective action in waste management: A comparative study of recycling and recovery initiatives from Brazil, Indonesia, and Nigeria using the institutional analysis and development framework. Recycling 5, 4.

Ohanyan, A., 2012. Network Institutionalism and NGO Studies. International Studies Perspectives 13, 366–389.

Ohunakin, O.S., Adaramola, M.S., Oyewola, O.M., Fagbenle, R.O., 2014. Solar energy applications and development in Nigeria: Drivers and barriers. Renewable and Sustainable Energy Reviews 32, 294–301.

Osman, F.A., 2018. Policy Network and Governance, in: Farazmand, A. (Ed.), Global Encyclopedia of Public Administration, Public Policy, and Governance. Springer International Publishing, Cham, pp. 1–6.

Ostrom, E., 1986. An agenda for the study of institutions. Public Choice 48, 3–25.

Ostrom, E., 1990a. Governing the commons: The evolution of institutions for collective action. Cambridge University Press.

Ostrom, E., 1990b. Governing the commons: The evolution of institutions for collective action. Cambridge University Press.

Ostrom, E., 1992. Community and the endogenous solution of commons problems. Journal of theoretical politics 4, 343–351.

Ostrom, E., 1993a. Design principles in long-enduring irrigation institutions. Water Resources Research 29, 1907–1912.

Ostrom, E., 1993b. Design principles in long-enduring irrigation institutions. Water Resources Research 29, 1907–1912.

Ostrom, E., 1999a. Coping with tragedies of the commons. Annual Review of Political Science 2, 493–535.

Ostrom, E. (Ed.), 1999b. Design principles and threats to sustainable organizations that manage commons.

Ostrom, E., 1999c. Self-governance and forest resources. CIFOR Bogor, Indonesia.

Ostrom, E., 2005. Understanding institutional diversity. Princeton university press, Princeton NJ:

Ostrom, E., 2008. Design principles of robust property-rights institutions: what have we learned. Elinor Ostrom and the Bloomington school of political economy: Resource governance 2, 215–248.

Ostrom, E., 2020. Tragedy of the Commons, in: Vernengo, M., Caldentey, E.P., Rosser Jr, B.J. (Eds.), The New Palgrave Dictionary of Economics. Palgrave Macmillan UK; Imprint: Palgrave Macmillan, London, pp. 1–5.

Ostrom, E., Gardner, R., Walker, J., Walker, J.M., Walker, J., 1994. Rules, games, and common-pool resources. University of Michigan Press.

Ostrom, L., Wilhelmsen, C., Kaplan, B., 1993. Assessing safety culture. Nuclear Safety 34, 163–172.

Owen-Smith, J., Powell, W.W., 2008. Networks and institutions. The Sage handbook of organizational institutionalism, 596–623.

Palit, D., Kumar, A., 2022. Towards convergence of central grid and decentralised electricity solutions–Assessment of Indian rural electrification cases using a socio-technical framework. Energy for Sustainable Development 71, 27–53.

Pan, R.K., Saramäki, J., 2011. Path lengths, correlations, and centrality in temporal networks. Physical review E 84, 16105.

Pande, R., Udry, C., 2005. Institutions and development: A view from below. Yale University Economic Growth Center Discussion Paper.

Pedersen, M.B., 2016. Deconstructing the concept of renewable energy-based mini-grids for rural electrification in East Africa. WIREs Energy and Environment 5, 570–587. https://doi.org/10.1002/wene.205.

Pérez-López, D., 2020. Success in Rural Electrification Regulatory Case Studies: UGANDA Uganda: A Bundled Approach to Mini-Grid Tendering. GET.transform, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. https://www.get-transform.eu/wp-content/uploads/2020/12/Success-in-Rural-Electrification_Case-Study-Uganda.pdf.

Peter V. Marsden, 1993. The reliability of network density and composition measures. Social Networks 15, 399–421. https://doi.org/10.1016/0378-8733(93)90014-C.

Peters, J., Sievert, M., Toman, M.A., 2019. Rural electrification through mini-grids: Challenges ahead. Energy policy 132, 27–31.

Pfahl, S., 2005. Institutional sustainability. International journal of sustainable development 8, 80–96.

Phillips, J., Attia, B., Plutshack, V., 2020. Lessons for modernizing energy access finance, part 2–balancing competition and subsidy: assessing mini-grid incentive programs in Sub-Saharan Africa. NI PB, 20-07.

Pinkerton, E., Weinstein, M., 1995. Fisheries that work: sustainability through community-based management. The David Suzuki Foundation. Vancouver.

Pitt, J., Diaconescu, A., 2016. Interactive Self-Governance and Value-Sensitive Design for Self-Organising Socio-technical Systems, in: 2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W), pp. 30–35.

Pitt, J., Ober, J., Diaconescu, A., 2017. Knowledge Management Processes and Design Principles for Self-Governing Socio-Technical Systems, in: 2017 IEEE 2nd International Workshops on Foundations and Applications of Self* Systems (FAS*W), pp. 97–102.

Pollitt, M.G., Shaorshadze, I., 2011. The Role of Behavioural Economics in Energy and Climate Policy. Faculty of Economics.

Polojärvi, D., Palmer, E., Dunford, C., 2023. A systematic literature review of sociotechnical systems in systems engineering. Systems Engineering 26, 482–504. https://doi.org/10.1002/sys.21664.

Polski, M.M., Ostrom, E., 1999. An institutional framework for policy analysis and design.

Poudel, B., Parton, K., Morrison, M., 2022. The drivers of the sustainable performance of renewable energy-based mini-grids. Renewable Energy 189, 1206–1217.

Powell, W.W., DiMaggio, P.J., 2012. The new institutionalism in organizational analysis. University of Chicago press.

Pratt, B.W., Erickson, J.D., 2020. Defeat the Peak: Behavioral insights for electricity demand response program design. Energy Research & Social Science 61, 101352.

Provan, K.G., Milward, H.B., 1995. A Preliminary Theory of Interorganizational Network Effectiveness: A Comparative Study of Four Community Mental Health Systems. Administrative Science Quarterly 40, 1–33. https://doi.org/10.2307/2393698.

Pryke, S., Badi, S., Almadhoob, H., Soundararaj, B., Addyman, S., 2018. Self-organizing networks in complex infrastructure projects. Project management journal 49, 18–41.

Rachel Freeman, Mike Yearworth, J. Y. Cherruault, 2013. Review of Literature on Systems Thinking and System Dynamics for Policy Making, in: .

Raffaele Vignola, Timothy L. McDaniels, Roland W. Scholz, 2013. Governance structures for ecosystem-based adaptation: Using policy-network analysis to identify key organizations for bridging information across scales and policy areas. Environmental Science & Policy 31, 71–84. https://doi.org/10.1016/j.envsci.2013.03.004.

Raisch, V., 2016. Financial Assessment of Mini-grids Based on Renewable Energies in the Context of the Ugandan Energy Market. Energy Procedia 93, 174–182. https://doi.org/10.1016/j.egypro.2016.07.167.

Reagans, R., McEvily, B., 2008. Contradictory or compatible? Reconsidering the “trade-off” between brokerage and closure on knowledge sharing, in: Network strategy. Emerald Group Publishing Limited, pp. 275–313.

Reisch, L.A., Zhao, M.I.N., 2017. Behavioural economics, consumer behaviour and consumer policy: state of the art. Behavioural Public Policy 1, 190–206. https://doi.org/10.1017/bpp.2017.1.

Rietbergen-McCracken, J., 2017. Participatory policy making. World Alliance for Citizen Participation.

Righi, A.W., Saurin, T.A., 2015. Complex socio-technical systems: Characterization and management guidelines. Applied ergonomics 50, 19–30. https://doi.org/10.1016/j.apergo.2015.02.003.

Rodriguez, F.S., Komendantova, N., 2022. Approaches to Participatory Policy Making Processes: Technical Report. United Nations Industrial Development Organisation. https://www.unido.org/sites/default/files/files/2022-03/PPM_WEB_final.pdf (accessed 19 February 2023).

Ronan Bolton, Timothy J. Foxon, 2015. Infrastructure transformation as a socio-technical process — Implications for the governance of energy distribution networks in the UK. Technological Forecasting and Social Change 90, 538–550. https://doi.org/10.1016/j.techfore.2014.02.017.

Ropohl, G., 1999. Philosophy of socio-technical systems. Society for Philosophy and Technology Quarterly Electronic Journal 4, 186–194.

Rose, R., 2005. A global diffusion model of e-governance. Journal of Public Policy 25, 5–27.

Saeed, A.-R., McDermott, C., Boyd, E., 2017. Are REDD+ community forest projects following the principles for collective action, as proposed by Ostrom? International Journal of the Commons 11, 572–596.

Sager, F., Gofen, A., 2022. The polity of implementation: Organizational and institutional arrangements in policy implementation. Governance 35, 347–364.

Samaneh Ghafoori Kharanagh, Mohammad Ebrahim Banihabib, Saman Javadi, 2020. An MCDM-based social network analysis of water governance to determine actors' power in water-food-energy nexus. Journal of Hydrology 581, 124382. https://doi.org/10.1016/j.jhydrol.2019.124382.

Sanchez, T., Tozicka, T., 2013. Energy for all 2030: Rural electrification: The role of the public sector and collective action on electricity access for the poor. Practical Action.

Sandström, A., Carlsson, L., 2008. The performance of policy networks: the relation between network structure and network performance. Policy Studies Journal 36, 497–524.

Sanne Hettinga, Peter Nijkamp, Henk Scholten, 2018. A multi-stakeholder decision support system for local neighbourhood energy planning. Energy policy 116, 277–288. https://doi.org/10.1016/j.enpol.2018.02.015.

Schnitzer, D., Lounsbury, D.S., Carvallo, J.P., Deshmukh, R., Apt, J., Kammen, D.M., 2014. Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. United Nations Foundation 8.

Schwartz, S.H., 1992. Universals in the content and structure of values: Theoretical advances and empirical tests in 20 countries, in: Advances in experimental social psychology, vol. 25. Elsevier, pp. 1–65.

SEforALL, 2019. Energising Finance: Taking The Pulse 2019. Energising Finance Report Series. Sustainable Energy for All (SEforALL), E3 Analytics, Catalyst Off Grid Advisors.

https://www.seforall.org/system/files/2019-11/EF-2019-TP-SEforALL-w.pdf (accessed 25 February 2023).

Seungtaek Lee, Yeowon Kim, Wai K. Chong, 2015. A Statistical Analysis of Effectiveness of Energy Policy in the United States: Incentives vs. Regulations. Procedia Engineering 118, 1282–1287. https://doi.org/10.1016/j.proeng.2015.08.483.

Shah, K.U., Niles, K., 2016. Energy policy in the Caribbean green economy context and the Institutional Analysis and Design (IAD) framework as a proposed tool for its development. Energy policy 98, 768–777.

Shi, X., Liu, X., Yao, L., 2016. Assessment of instruments in facilitating investment in off-grid renewable energy projects. Energy policy 95, 437–446.

Shyu, C.-W., 2012. Rural electrification program with renewable energy sources: An analysis of China's Township Electrification Program. Energy policy 51, 842–853.

Singleton, B., 2017. What's missing from Ostrom? Combining design principles with the theory of sociocultural viability. Environmental Politics 26. https://doi.org/10.1080/09644016.2017.1364150.

Stephanie Hirmer, Heather Cruickshank, 2014. The user-value of rural electrification: An analysis and adoption of existing models and theories. Renewable and Sustainable Energy Reviews 34, 145–154. https://doi.org/10.1016/j.rser.2014.03.005.

Stephenson, K., Zelen, M., 1989. Rethinking centrality: Methods and examples. Social Networks 11, 1–37.

Stovel, K., Shaw, L., 2012. Brokerage. Annual review of sociology 38, 139–158.

Stuart, E.W., Shimp, T.A., Engle, R.W., 1987. Classical Conditioning of Consumer Attitudes: Four Experiments in an Advertising Context. Journal of Consumer Research 14, 334–349. https://doi.org/10.1086/209117.

Sun, Q., Wang, Z., Zhao, D., Xia, C., Perc, M., 2022. Diffusion of resources and their impact on epidemic spreading in multilayer networks with simplicial complexes. Chaos, Solitons & Fractals 164, 112734.

Sunstein, C.R., 2015. Choosing not to choose: Understanding the value of choice. Oxford University Press, USA.

Taysom, E., Crilly, N., 2017. Resilience in Sociotechnical Systems: The Perspectives of Multiple Stakeholders. She Ji: The Journal of Design, Economics, and Innovation 3, 165–182. https://doi.org/10.1016/j.sheji.2017.10.011.

Tenenbaum, B., Greacen, C., Siyambalapitiya, T., Knuckles, J., 2014. From the Bottom Up: How Small Power Producers and Mini-grids Can Deliver Electrification and Renewable Energy in Africa. World Bank Publications.

Tenenbaum, B., Greacen, C., Vaghela, D., 2018. Mini-grids and arrival of the main grid.

Thaler, R.H., Sunstein, C.R., 2008. Nudge: Improving Decisions About Health, Wealth, And Happiness.

Thaler, R.H., Sunstein, C.R., Balz, J.P., 2013. The Behavioral Foundations of Public Policy: Choice Architecture. Princeton university press.

Tortoriello, M., McEvily, B., Krackhardt, D., 2015. Being a catalyst of innovation: The role of knowledge diversity and network closure. Organization Science 26, 423–438.

Treib, O., Bähr, H., Falkner, G., 2007. Modes of governance: towards a conceptual clarification. Journal of European Public Policy 14, 1–20. https://doi.org/10.1080/135017606061071406.

Treisman, D., 2002. Decentralization and the Quality of Government. unpublished paper, Department of Political Science, UCLA.

Trimble, M., Berkes, F., 2015. Towards adaptive co-management of small-scale fisheries in Uruguay and Brazil: lessons from using Ostrom's design principles. Maritime Studies 14, 1–20.

Tumwesigye, R., Twebaze, P., Makuregye, N., Muyambi, E., 2011. Key issues in Uganda's Energy Sector. Pro-Biodiversity Conservationists in Uganda (PROBICOU), International Institute for Environment and Development. https://www.iied.org/sites/default/files/pdfs/migrate/16030IIED.pdf (accessed 20 February 2023).

Twesigye, P., 2019. Scaling up Rural Electrification in Uganda: Innovative Technical and Financial Solutions Being Explored to Address Access Challenges. Energy Insights. Energy and Economic Growth. https://www.energyeconomicgrowth.org/publication/eeg-energy-insight-scaling-rural-electrification-uganda-innovative-technical-and (accessed 24 February 2023).

Ulsrud, K., Rohracher, H., Winther, T., Muchunku, C., Palit, D., 2018. Pathways to electricity for all: What makes village-scale solar power successful? Energy Research & Social Science 44, 32–40.

United Republic of Tanzania, 1996. The National Investment Promotion Policy.

UOMA, 2019. Market Map of off-grid energy in Uganda. Uganda Off-Grid Energy Market Accelerator. https://uoma.ug/wp-content/uploads/2019/07/UOMA-Market-Map_FullVersion-1.pdf (accessed 20 January 2022).

UOMA, 2020. Off-grid Energy in Uganda: Market Map: Mini-grid section. Uganda Off-Grid Energy Market Accelerator. https://uoma.ug/wp-content/uploads/2020/10/Download-2020-UOMA-Market-map_vFUpdated.pdf (accessed 10 February 2023).

UOMA, 2021. Off-grid energy in Uganda: Market Map. Uganda Off-Grid Energy Market Accelerator. https://uoma.ug/wp-content/uploads/2021/12/2021-UOMA-market-map-vFinal.pdf (accessed 10 February 2023).

UOMA, 2022. Off-grid energy in Uganda: Market Map. Uganda Off-Grid Energy Market Accelerator. https://uoma.ug/wp-content/uploads/2018/08/2022-UOMA-Market-Map-vFinal.pdf (accessed 10 February 2023).

UOMA, 2023. Off-grid Energy in Uganda: Market Map. Uganda Off-Grid Energy Market Accelerator. https://uoma.ug/wp-content/uploads/2018/08/2023-UOMA-Market-Map_vPublished-1_comp2.pdf (accessed 15 June 2024).

USAID, 2018a. Challenges and Needs in Financing Mini-Grids: What are the sources of capital for mini-grid projects? US Agency for International Development. https://www.usaid.gov/energy/mini-grids/financing/capital.

USAID, 2018b. Mini-grids: Fostering a Spportive Regulatory Environment for Mini-grid Development. US Agency for International Development. https://www.usaid.gov/energy/mini-grids/regulation.

USAID, 2018c. Mini-Grids Ownership Models. US Agency for International Development. https://www.usaid.gov/energy/mini-grids/ownership.

Venkata Bandi, Tiia Sahrakorpi, Jukka Paatero, Risto Lahdelma, 2022. The paradox of mini-grid business models: A conflict between business viability and customer affordability in rural India. Energy Research & Social Science 89, 102535. https://doi.org/10.1016/j.erss.2022.102535.

Wabukala, B.M., Bergland, O., Rudaheranwa, N., Watundu, S., Adaramola, M.S., Ngoma, M., Rwaheru, A.A., 2022. Unbundling barriers to electricity security in Uganda: A review. Energy Strategy Reviews 44, 100984. https://doi.org/10.1016/j.esr.2022.100984.

Wade, R., 1988. The management of irrigation systems: How to evoke trust and avoid prisoner's dilemma. World Development 16, 489–500.

Wasserman, S., Faust, K., 1994. Social network analysis: Methods and applications. 05213870.

White, T.A., Runge, C.F., 1995. The emergence and evolution of collective action: Lessons from watershed management in Haiti. World Development 23, 1683–1698.

Willcox, M., Cooper, D., 2018. NAE Case Study: Tanzania, Mini-Grids Regulatory Framework. Energypedia, Energypedia. https://energypedia.info/wiki/NAE_Case_Study:_Tanzania,_Mini-Grids_Regulatory_Framework (accessed 24 February 2023).

Yadoo, A., Cruickshank, H., 2010. The value of cooperatives in rural electrification. Energy policy 38, 2941–2947.

Yamaguchi, K., 1996. Power in Networks of Substitutable and Complementary Exchange Relations: A Rational-Choice Model and an Analysis of Power Centralization. American Sociological Review 61, 308–332. https://doi.org/10.2307/2096336.

Yi, H., 2017. Network Structure and Governance Performance: What Makes a Difference? Public Administration Review 78. https://doi.org/10.1111/puar.12886.

Zebra, E.I., van der Windt, Henny J., Nhumaio, G., Faaij, A.P., 2021. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews 144, 111036. https://doi.org/10.1016/j.rser.2021.111036.

Appendix A: Applied Centrality Measures

Table 14: Centrality measures applied in the study

Centrality measure	Definition	Model definition	Accruing advantage(s)
Degree centrality	Degree centrality measures the ratio of node degree (number of connections) to the maximum possible degree in the network (N-1 for an undirected network and 2(N-1) for a directed network)	Degree centrality $C_D(i)$ of a node i $$C_D(i) = \frac{k_i}{(N-1)}$$ Where k_i is the number of edges incident to node i i.e. the degree of node i, N is the total number of nodes in the network (Wasserman and Faust, 1994)	Influence comes from possessing a large number of direct ties or access, equivalent to close relationships to other actors in a network
Eigenvector centrality	Extent of closeness to highly connected nodes - assigns higher centrality scores to nodes that are connected to other highly central nodes.	$$A.v = \lambda.v$$ Where A is the adjacency matrix of the network, representing the connections between nodes. Each element A_{ij} of the matrix is 1 if there is a connection from node i to node j, and 0 otherwise. λ is the eigenvalue associated with the eigenvector v of the network, v is the eigenvector corresponding to the largest eigenvalue λ, representing the eigenvector centrality scores of the nodes. The eigenvector centrality v_i of each node i is given by the corresponding element of the eigenvector v. (Wasserman and Faust, 1994)	Influence of a node depends not only on the number of connections it has but also on the importance of those connections.
Effective size	The effective size of a node's ego network is based on the concept of redundancy. A person's ego network has redundancy to the extent that her contacts are connected to each other as well. The nonredundant part of a person's relationships is the effective size of her ego network.	Effective size S_i of a node i $$S_i = \frac{\sum_{j \epsilon N_i} k_j}{k_i(k_i - 1)}$$ Where N_i is the set of neighbours of node i, k_i is the degree of node i, and k_j is the degree of each neighbour j of node i (Borgatti and Everett, 1997; Burt, 2012)	A higher effective size indicates a node's contacts are less connected to each other, suggesting a greater number of unique connections to other players. The node has more diverse and varied access routes to other players compared to the interconnectedness of its contacts providing multiple avenues for obtaining resources, information, and opportunities within the network.
Bonacich' Power centrality	Defined by the notion that the power of a node is recursively defined by the sum of the power of its connections. Nodes either become more powerful as their direct neighbours become more powerful (as occurs in cooperative relations), or weaker	Power centrality $C_i(\alpha, \beta)$ Where: $\lvert\beta\rvert$ affects the degree to which distant ties are taken into account. If $\beta = 0$, $C_i(\alpha, \beta)$ is simply proportional to the degree of unit i, the number of actors with which it is connected, regardless of their centralities.	In bargaining situations, it is more advantageous to be connected to those who have few options; power comes from being connected to those who are powerless.

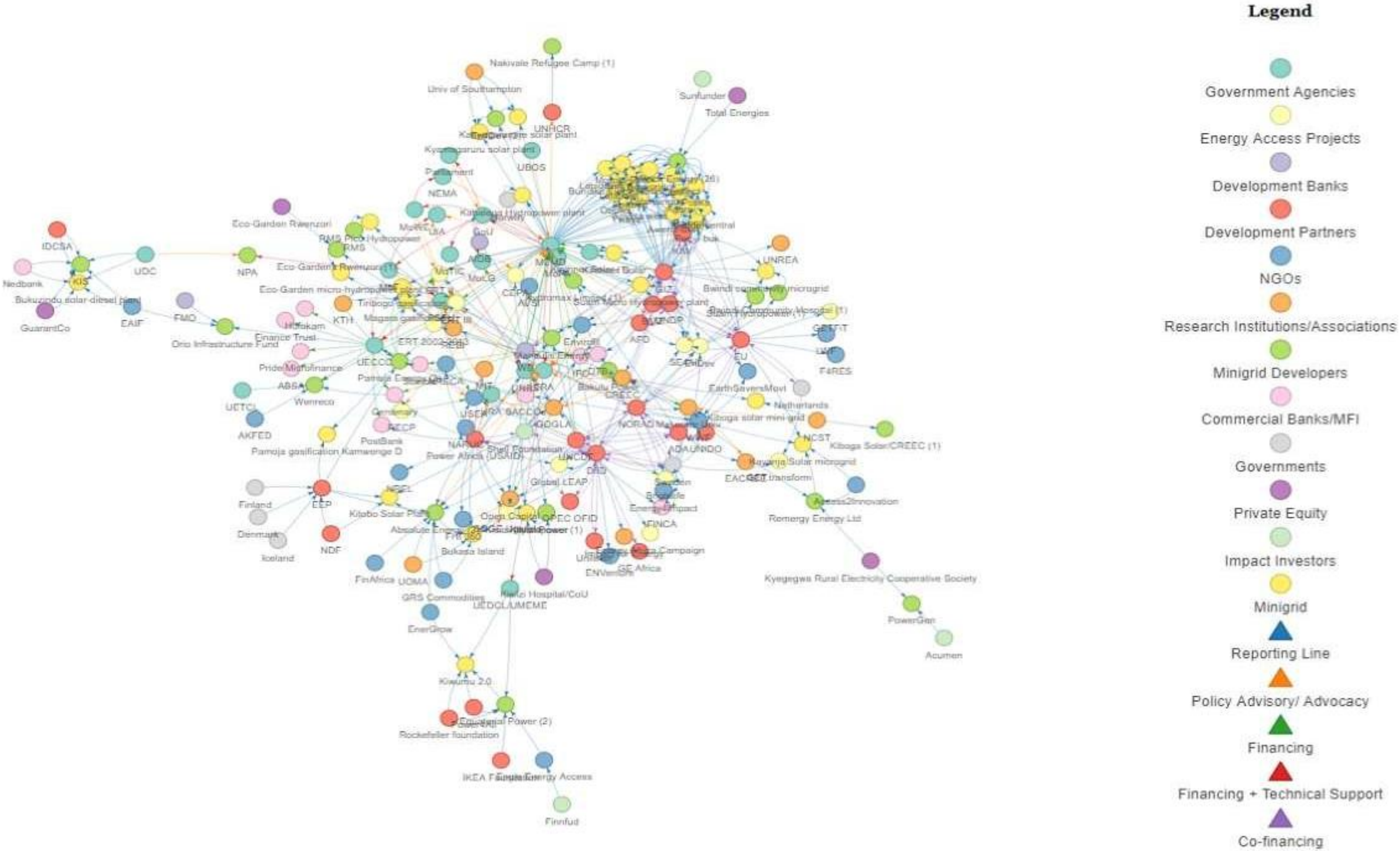
	the stronger their neighbours (as occurs in competitive or antagonistic relations) (Bonacich, 1987)	As $\|\beta\|$ increases, the centralities of direct actor connections are taken more into account, so that $C_i(\alpha,\beta)$ becomes a function of the indirect as well as the direct ties connecting it to the system[17]. $$C_i(\alpha,\beta) = \sum_j (\alpha + \beta C_j) R_{ij}$$ where R is a matrix of relationships (Bonacich, 1987)	
Betweenness centrality	The fraction of shortest paths in the network that pass through that node in the network. It quantifies the importance of a node in facilitating communication or resource flow between other nodes. (Freeman, 1977)	Betweenness centrality $C_B(i)$ of a node i $$C_B(i) = \sum_{s\neq i\neq t} \frac{s_{st}(i)}{s_{st}}$$ Where s_{st} is the total number of shortest paths from node s to node t, and $s_{st}(i)$ is the number of those shortest paths that pass through node i (Freeman et al., 1979)	Influence arises from linking together powerful but not directly connected actors or groups facilitating the ability to broker relationships between parties that lack other connections
Constraint	Proxy measure of structural hole(s) quantifying the extent to which a node's connections are redundant or constrained by the connections of other nodes in the network (Martin G. Everett and Stephen P. Borgatti, 2020).	Constraint $C_{CO}(i)$ of a node i $$C_{CO}(i) = \sum_{j\neq i} \sum_{k\neq i,j} \frac{1}{d_{jk}}$$ Where: d_{jk} is the effective resistance[18] between nodes j and k (Burt, 2018; Burt, 2012)	Nodes with high constraint scores have fewer opportunities to control or broker information flow between other nodes because their connections are redundant with those of other nodes. Conversely, low constraint nodes have more opportunities to serve as intermediaries or brokers between different parts of the network.
Closeness centrality	Closeness is the mean geodesic (i.e., shortest-path) distance between a vertex and all other vertices reachable from it. It quantifies the average distance from a node to all other nodes in the network.	Closeness centrality $C_C(i)$ of a node i $$C_C(i) = \frac{1}{\sum_{j=1}^{n} d(i,j)}$$ Where n is the total number of nodes in the network. $d(i,j)$ is the shortest path distance between node i and node j (Wasserman and Faust, 1994)	Influence comes from proximity to all other actors in the network. Where an actor is able to minimize the number of steps required to reach all other actors, that actor can potentially acquire and transfer resources more efficiently than other actors in the network.
Local Efficiency	The efficiency of the network when each node is removed, one at a time. Measure assesses how critical a node is to the overall network connectivity by observing how the	Local efficiency $$E_{loc}(i) = \frac{1}{N_i(N_i-1)} \sum_{j,k\in N_i, j\neq k} \frac{1}{d_{jk}}$$	Asseses the fault tolerance of networks and the efficiency of information or resource transfer within the local neighborhood of each node.

[17] This study adopts a $\beta = 0.5$ to reflect a balanced consideration of both direct connections and the importance of a node's neighbours within the broader network structure.

[18] Based on the concept of "effective resistance" in electrical network theory. In this approach, the constraint of a node is calculated as the sum of the effective resistances between the node and all other pairs of nodes in the network. The effective resistance between two nodes measures the resistance to flow of information or resources along the shortest path between them.

	efficiency of the network suffers when the node is not present.	Where N_i is the number of neighbors of node i, d_{jk} is the shortest path distance between nodes j and k within the subgraph formed by node i's neighbors. The sum is taken over all pairs of neighbors j and k of node I (Crucitti et al., 2003).	
Information centrality	Measure of the efficiency of a node in terms of its role in the network's information transmission capability (Stephenson and Zelen, 1989).	Information centrality $$C_{IC}(i) = \left(\frac{N}{\sum_{j,k\in N} d_{jk}}\right) \bigg/ \left(\frac{N-1}{\sum_{j,k\in N} d_{jk}{}^{(i)}}\right)$$ Where N is the total number of nodes, d_{jk} is the shortest path distance between nodes j and k, abd $d_{jk}{}^{(i)}$ is the shortest path distance between nodes j and k with node i removed from the network (Stephenson and Zelen, 1989).	A node's importance is derived from its role in facilitating or hindering the flow of information across the network. Losing a high information centrality node would significantly disrupt the network's ability to communicate internally.
Network density	Assesses how densely connected the network is by calculating the ratio of actual connections to potential connections.	Closeness centrality $C_C(i)$ of a node i $$C_C(i) = \frac{1}{\sum_{j=1}^{n} d(i,j)}$$ Where n is the total number of nodes in the network. $d(i,j)$ is the shortest path distance between node i and node j (Wasserman and Faust, 1994)	High-density networks often exhibit strong communication, collaboration, or social interaction, while a low density points to a sparser network with fewer interactions.
Global Network efficiency	The average inverse shortest path length in the network, used to assess the effectiveness of information or resource flow across a network	Efficiency $$E = \frac{1}{N(N-1)} \sum_{i\neq j\in N} \frac{1}{d(i,j)}$$ where N is the total number of nodes in the network, $d(i,j)$ is the shortest path distance between nodes i and j (Aytac and Atay, 2015).	
Average path length	The average number of steps along the shortest paths for all possible pairs of network nodes, providing a broad sense of the network's connectivity and the ease with which any two nodes can interact.	Average path length $$L = \frac{1}{N(N-1)} \sum_{i\neq j} d(i,j)$$ Where N is the total number of nodes in the network, and d(i,j) is the shortest path length between nodes i and j. The sum is taken over all pairs of distinct nodes (Bloch et al., 2023).	A low value suggests that the network has good connectivity, with relatively short paths between any two nodes. This is often indicative of efficient communication and quick dissemination of information or resources across the network, typical of "small-world" networks.

Appendix B: iGraph Network Map of Uganda's OFI Network



Appendix C: Uganda's OFI Nodes, Categories, Centrality Scores

Node	Layer	Eigen	Degree Centr	Effective Size_n	Power Centr	Constraint	InvConstraint_n	Betweenness_n	Closeness	Information Centr	LNE
ABSA	Commercial Banks /MFI	0.029	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
Centenary		0.112	0.023	0.050	0.484	0.302	0.163	0.003	0.002	0.668	0.257
DTB		0.069	0.012	0.024	0.481	0.556	0.056	0.000	0.001	0.478	0.333
Finance Trust		0.029	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
FINCA		0.044	0.023	0.046	0.482	0.342	0.136	0.021	0.002	0.636	0.361
Hofokam		0.029	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
IFC		0.128	0.017	0.034	0.481	0.405	0.104	0.000	0.002	0.619	0.611
Nedbank		0.000	0.012	0.019	0.486	0.681	0.033	0.000	0.001	0.152	0.500
PostBank		0.051	0.012	0.024	0.481	0.556	0.056	0.000	0.002	0.495	0.167
Pride Microfinance		0.029	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
SACCOs		0.034	0.012	0.024	0.481	0.556	0.056	0.000	0.001	0.484	0.167
Stanbic		0.087	0.012	0.026	0.481	0.500	0.070	0.000	0.001	0.492	0.250
AfDB	Development Banks	0.012	0.012	0.026	0.543	0.500	0.070	0.000	0.002	0.450	0.000
FMO		0.001	0.006	0.026	0.484	1.000	0.000	0.000	0.001	0.139	0.000
WB		0.445	0.121	0.361	1.000	0.090	0.713	0.101	0.002	0.918	0.108
ADA	Development Partners	0.204	0.087	0.211	0.672	0.177	0.328	0.168	0.002	0.829	0.255
AFD		0.169	0.046	0.099	0.299	0.246	0.216	0.018	0.002	0.751	0.248
BMZ		0.270	0.035	0.071	0.599	0.282	0.179	0.004	0.002	0.746	0.492
DfID		0.490	0.168	0.493	0.652	0.091	0.705	0.487	0.002	0.922	0.104
EEP		0.014	0.046	0.114	0.486	0.191	0.299	0.016	0.002	0.614	0.054
EU		0.369	0.121	0.344	0.618	0.110	0.570	0.261	0.002	0.870	0.154
GE Africa		0.032	0.006	0.026	0.481	1.000	0.000	0.000	0.002	0.285	0.000
GIZ		0.751	0.249	0.684	0.040	0.116	0.537	0.376	0.002	0.975	0.131
IDCSA		0.000	0.012	0.019	0.486	0.681	0.033	0.000	0.001	0.152	0.500
IKEA Foundation		0.000	0.006	0.026	0.482	1.000	0.000	0.000	0.001	0.113	0.000
KfW		0.560	0.179	0.463	0.686	0.143	0.423	0.064	0.002	0.952	0.128

NDF		0.003	0.012	0.018	0.485	0.707	0.029	0.000	0.001	0.384	0.500
NORAD		0.222	0.092	0.236	0.000	0.157	0.380	0.126	0.002	0.866	0.248
OPEC OFID		0.084	0.017	0.014	0.399	0.648	0.038	0.000	0.002	0.490	1.000
Power Africa (USAID)		0.346	0.133	0.378	0.425	0.108	0.581	0.143	0.002	0.924	0.127
Power4All		0.000	0.012	0.018	0.486	0.700	0.030	0.000	0.001	0.216	0.500
Rockefeller foundation		0.000	0.012	0.018	0.486	0.700	0.030	0.000	0.001	0.216	0.500
UNCDF		0.314	0.087	0.227	0.420	0.149	0.403	0.085	0.002	0.876	0.233
UNDP		0.408	0.075	0.176	0.682	0.195	0.292	0.133	0.002	0.839	0.291
UNHCR		0.066	0.012	0.026	0.484	0.500	0.070	0.027	0.002	0.303	0.000
UNIDO		0.036	0.023	0.031	0.388	0.458	0.083	0.001	0.002	0.571	0.417
Unilever		0.066	0.017	0.000	0.402	0.821	0.015	0.000	0.002	0.400	0.500
Brightlife	Energy Access Projects	0.066	0.029	0.062	0.483	0.277	0.184	0.032	0.002	0.709	0.425
CEPA		0.099	0.017	0.025	0.481	0.514	0.067	0.000	0.002	0.587	0.167
EnDev		0.132	0.052	0.122	0.492	0.205	0.273	0.023	0.002	0.814	0.278
Energy Africa Campaign		0.032	0.006	0.026	0.481	1.000	0.000	0.000	0.002	0.285	0.000
ERT 2002-2013		0.130	0.029	0.062	0.490	0.279	0.182	0.010	0.002	0.718	0.217
ERT II		0.226	0.035	0.079	0.481	0.239	0.225	0.000	0.002	0.764	0.307
ERT III		0.233	0.040	0.098	0.481	0.208	0.268	0.000	0.002	0.795	0.282
GET.transform		0.013	0.012	0.026	0.481	0.500	0.070	0.000	0.001	0.394	0.333
GETFiT		0.024	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
Global LEAP		0.069	0.017	0.037	0.481	0.368	0.121	0.000	0.002	0.613	0.611
RECP		0.024	0.012	0.017	0.473	0.723	0.027	0.000	0.001	0.431	0.500
SE4All		0.179	0.035	0.070	0.481	0.286	0.176	0.000	0.002	0.775	0.772
SOGE-Uganda		0.092	0.029	0.041	0.481	0.410	0.101	0.000	0.002	0.705	0.600
ERA	Government Agencies	0.284	0.069	0.190	0.442	0.134	0.455	0.572	0.002	0.879	0.163
GoU		0.110	0.064	0.178	0.370	0.127	0.484	0.243	0.002	0.789	0.026
MEMD		1.000	0.324	1.000	0.567	0.066	1.000	1.000	0.002	1.000	0.089
MoF		0.058	0.035	0.093	0.506	0.173	0.337	0.050	0.002	0.743	0.168
MoFA		0.023	0.017	0.022	0.537	0.556	0.056	0.007	0.002	0.472	0.000

MoLG		0.072	0.017	0.028	0.484	0.474	0.078	0.001	0.001	0.573	0.306
MoTIC		0.019	0.017	0.040	0.487	0.333	0.141	0.010	0.002	0.563	0.149
MoWE		0.042	0.023	0.057	0.510	0.250	0.211	0.020	0.002	0.635	0.111
NEMA		0.068	0.012	0.026	0.441	0.500	0.070	0.041	0.002	0.469	0.000
Parliament		0.014	0.012	0.006	0.540	1.000	0.000	0.000	0.001	0.259	0.000
PSFU		0.203	0.064	0.166	0.465	0.157	0.378	0.191	0.002	0.848	0.119
UBOS		0.065	0.006	0.026	0.441	1.000	0.000	0.000	0.002	0.300	0.000
UDC		0.000	0.017	0.033	0.489	0.414	0.100	0.000	0.001	0.248	0.167
UECCC		0.218	0.092	0.282	0.516	0.082	0.789	0.231	0.002	0.869	0.043
UEDCL/UMEME		0.019	0.017	0.033	0.486	0.422	0.096	0.055	0.002	0.399	0.167
UETCL		0.003	0.006	0.026	0.484	1.000	0.000	0.000	0.001	0.206	0.000
UIA		0.070	0.017	0.040	0.481	0.333	0.141	0.000	0.002	0.577	0.107
UNBS		0.113	0.040	0.101	0.480	0.196	0.290	0.061	0.002	0.770	0.248
URA		0.068	0.017	0.037	0.492	0.368	0.121	0.013	0.002	0.613	0.444
Denmark	Foreign Governments	0.001	0.006	0.026	0.482	1.000	0.000	0.000	0.001	0.217	0.000
Finland		0.001	0.006	0.026	0.482	1.000	0.000	0.000	0.001	0.217	0.000
Iceland		0.001	0.006	0.026	0.482	1.000	0.000	0.000	0.001	0.217	0.000
Netherlands		0.049	0.017	0.022	0.419	0.556	0.056	0.003	0.001	0.401	0.167
Norway		0.011	0.012	0.014	0.486	0.804	0.017	0.000	0.001	0.377	0.500
Sweden		0.154	0.064	0.149	0.668	0.199	0.284	0.044	0.002	0.798	0.251
Acumen	Impact Investors	0.000	0.006	0.026	0.484	1.000	0.000	0.000	0.001	0.000	0.000
Finnfud		0.000	0.006	0.026	0.483	1.000	0.000	0.000	0.001	0.030	0.000
Shell Foundation		0.312	0.081	0.206	0.473	0.161	0.369	0.049	0.002	0.876	0.217
Sunfunder		0.023	0.006	0.026	0.458	1.000	0.000	0.000	0.002	0.286	0.000
Agoro	Minigrid Project	0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Apwoyo		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Apyeta west		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Aweno-olwi		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Bukasa Island		0.058	0.035	0.068	0.481	0.292	0.170	0.000	0.002	0.715	0.217
Bukuzindu solar-diesel plant		0.000	0.035	0.033	0.481	0.468	0.080	0.000	0.001	0.227	0.167

Bunjako Electrification project		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Bwindi community microgrid		0.098	0.023	0.039	0.481	0.397	0.107	0.000	0.002	0.658	0.458
Eco-Garden micro-hydropower plant		0.002	0.012	0.015	0.481	0.771	0.021	0.000	0.001	0.311	0.500
Kabalega Hydropower plant		0.072	0.017	0.020	0.481	0.575	0.052	0.000	0.002	0.512	0.333
Kanyegaramire solar plant		0.071	0.017	0.022	0.481	0.549	0.058	0.000	0.002	0.492	0.333
Kayanja Solar microgrid		0.030	0.023	0.033	0.481	0.442	0.089	0.000	0.002	0.546	0.292
Kiboga solar mini-grid		0.007	0.012	0.026	0.481	0.500	0.070	0.000	0.001	0.382	0.250
Kirchner Solar		0.159	0.023	0.040	0.481	0.388	0.111	0.000	0.002	0.674	0.417
Kisiizi Hydropower		0.031	0.017	0.013	0.481	0.657	0.037	0.000	0.002	0.420	0.333
Kitobo Solar Plant		0.027	0.023	0.038	0.481	0.400	0.106	0.000	0.002	0.591	0.292
Kiwumu 2.0		0.002	0.029	0.039	0.481	0.421	0.097	0.000	0.001	0.342	0.150
Kyamagaruru solar plant		0.071	0.017	0.022	0.481	0.549	0.058	0.000	0.002	0.492	0.333
Labayango		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Lapideyenyi		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Lelapwot		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Magara gasification		0.074	0.023	0.046	0.481	0.339	0.137	0.000	0.002	0.623	0.194
Moroto-East		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Muddu-central		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Oboko		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Ogili		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Paloga		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417

Pamoja gasification Kamwenge		0.007	0.012	0.020	0.481	0.643	0.039	0.000	0.001	0.417	0.500
Penyi-buk		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Potika		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
RMS Pico Hydropower		0.014	0.012	0.012	0.481	0.849	0.012	0.000	0.002	0.378	0.500
Senyondo		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Suam Micro Hydropower plant		0.160	0.023	0.051	0.481	0.297	0.167	0.000	0.002	0.690	0.333
Tiribogo gasification		0.074	0.023	0.046	0.481	0.339	0.137	0.000	0.002	0.623	0.194
Ywaya		0.174	0.023	0.051	0.481	0.296	0.168	0.000	0.002	0.692	0.417
Kirchner Solar		0.125	0.017	0.027	0.484	0.488	0.074	0.000	0.002	0.600	0.417
Absolute Energy		0.091	0.064	0.168	0.487	0.151	0.396	0.041	0.002	0.812	0.121
Bakulu Power		0.066	0.012	0.026	0.481	0.500	0.070	0.000	0.002	0.451	0.063
Bwindi Community Hospital		0.064	0.017	0.024	0.484	0.529	0.063	0.000	0.002	0.579	0.500
Eco-Gardens Rwenzori		0.002	0.017	0.026	0.484	0.506	0.069	0.001	0.001	0.312	0.167
En4Dev		0.076	0.023	0.017	0.487	0.574	0.052	0.000	0.002	0.532	0.333
Equatorial Power	Minigrid Developers	0.001	0.035	0.061	0.484	0.327	0.145	0.002	0.001	0.294	0.100
Hydromax Limited		0.095	0.029	0.057	0.484	0.314	0.154	0.006	0.002	0.662	0.192
Kiboga Solar/CREEC		0.000	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.144	0.000
KIS		0.000	0.035	0.033	0.484	0.468	0.080	0.000	0.001	0.227	0.167
Kisiizi Power		0.031	0.017	0.013	0.484	0.657	0.037	0.000	0.002	0.420	0.333
Mandulis Energy		0.081	0.023	0.057	0.481	0.250	0.211	0.000	0.002	0.663	0.188
Nakivale Refugee Camp		0.004	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.117	0.000
NPA		0.004	0.012	0.026	0.481	0.500	0.070	0.000	0.001	0.337	0.000

Orio Infrastructure Fund		0.014	0.017	0.040	0.481	0.333	0.141	0.000	0.002	0.362	0.000
Pamoja Energy (3)		0.089	0.040	0.085	0.490	0.258	0.202	0.046	0.002	0.728	0.142
PowerGen		0.000	0.012	0.026	0.481	0.500	0.070	0.000	0.001	0.061	0.000
Remergy Energy Ltd		0.007	0.023	0.036	0.484	0.420	0.097	0.001	0.001	0.453	0.167
RMS		0.014	0.012	0.012	0.484	0.849	0.012	0.000	0.002	0.378	0.500
Suam Hydropower (1)		0.058	0.012	0.023	0.481	0.570	0.053	0.000	0.002	0.488	0.500
Wenreco		0.039	0.029	0.067	0.481	0.248	0.213	0.000	0.002	0.574	0.025
Winch Energy (26)		0.353	0.133	0.331	0.533	0.161	0.368	0.041	0.002	0.925	0.114
Access2Innovation		0.002	0.012	0.015	0.486	0.781	0.020	0.000	0.001	0.331	0.500
AKFED		0.003	0.006	0.026	0.484	1.000	0.000	0.000	0.001	0.206	0.000
AVSI		0.123	0.012	0.022	0.441	0.602	0.047	0.000	0.002	0.505	0.250
EAIF		0.001	0.017	0.033	0.489	0.414	0.100	0.000	0.001	0.254	0.167
EarthSavers Movt		0.032	0.012	0.026	0.481	0.500	0.070	0.000	0.002	0.476	0.250
EnerGrow		0.006	0.012	0.026	0.484	0.500	0.070	0.000	0.001	0.383	0.000
Energy4Impact		0.017	0.017	0.040	0.484	0.333	0.141	0.005	0.002	0.526	0.125
Engie Energy Access		0.000	0.012	0.026	0.482	0.500	0.070	0.001	0.001	0.114	0.000
ENVenture	NGOs	0.036	0.012	0.007	0.481	0.979	0.002	0.000	0.002	0.400	1.000
Envirofit		0.220	0.029	0.061	0.441	0.288	0.174	0.022	0.002	0.747	0.475
F4RES		0.024	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
FHI 360		0.036	0.017	0.021	0.484	0.569	0.053	0.000	0.001	0.572	0.417
FinAfrica		0.006	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.264	0.000
GRS Commodities		0.010	0.012	0.021	0.484	0.638	0.040	0.000	0.001	0.447	0.500
LWF		0.024	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.275	0.000
NARUC		0.041	0.012	0.024	0.504	0.565	0.054	0.000	0.002	0.493	0.500
NRECA		0.098	0.023	0.035	0.440	0.426	0.095	0.017	0.002	0.641	0.257
NREL		0.023	0.006	0.026	0.481	1.000	0.000	0.000	0.001	0.286	0.000

USEA		0.132	0.040	0.099	0.504	0.202	0.278	0.328	0.002	0.780	0.270
WWF		0.080	0.052	0.141	0.511	0.149	0.404	0.046	0.002	0.807	0.182
Eco-Garden Rwenzori	Private Equity	0.000	0.006	0.026	0.482	1.000	0.000	0.000	0.001	0.120	0.000
GuarantCo		0.000	0.012	0.019	0.486	0.681	0.033	0.000	0.001	0.152	0.500
Kisiizi Hospital/CoU		0.004	0.012	0.010	0.486	0.889	0.009	0.000	0.001	0.288	0.500
Kyegegwa Rural Electricity Cooperative Society		0.000	0.012	0.026	0.486	0.500	0.070	0.000	0.001	0.174	0.000
Total Energies		0.023	0.006	0.026	0.458	1.000	0.000	0.000	0.002	0.286	0.000
CREEC	Research Institutions/Associations	0.099	0.052	0.141	0.494	0.149	0.403	0.321	0.002	0.802	0.112
EACREE		0.016	0.012	0.022	0.481	0.601	0.047	0.000	0.001	0.453	0.500
GOGLA		0.172	0.052	0.146	0.473	0.134	0.455	0.321	0.002	0.850	0.230
Impact for Energy		0.032	0.006	0.026	0.481	1.000	0.000	0.000	0.002	0.285	0.000
KTH		0.015	0.017	0.023	0.486	0.540	0.060	0.000	0.001	0.517	0.333
Makerere Univ		0.042	0.040	0.087	0.480	0.251	0.211	0.087	0.002	0.727	0.258
MIT		0.111	0.017	0.017	0.472	0.609	0.045	0.006	0.002	0.507	0.250
NCST		0.003	0.017	0.040	0.490	0.333	0.141	0.000	0.001	0.374	0.083
Open Capital		0.116	0.040	0.080	0.487	0.279	0.182	0.023	0.002	0.776	0.386
REBI		0.030	0.035	0.079	0.495	0.242	0.221	0.031	0.002	0.642	0.100
Univ of Southampton		0.014	0.017	0.013	0.487	0.656	0.037	0.000	0.001	0.425	0.333
UNREA		0.049	0.006	0.026	0.481	1.000	0.000	0.000	0.002	0.295	0.000
UOMA		0.010	0.012	0.021	0.484	0.638	0.040	0.000	0.001	0.447	0.500