SUSTAINABILITY, INCLUSIVENESS AND GOVERNANCE OF MINI-GRIDS IN AFRICA (SIGMA) RESEARCH PROJECT

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ON THE TECHNICAL SUSTAINABILITY OF MINI-GRIDS IN DEVELOPING COUNTRIES: A COMPREHENSIVE REVIEW OF LITERATURE

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[1] De Montfort University until January 2022
[2] University of Huddersfield
[3] De Montfort University until February 2022 and University of Surrey. Corresponding author. Contact s.c.bhattacharyya@surrey.ac.uk
[4] University of Surrey
[5] The Open University, University of Johannesburg
[6] Centre for Frugal Innovation in Africa
[7] University of Ibadan
[8] TaTEDO
[9] Motu Research, Institute for Development Studies

Abstract

In the context of access to electricity, mini-grids have emerged as an electrification strategy in the developing world. However, various technical, economic, socio-political and governance issues militate against the sustainability of mini-grids. Sustainability here is defined as the ability of mini-grids – specifically, those powered wholly or partly by renewable sources - to meet present and future needs for domestic and productive energy uses in a reliable, accessible, efficient and cost-effective manner. The purpose of this paper is to critically review and synthesise the available literature on the technical sustainability of mini-grids with a special emphasis on sub-Saharan Africa (SSA), and highlight lessons for mini-grid projects in the region.

The paper has followed a structured review approach inspired by the systematic review methodology. The review is based on studies published since 2000 (when mini-grids began gaining sustained attention in the SSA region) covering both academic and policy-oriented literature which were identified through searches of various databases and websites using predefined search strings. Specific inclusion and exclusion criteria were then applied to the identified literature and the selected material was analysed using NVivo. The content was analysed around four themes considered important for technical sustainability as follows:

1. Quality of equipment and design or installation issues;
2. Technical indicators used;
3. Technical operations, repair and management;
4. Technical sustainability.

The paper found that the technical sustainability of mini-grids is influenced by system design, construction quality, operations and maintenance and future capacity expansion of the systems. Various choices at the design stage in terms of demand to be serviced, system sizing, construction, component matching, demand management, smart features, and consideration of non-technical issues affect the technical sustainability of mini-grids. Trade-offs for cost minimisation often compromise the flexibility of the system, affecting long-term prospects of the plant. A lack of accurate data on load, resource availability and adequate local skills have also affected mini-grid projects. Although smart systems have been introduced, their effectiveness depends on user-friendliness, robustness, and durability. Furthermore, the quality of installations and construction quality have also adversely affected performance where local skills are in short supply and the quality of supply is compromised. However, the embeddedness of the technology in the socio-cultural, political and environmental context also influences the technical sustainability of mini-grids. The quality of service (in terms of availability, reliability, power quality and adequacy) is directly influenced by the quality of maintenance and system operation. Inappropriate operation of the system for various reasons such as a lack of skilled operators, inability to strictly adhere to operating instructions and local enforcement issues of good practices or absence of user engagement and cooperation affects the plant performance and technical sustainability. Similarly, irregular or inadequate maintenance of the plants due to financial, skills or other

constraints (e.g. remoteness of the plant, availability of spare parts, etc.) significantly influences performance. Studies have reported the prevalence of poor operating and maintenance practices in the mini-grid space, resulting in poor consumer satisfaction. Although modular systems offer the advantage of easy capacity expansion to meet future needs, in reality such expansion remains aspirational due to poor financial resources of mini-grids.

Crucially, the paper identifies the limitations of existing frameworks for assessing the technical sustainability of mini-grids and proposes a streamlined yet expanded framework for measurement that incorporates the elements of renewability and adequacy of electricity supply over the long term.

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ON THE TECHNICAL SUSTAINABILITY OF MINI-GRIDS IN DEVELOPING COUNTRIES: A COMPREHENSIVE REVIEW OF LITERATURE

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Acronyms

AC	Alternating current
AMDA	African Minigrid Developers Association
DC	Direct current
ESMAP	Energy Sector Management Assistance Program, World Bank
EUEI-PDF	European Union Energy Initiative Partnership Dialogue Facility
GW	Gigawatt
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kW	Kilowatt
MW	Megawatt
NGO	Non-governmental organisation
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SDG	Sustainable Development Goals
SDG7	Sustainable Development Goal 7
SEforAll	Sustainable Energy for All
SHS	Solar home system
UNSD	United Nations Statistics Division
UNIDO	United Nations Industrial Development Organisation
WBREDA	West Bengal Renewable Energy Development Agency
WHO	World Health Organisation

1. INTRODUCTION

Access to modern energy, including electricity, is critical for the sustainable development of a community or a society. This has been globally recognised through the formal adoption of affordable and clean energy for all as United Nations Sustainable Development Goal 7 (SDG 7). Evidence of linkages between energy and the SDGs has been demonstrated via extensive literature reviews (e.g. Fuso-Nerini et al., 2018, McCollum et al., 2018, and Santika et al., 2019). However, 770 million people across the globe lived without access to electricity in 2021 (IEA, 2022), and there are fears that reaching the target of universal access by 2030 may not be achieved (IEA et al 2021). Thus, there is a pressing need to accelerate efforts to meet the universal electrification objective by 2030, which will require significant financial investment and a cost-effective application of complementary electrification strategies.

The current energy access deficit is more acute among rural and low-income populations: in 2019, 84% of those lacking access to electricity lived in rural areas, accounting for 640 million people (IEA et al 2021), of which many on an income of less than $1.90 per day. Hence, conventional grid extension which is often the initial or preferred mode of electrification by governments (Bhattacharyya, 2012) may not be the most technically appropriate or economically feasible option. In fact, the one-size-fits-all approach to electrification has been questioned by various authors (Szabo et al. 2013).

Within this context, mini-grids have emerged as a complementary electrification strategy to grid extension, including in areas faced with capacity constraints or weak distribution systems. Electricity provision by the use of mini-grids, if they are well designed, implemented, and operated, can fill a gap between conventional grid extension and stand-alone solar systems by compensating for some of the shortcomings of both. Mini-grids are however not new to the electrification landscape and played an important role in early electrification efforts (Korkovelos et al., 2020, Odarno et al., 2017). While in their historical applications, they were the starting points of electrification in major cities and highly populated urban centres, and they are now reappearing at a time when grid coverage dominates urban locations butis unavailable in many rural areas (Odarno et al, 2017). Indeed, although mini-grids could play a role in urban areas, this is expected to be marginal given that there are near-universal rates of electrification (97%) in urban areas as compared to rural locations (81%) globally (IEA et al, 2021). For Sub-Saharan Africa, urban electricity access reached 78% in 2020, and over three-quarters of the world’s remaining rural population without electricity access lived in the region (IEA et al, 2021). However, electricity access measurements in themselves do not necessarily represent the whole picture: reliability and sufficiency of electricity access is still an issue in many sub-Saharan African contexts, and informal and illegal electricity access is still prevalent in many urban contexts in the region (Kovacic et al, 2016). Most of the potential of mini-grids for universal electrification will therefore be in hard-to-reach rural areas and islands, far removed from grid coverage, with relatively low levels of income and population densities, where electricity demand is generally expected to be low compared with urban areas.

According to the Tracking SDG 7 report, the number of people connected to solar mini-grids globally has more than doubled to 11 million people in 2019, from 5 million in 2010 (IEA et al 2021) while the World Bank indicates that 47 million people across 134 countries are currently connected to 19,000 mini-grids of various technologies, predominantly hydro and conventional diesel (World Bank, 2019). The World Bank further suggests that 490 million people will be cost-effectively electrified by 210,000 mini-grids across the globe to attain universal access by 2030 (ibid).

Evidence on the sustainability of mini-grids is mainly based on project evaluation studies within a country or across different countries (e.g. Ilskog 2008, Ilskog and Kjellstrom, 2008; Mainali and Silveira, 2015; Katre et al. 2019). While this paper concentrates on the technical sustainability of mini-grids, from both the design and operational perspectives, we emphasise that there are many related economic, social, political, governance and environmental dimensions, which taken together can threaten or enable the long-term sustainability of such systems. Moreover, the observations and findings of this paper are made with the awareness that all electrification contexts are unique owing to the complexity of geophysical, socio-economic, technical, environmental and institutional factors at stake (Cherni et al., 2007).

This paper undertakes a critical review of the literature with the view to answering the following specific questions:

Q1: What pre-operational actions or considerations have hindered the sustainable implementation of mini-grids?

Q2: What are the main sustainability issues encountered by mini-grids at the operational stage?

Q3: What sustainability issues do mini-grids face with respect to future expansion?

Q4: How is the success or failure of mini-grids linked to their energy resource specificities?

2. REVIEW METHODOLOGY

The scope of the review drew from publications from the year 2000 in reflection of the emergence of mini-grid systems and related research on access to energy. The review was limited to technical aspects of mini-grids with a particular focus on sub-Saharan African countries, but references from other low- and middle-income countries were also included. Details are provided in Table 1.

Table 1- Scope of the review and inclusion criteria

Scope element	Inclusion criteria	Exclusion criteria	Comments
Electricity systems	Mini-grids	Centralised, on-grid electricity; Decentralised electricity through stand-alone systems e.g. solar home systems, diesel generators or solar lanterns	Mini-grids are defined as "localised power networks, distributing electricity to a defined area, which can consist of just a few customers in a remote settlement, or hundreds of thousands of customers in a town". The search included mini-grids from all generation sources, including renewable energy technologies, a combination of renewables and fossil fuels (hybrid-mini-grids), and fossil fuels. Articles that compared the performance of different types of mini-grids were included.
Geographical scope	Low and middle-income countries	High-income countries	While studies from Sub-Saharan Africa were given higher priority, the review also drew from a wide evidence base in other developing countries.
Publication date	2000 onwards	Pre-2000 studies	The literature about access to electricity mini-grids before this date is virtually non-existent
Publication format	Journal articles, working papers, evaluations, institutional reports, specialised news outlets.	Other (books, book chapters, student papers, dissertations, unpublished works)	Specialist news outlets can capture the current performance and constraints of mini-grids faster than academic and institutional literature. This allowed us to take the pulse of the sector alongside robust peer reviewed studies.
Methodological approach	Primary and empirical studies that employ quantitative or qualitative data to address our research questions.	Secondary, theoretical, simulations or conceptual studies	The quality of the evidence provided by the literature reviewed was assessed according to the framework presented in Section 5.
Aims of the study	The literature addresses one or several of our research questions and sub-questions	Other (i.e. technical design of mini-grids; least cost electrification planning or other planning studies; sizing of mini-grids)	

Scope element	Inclusion criteria	Exclusion criteria	Comments
Publication language	English and French	Other	English and French are spoken in many Sub-Saharan African countries, and literature about the sub-region is expected to be mainly available in one of both languages.

Literature search and elimination process: The review considered academic and grey (policy-oriented) literature. Various sources have been used for the literature search as presented in Table 2. For example, the SCOPUS database was mainly used for the peer-reviewed literature. Google Scholar and Google search engine were used to identify policy and grey literature. Websites of specific organisations supporting mini-grids in Africa were also considered.

Table 2: Sources of literature used in the review

Type of literature	Source
Peer reviewed literature	Scopus, snowballing
Working papers	Google Scholar, Google search engine
Evaluations and other institutional literature	Websites of specific institutions supporting mini-grids in Sub-Saharan Africa, such as the "Green Mini-Grid Helpdesk" hosted by the AfDB, the World Bank (ESMAP), DfID, the African Development Bank, the European Union, SIDA, AMDA, IRENA, USAID and IEA.
Specialised press	EU TAF Sustainable Energy News newsletter, Google news, Greentech media, Minigrids partnership newsletter.

Predefined search strings were used for the literature identification process. Keywords included: mini-grids (and variations thereof), sustainability, availability, data envelopment analysis, performance, adequacy, maintenance, operations, outage, and technical efficiency. As discussed in Table 1, the material covered both journal articles and grey literature – particularly those produced by international organisations, consulting companies and NGOs. The review did not include centralised grids, on grid supply and stand-alone units like solar home systems.

The review team logged all the searches and compiled the resulting studies in a spreadsheet under the following categories: title, year of publication, type of publication, geographic coverage, research questions addressed, relevance, and additional comments. The review team then categorised studies for inclusion based on the criteria in Table 1, logging decisions in the spreadsheet. Studies were categorised into three groups – excluded, noted for further assessment, and included.

Noted and included studies were then coded using NVivo and organised using Mendeley.

NVivo analysis - The identified literature was analysed using NVivo for which a range of codes were identified around different themes. Themes considered for technical sustainability included the following:

1. Quality of equipment and design or installation issues;
2. Technical indicators used;
3. Technical operations, repair and management;
4. Technical sustainability.

Table 3 indicates the nodes considered under different themes.

Table 3: Codes for the thematic analysis of the technical dimensions of mini-grid sustainability

Themes	Codes
Quality of equipment and installation or design issues	Design contractor issues
	Equipment Issues
	Safety of installations
	Technical design issues
	Indicators
Technical indicators used	Adequacy
	Affordability
	Availability
	Araciality of support infrastructure
	Capacity factor
	Compatibility with future grid service
	Conformance with national standards
	Constancy of energy
	Cost effectiveness of design
	Daily operation services
	Design
	Duration or availability
	Efficiency
	Energy utilisation
	Equality of energy distribution
	Legality
	Power quality
	Primary energy use
	Reliability
	Safety
	Security of supply
	Technical losses
	Technology
	Well maintained
Technical operations, repair and management	Availability
	Demand management issues
	Natural disasters, component breakdown and technology issues
	Reliability issues
	Repair and maintenance and spare parts
	Skills availability and training

	Theft and illegal connections
Technical sustainability conclusions	Conclusions reached on technical sustainability

3. OVERVIEW OF CONCEPTS ON MINI-GRIDS AND THEIR SUSTAINABILITY

While there are various complementary definitions in the academic and grey literature, the term mini-grid has "multiple meanings, purposes and functions and one through which the often-competing objectives of productive use, energy access and rural electrification are conflated" (Baker et al 2022:14). There is no consensus regarding the definition of a mini-grid, including in terms of system size, scale, technical features, ownership structure, service area, customer base, generation source and the nature of the local distribution network (Baker et al 2022). However, many sources seem to concur that a mini-grid operates at a low to medium voltage, uses a local distribution network for a local group of electricity users, and is standalone but can potentially interact with the centralised utility grid under certain circumstances (Bhattacharyya 2018, IEA 2011, UNIDO 2017, Bloomberg NEF and SEforALL 2020, ESMAP 2019, IRENA 2019, Tenenbaum et al. 2014, World Bank 2000 and Yan et al. 2017).

The installed capacity of a mini-grid can also vary considerably depending on the context and the country, but typically falls within a range of 10 kW to 10 MW (Muchunku et al 2018:7, EUEI PDF 2014). This, as compared to that of a micro grid which is usually between 1-10 kW (Muchunku et al 2018). Mini-grids can also be differentiated from solar home systems (SHSs), which are typically smaller, and primarily deployed for the provision of energy access such as lighting, radio and mobile telephone charging, using mobile payment technology for energy service payments. Mini-grids are therefore perceived as better able to support productive use – i.e., the use of energy for income-generating activities – in addition to household energy access (Bhattacharyya and Palit 2016, Peters et al 2019).

The system configuration of a mini-grid also varies widely. Generally, a mini-grid system consists of four elements: 1) generation sources; 2) control and monitoring systems; 3) an energy storage facility; and 4) a local distribution network. Different combinations of these components give rise to different configurations. Depending on the nature of the current flow in the network, mini-grid systems can be DC (direct current) or AC (alternating current) systems. DC systems avoid conversion losses, but they can serve only a small area due to supply quality issues (Boait, 2014). AC systems are quite common on the other hand and although single fuel systems (e.g., PV, diesel, mini-hydro, biomass) are widely used, hybrid systems that combine different generation sources e.g., solar PV and diesel, are gaining popularity due to greater reliability of supply. When the generation system is renewable-energy based, battery storage is generally considered to allow better supply reliability.

With the above considerations in mind, in this paper we use the term mini-grid to refer to local electricity generation from renewable and non-renewable sources and supply in both rural and peri-urban areas irrespective of size. According to our definition, the system may either be isolated from or connected to the main electricity grid in order to meet the diverse needs of local consumers.

4. ANALYSIS: EVIDENCE AND CASE STUDIES FROM THE LITERATURE

4.1 Mini-grid system design

4.1.1 Imported versus local designs and components

Based on the review of the UNIDO experience with mini-grid projects, Draeck and Kottasz (2017) remark that the technical design is essential, and the system design should focus not only on technical considerations but also on adapting to local community characteristics. Ulsrud et al. (2019) argued that flexibility of the system facilitated through technical and organisational solutions is essential for improvements in the quality of service. Smart meters and stand-by generators incorporated at the design stage can support flexible consumption patterns and supply-demand balancing. For a mini-hydro project in remote Sri Lanka "*the design of the renewable energy mini-grid system had to ensure that locally available resources were used*" (Draeck and Kottasz, 2017, p71). Similarly, in three Indian pilot projects, design modifications and local adjustments were made to foreign technologies. However, unforeseen technical challenges were faced at the project implementation and operation stages that required expert intervention and support (Draeck and Kottasz, 2017).

Drinkwaard et al. (2010) also report similar issues of technology mismatch for hydropower projects. For example, an imported turbine suitable for high water heads was a misfit for local low waterhead conditions, and the project developer had to develop turbines suitable for local conditions. The imported electrical control systems were incompatible with locally designed turbines and this required redesign of the control system itself. While this case offers new learning opportunities and the development of a niche low-cost technology, such component matching initiatives are not replicated everywhere and many projects continue to rely on imported designs and components.

A related issue was highlighted by Drinkwaard et al. (2011) regarding the availability of suitable technical design capacity locally. In one project they found that the funding agency asked the municipalities to submit the design of the mini-hydro plant for approval. "*Since local communities lack the knowledge to design a plant and municipalities rarely know where to find an engineer or organization capable of doing so, their proposals usually have no chance of approval. Those who do know where to get a design done often do not have sufficient financial resources to pay for it.*"

(p236). Although funding for contracting out the design solves the financial issue, "*the problem of finding an experienced person or organization to do the design' remains unresolved*" (Drinkwaard et al., 2011, p236).

4.1.2 Sizing, demand estimation and demand-side management

The literature discusses the importance of appropriate system sizing in mini-grid design, which faces significant challenges such as the lack of data for accurate demand estimation, long-standing assumptions regarding demand growth over time, and managing excess or lack of capacity to ensure sustainable operation (Fowlie, et al. 2018; Boait et al., 2015). Several issues related to appropriate system design are discussed in the literature, including using oversized generators, which affect financial viability through cost recovery but also create supply-demand mismatches and potential operational issues (Almeshqab and Ustun 2019, Schnitzer et al. 2014). Undersizing a project can lead to other problems, such as significant degradation of the system and wear and tear over time (Arnaiz et al 2018).

The lack of available survey data to generate reliable primary load profiles is often a challenge in the system design phase. Alternatives include using load estimates based on previous experience with similar installations (Blodgett et al., 2017), but these may have questionable generalisability. Additionally, the energy resource base of many locations is often unknown, so satellite database platforms are mostly relied upon. While solar and wind resource datasets are readily available from these sources, the same cannot be said for others, such as biomass and hydro resources, which must be locally estimated, surveyed, or produced. For hydro, the data is said to be unavailable because gauging the flow duration curves of rivers is proven to be technically challenging, expensive, and time-consuming (Arnaiz et al., 2018).

Generally, the more sophisticated a system is, the higher its initial investment. However, an expensive and complex system may not be appropriate for a rural resource-constrained area lacking skilled personnel. In this sense, the cost of such a system may outweigh the benefits (Shakya et al., 2017). A compromise is sometimes made in sizing solar PV mini-grids where the ability to pay is low relative to the cost of such systems (Valer et al. 2017), yet this can lead to a plant capacity that offers limited flexibility for load growth. Unanticipated increases in demand and load variations in a small system can be quite significant, especially as the arrival of electricity in a community can attract settlers from nearby locations and swell the local population quickly (Valer et al. 2017, Ulsrud et al., 2019). Another problem that can arise from survey information is that users sometimes give a lower estimate of their electricity use than they plan to use to economise on the cost of the initial connection and any future monthly payments. This can lead to inappropriate sizing of the connection and the generation plant (Winther 2012).

While assumptions are often made regarding the increase in electricity demand over time by mini-grid users, a number of studies report that this is not always the case, particularly in remote locations where plants may be operating at significantly lower loads than expected (Diaz et al. 2011, Katre et al. 2019, Schnitzer et al. 2014, Lopez-Gonzales et al. 2019, Ulsrud et al. 2019). In such cases, there is significant potential to incorporate new or increased demand growth from existing customers. However, other studies found that the limits of installed capacity were reached quickly. Ulsrud et al. (2019) found that a solar PV mini-grid in Senegal reached capacity within 15 months of its installation, as a result of which the reliance on diesel generators increased. Low or no electricity tariffs incentivised users to add new appliances, but the plant could not cope with the increase in demand, which led to more frequent power cuts. Shakya et al. (2019) also observed similar issues: the mini-grid with the most affordable tariff and non-metered connections incentivised the users to use electricity inefficiently, leading to a much higher average consumption level. Lopez-Gonzales et al. (2019) offer examples of both excess capacity and capacity constraints in their micro-hydro system case studies from Venezuela. While systems serving communities connected to road infrastructure have seen demand growth reach the installed capacity of the system due to new trade and commercial activities, systems serving remote communities have significant spare capacity even after a long period of operation. Valer et al. (2017) highlighted that there is demand diversity among rural consumers even within the same community, and although most consumers have a low consumption profile, some with high consumption comparable to urban users observed.

It is important to highlight that in a resource-constrained system, there is potential for cost-reliability trade-offs. Shakya et al. (2019) suggest that mini-grid users may prefer accepting reduced reliability over cost, and the system design could take advantage of such opportunities. Schnitzer et al (2014) highlight that estimating demand and demand growth for mini-grid systems can be achieved through benchmarking against nearby communities that have previously been electrified. Fowlie et al (2019) highlighted the case of Gram Power in India, who investigated consumer ability to pay, willingness to pay via monthly payments, daytime and nighttime loads prior to electrification, and then sized the system so as to allow for modular expansion over time as demand grew.

Hydro mini-grids face challenges in system design and sizing, as flow duration curves and volumes are essential for understanding seasonal variation and long-term water availability. Spot measures have led to inappropriate system designs, as seen in Malaysia and Cambodia (Murni et al, 2013). Dynamic load management is more beneficial for different types of mini-grids, such as solar PV mini-grids, which require battery storage for peak nighttime demand (Arnaiz et al, 2018: Van Gevelt et al, 2020). Demand management options include load-limiting fuses, mini circuit-breakers, load-shifting agreements, pre-payment meters, and remote communication and control systems (Schnitzer et al., 2014, Ulsrud et al., 2018, Azimoh et al., 2017, Shakya et al. 2019). In some cases, developers undertook energy efficiency interventions even prior to the commissioning of the project. These include training users on the efficient use of energy (Ferrer-Marti, 2012), converting existing inefficient lamps to efficient ones and providing solar water heating and LPG cookstoves to reduce the potential demand (Azimoh et al., 2017).

Shakya et al (2019) report a case in Bhutan, a mini-hydro system was prevented from overloading at peak times using a colour-coded grid health system. However, there can be issues with demand management systems, as load limiters were fitted to distribution lines rather than individual premises, removing groups of consumers from the network when overloaded Murni et al (2013). Modular system design and expansion can be an alternative solution to demand management. However, funding agencies are often unwilling to support incremental expansion and tariff income is generally considered too low to support it. The case of West Bengal Renewable Energy Development Agency (WBREDA) exemplifies organisational learning in electrification projects, with later installations having up to 110 kWp of PV, micro-wind, and biomass gasifiers Ulsrud et al (2011). Biomass gasifiers also offer advantages, serving community, commercial, and domestic daytime loads, while PV and storage systems can serve nighttime loads of predominantly lighting (Ulsrud et al, 2011).

Drinkwaard et al. (2011) emphasise the importance of appropriate network design to support demand growth and local economic development. Single-phase distribution networks for rural electrification can hinder the integration of productive loads into the grid, preventing the realisation of the economic development potentials of communities.

4.1.3 Smart systems

The use of tools such as real-time monitoring systems could help to address some of the challenges of demand management in mini-grids and allow for more efficient resource use (Katre et al., 2019). Schnitzer et al. (2014) remarked that it is not always easy for developers to decide the level of sophistication to go for. The developers they interviewed indicated that "*they regretted not having more sophisticated technology integrated into their installed microgrids, such as smart meters, automated payment collection technologies, or load controlling devices. Many of them did not have the option to install all the devices they would have liked, because they were either not available or too expensive at the time of installation*" (p84).

Fowlie et al. (2018), however found that a mini-grid company that pioneered smart mini-grids in India faced several issues, including that although the smart meters were capable of detecting theft, the local operators did not penalise theft in their localities, which in turn affected the financial viability of the mini-grids. "*Even the smartest technology can be ineffective if it requires human intervention and the incentives of the agents are not perfectly aligned with system success*" (Fowlie, et al., 2018, p13).

Ulsrud et al. (2019) recommended that "*The technical equipment not only must have advanced functions but also should be easy to use, robust, and durable. Equipment* *design must take into account that not everyone will handle equipment carefully and correctly*" (p100).

4.1.4 Influence of non-technical dimensions at the design stage

The disregard of non-technical issues at the design stage includes uncontrolled connections, disputes between different parties, and a breakdown of trust between the community and government structures. Such issues can lead to system overload, disconnection and the unsustainable operation of the system (Brent and Rogers 2010). Moreover, dissatisfied users are less likely to pay for the service.

In one example from Peru described by Lillo et al. (2015), the communities were not included in the system design decision-making process, as a result of which the system failed to fully meet their needs. For instance, a DC system was installed in one location but because of the difficulties in finding appropriate DC appliances for use in remote areas the users were unhappy. In another example, Shakya et al. (2019) observed that mini-grids without metering arrangements at the customer premises did not encourage users to save electricity and in some cases, users did not bother to switch the lights off during the day.

4.1.5 Construction, installation and equipment

The construction and plant development phase is also important for project sustainability. Ahlborg and Sjöstedt (2015) in the case of Tanzania and Butchers et al (2020) in the case of Nepal both found that delays in construction and poor construction durability affected the sustainability of hydro mini-grids.

Derks and Romijn (2019) reported issues both with a lack of coordination between consultant designers and construction contractors, and contractors' performance guarantees for the construction with mini-grid projects they examined in Indonesia. Local governments did not always hire professional services to consult with construction workers to save costs, leading to improper installations. (Derks and Romijn, 2019).

Valer et al. (2017) reported poor electrical installations in their case study of Brazil. "*In field observations, it is not uncommon to encounter poorly made installations, which offer risks to the users and to the system itself. In many communities it was noted that the electrical installations of consumer units did not have switches, circuit breakers, or any protection devices, which is a hazard, and inefficient energy use*" (Valer et al. 2017, p1039).

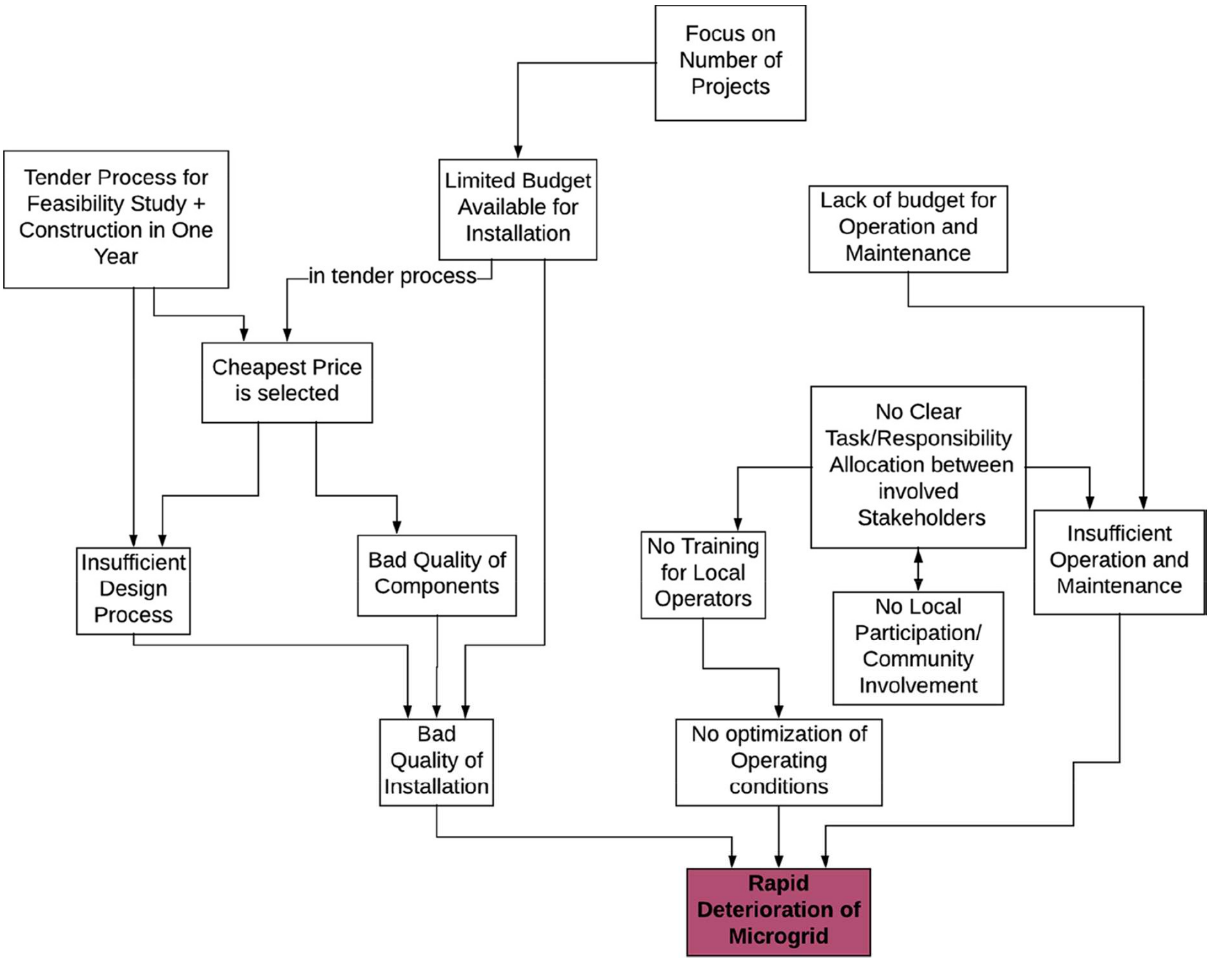
Arnaiz et al. (2018) found that, in the case of the Philippines, "*local expertise extends to a handful of NGOs dependent on international aid. There is no capability in private commercial industry to build schemes or manufacture machinery, forcing local developers to import equipment, hence increasing scheme cost*" (p56). The problem gets more complex with local content requirements (LCR) specified in some regulations. Derks and Romijn (2019) remarked that in Indonesia, the regulations require 30-70% local content in terms of components for mini-grids, but because the local manufacturing quality is not comparable to international standards, "*this results in poor-quality components. Alternatively, it leads to increased costs, when components are imported as disassembled parts and then assembled in Indonesia to comply with the LCR requirement*" (p64).

One element that has influenced technical sustainability is the quality of installations. Derks and Romijn (2019) reported that in Indonesia, there was an emphasis on increasing the number of installations while ignoring the quality of service. Poor quality installations have resulted from a focus on price, which resulted in low quality components and low-quality design. The focus on price results in an inadequate budget for operation and maintenance, which can in turn lead to the rapid deterioration of system quality.

Poor quality can also be attributed to weak regulations that, for instance, do not specify or incentivise the quality and frequency of maintenance or include sanctions for noncompliance. In the case of Indonesia, annual changes in central government policies also act as a disincentive for local governments to allocate sufficient budgets for operation and maintenance (see Figure 2). Wiemann et al. (2014) argued that the economic context in rural areas encourages a short-term view of compromising on quality which then tends to affect the long-term prospects and the lifetime of the projects.

The quality of and delivery of materials has been identified as an issue in some projects, for instance, equipment being delivered in open boxes (as opposed to original boxes), missing items at delivery and items failing within warranties (Draeck and Kottasz 2017). Similarly, Arnaiz et al (2018) report equipment lifetimes being reduced by insufficient maintenance regimes, as well as communities repairing civil works (such as de-silting bays) but unable to repair electronic failures in powerhouses themselves.

Fig. 2: Factors affecting the construction activities of mini-grids in Indonesia



Source: Derks and Romijn (2019).

Palit and Chaurey (2011) argue that quality standards for solar panels, batteries and other components approved by national technical standards committees have ensured success of solar PV programmes in various South Asian contexts. However, a lack of standardised performance-oriented technical specifications for biomass gasifiers has been identified as a factor affecting the quality and performance of biomass gasifiers in the Indian context.

Numminen and Lund (2019) found that poor quality inverters were a source of failure of AC systems and this affected the reliability of supply due to long repair times and the inability of vendors to deliver spare parts at remote locations. Quality problems were also reported for control electronics and smart meters. Similarly, the quality of batteries affects solar PV mini-grid operations. Ulsrud et al. (2011) noted that operators have complained about the quality of batteries in the Indian project they investigated. Yadoo & Cruickshank (2012) also found the use of lower-cost components in small hydro plants to be a contributing factor in component failure. Butchers et al (2020) reported that old electronic load controller designs were a cause of frequent failures in Nepalese projects, and more modern designs would mitigate this issue.

4.2 Operation and maintenance of mini-grids for sustainability

4.2.1 Availability

The availability indicator in various studies has been a topic of interest in the literature. The average duration of supply per day is often reported through surveys or plant records, with some studies focusing on plant availability. For example, in Nepal, Shakya et al. (2019) reported that the supply availability for solar, solar-wind, and solar-diesel mini-grids is less than 8 hours per day, while mini-hydro sites offer 23 hours per day. The capacity constraints of these plants and the variability of supply are major factors contributing to the limited duration of supply. In Western China, supply durations have declined from 12 hours to 3 hours over 5 years due to irregular supply schedules (Shyu, 2013). Planned maintenance is often factored into possible operating hours, indicating lower availability. Micro-hydro plants in Sulawesi and Sumatera were available on average for 63% of the expected time, while the highest was 96% (Purwanto and Afifah, 2016). Common faults in electro-mechanical equipment and problems with channels, forebays, and blockages were reported. Katre et al. (2019) found that in India, energy use remained low and much below the available capacity, with the daily average plant capacity use being 37% across the projects surveyed. The oldest site recorded a 48% capacity use, indicating that demand growth is not automatic. Public lighting performance was poor, with only 13% of sites meeting internal lighting targets due to malfunctions, poor quality components, and limited plant capacity. Lopez-Gonzalez et al. (2018) found that the average annual consumption of communities does not exceed 63% of the generating capacity, confirming the system design's ability to meet local community demand but also suggesting that spare capacity could be used to support future demand.

4.2.2 Reliability

Reliability of supply normally indicates the quality of service in terms of frequency and duration of interruptions. While users usually prefer an uninterrupted supply, evidence from the literature suggests that this hardly exists in the context of mini-grids, especially beyond the first few years of installation(Sakya et al., 2019; Ngowi et al., 2019; Purwanto and Afifah, 2016; Ribeiro et al., 2012; Shyu, 2013). In Nepal, micro-hydro and PV-battery mini-grids faced an average of 3 interruptions per week, while solar-wind and solar-diesel had more, ranging from 4 to 14 interruptions weekly (Sakya et al., 2019). Some micro-hydro projects experience 2 to 4 outages per month due to garbage blockages (Purwanto and Afifah, 2016). In some cases, outages were attributed to user behaviour and expectations, e.g. exceeding load limits in a Senegalese case (Ulsrud et al., 2019), while in other cases, such as in Venezuela, 76.1%

of end-users were satisfied with the low failure rate of hybrid microgrids (Lopez-Gonzales et al., 2018).

Maintenance practices and technical Issues also affect minigrid reliability. Proper maintenance plays a role in minimizing downtime, as evidenced by Husk Power Systems (HPS) mini-grids (Schnitzer et al., 2014; Almesqab and Ustun, 2019). They achieved this through a thorough risk evaluation of the services, covering the design, fuel supply and maintenance. Regular maintenance work by the company has been identified as the main factor behind this achievement (Almesqab and Ustun, 2019).

Conversely, in Haiti, diesel systems suffered from poor functionality, high losses, and theft, while in India, plants operated by DESI experienced higher downtime due to cable problems (Almesqab and Ustun, 2019). Exceptional performance with no interruptions in the second year of operation was reported in a solar and wind system, showing the impact of well-maintained and well-designed systems (Ribeiro et al., 2012).

Some cases highlight the unpredictable nature of supply, which hampers reliability. For instance, in China, the irregular supply was a common complaint from households (Shyu, 2013), while overloaded plants failed to provide reliable supply during specific hours in a case in Tanzania (Ngowi et al., 2019). Odarno et al (2017) reports a case from Tanzania where a mini-hydro plant needed to shut down during a low-flow period: water flows were low enough that the plant was only able to generate 40% of its nameplate capacity, and needed to shut down to prevent turbine damage due to cavitation issues from the reduced flow.

However, Ulsrud et al. (2019) reported that detailed information on outages is not always available. In one of the Senegalese villages, users reported several hours of outages a number of times per week but were unable to provide more precise detail. These outages were apparently due to limited battery capacity and battery failure resulting from excess demand. “One reason for such power outages was the overloading of appliances by the customers. If they exceeded the power limit for the Block they had subscribed to, the smart meter would automatically switch the electricity supply off for this connection. The electricity would come back on automatically” (Ulsrud et al. 2019, p79). In a comparable study, Murni et al. (2013) suggested that where the load limit is more generous and the system has excess capacity, users could afford to use more appliances without causing system outages or overloading.

Reliability of supply has also been compromised due to natural calamities or extreme events. For instance, Sharma and Palit (2020) reported damage to an inverter due to a lightning strike at a site in India while Lopez-Fernandez et al. (2019) highlighted supply interruptions of hydro plants during dry seasons and distribution system failures due to lightning.

Schnitzer et al. (2014) highlight the importance of a reliable supply for making a viable mini-grid business. When the service is reliable, users are willing to pay for the service but if the tariffs are not high enough, the operator is unable to pay for fuels and undertake maintenance. The service becomes erratic and the mini-grid ceases to function. A delicate balancing act is therefore required.

4.2.3 Power quality

Lillo et al. (2015) in their study of mini-grids in Peru found that the quality of service varies by technology and the system type (individual or mini-grid). The service quality was better for mini-hydro systems, due to the ease of operations and maintenance tasks in centralised systems compared to other technologies, and the failure rate was higher in individual systems compared to mini-grids, attributed to a lack of user experience and training. Ulsrud et al. (2019) found that the quality of service is closely related to the flexibility offered by the system through technological and organisational solutions. Stand-by generators that could be brought in when demand exceeded capacity improved availability and reduced outages.

Arnaiz et al. (2018) remarked that the distance to the repair shop and lack of availability of replacement parts affected the quality of service. Azimoh et al. (2017) noted that the "*a majority of the representatives from households, businesses and public institutions stated that they experience fluctuation in the electricity supply, which has damaged both household and business appliances. Fluctuations in the electricity supply are also caused by the issues of the synchronization of the generators with the PV system, resulting in manual operation and unscheduled interruption during the process*." (p226).

4.2.4. Adequacy

The adequacy of power supply from the mini-grids has been commented on by several authors.

Lopez-Gonzales et al. (2018) found in their case study of hybrid micro-grids in Venezuela that the weighted average consumption per house was 89% of the value considered at the design stage, confirming that the technical design of the hybrid mini-grid was consistent with the real consumption of rural communities. They also found that consumption in micro-hydro communities was 40% higher than rural communities connected to the grid, meaning the plant was able to supply the demand of the community and improve their quality of life.

However, Shyu (2013) found that most users (more than 70% of survey participants) expressed frustration over the inability of the solar PV station to meet the demand, which resulted from insufficient capacity. The supply duration was short and unpredictable.

Similarly, for a Tanzanian mini-hydro plant, Ngowi et al. (2019) reported that the installed plant capacity was not adequate to meet the peak demand.

Arnaiz et al. (2018) also found that users have reported concerns about adequate power supply from the mini-hydro plants they surveyed as demand increases over time. Derating (reduction in generation capacity) of plants due to aging made it difficult for plants to cope with demand growth.

4.2.5 Maintenance

Maintenance requirements, and the challenges caused by insufficient maintenance, have also been commented on in the literature:

Butchers et al. (2020) emphasise the importance of regular maintenance on system reliability and that the plant operators must carry out a minimum number of preventive maintenance activities to ensure proper functioning of the system. However, of the 24 mini-hydro plants they studied in Nepal, only one had a maintenance schedule of which the activity was mostly corrective in nature.

Numminen and Lund (2019) identified technical problems with inverters affecting the reliability of supply, and further issues from long repair times and the refusal of repair companies to service remote areas. Azimoh et al (2017) noted that the availability of spare parts for imported mini-grid components was a challenge. Perhaps for this reason, Mainali & Silveira (2015) concluded that low-maintenance technologies and those with well-defined supply chains and technical expertise availability are preferable in mini-grid contexts.

Valer et al (2017) noted that reductions in failure rates through better servicing leads to overall cost savings, and increased numbers of components, the use of several manufacturers for components and challenges in finding expertise impact the provision of better services.

Ulsrud et al. (2011) noted that maintenance contracting does not always work, particularly in the case of short-term contracts which can lead to reduced contractor investment in the project, and broken contracts to take on other work or move to other areas. WBREDA, the implementing agency, previously contracted local organisations for limited periods of time, from six months to a year, and instead began developing longer-term contracts of up to 10 years, that covered both operations and comprehensive maintenance of plants, to incentivise better levels of service from contractors.

4.2.6 Other considerations and challenges

Writing about mini grids in Senegal, Ulsrud et al. (2019) highlighted the importance of flexibility as an aspect of electricity service. "*The Enersa mini-grids were characterized by high flexibility for the users, much more so than other solar micro-and mini-grids. There was flexibility in terms of the various subscriptions, and flexibility in terms of the timing of consumption. Electricity could be used at any time, and the amount consumed could be varied from day to day. The possibility of receiving additional power and thus adding larger loads also provided flexibility. This flexibility was facilitated by technical and organisational solutions, such as the smart meters, which facilitated the Block system, the upfront payments, the company's willingness to* *accept breaks in supply, and the use of a diesel generator. The generator could be switched on when there was high demand for power. The degree of flexibility was further influenced by the power capacity of each power plant relative to the local demand for electricity*" (Ulsrud et al., 2019, p80).

Draeck and Kottasz (2017) reported the synchronisation issue of a solar PV system with the diesel generator set in a project in the Gambia. The voltage fluctuation of the gen-set was the main issue and an automatic voltage regulator was required to maintain the voltage excursion within limits. There were initial issues with batteries as well at the same site. Batteries cracked during off-load and had to be replaced. Additional air-conditioning arrangements had to be made to ensure appropriate operating temperatures of the batteries. Diaz et al. (2011) noted that "*if load consumption is low, whatever the reason, batteries prone to overcharge. Then, the PV array generation is regulated or even interrupted to protect them*" (p2514).

For a hybrid system involving a small hydropower plant and a bio-gasifier in Sri Lanka, Draeck and Kottasz (2017) found that the bio-gasifier required sophisticated inputs and that the locally collected feedstock did not often meet the technical requirements. Inappropriate operation of the system led to its break-down. The remote location also required that local operators from the community had to be trained to maintain the plant alongside ensuring the availability of expert advice and support on-demand from nearby towns. This case also highlighted the issue of technology adaptation to local environments. The technology supplier may not fully realise the local challenges and local stakeholders need time to undertake numerous trials and experiments to develop a full appreciation of the technology. Expert intervention and sufficient time are required to ensure success of adaptation of innovative technologies.

4.3 Assessing the technical sustainability of mini-grids

4.3.1 Existing approaches and frameworks

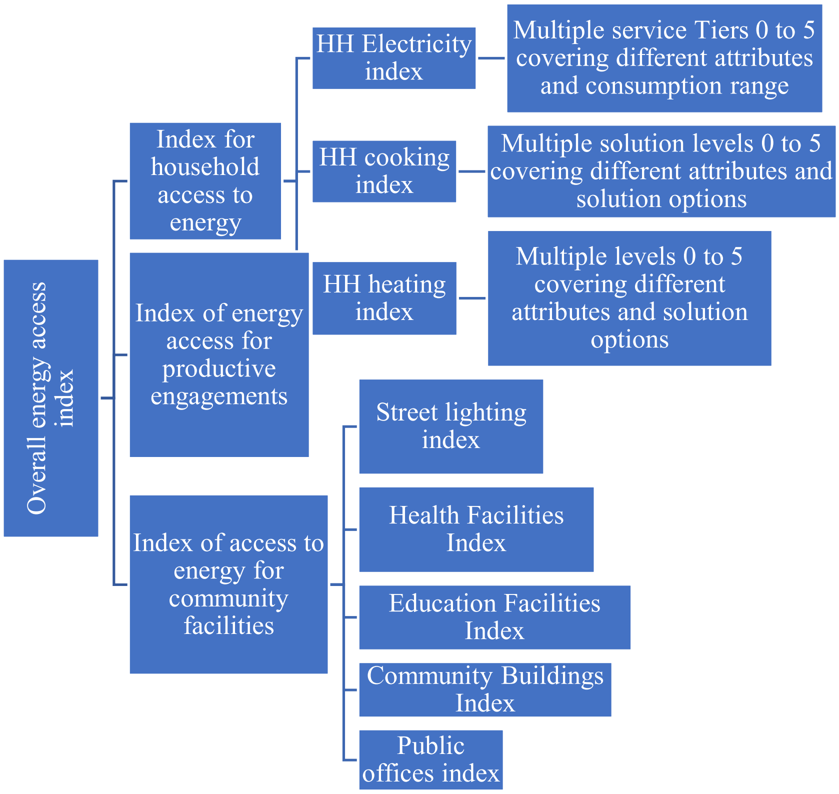
Ilskog (2008) and Ilskog and Kjellstrom (2008) present an early attempt at sustainability assessment of rural electrification where they defined technical sustainability as follows: "*the technical sustainability is facilitated if the technical infrastructure locally available meets the requirements of the technology installed, if the technology used can provide the service needed and if favourable technical performance leads to low costs for the services*" (Ilskog and Kjellstrom, 2008, p2667). This definition places emphasis on maintaining the service during the entire project lifetime but appears to ignore the issue of continuing the service beyond the project life. It also pays little attention to clean and renewable energy supply. Accordingly, a diesel power plant will be a sustainable option if it is maintained well, meets all national standards and manages client relations well. This definition requires qualifiers to ensure technical sustainability.

According to Bhattacharyya (2012) and Bhattacharyya et al. (2014), technical sustainability of an energy service is achieved when the system can meet the present and future needs reliably, efficiently and by using clean and renewable sources. While this definition is better aligned with the United Nations SDGs, Katre and Tozzi (2018) point out the weakness in terms of measurability and suitability to case applications. Rahmann et al. (2016) on the other hand place the emphasis on currently available technologies and claim that technical sustainability must ensure that the implementation of the project is possible with the "*current available technologies without compromising the operation of critical elements*" (p1163:4). This definition neither considers the needs of the future generations nor pays attention to cleaner sources of supply.

Mainali and Silveira (2015) have designed and applied a multi-dimensional Energy Technology Sustainability Index consisting of five dimensions: technical, economic, social, environmental and institutional. The technical dimension measures the reliability and efficiency of the technology using three indicators: energy availability, system conversion efficiency and reliability. The application of the index to different technologies was done for three different years – 2005, 2010 and 2015 to capture technological advancements and changes in the market conditions. They also assess the uncertainty of economic data using three cost scenarios (minimum, probable and maximum). However, the technical dimension does not focus on the renewability of resources and the ability of the system to meet the present and future needs of the users.

Since ESMAP (2015) proposed the multi-tier framework (MTF) for measuring energy access, researchers have adopted the idea for analysing technical sustainability. The MTF disaggregates overall energy access into household energy access, access to productive use of energy and access to energy for community facilities. Each component is assessed with a specified set of sub-components where each sub-component considers different socio-economic tiers and a range of attributes to measure energy access (see Fig. 3). For example, seven attributes are considered for household electricity supply, namely capacity, duration of supply, reliability, quality, affordability, legality and health and safety. Similarly, different attributes are used for electricity consumption, cooking energy supply and heating services. Although the purpose of the MTF is to assess energy access, the attributes and socio-economic contexts are relevant for sustainability analysis.

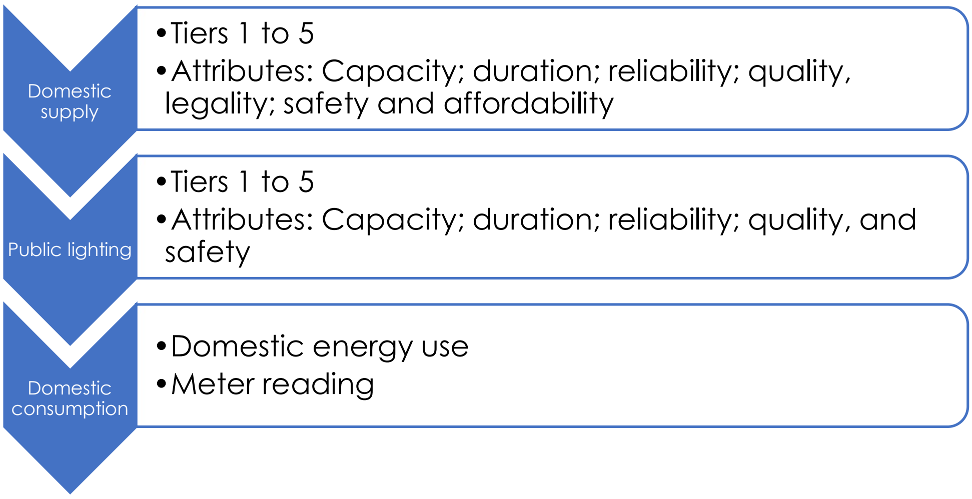
Fig. 3: Multi-tier framework for energy access measurement



Source: based on ESMAP (2015)

Katre and Tozzi (2018) have used the MTF principles for their technical sustainability assessment of decentralised energy systems. The technical dimension is disaggregated into three components (see Fig. 4): domestic supply, street lighting and domestic consumption. For each component, five tiers of service and seven attributes as suggested in the MTF for household electricity supply are considered.

Fig. 4: Technical sustainability framework used by Katre and Tozzi (2018).



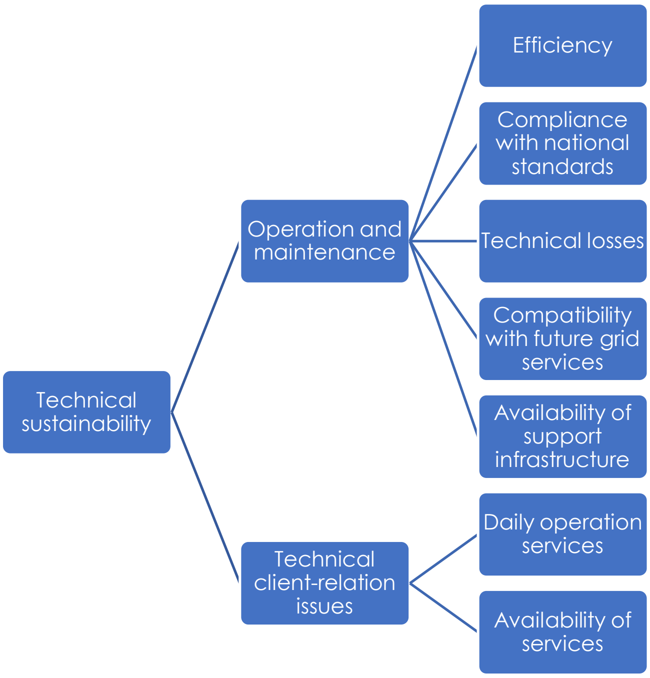
Source: Katre and Tozzi (2018)

While this approach allows a detailed assessment of services considering different uses and consumption patterns, extensive data requirements makes this approach less user-friendly. Groh et al. (2016) argue that the MTF is confusing as it combines supply with energy poverty and the indices have some redundancy and ambiguity. They also argue that measurements using the MTF are sensitive to "*parameter changes, the application of different algorithms and data availability*" (p30). We also note that there is no specific attention to assess the ability of the system to meet current and future needs, which reduces its appeal for measuring technical sustainability of mini-grid systems.

4.3.2 Indicators for technical sustainability

Ilskog (2008) and Ilskog and Kjellstrom (2008) used seven indicators to assess technical sustainability grouped under two themes: operation and maintenance and technical client-relation issues (see Fig. 5).

Fig. 5: Technical indicators used by Ilskog (2008)



Source: Ilskog (2008).

Bhattacharyya (2012) and Bhattacharyya et al. (2014) have used the following seven indicators to measure technical sustainability of a service:

1. Ability to meet present and future domestic needs;
2. Ability to meet present and future productive needs;
3. Reliability of supply;
4. Reliance on clean energy sources;
5. Technical efficiency
6. Reliance on local resources;
7. Availability of support services.

However, the indicators were not elaborated, and these studies offered a high-level application that limits its applicability to mini-grid projects.

The MTF-based assessments use a differentiated level of service attributes for different service tiers (see Table 5). It can be noticed that the prescriptive nature of various attributes (such as capacity or usage, availability or reliability) and the subjectivity of the chosen values make the framework less aligned with the concept of sustainability. For example, there is a presumption that higher tiers of service will offer a better quality of life, and this sets the aspirational goal of the population at the highest tier of service (Tier 5). However, as the framework is silent about the nature of energy resources, the higher tier of service and the representative values used for them may be in direct conflict with the environmental dimension of sustainability.. These aspects have not received adequate attention in the applications of MTF for sustainability analysis of energy services such as those reported by Katre and Tozzi (2018) or Katre et al. (2019).

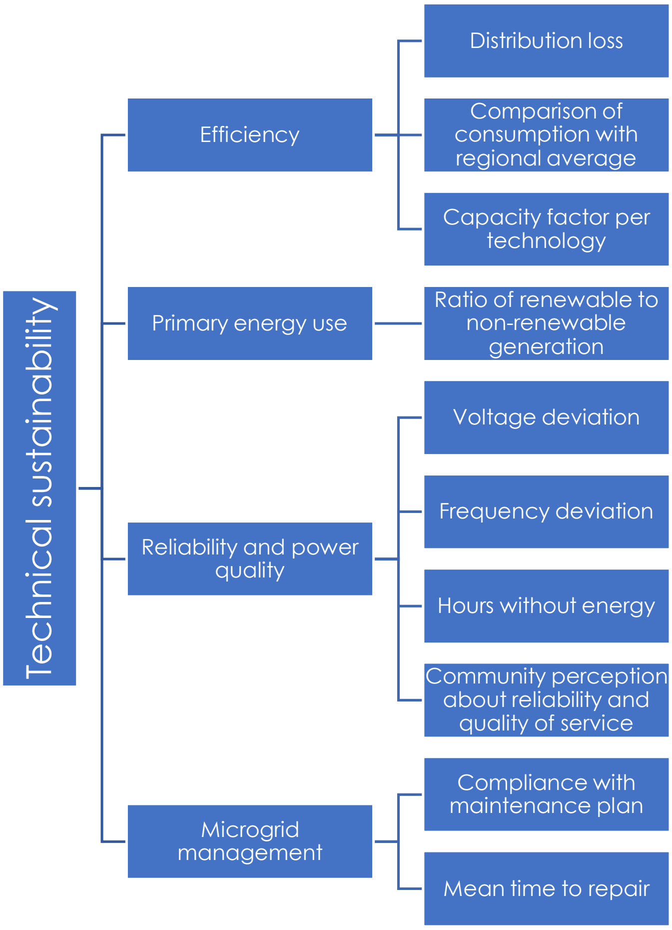
Table 5: Indicators and attributes used in the Multi-Tier Framework for Household Electricity Access

Attributes	Units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Peak capacity	Watts		Min 3	Min 50	Min 200	Min 800	Min 2000
	Daily Watt-hours		Min 12	Min 200	Min 1000	Min 3400	Min 8200
	OR services		Lighting of 1000 lmhr/day	Electrical lighting, air circulation, television and phone charging are possible			
Availability	Hours per day		Min 4 hours	Min 4 hours	Min 8 hours	Min 16 hours	Min 23 hours
	Hours per evening		Min 2 hours	Min 2 hours	Min 3 hours	Min 4 hours	Min 4 hours
Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hours
Quality						Voltage problems do not affect the use of desired appliances	
Affordability					Cost of a standard package of 365 kWh/year <5% of household income		
Legality						Bill is paid to the utility, pre-paid card sellers or authorised representative	
Health and safety						Absence of past accidents and perception of high risk in the future	

Source: ESMAP (2015).

Rahmann et al. (2016) assessed the technical sustainability of mini-grids from four perspectives: efficiency, implying the proper use of energy by the users; nature of primary energy use; reliability and power quality; and microgrid management. Figure 6 presents the indicators used to measure these perspectives. Note that indicators used here are not always conventional, and some may be difficult to relate to. For example, the efficiency dimension has considered distribution losses, which may not be a major issue for a mini-grid and may not be easy to estimate. The purpose of comparing the consumption against the regional average is not evident and it is unclear how this relates to resource use efficiency. The primary energy use dimension deals with renewable energy share in the generation mix and could have been termed more appropriately. In terms of reliability and quality, the data on frequency and voltage deviations at the local level are unlikely to be available. More importantly, no consideration is given to issues like component failure, supply inadequacy, and ability of the system to meet future needs.

Fig. 6: Indicators used for technical sustainability in the Composite Sustainability Index proposed by Rahmann et al. (2016)



Source: Rahmann et al. (2016)

It is clear from the above review that there is no consensus regarding the indicator-based analysis of technical sustainability of mini-grids or energy access projects. Studies have not always considered the data requirements for such evaluations and data limitations reduce the replicability of the evaluation schemes as well.

5.0 DISCUSSIONS AND FRAMEWORK FOR TECHNICAL SUSTAINABILITY

5.1 Reflection on literature review

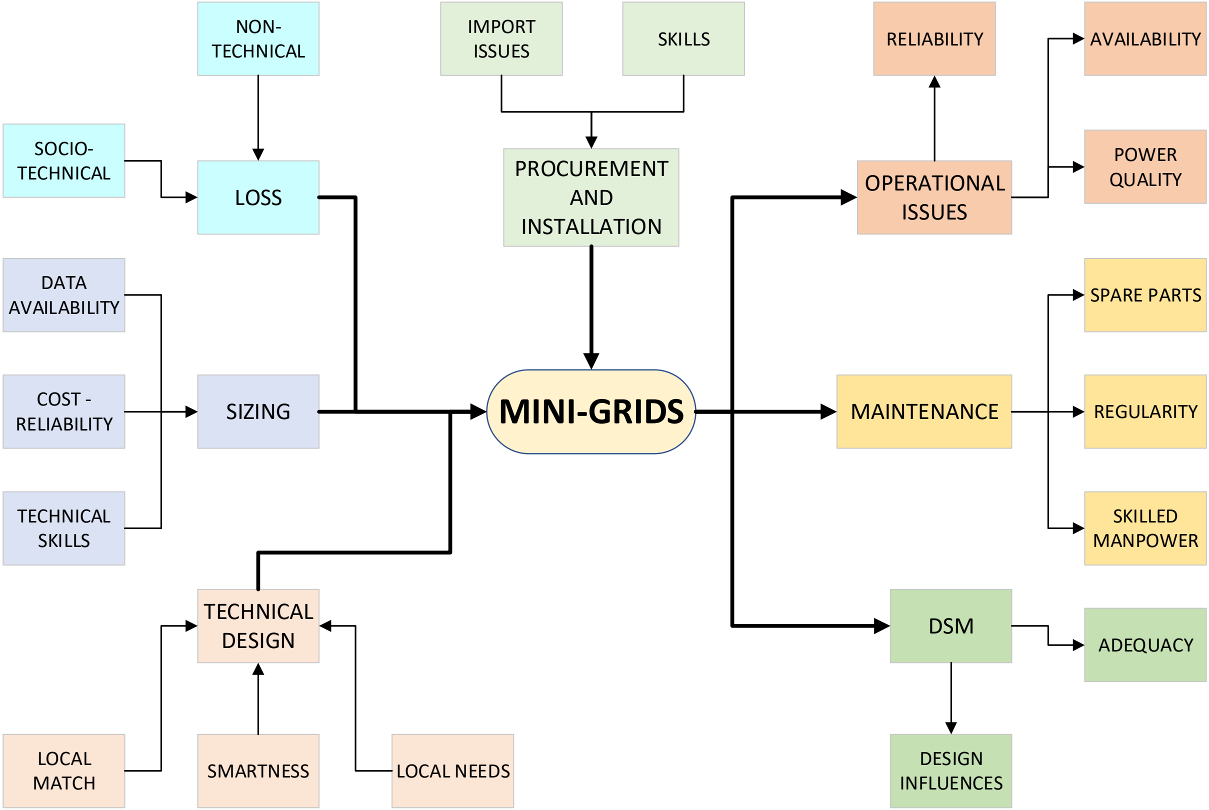
Several observations can be made regarding the technical sustainability of mini-grids:

1) Ensuring adequate, reliable and cost-effective renewable energy-driven electricity supply in the long-term through mini-grids requires careful planning, design, development and operation of the plants. Strong path dependence is introduced through technology selection and design choices made ex-ante at the time of project identification, site selection and project design. These choices influence the long-term prospects of a plant and unless these activities are appropriately carried out, the technical performance of the plant will be compromised, and the technical sustainability of the project affected.
2) Being technical in nature, the system design choices made at the project preparation stage are influenced by expert judgements and trade-offs involving non-technical considerations (such as initial investment cost). The literature offers various examples questioning the appropriateness of the resulting solution to the local conditions, including the following:
    - oversized micro-hydro projects that remained underutilised for most of the project life (e.g. Almeshqab and Ustun (2019), Schnitzer et al. (2014), Butchers et al (2020)),
    - inadequately sized systems that failed to cater to demand growth and became a source of user dissatisfaction (e.g. Arnaiz et al. (2018), Murni et al. (2013), Ulsrud et al. (2019));
    - poorly chosen smart metering systems that hindered the operational performance of the system instead of enhancing it (e.g. Fowlie, et al., 2018; Shakya et al. 2019).
3) Inappropriate technology choice can arise due to several factors such as lack of accurate data and information and lack of user participation at the design stage. Use of proxies for local demand, demand growth and resource availability (such as water flow for hydropower) has been widely reported as a challenge. In addition, poor engagement with local stakeholders also leads to user dissatisfaction due to systems not meeting their needs (Lillo et al., 2015).
4) Governments and donors can sometimes influence technology selection for mini grids. For example, in Tanzania a solar PV mini-grid was developed in a village 4 km away from the existing medium voltage line of the central grid system, where extending the line would have been a better option (Odarno et al, 2017).
5) A supportive regulatory environment and aligned policies can foster quality control, set standards, and encourage responsible practices in system design. This aids in overcoming challenges like poor quality of installations, weak regulations, and cost reduction focus at the expense of system integrity and safety.

6) The reliability of mini-grid systems has been affected by the quality of installations, particularly civil works for hydropower stations, and the quality of materials supplied (either missing items or items failing within the warranty period). Poor quality of installations has also been associated with poor skills of the workforce but the focus on cost reduction and the prevalence of weak regulations are also highlighted as contributing factors.
7) The trade-offs between technology options and cost saving options often play an important role in the availability of plants and reliable performance. Preference for cost minimisation can lead to limited capacity, sacrifice of components (such as batteries in a PV system) or compromises that can have health and safety implications.
8) The quality of equipment supply and availability of skilled manpower affects project in the implementation stage. Delays in the deliveries of imported components and supplies as well as poor quality and incomplete supplies have been reported. The appropriateness of imported technologies for the local conditions has also been indicated as an issue affecting the project implementation and long-term performance of mini-grid projects.

The relationship between the different elements discussed above is captured in Fig. 8.

Figure 8: Elements of mini-grid technical sustainability



Source: Author's own work

Long-term reliable operation of mini-grids depends on ex-ante design and project implementation factors as well as post-implementation operation, maintenance and planned expansion activities. Adequacy of a mini-grid in terms of its ability to meet the needs of the users is closely related to plant sizing decisions, attrition or loss of capacity over time due to wear and tear (e.g. PV derating per year) as well as demand growth that happens post installation. Excess capacity at the initial stage acts as an insurance for future demand growth, but the high initial cost can make the project less attractive to the users and project developers. Low reserve margin at the project development stage on the other hand introduces the risk of poor reliability of supply as the demand grows or capacity derates. For systems with modular designs, like some PV systems, capacity can be expanded as de-rating occurs and new modules added, however this incurs further costs for developers and operators. The delicate balance is not easy to strike and flexibility options such as demand side management or user expectation management play an important role here.

The operating performance of mini-grids decides the availability of mini-grids as well as its service quality in terms of reliability and power quality. The availability of skilled manpower in remote rural locations remains a major challenge and the reliance on make-shift operators with limited technical training exposes the technical system to operating risks. In addition, the absence of scheduled maintenance due to cost considerations and lack of maintenance capacity at the local level make the system vulnerable to malfunctioning and reduces the reliability of supply. Ultimately, consumer satisfaction is compromised, which affects cost recovery and makes a project economically vulnerable.

The ability to expand the system thus becomes hostage to the financial strength of the mini-grid. Although the design considerations may offer expansion opportunities (e.g. the modular design of PV systems), the ability to realise these options ultimately hinges on the financial strength of individual projects. Given that many projects hardly generate any financial surplus and given the lack of support for funding such expansions from other sources, the long-term technical sustainability of mini-grids remains a challenge.

5.2 Framework for technical sustainability

This review of technical sustainability indicates that while a wide range of indicators have been considered, several issues remain. First, the ability of the indicators to measure the desired effect is not always clear. For example, the comparison of consumption with the regional average used in Rahmann et al. (2016) or the prescriptive thresholds for different tiers used in the MTF framework are difficult to justify. Second, data availability limits the application of very data intensive frameworks. A framework that can provide a reasonable picture of the technical sustainability need not be too complex or impose too much demand on data. Third, the framework must consider long-term perspectives and respect renewability and future demand growth. Fourth, the framework should be easy to use and interpret and should allow comparison across different mini-grids at a specific time and at different points in time.

Based on the above, a simple index is suggested here in Fig. 9. Five weighted indicators are used in the framework, namely adequacy, availability, reliability, renewability and quality.

Fig 9: Technical sustainability framework

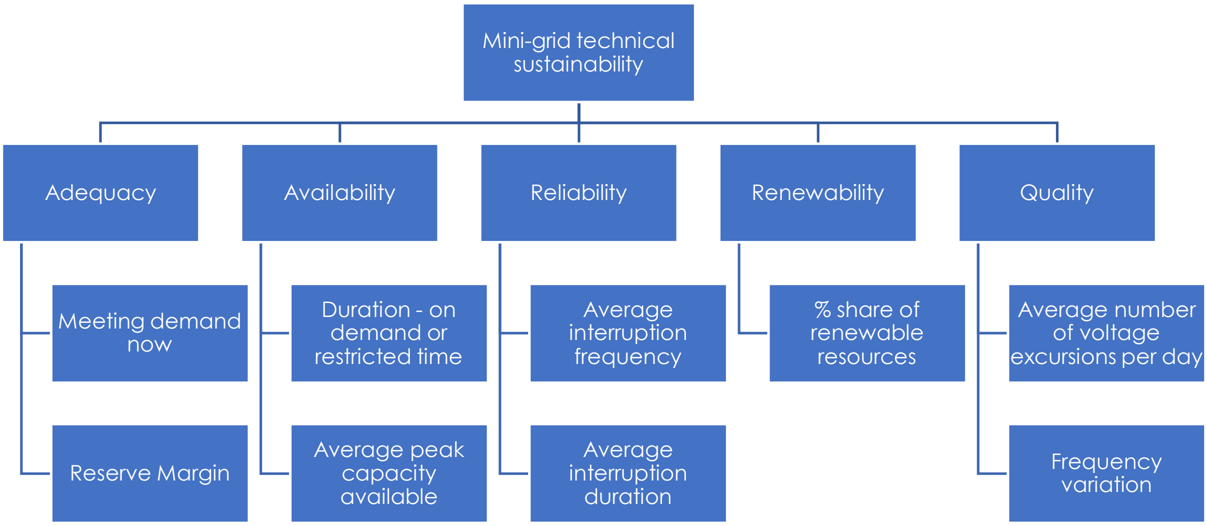


Table 6: Scoring methodology

Measures	Indicators	Weight	Base (=1)	Standard (=3)	High (=5)
Adequacy	Ability to meet demand now	60%	Barely meeting the demand	Meeting most of the time	Always meeting the demand
	Reserve margin	40%	0-5% margin	10-20% margin	25% margin
Availability	Duration	50%	Only for limited or restricted time	Available during specified hours	On demand (anytime)
	Peak capacity	50%	Basic lighting and phone charging	Supply to support commonly used appliances	Supply to support aspirational needs
Reliability	Average number of interruptions	40%	<1 per week	<1 per month	<2 per year

	Average duration of interruption	60%	<10 % of time	<5% of the time	<1% of time
Renewability	% of renewable supply	100%	<50%	50-80%	80-100%
Quality	Average number of voltage excursions	50%	<10 per day	<5 per day	<1 per day
	Frequency variations	50%	+/- 2Hz	+/- 1 Hz	+/- 0.5 Hz

Adequacy in this framework addresses how well the mini-grid meets the demand of the users. High scores will meet the demand almost always (allowing for occasional, unforeseen failures), while low scores will struggle to meet the desired demand. The second metric, reserve margin, addresses the resilience and expandability of the mini-grid: low scores will have very little reserve margin, while high scores will have a margin of up to a quarter over the current demand level. Availability addresses the duration of supply and ability to meet peak capacity: high scores will have near-constant supply availability, and the ability to meet aspirational demands (such as productive use), while low scores will only be able to support basic needs (such as lighting), and only intermittently.

Reliability in this framework assesses the ability of the mini-grid to deliver reliable electricity supply, regardless of the level of that supply. The metric for this is interruptions to supply: high scores will have very few interruptions, with a short duration each time, while low scores will have frequent, longer interruptions. Renewability is a single-metric measure of how much of the installed capacity of the mini-grid is from renewable sources, contributing to sustainability goals. High scores will have over 80% of the installed capacity from renewable energy sources, while the threshold for low scores is set at less than 50% renewable capacity. Finally, Quality addresses the quality of electricity supply from the mini-grid in terms of voltage and frequency. Mini-grids with high numbers of voltage excursions from the nominal level will score poorly, as will mini-grids with more variable frequencies of supply, while mini-grids with consistent voltages and frequencies will score well.

These factors combined present a set of aspirational features for well-performing mini-grids, backed by a mixture of measurable quantitative and qualitative variables. A well-performing mini-grid will provide stable, reliable connections, on-demand for the users, which are able to meet the requirements of those connected with capacity to spare for aspirational needs. Conversely, poorly-performing mini-grids will provide a minimal service level, with frequent outages and poor-quality electricity during operational hours, with limited capacity for expanding connections or connecting aspirational loads.

The final score for a mini-grid in this framework will be out of 25, but for ease of appreciation, this should be multiplied by 4 to be a score out of 100. Mini-grids scoring 20 will be considered as poorly sustainable, those between 20 and 60 are moderately sustainable and those with scores above 60 will be considered as sustainable.

6. CONCLUSION

This working paper has provided a review from the literature of the technical sustainability of global mini-grid projects, and the dimensions associated with technical sustainability. It has, through an extensive literature search and qualitative literature analysis, identified the key concepts relating to technical sustainability as defined in the literature, and grouped these concepts into categories of features that mini-grids share, and that can be assessed and measured on the ground to determine the technical sustainability of a project.

Mini-grid technical sustainability emerges through two distinct phases: first in the design phase, where the mini-grid system is being determined and significant path-dependency can be found, and secondly in the operations and maintenance phase, where the system is operational and needs to be maintained in order to realise its potential. In the design phase, factors such as the quality of installation, the sizing and component matching of the system, the appropriateness of the technology and the availability of locally-manufactured components and expertise to install them all contribute to the potential future technical sustainability of the system. In the operational phase, maintaining the supply of the mini-grid is critical to the technical sustainability of the system, which includes maintaining the availability of supply, the adequacy of supply, the reliability of supply and the quality of supply. These factors all feed into consumer satisfaction, which is maintained if the system can keep up with both the demands of the users (both domestic and commercial) at the time of installation, and the aspirational demands of users both current and potential into the future.

However, this review has also assessed the current frameworks available in the literature for determining the technical sustainability of mini-grids, and identified a number of critical gaps in their assessment criterion, including the lack of assessment of the renewability of energy used in the mini-grid, and the lack of assessment of the potential of mini-grids to supply future, aspirational energy needs for consumers. This has led to the proposal of a new assessment framework for the technical sustainability of mini-grids, focusing on five primary indicators and nine sub-indicators, each with an assigned weighting, that will be simple to use both in-the-field and at the design stage. This assessment framework captures the adequacy of supply, the availability of supply, the reliability of supply, the renewability of energy sources, and the quality of electricity provided, in order to determine the ability of a mini-grid to meet the present and future needs of connected consumers.

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