IGC

State Fragility initiative

POLICY TOOLKIT

Data and technology: Challenges and opportunities for solar mini grids in fragile contexts

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There are a range of emerging data and technological innovations that can support better energy planning, help identify high potential sites for locating mini gids, enable remote monitoring of mini grid functionality and end-users' energy consumption, and ease end-users' ability to pay for electricity services. This toolkit outlines the challenges and opportunities these innovations present for fragile and conflict-affected settings.

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In this paper

This paper is intended to help equip policymakers in fragile settings with an understanding of the data and technological innovations that support better energy planning, help identify high potential sites for locating mini grids, enable remote monitoring of mini grid functionality and end-users' energy consumption, and ease end-users' ability to pay for electricity services. It also looks at the various challenges and opportunities associated with using data and technology in planning and operating solar mini grids in fragile contexts. To scale up solar mini grids in fragile settings, collaborative efforts are required from a range of stakeholders, including donors, development finance institutions, philanthropic entities, private investors (both domestic and international), and energy project developers. Consequently, this paper outlines important lessons for other key stakeholders too.

The technological scope of this toolkit focuses on solar mini grids. However, these are only a part of a necessary wider, integrated energy strategy that should include additional off-grid and grid-based technologies. Where relevant, we draw lessons from other technologies, such as solar home systems.

List of abbreviations

Abbreviation	Meaning
ACLED	Armed Conflict Location and Event
AI	Artificial Intelligence
AMDA	Africa Mini Grid Developers Association
DRC	Democratic Republic of Congo
E-Guide	Electricity Growth and Use in Developing Countries
EU JRC	European Union Joint Research Centre
FAO	Food and Agriculture Organisation
FCS	Fragile and Conflict-affected Settings
HOMER	Hybrid Optimisation Model for Multiple Energy Resources
IEA	International Energy Agency
IoT	Internet of Things
IRENA	International Renewable Energy Agency
kWh	Kilo-watt hour
MTF	Multi-Tier Framework
NGO	Non-government organisation
O&M	Operations and Management
PV	Photovoltaic
REA	Rural Electrification Agency
SDG	Sustainable Development Goal
SHS	Solar Home Systems
SME	Small- and Medium-sized Enterprises
UNSD	United Nations Statistics Division
WHO	World Health Organisation
Wp	Watt peak

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Executive summary

There is a critical need to address energy poverty in fragile and conflict-affected states (FCS), where more than a billion people live, and where more than two-thirds of the world's poor will reside by 2030.[1] With an average of only 58% of the population in these regions having access to electricity (with access in rural areas being significantly lower than in urban areas), the importance of scaling up energy access to achieve Sustainable Development Goal (SDG) 7 is undeniable. Achieving this goal requires innovative, cost-effective approaches, data-driven solutions, and new ways of working, especially in areas where traditional centralised energy infrastructure is not viable. Solar mini grids offer a viable alternative as they can operate in a decentralised manner independent of the main grid, be deployed quickly, and reduce reliance on diesel generators that are often expensive, difficult to maintain, and suffer from unreliable fuel supply chains in FCS.

One of the key challenges in expanding electricity access is the limited availability and accessibility of quality data in many low-income countries, especially FCS. Both the World Bank and the International Energy Agency (IEA) measure energy access in a binary manner, i.e., either a household is connected, or it is not. Essential data on electricity consumption trends, affordability and reliability of electricity supply, and its contribution to the quality of life have not traditionally been tracked, although these are crucial to understanding the existing gaps for better targeting.

The lack of granular data hinders accurate identification of unelectrified communities and their energy needs and impedes energy planning. On-the-ground surveys to collect this data are prohibitively expensive and can be too dangerous to undertake in situations of fragility and conflict. New geospatial technologies have emerged as promising solutions to fill this gap, enabling national planners and mini grid developers to optimise electrification strategies.

Geospatial technologies can pool datasets collected from a range of sources, including:

- Open-source databases, e.g., energydata.info and OpenStreetMap
- Proprietary databases for more granular remote sensing and satellite imagery (e.g., Maxar's building footprint)
- International organisations, e.g., World Bank, IEA, and the International Renewable Energy Agency (IRENA)
- National and sub-national government departments, e.g., census bureau, statistics department, and ministries of electricity and energy.

They integrate data on both energy demand and supply, as well as location-specific information – data often covers demographics (e.g., population number and distribution, poverty rates, urbanisation rates), social and productive uses of energy (e.g., education and health facilities, agricultural crops, location of markets and mines), energy resources (solar

1 This toolkit uses the World Bank's list of countries classified as facing situations of fragility and conflict. The World Banks updates this list annually, and the countries on the latest list are shown in Figure 1.

irradiance, hydro resources, wind speed), and infrastructure (roads, electricity transmission and distribution lines).

Geospatial tools can reduce costs, increase transparency, and can be used to identify high-potential sites for solar mini grids. However, least-cost electrification plans in FCS must also take into account aspects of fragility and conflict to ensure that proposed plans are viable in these settings. For example, WAYA Energy's tool incorporates data from ACLED on frequency and intensity of conflict incidents in specific areas.

Another major challenge for FCS is the complexity of implementing smart and digitalised mini grids. These grids, equipped with advanced hardware like smart meters and inverters, and supported by software solutions, can greatly optimise energy generation and storage, particularly with intermittent solar power. They can also significantly improve monitoring and control of mini grids, including remotely, which is critical for FCS where travel may be difficult or risky. This digitalisation promises to enhance the efficiency and sustainability of mini grids, while reducing operational costs. Yet, implementing these smart technologies in FCS remains difficult due to high costs, limited local capacity, and poor internet and mobile network penetration.

For FCS specifically, the combination of challenges around accessing reliable data and deploying digitalised mini grid technologies requires flexible, context-specific solutions that balance technological innovation with the realities of fragile environments. Some of the ways in which policymakers, mini grid developers, and other actors can navigate the challenges posed by FCS include:

- International organisations tasked with monitoring progress towards SDG 7 should establish a **common framework and build consensus on data sources, collection methods, and assumptions**. This is necessary to enable improved measurement of electricity access data.
- Governments should develop **technology-neutral national electrification plans** that go beyond the usual least-cost electrification thinking and are sensitive to the inherent risks prevalent in FCS. Engaging private sector actors in developing electrification plans can assist with better integration of on-the-ground realities and experiences and can assist planners with setting realistic timelines to achieve national electrification targets.
- When geospatial electrification plans are developed by third parties (as is often the case), governments should require that these third parties **build the capacity of the government counterparts** who will be responsible for maintaining the database and the electrification model.
- Within the confines of established ethical standards, governments, mini grid developers, and development partners should endeavour to **share more data** with each other to foster more evidence-based decision-making. Data that can be shared should be shared with peers to foster learning within the mini grid community, with partners where there is a legitimate business need, and with the general public for awareness where possible.

This policy toolkit is designed to support policymakers of FCS in addressing the opportunities and challenges in leveraging recent innovations in data methods, tools, and advances in solar mini grid technology. The toolkit is also relevant to policymakers in countries transitioning out of fragility and conflict, as well as private developers and investors working toward the goal of universal energy access.

1. Introduction

Strategic infrastructure in FCS, including electricity generation and network assets, are often the target of competing control by conflicting parties and political interests, making them particularly vulnerable to damage. Mini grids offer a viable alternative to the traditional main grid in these settings as they can be deployed in a decentralised manner and use local renewable sources for energy generation, making them more resilient. Solar mini grids, for example, reduce dependency on fossil fuels and their supply chains which are expensive and difficult to maintain in conflict-affected areas.

Recent innovations in data collection methods and tools, such as geospatial analysis, supplemented by artificial intelligence and machine learning, have empowered national planners and solar mini grid developers to design electrification plans that precisely target unelectrified and underserved communities and assess their estimated electricity demand. These innovations have significantly reduced the time and costs typically required for such exercises. Additionally, advancements in solar mini grid equipment, including smart meters and inverters, as well as digital solutions like mobile money, have enhanced operational efficiency, enabling developers to make informed, data-driven decisions.

This policy toolkit aims to document both the opportunities and challenges of applying these data innovations and technological advancements for scaling up solar mini grid deployment in FCS. It provides recommendations for policymakers, solar mini grid developers, and international organisations on policies and initiatives that could leverage data and technology to expand energy access. Additionally, the toolkit offers insights for other key stakeholders, including multilateral development banks (MDBs), development financial institutions (DFIs), bilateral donors, private sector actors, impact investors, and philanthropic foundations, who are working to achieve SDG 7 by 2030.

The policy toolkit is informed by two primary sources: existing literature on solar mini grids, electricity access, and relevant technologies; and consultations with experts, researchers, and practitioners in the mini grid sector. Special attention has been given to contextualising findings for FCS settings.

The structure of the toolkit is as follows: section 2 covers how electricity access is measured, the criteria used, and the need for more granular data to better target unconnected communities; section 3 explores how geospatial planning can bridge gaps in energy access data and support national-level electrification and solar mini grid project planning; section 4 examines digital hardware and software that have enabled the rise of smart grids; section 5 addresses the importance of data protection and confidentiality; section 6 provides the conclusions, and the final section offers policy recommendations.

2. Measuring electricity access data

Understanding the electricity access challenge, necessitates understanding how electricity access is calculated. SDG 7 embodies the global commitment towards ensuring universal access to affordable, reliable and modern energy by 2030.[2] Five custodian agencies have been mandated to track the progress on SDG 7, namely the World Bank, World Health Organisation (WHO), International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and the United Nations Statistics Division (UNSD). Relevant SDG 7 targets, indicators, and custodian agencies are outlined in **Table 1**.

Table 1 SDG 7 targets, indicators, and custodian agencies[3]

Target	Indicator	Custodian Agencies
7.1: By 2030, ensure universal access to affordable, reliable, and modern energy services.	7.1.1: Proportion of population with access to electricity.	World Bank
	7.1.2: Proportion of population with primary reliance on clean fuels and technology for cooking.	WHO
7.2: By 2030, increase substantially the share of renewable energy in the global energy mix.	7.2.1: Renewable energy share in total final energy consumption.	IEA, IRENA, UNSD
7.3: By 2030, double the global rate of improvement in energy efficiency.	7.3.1: Energy intensity measured in terms of primary energy and GDP.	IEA, UNSD
7.a: By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.	7.a.1: International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems.	IRENA, Organisation for Economic Co-operation and Development (OECD)
7.b: By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states, and landlocked developing countries, in accordance with their respective programs of support.	7.b.1: Installed (renewables-based) generating capacity in developing countries (in watts per capita).	IRENA

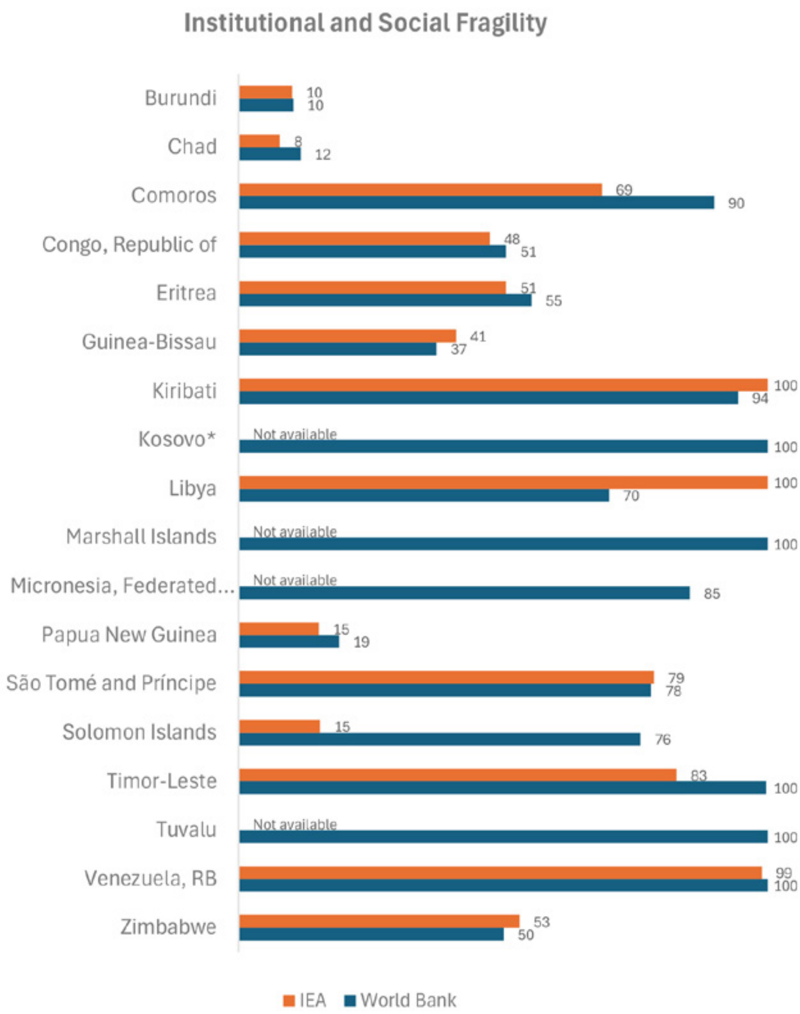
2 UNEP, n.d. The 17 SDGS, also known as Global Agenda 2030, were unanimously adopted by the 193 Member States of the United Nations during the General Assembly in 2015 - United Nations, n.d.

3 IEA, IRENA, UNSD, World Bank & WHO, 2023.

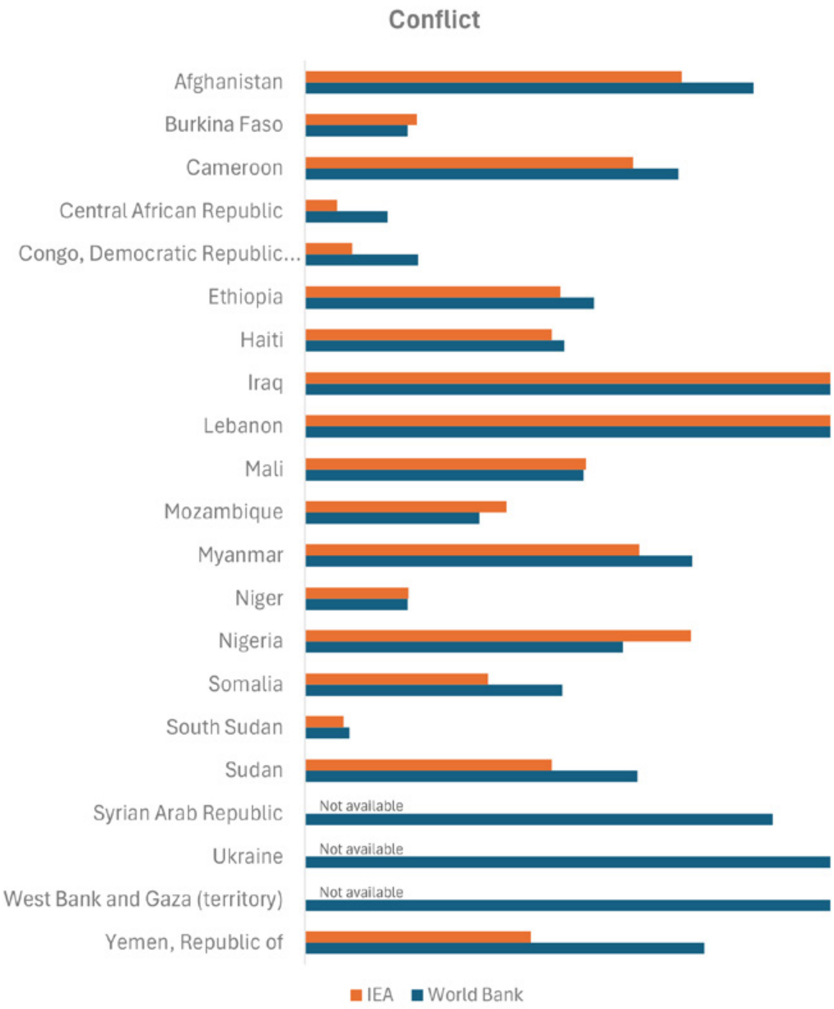
2.1. Status quo of measuring electricity access data

The World Bank is the primary agency authorised to report on the progress countries have made on electricity access. However, the IEA also publishes this information separately. Both produce electricity access data at the national-level (as well as disaggregated between demarcated rural and urban areas) as a binary variable, i.e., whether the household has electricity connection or not. **Figure 1** shows the electricity access data reported by the World Bank and IEA on the countries that have been classified as FCS by the World Bank. The World Bank classifies countries as 'fragile' if they display heightened institutional and social instability, and as affected by 'conflict' if they suffer from violence and unrest and have experienced conflict-related mortalities beyond a specified threshold.[4] This list is updated annually.

Figure 1 Electricity access rates for World Bank list of FCS FY25 (2022)[5]



4 World Bank, 2024.
5 World Bank Open Data, 2022; IEA, n.d.a.



As can be observed from **Figure 1**, the World Bank's access to electricity data differs in most instances from the IEA, and this is most notable for Comoros, Libya, Solomon Islands and the Republic of Yemen. These differences arise because of the following variations:

- **Classifications for defining electricity access** – The World Bank categorises a household as connected if it receives at least 3 watt peak (Wp)[6] and above per day, which equates to at least 4 hours of electricity with sufficient capacity for one task lighting (e.g., for reading, writing, cooking, sewing, etc.) and for charging a mobile phone or listening to the radio.[7] This energy access can be adequately provided by a small solar multi-light system.[8] In contrast, the IEA considers a household to have electricity access if it is receiving at least 10 Wp and above per day, which can power more than one task lighting, phone charging and radio.[9]

6 Note: Watt peak is 'the maximum electrical power that can be supplied by a photovoltaic panel under standard temperature and sunlight conditions'; Energuide, n.d.
7 World Bank, n.d.
8 IEA, 2023a.
9 Ibid.

- **Sources and methodology** – The World Bank collects electricity access data from demand-side sources through end-user surveys and/or censuses. The IEA, on the other hand, uses supply-side data gathered from utilities, distribution system operators, mini grid operators, and other suppliers of electricity,[10] obtained through the relevant ministries of energy, power, and electricity.[11]

Furthermore, national governments and other international agencies may use different criteria for measuring electricity access. For instance, governments in the Democratic Republic of Congo (DRC), Ethiopia, Mozambique, and Nigeria have established a lower minimum power capacity (compared to World bank and IEA) for a household to be considered as 'connected'. This is done to document a household's first step and subsequent progress on the electricity ladder.[12]

Differing definitions of electricity access makes targeted policymaking, interventions and investments towards scaling up electricity access challenging. Establishing a common framework and building consensus on data sources, collection methods and assumptions is the first step towards improving measurement of electricity access data.[13]

2.2. Improving granularity of electricity access data

Country-level electricity access data published by the World Bank and the IEA is binary, i.e. either a household is connected or not. Essential data on electricity consumption trends, affordability and reliability of electricity supply, and its contribution to the quality of life were not traditionally tracked, although these are crucial to understanding the existing gaps for better targeting.

In 2015, the World Bank launched the Multi-Tier Framework (MTF) initiative to measure electricity access across seven attributes:

i. capacity (measured in watts);

ii. availability (number of hours available daily, both during the day and in the evening);

iii. reliability (number of disruptions);

iv. quality (whether the voltage received enables the use of desired appliances);

v. affordability (cost of standard consumption package);

vi. formality (whether the bill payments are made or not); and

vii. health and safety (serious or fatal accidents due to electricity connection).[14]

10 Ibid.
11 IEA, n.d.a.
12 IEA, 2023a.
13 Ibid.
14 World Bank, n.d.

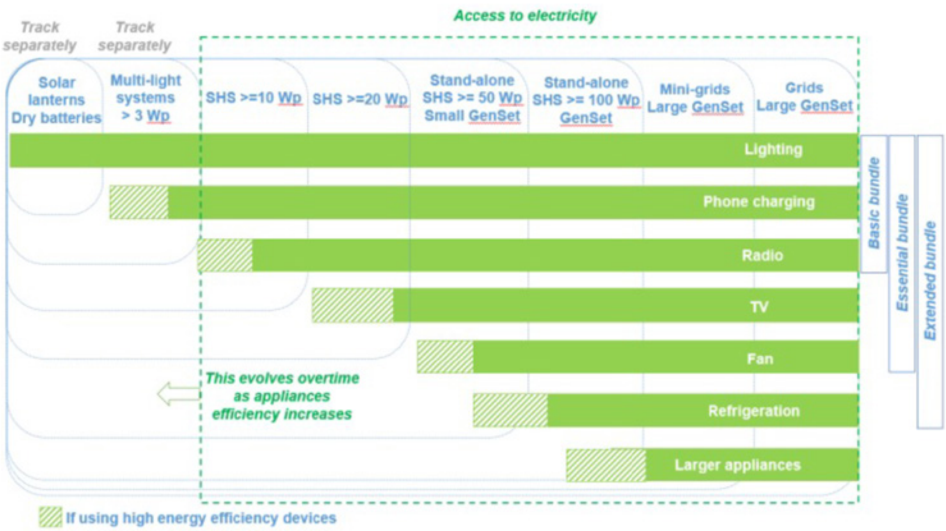
The MTF classified a household's access to electricity across six tiers, with higher tiers corresponding to more capacity and more hours of electricity.[15] **Figure 2** shows the MTF with attributes associated with each tier.

Figure 2 The World Bank's Multi-Tier Framework[16]

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3[b]	TIER 4	TIER 5
Capacity	Power capacity ratings (W or daily Wh)	Less than 3 W	At least 3 W	At least 50 W	At least 200 W	At least 800 W	At least 2 kW
		Less than 12 Wh	At least 12 Wh	At least 200 Wh	At least 1 kWh	At least 3.4 kWh	At least 8.2 kWh
	Services		Lighting of 1,000 lmhr per day	Electrical lighting, air circulation, television, and phone charging are possible			
Availability[a]	Daily Availability	Less than 4 hours	At least 4 hours		At least 8 hours	At least 16 hours	At least 23 hours
	Evening Availability	Less than 1 hour	At least 1 hour	At least 2 hours	At least 3 hours	At least 4 hours	
Reliability		More than 14 disruptions per week			At most 14 disruptions per week or At most 3 disruptions per week with total duration of more than 2 hours"	(> 3 to 14 disruptions / week) or ≤ 3 disruptions / week with > 2 hours of outage	At most 3 disruptions per week with total duration of less than 2 hours
Quality		Household experiences voltage problems that damage appliances				Voltage problems do not affect the use of desired appliances	
Affordability		Cost of a standard consumption package of 365 kWh per year is more than 5% of household income			Cost of a standard consumption package of 365 kWh per year is less than 5% of household income		
Formality		No bill payments made for the use of electricity				Bill is paid to the utility, prepaid card seller, or authorized representative	
Health and Safety		Serious or fatal accidents due to electricity connection				Absence of past accidents	

In 2023, the IEA published a guidebook to improve tracking of electricity access trends. It defined the electricity access of a household at three different levels: basic, essential, and extended bundle to track those that are on the first step of the electricity ladder as well as those gradually increasing their uptake of electricity services. The guidebook also provides methodology to incorporate electricity access provided by mini grids and stand-alone systems that are increasingly being deployed as part of an integrated approach to achieving universal electricity access (along with the national grid).[17] **Figure 3** shows how IEA measures electricity access thresholds, and the associated technologies capable of providing them.

Figure 3 IEA access to electricity by technology[18]



15 Ibid.
16 Ibid.
17 IEA, 2023a.
18 Ibid.

Electricity access planners are encouraged to collect data on both energy demand and supply to complement the strengths and overcome the weaknesses of both. These data can include:

For instance, surveys provide a detailed picture of end-user characteristics but are expensive to administer and have long time lags (5-10 years) between them because they are costly.[19] Data collection from electricity distributors, on the other hand, is comparatively low-cost and relatively easier to obtain on a more regular basis.

Achieving universal electricity access and ensuring no one is left behind, however, requires more granular data be more easily available, both in terms of costs and time. Data must be able to identify both where unelectrified households are located and give an estimation of their electricity demand within acceptable levels of accuracy.

The ideal situation would be to apply MTF or IEA bundles in every country, but this will require massive survey and data collection efforts, along with being extremely time consuming and expensive. For example, between 2015 and 2019, MTF surveys were conducted in 17 countries across Latin America, Africa, and Asia. The sample size of an MTF survey in each country was approximately 3,500 households (divided between urban and rural areas) and cost an estimated USD 300,000. Conducting such survey activities would be especially challenging in FCS experiencing displacement, damaged infrastructure, and social tensions or conflict.

It is equally important to track the energy access of non-residential end-users, such as public service facilities, commercial buildings, small businesses, and other activities involving the productive use of energy, as these consumers can serve as anchor loads and are essential for both mini grid viability and broader socio-economic development.[20] These end-users are not currently tracked by the World Bank or the IEA.

Geospatial data and analytical tools that enable analysis of that data are increasingly being used to address the current gaps in measuring electricity access. Geospatial data is location- and time-based and provides information about objects and events on the Earth's surface.[21] It can be combined with other types of data, such as satellite imagery and remote sensing data (e.g., night-time lights) and census, weather, cell phone, and social media data, etc.[22] These data can be used to create visualisations (e.g., maps, graphs) that enable faster, easier, more accurate, and cheaper data analysis for decision-making. Given these attributes, analysis of geospatial data is increasingly being applied for least-cost electrification planning at the national level and for rapid site assessment at the project level.[23]

19 IEA, 2023a.
20 IEA, 2020.
21 IBM, n.d.
22 Ibid.
23 ESMAP, 2022.

3. Applying geospatial analysis for electrification planning

Recent innovations in geospatial analysis, supplemented by artificial intelligence (AI) and machine learning, have empowered national planners and solar mini grid developers to design electrification plans that precisely target unelectrified and underserved communities and assess their estimated electricity demand. These innovations have significantly reduced the time and costs typically required for such exercises.

3.1. National level electrification planning

Planners are using geospatial analysis to generate national level least-cost electrification plans through optimising the combination of technologies available (grid, mini grid or stand-alone systems) that can be deployed most cost-effectively for powering unconnected or underserved communities. Geospatial analytics tools do this by looking at the characteristics of the location, as well as factoring in the time that would take to deploy the technology. Even when expanding the grid may be the most cost-efficient option, it is prudent to consider alternative decentralised solutions (i.e. mini grids or stand-alone systems) because of the time it may take to extend the grid network to certain areas. In low-income countries and FCS, estimating time for deployment would need to factor in the fiscal constraints and competing priorities faced by governments that can further delay or halt network expansion. It is also necessary to consider how easily different locations can be accessed with existing transport infrastructure, the resilience of a particular technology, whether expanding the grid is feasible in the security context, and what risks of sabotage or damage may exist.

The declining cost of solar mini grid equipment, especially solar photovoltaic (PV) and batteries, in recent years has raised the likelihood of solar mini grids being both the least-cost option and the most feasible technology to deploy in many parts of FCS. In contrast, costs of transmission (notably the cost of copper wire) have not declined and are unlikely to do so. These trends have made policymakers increasingly interested in understanding the role decentralised solar energy solutions can play in national electrification planning to support electricity access and to improve the quality and reliability of electricity.

There are multiple organisations that offer geospatial analysis that can be used by governments for national electrification planning. Some have developed open-source, interactive, online platforms using publicly available data that can be used by anyone interested in understanding the country-level electricity landscape. These platforms allow users to apply different filters to select and display the information they are interested in. Others offer customised solutions at a cost, using proprietary data or data that has had to be purchased (for instance, when greater granularity is required than what is publicly available).

Geospatial planning tools combine various electricity demand and supply indicators identified as being informative for national least-cost electrification planning, as well as the costs associated with different technologies. The demand and supply indicators used can vary depending on the objectives behind developing different plans, and costs of deployment will vary based on context-specific factors, such as whether supply chains exist are in place. Generally, these tools incorporate the following datasets:

- **Current and potential demand of electricity**[24]
  - *Demographics* – Population and population growth, household size, poverty rates, urbanisation rates, mobile phone ownership, radio ownership, iron sheet roofing, livestock ownership, and household electrification.
  - *Social and productive uses* – Education facilities, health facilities, administrative offices, agricultural zones, mines and quarries, commercial activities and small- and medium-sized enterprises (SMEs), public institutions and night-time lights.
- **Current and potential supply of electricity**[25]
  - *Resources* – Solar irradiance, wind speed, hydro resources, biomass, and geothermal potential.
  - *Infrastructure* – Transmission and distribution networks, existing power plants and mini grids, and accessibility to urban areas.
- **Current and projected cost parameters for different technologies**
  - This includes costs of equipment and low- and medium-voltage lines for grid extensions, mini grids and stand-alone systems, forecasted cost projections, and discount rates (where applicable).[26]

Datasets can be collected from a number of different sources, including:[27]

- Open-source databases (e.g., energydata.info, OpenStreetMap, Humanitarian OpenStreetMap, etc.)
- Proprietary databases for more granular remote sensing and satellite imagery (e.g., Maxar's building footprint)
- International organisations (e.g., World Bank, IEA, Food and Agriculture Organisation (FAO), IRENA, European Union Joint Research Centre (EU JRC), World Resources Institute, etc.)
- National and sub-national stakeholders (e.g., census bureau, statistics department, electricity and energy ministries, education and health ministries, etc.)

24 Adapted from World Resources Institute, 2019.
25 Ibid.
26 Adapted from ESMAP, 2022.
27 Ibid.

Geospatial analytics tools can factor in different constraints, depending on the context for which the electrification planning exercise is being conducted. These can include electricity demand targets and projections, ability to pay of consumers, cost and service standards for the network, cost of equipment for decentralised technologies, the priority and sequence assigned to different areas or regions to be electrified, and policy mandates (e.g. electricity access equity). The tools develop different scenarios based on these constraints, which help define the national least-cost electrification plan through either minimising the total financing that is required to achieve the desired connectivity or maximising connectivity for the financing earmarked for this purpose.[28]

In FCS, where data quality shortcomings can result from lack of capacity, source data challenges, poorly funded public statistics systems, and inadequate information and communication technology infrastructure, applying geospatial analysis to develop national electrification plans is particularly promising and can help leapfrog these constraints.[29] **Box 1** provides details on Open Energy Maps, an open-source data portal that uses satellite imagery of entire countries to identify unconnected communities to target for electrification.

BOX 1 OPEN ENERGY MAPS[30]

To address the data challenge around understanding electrification levels and energy demand at the community level, the IEA, Massachusetts Institute of Technology (MIT), University of Massachusetts Amherst, and Electricity Growth and Use in Developing Countries (e-GUIDE) launched Open Energy Maps in March 2024. This open-source data portal matches satellite images and building footprint data with electricity consumption data from utility company meters across Africa, as well as other remote sensing data (night-time lights, internet speed, land-cover, land-use datasets) and uses AI algorithms to assist national planners and private companies with identifying communities to target for electrification. **Figure 4** provides information on the model's approach.

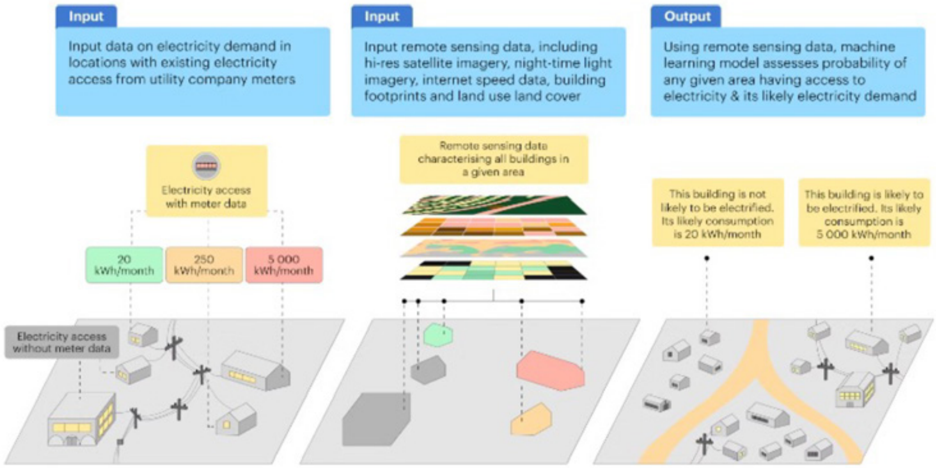
To assess the probability of a given building having **electricity access**, the model utilises night-time lights methodology (using streetlights as a proxy), layers it with additional datasets that track geolocations, e.g., internet speed, and applies AI algorithms that can predict with more than 80% accuracy whether a building currently has access to electricity. Knowing areas and communities that are unconnected or underserved close to those that are connected is useful information for planners and private companies as these may be the most least cost to electrify first (subject to national priorities and sensitivities), because the additional costs involved with connecting these potential customers may be marginal. Moreover, it can be expected that these areas are more likely to increase their electricity consumption as their willingness and ability to pay may increase more rapidly compared to unconnected communities in more remote areas.

28 Ibid.
29 IMF, 2022.
30 IEA, 2024.

To estimate the **electricity demand** (both for buildings already electrified and those for which consumption data is unavailable), the AI algorithms are trained to identify and match the characteristics of these buildings (e.g., whether it is residential or commercial or industrial, the number of floors, whether it is connected to roads, the density of the area, etc.) with buildings for which real utility data is available. For example, when applied to Ghana, Senegal and Uganda, the model identified buildings that were commercial or industrial, multi-story, and situated in dense urban areas as end-users with higher demand (and with a likely higher ability to pay). When this analysis was compared to a separate geospatial analysis looking at estimating per capita income, the findings coincided strongly with the electricity demand of the building estimated by the model, i.e., higher incomes overlapped with buildings estimated by the model to have higher electricity demand.

Open Energy Maps aims to improve national planners and private companies' ability to identify end-users to target for electrification, which traditionally has been an expensive exercise involving on-the-ground surveys. The tool can adapt to the local context and characteristics (such as climate and culture) when trained on a representative sample of communities and a map of country-level satellite images.

Figure 4 Building-level access status and electricity demand estimation model[31]



Although applying geospatial analysis to develop national electrification plans is designed to be context specific, the ESMAP's Mini grids for half a billion people report observed a few generalisations that can be drawn, including:

- High demand customers prefer to be connected to the grid or the mini grid, whereas low demand customers prefer stand-alone systems.

31 IEA, 2024.

- Large residential loads closer to the grid are least costly to connect via extending the grid, and smaller loads further away are least costly to connect through mini grids
- Distribution networks powered by the grid or mini grid are generally only justified when residential electricity demand is at MTF tier 3 or higher
- Productive loads (e.g. milling, carpentry, sewing, water pumping, etc.), and public uses (such as education and health centres, and administrative offices) are better supported by grid and mini grids.

3.2. Solar mini grid project level electrification planning[32]

Beyond national planners, solar mini grid developers are increasingly applying geospatial modelling, demand assessment, and energy systems simulations in order to identify sites, develop appropriate financing models, and deploy mini grids. The proliferation and availability of geospatial platforms and tools has reduced the time taken and cost incurred for scoping solar mini grid projects compared to traditional approaches of dispatching field teams to conduct on-the-ground surveys to assess the potential for mini grid electrification. It has also allowed developers to think beyond single projects and plan for portfolios.

ESMAP's handbook on *Mini grids for half a billion people* provides details on the process developers undertake for mini grid electrification planning. These steps are covered in detail below.

3.2.1. Identifying population clusters

The first important step is to **identify sites** that have population clusters that are attractive for mini grid deployments. In some cases, the boundaries of administrative units (provincial, divisions, districts, municipality, wards, etc.) will be clearly demarcated. However, in most cases, especially in FCS, this information would not be available. In these instances, alternative methods, such as analysing distribution of buildings or rooftops, can be used to generate population clusters. In Nigeria, for example, the World Bank identified population clusters using OpenStreetMap data (covering buildings, land use (residential, industrial), roads, water bodies, etc.), high resolution settlement data (for estimating population distribution) and administrative boundaries, and ran an algorithm to estimate the size, area, and density of villages. **Box 2** provides details on VIDA, a map-based software that allows subscribers to identify solar mini grid sites that align with their respective criteria.

32 Adapted from ESMAP, 2022.

BOX 2 VIDA

VIDA is a map-based software that allows users to assess site-specific infrastructure opportunities and risks for any location around the world. It was launched in 2019 by founders who had worked in the renewable energy sector and realised that the absence of transparent and easily accessible data was holding the sector's development back. National planners and private companies were constrained because they did not have a good understanding of where settlements were located, which ones were electrified, how close or far away they were from key infrastructure (e.g., transport and grid networks), whether they had productive activities, etc. Insufficient data was hindering effective decision-making.

VIDA's software has more than 50 data layers on location characteristics, including demographics, renewable energy potential, socio-economic infrastructure (educational and health facilities, administrative offices, etc.), accessibility to transport infrastructure, agricultural productivity, environmental characteristics (land-use, and land-cover) climate risks (that has been recently added), etc.[33] It also has information on the local security situation, which is critical for FCS. This data is curated from a range of sources, both open-source and procured at a cost from the public domain, national governments, and international organisations.

For instance, VIDA uses earth observation data from Sentinel-I and Sentinel-II satellite imagery operated by the European Space Agency,[34] on-the-ground survey data collected by national departments, and Internet of Things (IoT)35 data from operational mini grids. Additionally, VIDA has developed a set of machine learning algorithms. For example, VIDA's Gridlight algorithm can predict the electrification status of settlements using night-time satellite images. Their spatial clustering algorithm can identify every single settlement in a country using building footprint data as input.

VIDA's software allows users to apply different filters to shortlist locations that align with their defined criteria. For instance, a mini grid developer looking for financially viable sites may decide that they only want to select villages that have more than 200 potential customers, more than 4,000 kWh per month predicted demand, and that are more than 20 kilometres away from the existing grid. These thresholds can be applied when making the selection. This can potentially save the developer time and cost in developing the project or portfolio of projects as on-the-ground surveys can be targeted to the shortlisted sites. Similarly, VIDA's software supports governments looking to develop national electrification plans, identifying where they should prioritise the expansion of the national grid, mini grids, and stand-alone systems. It can also assist governments in developing a result-based subsidy program, support with mini grid tendering, perform impact monitoring, etc.[36]

33 Alliance for Rural Electrification, 2024.
34 European Space Agency, n.d.
35 Note: IoT is a system of interconnected sensors.
36 European Space Agency, n.d.

An important feature of VIDA is that the source of every dataset uploaded on the platform is visible within the software. Additionally, VIDA aims to make the latest data available. For instance, realising that the security situation in any location is dynamic and can change rapidly, VIDA recently signed an agreement with Armed Conflict Location and Event (ACLED) to provide users with the highest quality real-time data on political violence and protests around the world. This is particularly important in FCS context.

VIDA's software has been used to analyse more than 1,000,000 locations across more than 80 countries.

3.2.2. Ranking population clusters based on criteria

After population clusters are identified, relevant site-specific characteristics are added to the settlements. These attributes include the population, building footprint, existing electrification rate measured through night-time lights, distance to physical infrastructure (e.g. roads, distribution network), number of public institutions (health, education and administrative facilities), commercial buildings and anchor loads (e.g., telecommunication towers), agricultural activity (crops, milling, cooling, storage, etc.), resource availability (solar, wind, hydro, biomass, etc.), and other socio-economic characteristics (poverty rate, income level, household assets, etc.). Once the population clusters have been attributed, they are then **ranked** to identify the clusters that align most strongly with the criteria the developer has defined for mini grid deployment. Clusters that don't fulfil the criteria are eliminated. For instance, clusters that are already grid connected and electrified do not need a mini grid and will not be of interest to a mini grid developer. Similarly, a buffer zone (that can be 5 km, 10 km etc. depending on the government's policy priorities) can be drawn around the grid connected clusters under the assumption that they are best suited for grid extension and, therefore, also not viable for mini grids.

Geospatial analysis shortlists population clusters that are most suitable for mini grid deployment based on existing data from available sources, as well as on assumptions and constraints applied. The analysis, therefore, is dependent on the quality of data entered and the degree of accuracy of the assumptions made. Therefore, physical validation and verification checks should still be undertaken on the sites prioritised for mini grid deployment. This can be done through phone surveys (e.g., calling a resident and inquiring about the connectivity status of the community) or sending an agent to the community to check the electrification status, before sending teams to conduct detailed feasibility studies and engage with the community.

3.2.3. Estimating the load profile of population clusters

The next step is to **estimate the load profile** of the community. The load profile of any customer category, i.e. residential, commercial, public, agricultural (including any additional demand from irrigation and agricultural equipment) is their estimated demand for electricity during a given time period (e.g., an hour or a day). This can be estimated in two ways:

- **Use available geospatial data** and make assumptions on e.g., the percentage of the overall community that would be interested in connecting to the mini grid, demand estimates (i.e. electricity consumption per kWh per day) of residential, commercial, public, and agricultural consumers and anchor loads.

- **Send enumerators to identified communities** to collect data on the different customer categories, such as household sizes (small, medium, large), major productive use of energy appliances, loads (large, daytime, productive, commercial), as well as information on affordability, current expenses incurred on using diesel generators and on candles, kerosene and dry cell batteries. This gives more accurate estimates and may be needed where there are gaps in satellite data (e.g. satellite imagery has limited visibility when there is tree cover). **Box 3** provides an example of how practitioners developed an innovative methodology to estimate demand of new villages when geospatial data is limited.

BOX 3 ESTIMATING THE COST OF ELECTRIFYING A VILLAGE[37]

A major challenge when expanding electricity access to rural areas is the difficultly of estimating demand. Accurately forecasting demand leads to better sizing of the mini grid and helps avoid building excess capacity (which leads to higher electricity costs for end-users) or installing lower capacity that can affect the functioning of the mini grid and harm assets.

Where detailed objective data is missing, on-site demand assessment surveys are useful but may be affected by subjective bias, especially where the communities have never experienced electricity, and can become prohibitively expensive and time-consuming to undertake in remote rural areas and fragile contexts.

To address this challenge, practitioners working at Engie, a French electricity utility company active in solar mini grid deployment and operations in Africa, developed an innovative methodology that used limited geospatial data to estimate the demand of new villages. This included using roof sizes as a proxy for wealth (e.g., economic activities using productive use of energy are often carried out in large buildings), and the remoteness and density of a building (e.g. those situated at the centre of a dense area can be expected to have higher demand). These datasets were layered with poverty rates.

Machine learning algorithms were then applied to this data to try to predict for each building whether it would connect to the grid, its consumption profile (i.e. residential or productive), and its peak consumption. Once the demand for a village was forecasted, a mathematical approach was applied to establish the optimal sizing of the mini grid's generation and storage assets and the distribution network layout that would minimise the total cost of electrifying the village. The model was also used to perform sensitivity analyses to

37 Abada et al., 2021.

understand the trade-off between whether a particular building was better served through distribution lines or solar home systems (SHS).

Table 2 shows the load forecast, and optimal generation capacity and grid sizing for Kokoloko, an unelectrified village in Niger, as forecasted by the model. **Figure 5** shows an aerial image of Kokoloko with roof demarcation and **Figure 6** shows the distribution network forecasted by the model. These were not validated to verify how closely they matched the observations on ground as the village was not later electrified. However, the model was applied to Barikiwa, an electrified village in Tanzania, and it accurately estimated village consumption, number of connections, as well as distribution, but overestimated peak demand.

Table 2 Load forecast, and optimal generation capacity and grid sizing for Kokoloko

Load forecast	
Connection rate (%)	21.6
Village daily consumption (kWh)	37
Village daily consumption (kWh)	6
Optimal generation capacity	
PV capacity (kW)	7
Battery capacity (kWh usable)	4.4
Gensets capacity (kW)	1.8
SHS PV capacity (kW)	2.8
SHS battery capacity (kWh usable)	5.6
Optimal sizing of the grid	
Total length of lines (km)	4.7
Number of poles	75

Figure 5 Aerial image of Kokoloko

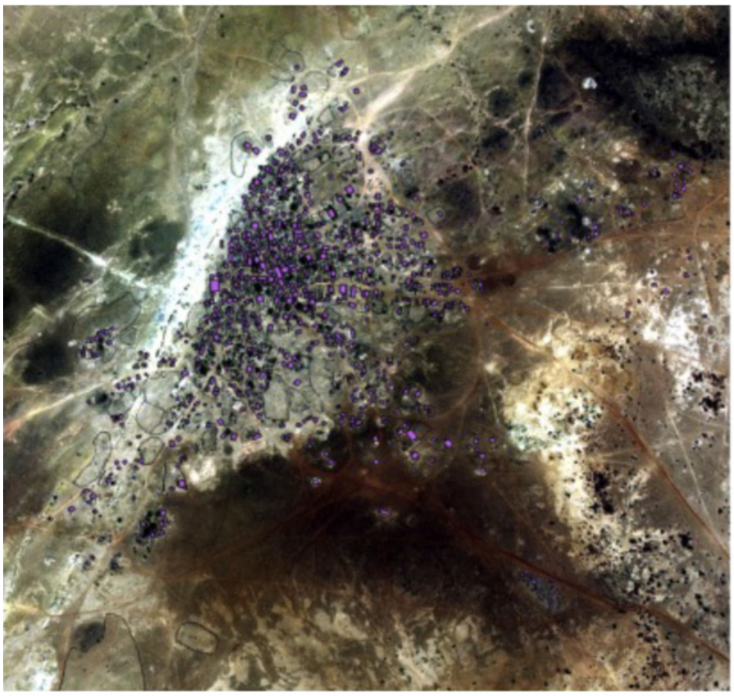
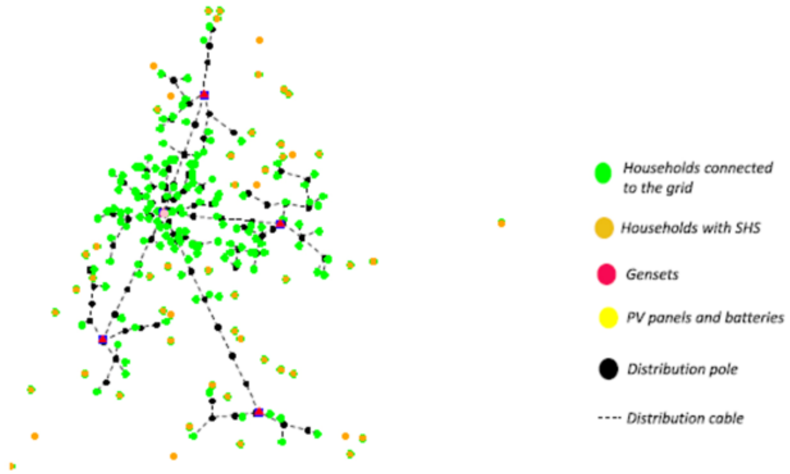


Figure 6 Forecasted distribution network of Kokoloko



3.2.4. Determining the optimal mini grid design

The load profile of a community is then used to determine the **optimal mini grid system design** that includes the quality and quantity of generation assets (e.g. solar PVs, batteries, generators, inverters, etc.), as well as distribution assets (e.g., low- and medium-voltage distribution lines and other network assets such as poles and transformers).
At times, the government may have established minimum technical requirements related to the size and quality of equipment and expected service (e.g. thresholds on the number of hours of scheduled or unscheduled maintenance), as well as any minimum production from the renewable source (such as solar). The developers have to abide by these requirements when developing the mini grid system design. The initial cost estimates of both capital and operational expenses expected over the lifetime of the project cycle are also calculated at this stage, and the bill of materials is developed.

There are different modelling software options that can be integrated with geospatial planning platforms to support developers with system design and optimisation. Examples include Hybrid Optimisation Model for Multiple Energy Sources (HOMER), Reference Electrification Model, Renewable Energy Integration and Optimisation (REopt), Village Infrastructure Angels, Integration, and VIDA. **Box 4** provides details on Off Grid Planning tool, an online tool that optimises energy system design.

BOX 4 OFF GRID PLANNING TOOL

The People Power: Optimising Off Grid Electricity Supply Systems in Nigeria (PeopleSuN) research project was launched in Nigeria in 2020 with the aim of enhancing reliable and sustainable electricity access in underserved areas. The researchers identified three obstacles to off grid (i.e. mini grids and SHS) electrification in these areas:

i. information on the demand for electricity and end-user's ability to pay was missing;

ii. technical know-how on optimal sizing of off gird systems and distribution grid was lacking; and

iii. there was a gap between the varied socio-economic needs of the communities and delivering energy solutions that are sustainable and scalable.[38]

These findings led to the development of the Off Grid Planning Tool. This online, open-source tool can be used to conduct pre-feasibility studies to assess the optimal sizing of off grid energy systems and distribution grids in Nigeria. The tool supports project development through selecting the site and modelling demand (more than 5,000 household and business surveys were conducted to understand parameters like appliance ownership and usage, and time durations for which business are open). It identified potential end-users that would be very expensive to connect to the mini grid (relative to their electricity consumption) and which would be better suited for SHS (as shown in **Figure 7**). It clustered end-users and geolocated the centre of the cluster for placement of poles and spatially optimised the distribution grid so that all poles are connected using minimum cable length (as shown in **Figure 8**). It also simulated the energy system design and the saving in carbon emissions from deploying the proposed energy system.

The tool currently has Nigeria-specific data at the backend, with the researchers planning on adding more countries to the tool.

38 PeopleSuN, n.d.

Figure 7 Map of end-users served by solar mini grid and SHS

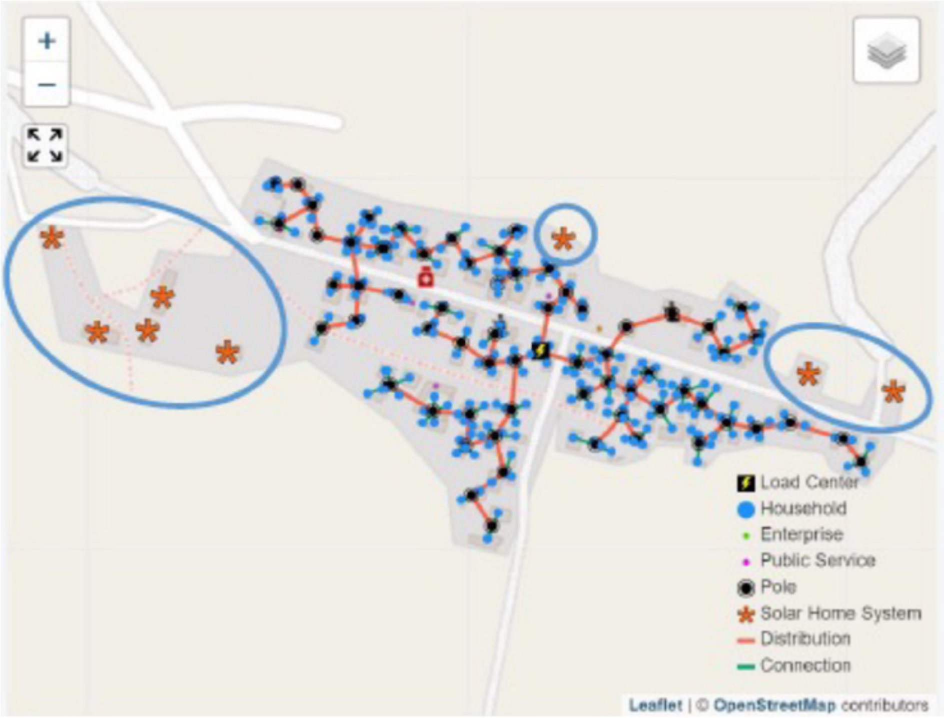
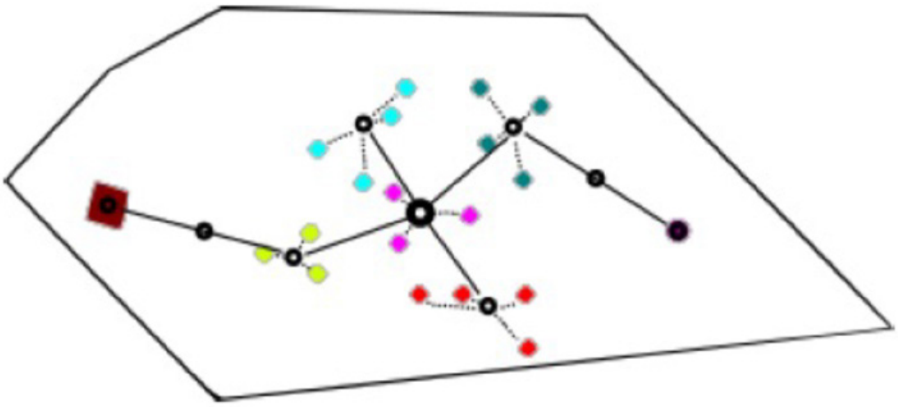


Figure 8 Spatial optimisation of distribution grid



3.2.5. Developing the most viable financial model

The optimal design solution is then tested on different input parameters (such as different levels of demand, service quality, percentage of electricity generated through renewable sources) and financial parameters (such as discount rate, interest rate, generation and distribution system assets, tariff structure, etc.) to assess how sensitive it is to varying these parameters in order to build the most **viable financial model** given the characteristics of the selected site. The financial model includes an income statement, balance sheet, cashflow statement and key performance indicators (e.g., profit margin, levelized cost of electricity, payback period, etc.). In order to conduct sensitivity analysis to assess sites that are viable, different scenarios can be created with and without (or minimum and maximum) dependence on productive load, and modelling different tariff structures (such as time-of-use tariffs), etc.

Third-party providers have developed online digital platforms to support governments and developers to manage all the stages of the solar mini grid lifespan (from planning and procurement to operations and maintenance) within the platform across a portfolio of up to thousands of projects. For instance, Nigeria's Rural Electrification Agency uses the Odyssey Energy Solutions to manage the different stages of the project lifespan of all their mini grid sites.[39] **Box 5** provides more detail on the services Odyssey offers.

BOX 5 ODYSSEY

Odyssey Energy Solutions is a web-based platform that serves as an end-to-end solution provider for designing, building and operating mini grids.[40] The platform acts as an online marketplace, connecting mini grid operators to equipment suppliers (to streamline procurement), financiers to mini grid operators (to facilitate dealmaking, reduce transaction costs and track project progress), and government and donors to investors and mini grid operators (to support with the complete mini grid tendering process). Examples of different ways Odyssey is contributing to the mini grid sector include:

- **Procurement market for mini grid components** – A major challenge the founders wanted to address when developing Odyssey was the inability of solar mini grid developers in frontier markets to purchase components in a timely manner and at a good price. This was primarily because these developers were often small- and medium-sized private companies with small purchase orders, making them low priority for manufacturers. Odyssey's solution was to **aggregate equipment demand** of different developers, and leverage this to negotiate better prices and delivery times for them. They also supported mini grid developers, who lacked the ability to pay upfront for the equipment by offering to pay the suppliers if the developers were able to make a down payment of 15%. Odyssey was able to do this because the demand for equipment was so high that even in situations where a developer's project proposal fell through, there were other developers on the platform who would readily purchase the equipment.[41]
- **Government (and donor) tenders** – Odyssey developed a customised version of the platform for Nigeria's Rural Electrification Agency (REA) to support tendering of mini grids for a World Bank project that had earmarked USD 150 million for this project. The REA carried out an extensive geospatial and socioeconomic analysis, shortlisting an initial 8,000 potential sites that could support financially viable mini grids to a final list of 250.[42] This data was fed into the Odyssey platform, analysed and made available to relevant stakeholders who had registered on the platform. Interested developers prepared their bids by entering their project data into standardised, data-driven proposals that were automatically vetted and validated

39 Presentation by Rural Electrification Agency, 2020.
40 ESMAP, 2022.
41 Chant, 2023.
42 ESMAP, 2022.

by the platform and inconsistencies were flagged so that the developers could address them.[43] The submitted proposals were reviewed by the REA and the World Bank and those successful were eligible to receive upfront subsidy on the capital cost.[44] The platform tracked progress on construction and operations through dashboards. It incorporated remote verification of the number of end-users the developer had successfully connected to unlock result-based financing. Real-time data from smart meters and investors were collected to monitor site and equipment performance to ensure that these comply with required quality standards. Finally, Odyssey analyses the large amount of data that is generated and collected through machine learning algorithms to generate sector insights.[45]

- **Investment market for mini grid portfolios** – Developers can use the platform to assess the site, generate demand forecasts, design energy systems, model tariffs, and produce financial statements. These details can then be shared directly with interested financiers on the platform to secure investment. Odyssey supports financiers by allowing them to evaluate the different mini grid proposals on the platform using the standardised metrics. For projects that get deployed, financiers can evaluate the progress against designated benchmarks through analysing operational data for better insights. This allows them to compare the performance across the different projects and work proactively with developers to meet targets.[46]

Odyssey is particularly well suited when a county is tendering for a large number of mini grids sites, where there is geospatial data available, where financiers are looking to invest in mini grid portfolios, and when developers have built the capacity and can provide the multiple parameters required to be able to make the most use of the platform.[47]

3.3. Opportunities and challenges ahead

Over the years, geospatial electricity planning models have become more sophisticated as more data has become available. The electrification plans developed can help policymakers decide on how to phase new connections using grid and decentralised solutions. In particular, where governments have limited financial resources and private capital has to be crowded in, least-cost electrification plans can support with identifying high-potential sites for mini grids and stand-alone systems. They can also analyse the profitability of various business models and the tariffs or subsidies required to attain the desired profitability levels. International institutions such as the World Bank often provide funding for development of these plans, which are then operationalised by the beneficiary government.[48]

43 Presentation by Odyssey & ESMAP, 2020.
44 ESMAP, 2022.
45 Presentation by Odyssey & ESMAP, 2020.
46 ESMAP, 2022.
47 Ibid.
48 Duren et al., 2020.

A major challenge pertains to the availability of quality data – the higher the quality of data, the better the result and predictions. Moreover, where quality data is available, it may not necessarily be easily accessible due to privacy and confidentiality concerns. Organisations that have these data repositories may have little incentive to share them unless there is some benefit to them for doing so. Another major challenge relates to the regular maintenance and updating of the electrification plans, which can get costly and time-consuming, particularly when the required capacity does not exist locally. When geospatial electrification plans are developed by external parties (as is mostly the case), they should be encouraged to build the capacity of the policy counterparts who will be responsible for maintaining the database and the electrification model.

In FCS, another challenge is that electrification planning that focuses simply on achieving a least-cost technology mix without adequately internalising fragility and conflict parameters can result in unrealistic infrastructure deployment plans. In the decade starting 2010, more than 1500 targeted attacks were carried out on energy infrastructure by non-state actors, with almost half of them were aimed at transmission networks.[49] In Afghanistan, for example, the transmission lines from Uzbekistan to Kabul traversed over unstable regions of Dand-e-Ghori and Dand-e-Shahabuddin and were frequently sabotaged, making the protection and repair in these areas expensive. The electrification plans that had been developed for Afghanistan had failed to take instability into consideration and had recommended the construction of transmission networks over these regions.

The researchers studied how incorporating conflict and fragility into a standard geospatial planning tool influenced electrification planning in Afghanistan. They did this by adjusting for the higher costs of capital (due to risks associated with delays in construction, loss of assets, and failure by end-users to pay their bills timely) and higher fixed costs (associated with e.g., underground transmission and site security to make electricity infrastructure more resilient) and variable costs (from fuel costs and/or shortages, and lack of skilled labour to repair energy system failure, etc.). They found that **incorporating local conflict risk and cost dynamics greatly influences the least-cost electrification technology mix**.[50] Recent years have seen efforts being made to develop national electrification plans that are sensitive to ongoing instability. WAYA Energy has developed a planning and analysis software for designing national electrification plans for different governments. When developing these plans, they create 'what if' scenarios that internalise the dynamic nature of conflict to allow the government flexibility to choose the scenario that best fits the situation on the ground.[51]

49 Korkovelos et al., 2020.
50 Ibid.
51 Iattoni et al, Data, technology and e-waste webinar, 24 July 2024.

An important advantage of using geospatial tools is that it can encourage greater transparency as well as improve accessibility of the electrification plans for relevant stakeholders. Citizens would know government's priorities for expanding and improving energy access, making it more accountable. Investors would be able to identify the most feasible sites for their investments if they know the grid extension plans and areas identified for distributed electricity alternatives. International organisations can support when they have better visibility and understanding of the government's plans to achieving electrification targets.

However, in FCS this information can also become highly sensitive. Non-state actors may actively sabotage government electrification plans in order to undermine government's legitimacy and inhibit its ability to deliver. Furthermore, in the politically charged environments that are prevalent in such settings, rogue elements may use this information to exacerbate historical or ongoing feelings of marginalisation if a group or a region is deemed to have been treated preferentially. It will depend on policymakers in these settings to navigate the domestic socio-political dynamics when deciding on who should have access to electrification plans.

The next section looks at how innovations in digital technologies has enhanced efficiency (both through reducing time and cutting costs) and the resilience of solar mini grids by providing access to better data and analytics and improving the decision-making of operators and relevant stakeholders.

4. Digitalisation potential for operationalising solar mini grids

Digitalisation solutions leverage information and communication technologies (ICT) through the application of multiple different technologies and functionalities. For the electricity sector, the digitalisation opportunity has been transformational in improving data collection and analysis and facilitating greater connection between devices that has resulted in better visibility, control, and automation of energy systems.[52] Digital technologies can direct electricity supply to where it is needed most, in real-time, at the lowest cost, and with the least amount of emissions.[53]

Smart mini grids, also referred to as mini grids of the future[54] and third-generation mini grids, apply digitalisation solutions that assist with maintaining grid stability and reliability through enhanced syncing of electricity supply to demand in real-time.[55] Smart solar mini grids utilise both digital hardware and software technologies that interact with one another. Digital hardware includes smart meters (and demand limiting devices), smart inverters, and smart controllers. Software solutions are designed to optimise the use of digital hardware by adding capacities[56] to balance and manage the energy system functions for:

- **Generation and storage** – such as solar energy forecasting algorithms, intelligent battery management, and optimal hybrid operations.
- **Distribution and control** – such as remote monitoring and smart maintenance.
- **Demand-side management** – such as demand forecasting algorithms, mobile payments, and peer-to-peer electricity sharing (where prosumption is allowed).[57]

Other digital systems such as Supervisory Control and Data Acquisition (SCADA) and Internet of Things (IoT) consist of both hardware and software components. SCADA systems support developers by providing monitoring and control in real-time of solar mini grid equipment and operations and sending notifications when things are out of order. IoT systems interconnect embedded sensors that record and transfer data collected from the equipment as well as the environment via the internet, with data then being analysed to support with predictive maintenance and automated decision-making.

The following sub-sections discuss the evolution of the smart grid and the different digital tools they employ in detail.

52 IEA, 2023a.
53 IEA, n.d.b.
54 IRENA, 2020.
55 IEA, n.d.c.
56 IEA, 2023a.
57 Adapted from Mereu, 2022.

4.1. Evolution of the smart grid

First generation mini grids emerged more than a century ago in highly populated urban areas or where there were lower costs associated with supplying electricity. They were critical to the industrialisation of rising economies including China, the United Kingdom, and the the United States.[58] Over time, increasing demand and better technologies enabled the construction of bigger generation and distribution systems that later connected to form the main grid. The smaller mini grids that had initiated this evolution were later either integrated into the expanding main grid or were left stranded.

Second generation mini grids emerged in lower-income countries. They started by establishing the main grid and deployed large generation and distribution systems in urban centres, as these technologies had already matured around that time. Due to socio-economic and logistical constraints, however, they were not able to connect rural and remote areas to the main grid. As a result, second generation mini grids were designed to electrify unserved communities. These typically used hydropower or diesel and were operated locally by communities or non-governmental organisations (NGOs). When the main grid arrived (if at all) in these areas, the mini grids were either abandoned or integrated into the main grid.

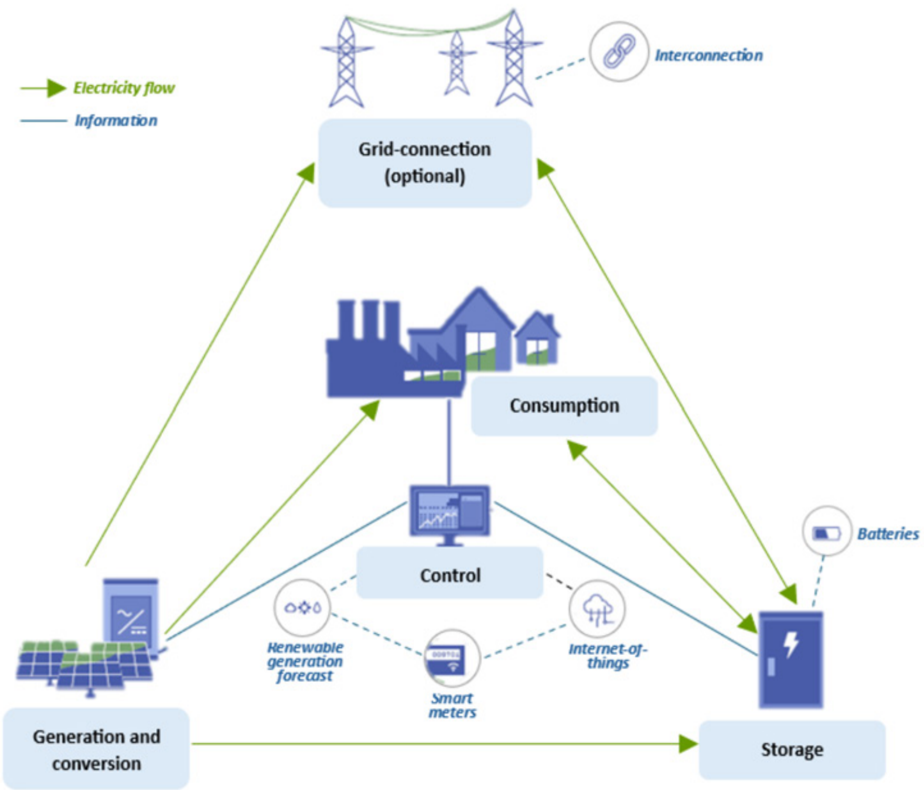
Third generation mini grids arrived in recent years. These smart mini grids are different from the second generation as they are primarily dominated by modular technologies, such as solar PV, and apply the latest digital technologies and solutions to support better matching of electricity demand and supply in real-time. This is important given the variable nature of solar irradiance as an energy source and it helps reduce costs and maintain the stability of the grid. Smart mini grids are usually designed to be grid-interconnection ready and are increasingly being operated by private developers. **Figure 9** illustrates a smart mini grid.

Figure 9 Evolution of the smart grid

Second generation mini grid

58 ESMAP, 2022.

Third generation mini grid[59]



For FCS, smart mini grids hold great potential. Digital technologies such as smart meters and mobile payment systems reduce the need for costly and logistically challenging on-site visits. By enabling remote management of energy generation and consumption, these digital tools help lower operational costs and improve the reliability of electricity supply, which is critical in regions where physical access is limited. Additionally, for the first time, it is possible to have electricity generation that is completely renewable, which reduces reliance on diesel generators that are often expensive, difficult to maintain, and depend on complex fuel supply chains that may be controlled by conflicting parties or political interests making them unreliable.

4.2. Digital hardware

A challenge with solar energy is its intermittency, i.e., it reduces when the sky is cloudy, at night, and across seasons. Digital innovations in standard solar mini grid hardware have helped address this problem to a great extent by monitoring, regulating, and stabilising the voltage and frequency of the solar power generated. This can minimise losses and optimise utilisation. Digital payments through smart meters have enabled remote bill payment, reducing the need to maintain a bill collection team on the ground, which is valuable in areas with limited mobility, logistical challenges, and insecurity.

59 Adapted from IRENA, 2020.

4.2.1. Smart PV and battery inverters

Traditional PV inverters simply converted direct current (DC) generated by solar energy to alternating current (AC), which almost all conventional appliances require to operate. As solar mini grids grow in scale (and especially where developers have a geographically clustered portfolio), smart PV inverters assist with the stability of the mini grid (which may be compromised due to the intermittency of solar power) by regulating the voltage and frequency. They do so by going on standby mode and riding through small disturbances in voltage and frequency or turning off if the disturbances are prolonged.[60] This functionality becomes increasingly important with the rise of extreme weather events. In addition, where the third generation mini grids are designed to be grid-interconnection ready, smart inverters can facilitate the inclusion of renewable energy into the traditional energy mix when (if at all) the opportunity to connect to the main grid arises, thereby reducing the need to develop expensive new grid infrastructure and supporting countries in meeting their clean energy targets.[61]

Battery inverters, on the other hand, convert the AC generated by PV inverters back to DC to be stored in the batteries when excess solar energy is produced. It then converts the DC stored in the batteries back to AC when discharging to end-users at a later stage when solar energy generation is low (e.g., during cloudy days or at night). Smart battery inverters can autonomously manage efficient energy distribution by consistently maintaining the voltage and frequency of the electricity and controlling for fluctuations and damage to end-users' electric devices.[62]

Smart PV and battery inverters can be separate hardware components or a single hybrid hardware that can intelligently manage the flow of electricity between solar panels and the batteries. This improves performance as there are fewer power conversion steps required.[63] For instance, in Tanzania, PowerGen, a renewable energy company, has been using smart inverters to coordinate a pair of solar panel arrays and battery systems half a kilometre apart to provide uninterrupted electricity supply to households and businesses in a small village of 2,000 people. The inverters support with monitoring and regulating the frequency of the mini grid, directing excess energy to batteries when generation is high and to end-users when generation is low.[64]

4.2.2. Smart controller

Smart controllers support with harmonising coordination between the different components of a mini grid. They do this by:

- Efficiently distributing energy within the mini grid through monitoring and regulating the available energy resources for optimal utilisation, so that energy losses are minimal and operational costs are reduced.
- Ensuring that the solar energy potential is utilised to the full extent possible where the developer is using diesel gensets as backup, so that the use of non-renewable sources is minimised.

60 Invertor.com, 2020.
61 IEA, n.d.c.
62 SMA, n.d.
63 USAID, n.d.
64 Renewable Energy World, 2020.

- Taking corrective measures when the mini grid operates beyond the defined thresholds to maintain the stability of the mini grid and reduce the probability of power outages.

In instances where the mini grid is connected to the main grid (although this may be an unlikely scenario in FCS), smart controllers ensure that the mini grid continues to operate whenever there are disruptions to the main grid.[65]

4.2.3. Smart meters

Smart meters can transmit data to and from the solar mini grid to the end-user wirelessly through short message service (SMS) or internet protocol via mobile phone networks or through satellite where there is no mobile network penetration.[66] Smart meters can accommodate both pre-paid and post-paid features and gather data on end-user consumption and payment patterns, as well on electricity quality and reliability. They support with remote monitoring and meter reading, substantially reducing electricity theft and labour costs associated with bill collection.[67] Non-paying end-users can be remotely disconnected. Consumption data collected can assist with scheduling loads efficiently. Smart meters can alert operators to electricity quality issues so that local technicians are mobilised to address the problem in a timely manner before it escalates. **Box 6** discusses SteamaCo's journey from a smart meter provider to providing backend digital solutions for bill collection.

BOX 6 STEAMACO

SteamaCo was launched in 2012 in Kenya with the vision to provide reliable and affordable electricity to unconnected communities. The company started with building wind turbines from scrap materials and then transitioned to establishing solar mini grids across various locations in East Africa. A major challenge that they faced in their operations was collecting cash payments for the electricity sold from the solar mini grids. To address this, they searched for a smart metering solution that would work in the African context and, when unsuccessful, they built a smart meter and the backend cloud-based system themselves.

Simultaneously, other mini grid developers operating in Africa were facing similar issues with collecting payments as SteamaCo. Especially in areas that lacked internet coverage or suffered from unreliable access, there were lags between when the end-user made a payment and when their electricity was switched back on (i.e., pay-to-power), potentially affecting developers' credibility with end-users. SteamaCo pivoted to selling turn-key smart metering solutions to these developers, using its own hardware.

65 Mesa Solutions, 2023.
66 Duren et. al, 2020.
67 ESMAP, 2022.

Over the years, however, varied smart meter hardware compliance requirements in different countries' jurisdictions, combined with the increasing competition and improved functionality from Chinese-manufactured meters, presented both a challenge and an opportunity for SteamaCo. This market shift convinced SteamaCo to move their strategic focus to develop deeper expertise as an interoperable cloud-based software company integrating with a wide range of third-party smart meters.

SteamaCo's smart metering solutions to mini grid developers now include:[68]

- Remote management of energy performance at the site- and end-user-level in real-time (every 15 minutes), which reduces the number of on-site visits required.
- Bill payment through mobile money, point-of-sales agents, or through SteamaCo's Agent app that the mini grid's local staff can use to collect cash. End-users can access electricity in a minimum of three minutes after payment has been made.
- Support with dynamic tariff pricing to encourage end-users to increase or decrease their consumption at different times of the day, by reducing or raising tariff respectively.
- Allowing remote switch-off. For example, in Myanmar, households were allocated 15-minute slots to use their rice cookers to avoid everyone using them at the same time in order to maintain stability of the systems when electricity availability was low.
- Support with demand stimulation by enabling visibility over credit and payment history of end-users to identify those who could be targeted for leasing appliances (such as mobile phones, televisions, refrigerators, welding, grain milling, etc.).
- Support with managing end-user relations, e.g., through allowing communication in nine languages and providing end-users access to check their balance via mobile phone.

SteamaCo continuously aims to innovate. They are looking to develop weather forecasting and battery management functionalities, as well as exploring carbon credit registration for electric cooking.[69] At the same time, they are working towards making sure their services are affordable, including looking at solutions to minimise expensive and volatile data costs.

68 SteamaCo, n.d.
69 Gunning et al., n.d.

4.3. Digital software

Digital software technologies are applied to smart digital hardware in order to optimise their functionalities across the lifespan of the solar mini grid, as discussed below.

4.3.1. Generation and storage

Solar energy forecasting – Solar power forecasting plays a crucial role in addressing the challenges posed by solar energy's intermittent nature. Traditional methods for predicting solar energy were a laborious exercise based on manual calculations of historical data and meteorological- and weather-related parameters and applying simple assumptions that were often prone to errors.[70] The latest machine learning algorithms have revolutionised solar energy forecasts by increasing the precision and accuracy of solar energy forecasts. When trained on historical solar electricity generation data and relevant meteorological- and weather-related parameters, they can identify and predict patterns about future solar energy production.

Intelligent battery management – Battery management systems play a critical role in efficient regulation and utilisation of the intermittent electricity generated from the solar panels, and matching this to fluctuating electricity demand through efficiently managing energy storage in batteries. They optimise energy storage and utilisation through advanced algorithms and artificial intelligence, thus ensuring that end-users receive a continuous power supply as and when needed. They help expand the lifespan of batteries from premature wear and tear by preventing overcharging and, as a result, reduce how often batteries need to be replaced. Developers have access to comprehensive insights on end-user electricity consumption patterns through the real-time monitoring and data analysis these systems provide. An added feature that some of these systems have is the capability to remotely monitor electricity storage.[71]

Optimal hybrid operations – Due to the variable and random nature of solar energy, developers at times maintain diesel generators as back-up in addition to battery storage. For smart mini grids that use diesel generators as back-up, controllers support with optimising the utilisation of renewable resources so that fossil fuel consumption remains low.[72]

4.3.2. Monitoring and control[73]

The ubiquitous presence of sunlight and the declining costs of key solar mini grid equipment (especially solar PV and batteries) has led to increased deployment of solar mini grids as a solution to address the energy access challenge in remote and hard-to-reach places. While this is encouraging, the remoteness of locations where the mini grids are often installed can create significant operational and maintenance (O&M) challenges for the developer. There are three broad categories of O&M costs that a developer incurs that can arise from:

70 Chehri et. al, 2023.
71 Adapted from Gerchamp, n.d.
72 Fritzsche et.al, 2019.
73 Adapted from AMMP, 2018.

- **Component repair and replacement** – Solar PV panels, batteries, meters, distribution cables, etc. undergo the usual wear and tear over the lifetime of the solar mini grid (usually 20 plus years). Batteries, especially, lead-acid batteries have a lifecycle of 5 to 10 years and need to be replaced more frequently than other components. Other factors such as extreme weather events and, in the case of FCS, targeted attacks on electricity assets, can shorten the average lifespan of the components and make the need for the repair and replacement earlier than planned, thereby increasing costs and affecting the profitability margins of developers.

- **Logistics** – Remote locations of solar mini grids means that there are significant costs associated with conveyance for site trips for scheduled or unscheduled maintenance. Site trips are conducted to carry out repair and replacement of equipment and when prior information about the complexity and urgency of the issue is unknown or incomplete, making it difficult to determine beforehand if the site visit was indeed required. In FCS, mobility may further be restricted if the areas serviced by the mini grid or route to the service areas becomes unsafe and travel distances to the site become longer to circumvent regions of unrest.

- **Labour** – This comprises the highest share of O&M costs and is associated with the time labour spends on identifying and rectifying problems as well as the time taken for any ancillary actions required (such as procurement to repair or replace damaged components, etc.). Furthermore, skilled labour may not be easily available close to the site, increasing the time and cost of problem redressal.

These O&M costs can be reduced by maintaining the health of the energy systems to prolong the longevity of the equipment; identifying promptly when issues require urgent site visits and which can be combined and performed during pre-scheduled on-site visits; and managing more efficiently the average time allocated to resolve problems so that the assigned labour can undertake more tasks with the time saved, thereby reducing personnel costs.

Digital solutions for remote monitoring can assist with reducing these O&M costs. These solutions are provided either directly by the manufacturers of solar mini grid components (such as sensors, smart meters, and PV and battery inverters, etc.) or by third-party providers. Parameters are monitored remotely and in real-time to ensure that they remain within expected ranges, including PV generation, battery voltage and storage levels, energy system and ambient temperature, and end-user energy consumption. The data collected is used to create deeper operational insights through advanced analytics. For instance, advanced monitoring solutions can help maximise the lifetime of batteries by monitoring battery temperature to ensure it is within acceptable threshold by assessing the effectiveness of the cooling systems and preventing over-discharge by triggering load shedding (i.e., shutting down power).

Remote monitoring reduces the need for site visits that would otherwise have been carried out if there was no remote monitoring. Examples include identifying which device had undergone the short circuit that raised an overload alert on the inverter; locating a damaged cable by identifying where the voltage has dropped between different distribution nodes; and assessing whether there is sufficient load capacity when a business end-user wants to add a new productive use appliance. Remote monitoring supports reduction in labour costs by providing technicians real-time access to data and advanced algorithms that can analyse interdependence between a range of parameters for pre-emptive maintenance and prompt redressal. For example, irregular PV performance can be identified by linking solar irradiation to solar generation output and locating a power cable issue can be done accurately by comparing the voltage level from the inverter installed at the mini grid and the smart meter installed at the end-user premises. A study looking at the impact of remote monitoring of a portfolio of eight mini grids in rural Tanzania found that the cost of O&M reduced significantly by 30%.

4.4.3. Demand-side and customer management

Demand forecasting – Demand forecasting is the method of predicting end-user demand of electricity over time.[74] Measuring end-users' electricity consumption is tricky because it is not constant over a period of time, but rather fluctuates during the short term (such as during different times of the day) and is seasonal over the long term (when considering a year). The main parameters influencing demand are:

- Forecasting timeline, i.e., the time period for which the demand is being projected.
- Socio-economic factors, such as population growth, electricity cost, economic development, etc.
- Weather conditions, such as temperature, irradiance, humidity, wind speed etc.
- Customer characteristics, in particular, customer type (residential or commercial and industrial), equipment and appliance ownership, etc.[75]

Uncertainty of end-user behaviour makes demand forecasting challenging. Machine learning techniques can be leveraged to improve future demand projections. Accurate predictions of future demand help developers better estimate load forecasts, i.e., how much electricity will be needed at a particular time.[76] This helps prevent waste and inefficiency, reduces stress on the energy system, and expands the overall lifespan of essential mini grid components, especially batteries.[77] Improved demand forecasts also allow the developers to implement flexible tariffs whereby algorithms are used to alter electricity prices throughout the day depending on the energy that is being generated in order to divert non-essential consumption during busy hours[78] and incentivise consumption during times when sufficient electricity is available.[79]

74 Aguiar-Pérez, 2023.
75 Ibid.
76 McGrath, 2024.
77 Fritzsche et.al, 2019.
78 Aguiar-Pérez, 2023.
79 Fritzsche et.al, 2019.

Digital payments – These refer to all non-cash payments that are initiated electronically.[80] It is important for developers is to ensure that bills from the end-users are collected promptly and there are different ways this can be done digitally. Over the years, mobile money has emerged as a significant contributor in the expansion of electricity access because of the utility it provides to all the three parties involved in the transaction:

- *For end-users*, the option to use mobile money eases the process of making payments for electricity consumption as it is similar to how they pay for their mobile service usage.
- *For mini grid operators*, it lowers operational costs by reducing the need to retain bill collection agent networks and the risks (such as theft and fraud) associated with handling cash. Furthermore, for operators looking to expand their business by facilitating loans to end-users to purchase household- and productive use appliances, historical digital bill payment information provides useful details to assess creditworthiness and identify who to target for appliance purchases.[81]
- *For mobile operators*, the increasing integration of mobile money in mini grid business models provides them with an important opportunity to also diversify their revenues and push higher mobile penetration and usage.[82] Moreover, since mobile payments can only work where there is mobile coverage, mini grid developers can leverage telecommunication towers as anchor clients.

4.4. Opportunities and challenges ahead

An important advantage of third generation smart mini grids is that they can generate electricity purely from renewable sources. In FCS, this is particularly important as it nullifies the dependency on fossil fuels, making the systems more resilient. Moreover, fuel transports can be a target in conflict zones, and conflicting groups and political interests frequently vie for control of fuel supply chains.

For solar mini grids, digitisation holds considerable promise. Solar energy generation is dependent on prevailing weather conditions, leading to unpredictable energy output. Hence, electricity cannot be generated based on end-user demand.[83] Digital tools optimise solar generation through adjusting the operations of the solar panels by analysing changing weather patterns, for example.[84] The intermittent nature of solar energy also raises the need for developers to maintain batteries so electricity can be stored for usage during night hours and in rainy and cloudy weather. Digital tools support optimisation of battery functionality to increase the longevity of the batteries and delay the need for repair and replacement. For FCS, where mobility can be restricted, the option for digital bill payments through mobile money can greatly reduce the operational costs of developers by removing the

80 Duren et. al, 2020.
81 Ibid.
82 GSMA, 2019.
83 USAID, n.d.
84 Kaplan, n.d.

need to maintain a bill collection team in the serviced area and eases the bill payment process for end-users. Remote monitoring and predictive maintenance can help reduce the number of site visits required by technicians to address issues that arise, thereby reducing costs.

In FCS, however, the digital opportunities also come with local context-specific challenges and limitations. Smart equipment and components are comparatively expensive and are most likely imported, making subsequent repair and replacement costly. Given the range of smart components that go into building a smart grid and the different manufacturers who make them, interoperability between different devices may be a challenge. Labour with the skills needed to conduct O&M for smart equipment may not exist and will have to be trained, adding to costs. Regulations on equipment specifications and quality may not exist and, where they do, they may not be fully implemented. Moreover, it is not only the developer who has to invest in smart technology, end-users will also have to invest in smart mobile devices, for example, to fully benefit from digitalisation. Smart mobile ownership in FCS can be expected to be low due to low affordability levels of end-users as well as low literacy and digital skills.

Another challenge that exists is the storage and transfer of data. Embedded sensors can generate a wide array of parameters, but there is trade-off between the amount of data produced to be utilised for analytics and improved decision-making to be of value to the developer, and the costs associated with storage (usually through a cloud provider, such as Amazon Web Services or Google Cloud, which charge a service fee depending on usage) and standardisation of that data.[85] Moreover, the data that is generated is transmitted over mobile and internet networks. In FCS, mobile network penetration (per 100 people) is low and was 70% of the global average in 2023.[86] Similarly, internet coverage in FCS also lags behind, with 38% of the population using internet compared to the global average of 63% in 2023.[87] In areas where mobile and internet penetration is low, satellite communication can be used to transfer data, but it is a more expensive option.[88] Developers figuring out where to deploy smart mini grids would factor in the ease of transmitting data from the site. It can be expected that if this infrastructure exists in FCS, it would most likely be established in relatively better-off and secure areas. Policymakers must assess whether focusing energy investments in such areas may inadvertently create sentiments of marginalisation and discrimination against those areas that are already being left behind.

Lastly, given the huge amount of data created as a result of using digital technologies, privacy concerns around data acquisition, data storage and retention, use, and presentation are paramount. Especially in the context of FCS, failure to protect privacy can result in dire security implications for individuals and communities.[89]

85 Energy Catalyst, 2021.
86 World Development Indicators, 2023.
87 Ibid.
88 Energy Catalyst, 2021.
89 Idrees, 2019.

5. Data protection and confidentiality

Developers collect end-user data when conducting feasibility studies on potential sites to determine potential demand and the ability of potential consumers to pay for that demand. There can be different ways of collecting this data, either through door-to-door surveys, through surveying a representative sample of the community or conducting consultative meetings. Once deployed, smart grids generate large volumes of data through their operations. This data is created by sensors embedded in smart meters, smart inverters, smart controllers, etc. This data allows developers to use advanced analytics, enhance the accuracy of forecasts, and for remote monitoring and control.

However, this also raises questions around the protection and confidentiality of that data. Realising this, the Alliance for Rural Electrification (ARE), Africa Mini Grid Developers Association (AMDA), and Smart Power India launched the *Consumer Protection Principles for Clean Energy Mini Grids* in 2019 to protect the rights of end-users, the majority of whom are rural and poor. The principles focused on six themes, including one on data privacy that emphasised the security and confidentiality of end-user data through ensuring consent is acquired and using that data for necessary business purposes only.[90] Beyond this, effective data management entails training staff on data usage, compliance, and protection; designing the company data policy to align with the country's data policy (if one exists); and reviewing and updating data policies and protocols on a regular basis. Ensuring data protection and confidentiality may be especially critical in FCS where data breaches can expose vulnerable populations to harm.

Industry players understand the importance of protecting data and maintaining privacy. Nuru, a private solar mini grid company with assets in eastern Democratic Republic of Congo protects their end-user data by safeguarding security of the servers where data is stored and limiting access to only those necessary. They ensure that respondent consent is acquired when conducting surveys. In instances where data has to be shared with partners, it is only done after a non-disclosure agreement has been signed and then only for legitimate business purposes with the aim of improving energy services. Even then, they ensure that personally identifiable information is not relayed. When data has to be released publicly, they share aggregated data to prevent exposing individuals.[91]

Another example is Odyssey, a web-based platform for developers to design, build, and operate mini grids. Odyssey maintains a high standard of data integrity as an organisational priority and to comply with client requirements (such as the World Bank). The platform has been designed to ensure only the developer and those authorised by the developer have access to the respective account. In this case, the developer remains the owner of all the data they upload on the platform with no oversight from the platform operators.[92]

90 ARE, AMDA, Smart Power India & SwedFund, 2019.
91 Iattoni et. al, Data, technology and e-waste webinar, 24 July 2024.
92 Interview with Odyssey Energy Solutions, 3 May 2024.

Jultud,
Getty Images

At the same time, however, it is important to acknowledge that data is critical for generating valuable insights that can create industry-wide learning and help accelerate electricity access. Government policies and guidelines on data protection and confidentiality should ensure that their compliance does not become burdensome for developers and consequently discourage them from making investments in data and technology. Sharing of non-personal identifiable data to improve forecasting and projections on various electricity parameters should be encouraged.

6. Conclusion

Solar mini grids and digitalisation present critical solutions for improving electricity access in FCS. One of the key advantages of these technologies is their ability to leverage geospatial analysis to deliver accurate and timely predictions without the need for on-site travel. This is particularly valuable in FCS, where access to remote areas is often restricted or dangerous. The use of geospatial planning allows for efficient measurement of electricity access and better planning for future electrification efforts.

Digital tools for mini grid O&M enhance the viability of these systems in FCS. Digital technologies such as smart meters and mobile payments reduce the need for on-site visits or for end-users to travel to make payment for their electricity consumption. Remote management of electricity generation and consumption helps lower operational costs and improve the reliability of electricity supply, which is crucial in regions where physical access and mobility is restricted.

Solar mini grids offer additional benefits that make them particularly well-suited for FCS. Unlike central grid infrastructure, which is vulnerable to damage and destruction in conflict zones, mini grids operate on a decentralised model. Relying on local renewable energy sources, such as solar power, makes them more resilient and independent from large, centralised systems. This is especially important in FCS, where rebuilding traditional infrastructure can be slow and costly. Solar mini grids can be deployed much more quickly, enabling faster recovery and providing essential services especially during reconstruction efforts.

Moreover, solar mini grids help reduce reliance on fossil fuels and diesel generators, which are often expensive and difficult to obtain in conflict-affected areas. Diesel supply chains are frequently controlled by conflicting parties or political interests, making them unreliable. By shifting to local renewable energy sources, mini grids provide a more sustainable and cost-effective alternative, while also contributing to global climate goals by reducing carbon emissions.

Solar mini grids combined with digital tools offer a powerful solution for achieving SDG 7 in FCS. Their ability to bypass the need for vulnerable central grid infrastructure, reduce operational costs, and provide a resilient and sustainable energy supply makes them a vital enabler for expanding electricity access in some of the world's most challenging environments.

7. Policy recommendations

Digital solutions have created a pivotal opportunity to tackle the energy access challenge. Their implementation will require concerted efforts by key stakeholders who can play a critical role in creating conditions for their effective deployment and scale-up.

7.1. Recommendations for policymakers

1. Develop a **technology-neutral national electrification plan** that goes beyond the usual least-cost electrification thinking and is sensitive to the inherent risks prevalent in FCS. Engaging private sector actors in developing the electrification plan can assist with better integration of on-the-ground realities and experiences and can assist planners with setting realistic timelines to achieve national electrification targets. For instance, it may make logistical sense to focus initially on areas least affected by unrest where mini grids are more financially viable as they could attract private investment. However, such decisions need to be grounded on existing socio-economic dynamics to prevent further alienating marginalised groups.

2. Build **transparency** around the national electrification plan to the extent possible. The knowledge on where and when grid expansion would take place can hugely support solar mini grid developers to identify potential sites and build business models. However, in the context of potential spoilers in FCS exploiting public information for their purposes, the decision on whether to make the national electrification plans public or share access to relevant stakeholders would be subject to the local political economy context.

3. Develop **regulatory frameworks that encourage and facilitate the use of digital technologies** through:

    - Enabling financial regulations that allow developers to charge tariffs that make investments in digital technologies financially viable.
    - Establishing quality standards for digital technologies.
    - Setting clear data privacy and confidentiality guidelines for end-user protection so developers can design their internal data protocol accordingly. At the same time, encourage the sharing of non-personal identifiable data to improve forecasting and projections on various electricity parameters and facilitate industry-wide learning.

4. Use **digital platforms for tendering and procurement** of portfolios of mini grid sites, for monitoring and verification of performance and quality indicators (e.g., in instances where result-based financing is operational) to support greater transparency for developers and better oversight for donors and financiers.

5. When geospatial electrification plans are developed by third parties (as is often the case), government should require that these third parties **build the capacity of the government counterparts** who will be responsible for maintaining the database and the electrification model.

7.2. Recommendations for solar mini grid developers

1. Work with relevant government counterparts to **streamline the use of digital technologies** within the project lifespan and work with serviced communities to **design digital solutions** that address their needs.
2. Build the capacity of serviced communities to understand the benefits of digital technologies and how to use them and train them so that repair and maintenance can be undertaken locally.
3. **Share data**, within the confines of the established ethical standards, with government partners and donors to help them with evidence-based decision-making and for reporting purposes. Data that can be shared should be shared with peers to foster learning within the mini grid community, with partners where there is a legitimate business need, and with the general public for their awareness.

7.3. Recommendations for international organisations

1. Establish a **common framework** and build consensus on data sources, collection methods and assumptions, to enable improved measurement of electricity access data.
2. **Create and earmark funding streams** for digital technologies and solar mini grid projects that apply digital solutions to encourage greater diffusion.
3. Design tenders that require developers to **incorporate digital technologies** in their business plan in cases where digital solutions can yield comparative advantage for the developer and the serviced community over the standard mini grid design.
4. **Incentivise ethical sharing of data** through supporting the creation of centralised data repositories for solar mini grid projects they fund. The data stored can be analysed to create insights and knowledge for the broader solar mini grid sector and context-specific solutions for affected communities. Relevant data can also be made accessible to key stakeholders and, where possible, the public.
5. **Build the capacities of governments and developers** to better understand, interact with, and apply digital technologies.

References

Abada, I., Othmani, M., & Tatry, L. (2021). An innovative approach for the optimal sizing of mini-grids in rural areas integrating the demand, the supply, and the grid. *Renewable and Sustainable Energy Reviews.*

Aguiar-Pérez, J. M., & Pérez-Juárez, M. Á. (2023). An insight of deep learning based demand forecasting in smart grids. *Sensors, 23*(3).

Alliance for Rural Electrification. (2024, February 6). Take a data-led approach to scale clean energy access with ARE member VIDA. *Alliance for Rural Electrification.* Accessed at https://www.ruralelec.org/take-a-data-led-approach-to-scale-clean-energy-access-with-are-member-vida/

AMMP. (2018). Reducing the cost of operations and maintenance for remote off-grid energy systems: The impact of remote monitoring. *Asset Monitoring and Management Platform*.

ARE, AMDA, Smart Power India & SwedFund. (2019). Consumer protection principles for clean energy mini-grids.

Chant, T. D. (2023, May 19). From seed to series A in 7 months: Why and how Odyssey Energy solutions moved quickly. *TechCrunch*. Accessed at https://shorturl.at/v42CL

Chehri, A., Chebak, A., Saadane, R., El Aroussi, M., El Maghraoui, A., & Ledmaoui, Y. (2023). Forecasting solar energy production: A comparative study of machine learning algorithms. *Energy Reports,* vol 10: 1004-1012.

Duren, W., Raisin, P., Duby, S., Troost, A., & Engelmeier, T. (2020). Energy Access, data and Digital Solutions. *TFE Energy.*

Energuide. (n.d.). Energy-conscious or passive construction. *Energuide*. Accessed at https://shorturl.at/6mvZh

Energy Catalyst. (2021). How are digital technologies impacting energy access markets? *Energy Catalyst*. Accessed at https://shorturl.at/UVRje

ESMAP. (2022). Mini grids for half a billion people: Market outlook and handbook for decision makers. *Energy Sector Management Assistance Program.*

European Space Agency. (n.d.). VIDA. *European Space Agency*. Accessed at https://business.esa.int/projects/vida

Fritzsche, K., Shuttleworth, L., Brand, B., & Blechinger, P. (2019). Exploring the nexus of mini-grids and Digital Technologies. *IASS*.

Gerchamp. (n.d.). Smart energy storage: Integrating battery management systems into solar solutions. *Gerchamp.* Accessed at https://shorturl.at/P4jtk

GSMA. (2019). Mini-grids, macro impact?. *GSMA*. Accessed at https://shorturl.at/s1jjG

Gunning, R., Bharadwaj, A., Jaoko, B., Evans, B., & Dalle, M. (n.d.). Tackling challenges in mini-grid development: An innovation showcase. *Energy Catalyst.*

Iattoni, G., Hamilton, K., Amatya, R., & Jenks, A. (2024, July 24). Data, technology and e-waste webinar. *International Growth Centre.* Accessed at https://www.theigc.org/events/data-technology-and-e-waste-webinar

IBM. (n.d.). What is geospatial data?. *IBM*. Accessed at https://www.ibm.com/topics/geospatial-data

Idris, I. (2019). Benefits and risks of big data analytics in fragile and conflict affected states. *Knowledge, evidence and learning for development.*

IEA, IRENA, UNSD, World Bank & WHO. (2023). Tracking SDG7: The energy progress report 2023. IEA, IRENA, UNSD, World Bank & WHO.

IEA. (2020). Defining energy access: 2020 methodology. *International Energy Agency.* Accessed at https://www.iea.org/articles/defining-energy-access-2020-methodology

IEA. (2023a). Guidebook for improved electricity access statistics. *International Energy Agency*.

IEA. (2023b). Unlocking smart grid opportunities in emerging markets and developing countries. *International Energy Agency*.

IEA. (2024). Africa's electricity access planners turn to geospatial mapping. International Energy Agency. Accessed at https://www.iea.org/commentaries/africa-s-electricity-access-planners-turn-to-geospatial-mapping

IEA. (n.d.a). Access to electricity – SDG7: Data and projections – analysis. *International Energy Agency*. Accessed at https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity

IEA. (n.d.b). Digital Demand-Driven Electricity Networks Initiative – Programmes. *International Energy Agency*. Accessed at https://www.iea.org/programmes/digital-demand-driven-electricity-networks-initiative

IEA. (n.d.c). Smart grids. *International Energy Agency*. Accessed at https://www.iea.org/energy-system/electricity/smart-grids

IMF. (2022). The IMF strategy for fragile and conflict-affected states. *International Monetary Fund.*

Invertor.com. (2020). What does a solar inverter do?. *Inverter.com*. Accessed at https://tinyurl.com/ymc7wzvc

IRENA. (2020). Quality Infrastructure for smart mini-grids. *International Renewable Energy Agency.*

Kaplan, S. (n.d.). Accelerating progress: Digital transformation and its role in solar and wind power industry. *Praxie*. Accessed at https://praxie.com/digital-transformation-in-solar-and-wind-power-industry/

Korkovelos, A., Mentis, D., Bazilian, M., Howells, M. I., Saraj, A., Hotaki, S. F., & Missfeldt-Ringius, F. K. (2020). Supporting electrification policy in fragile states: A conflict-adjusted geospatial least cost approach for Afghanistan. *The World Bank*.

McGrath, A., & Jonker, A. (2024). What is load forecasting?. *IBM.* Accessed at https://tinyurl.com/27nns7fk

Mentis, D., Odarno, L., Wood, D., Jendle, F., Mazur, E., Qehaja, A., & Gassert, F. (2019). Energy access explorer: Data and methods. *World Resources Institute.*

Mereu, R. (2022). Accurate map of digital technologies components and systems for mini grids at technical system and operational levels dedicated to African needs. *LEAP-RE*.

Mesa Solutions. (2023). Microgrid controllers: Functions and benefits. *Mesa Solutions.* Accessed at https://tinyurl.com/bdffvedf

Odyssey & ESMAP. (2020). Mini-grid action learning event: *Odyssey Training.* https://esmap.org/sites/default/files/Presentations/Odyssesy ESMAP Addis Training.pdf

PeopleSuN. (n.d.). PeopleSuN: Off-grid energy systems: Nigeria. *PeopleSuN.* Accessed at https://www.peoplesun.org/about

Renewable Energy World. (2020). Smart inverters and mini-grids: Has the grid of the future arrived in Africa?. *Renewable Energy World.* Accessed at https://tinyurl.com/yjkdrhup

Rural Electrification Agency. (2020). Nigerian Rural Electrification Agency: Mini-grid action learning event. *Energy Sector Management Assistance Program*. Accessed at https://esmap.org/sites/default/files/events-files/5th Mini Grids Event/3.2 UCHE_Learning from abroad.pdf

Shouman, E. R. M. (2024). Solar power prediction with Artificial Intelligence. *IntechOpen.* Accessed at https://www.intechopen.com/chapters/1152404

SMA. (n.d.). SMA battery inverter: A comprehensive overview. *SMA*. Accessed at https://www.sma.de/en/products/battery-inverters

SteamaCo. (n.d.). The complete off-grid smart metering platform. *SteamaCo*. Accessed at https://steama.co/off-grid-smart-metering-platform

UNEP. (n.d.). Goal 7: Affordable and Clean Energy. *United Nations Environment Programme.* Accessed at https://tinyurl.com/2zhftfrf

United Nations. (n.d.). Historic new sustainable development agenda unanimously adopted by 193 UN members. *United Nations.* Accessed at https://tinyurl.com/b8sh5ew7

USAID. (n.d.). What are the technical components of a mini-grid?. *United States Agency for International Development*. Accessed at https://www.usaid.gov/energy/mini-grids/technical-design/components

World Bank Open Data. (2022). Access to electricity (% of population). *The World Bank.* Accessed at https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

World Bank. (2024). FY25 List of fragile and conflict-affected situations. *The World Bank.* Accessed at https://tinyurl.com/4c85dpw8

World Bank. (n.d.). Electricity: Multi-Tier Framework. *The World Bank.* Accessed at https://mtfenergyaccess.esmap.org/methodology/electricity

State Fragility initiative

IGC

The **State Fragility initiative** (SFi) is an International Growth Centre (IGC) initiative that aims to work with national, regional, and international actors to catalyse new thinking, develop more effective approaches to addressing state fragility, and support collaborative efforts to take emerging consensus into practice. SFi brings together robust evidence and practical insight to produce and promote actionable, policy-focused guidance in the following areas: state legitimacy, state effectiveness, private sector development, and conflict and security. SFi also serves as the Secretariat for the Council on State Fragility.

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