Introduction

Mini-grids have been used for rural electrification to help improve people's quality of life quality of life (e.g. health and educational opportunities) and economic opportunities. Traditionally, rural electrification has expanded through grid extensions, but progress has been slow. However, with the sharp decrease in the cost of solar panels and batteries over the past 15 years, least-cost electrification modelling has increasingly identified off-grid technologies (both stand-alone systems and mini-grids) as cost-effective solutions in rural settings. This fact sheet focuses on renewable energy (RE) mini-grids in Zambia.

Key Facts of the Application Environment

In 2020, 77% of the people in sub-Saharan Africa had no access to electricity.[1] In Zambia, access to electricity rose by 23% reaching nearly 45% between 2010 and 2020,[2] and thus catching up with the regional average of 48%. However, in rural areas access has only increased from 4% to 14% during that same time period, thus failing to catch up with the regional average. The total addressable market for mini-grids is estimated at 200,000 connections (both residential and commercial) spread over 500 to 2,000 sites.[3]

Although mini-grid technologies are mature, the markets remain relatively nascent in Zambia, and more generally, across sub-Saharan Africa. Established firms need to scale up their operations to realise the benefits and advantages of economies of scale, and achieve financial sustainability. In 2019 in Zambia, only 13 mini-grids[3] of a capacity below 1MW were operational or under construction, out of which five were private investments—one small hydro project and four PV projects. Due to high debt levels in countries across the African continent (e.g. government debt at 120% of GDP in Zambia in 2020)[4] and the large investments needed to reach universal access to energy, governments are increasingly supporting private sector participation in rural electrification and enacting policy frameworks and regulations to that effect.

Zambia has followed this trend and enacted a new National Energy Policy in 2019, which promotes an enabling environment for private sector participation (including costreflective tariffs) that emphasises the role of renewable energy and energy efficiency. Although there is no specific mini-grid regulation, the Energy Regulation Board (ERB) adopts a lighthanded approach to some procedures, which it applies to the electricity sector in general. For example, for mini-grids, it delivers a combined generation, distribution, and retail licence as well as a fast-tracked tariff approval.

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23%

increase in electricity access between 2010 and 2020 in Zambia

Application in a Nutshell

Technology	Renewable energy (RE) mini-grids.
Application	Population centres; commercial customers; and anchor customers, such as industrial (C&I) entities (e.g. telecom towers, mines) and drinking water utilities, which strengthen the financial viability of a project while lowering energy expenditure.
Technology Overview	The technological composition, sizing, and performance of RE mini-grids vary widely. However, all RE mini-grids include: power generation assets as well as load control systems and distribution networks to serve households and businesses. Mini-grids can be grid-connected, but most are isolated grids. Direct current (DC) grids can be used for basic energy services, but most grids run on alternating current (AC) to offer the full range of energy services to end users.
Economic and Financial Feasibility	RE mini-grids are characterised by high upfront CAPEX investment and relatively low running costs. Careful dimensioning and sizing are critical for ensuring the sustainability of a minigrid investment. Given the low ability to pay in rural areas, tariffs often need to be below cost-reflective levels; and most mini-grid investments for rural electrification therefore require significant subsidies.
Benefits and Outcomes	Mini-grids are a cost-effective option for many remote population centres, and often provide a very reliable power supply to their consumers. By gaining access to electricity, people can increase their economic activities, gain more income, and then increase their ability to pay. Additionally, mini-grids can contribute to promoting inclusive growth (including gender-inclusive growth) and improving the overall quality of life (e.g. health and educational opportunities).
Constraints and Risks	Beyond the low ability to pay in rural areas, the absence of an enabling environment has been a barrier to mini-grid deployment in many countries. Security risks, foreign exchange risks, and political interference, combined with the lack of an insurance market, all contribute to increasing investors' uncertainty. Additionally, there are technical constraints, such as the patchiness of mobile phone networks, which prevent the use of digital control and payment systems and thus increase operational costs.
Future Perspectives	To reach universal access to energy in rural areas, the enabling environment must include substantial subsidies, patient capital, and tariffs in line with the ability to pay. It must also make room for the productive use of energy (i.e. the use of energy, specifically electricity, for activities that increase income). However, increasing productive use of energy is stifled by high upfront investment costs for machinery and equipment. It would be possible to overcome this barrier by using financing options, but these are still lacking, particularly for households and informal businesses. Digitalisation will support the cost-efficient management of the entire system.


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Technical Information

The technological composition, sizing, and performance of RE mini-grid models vary widely. However, all RE mini-grids include: power generation assets as well as load control systems and distribution networks to serve households and businesses. Solar PV panels and batteries produce DC current, which needs to be converted into AC through inverters before being injected into an AC grid.

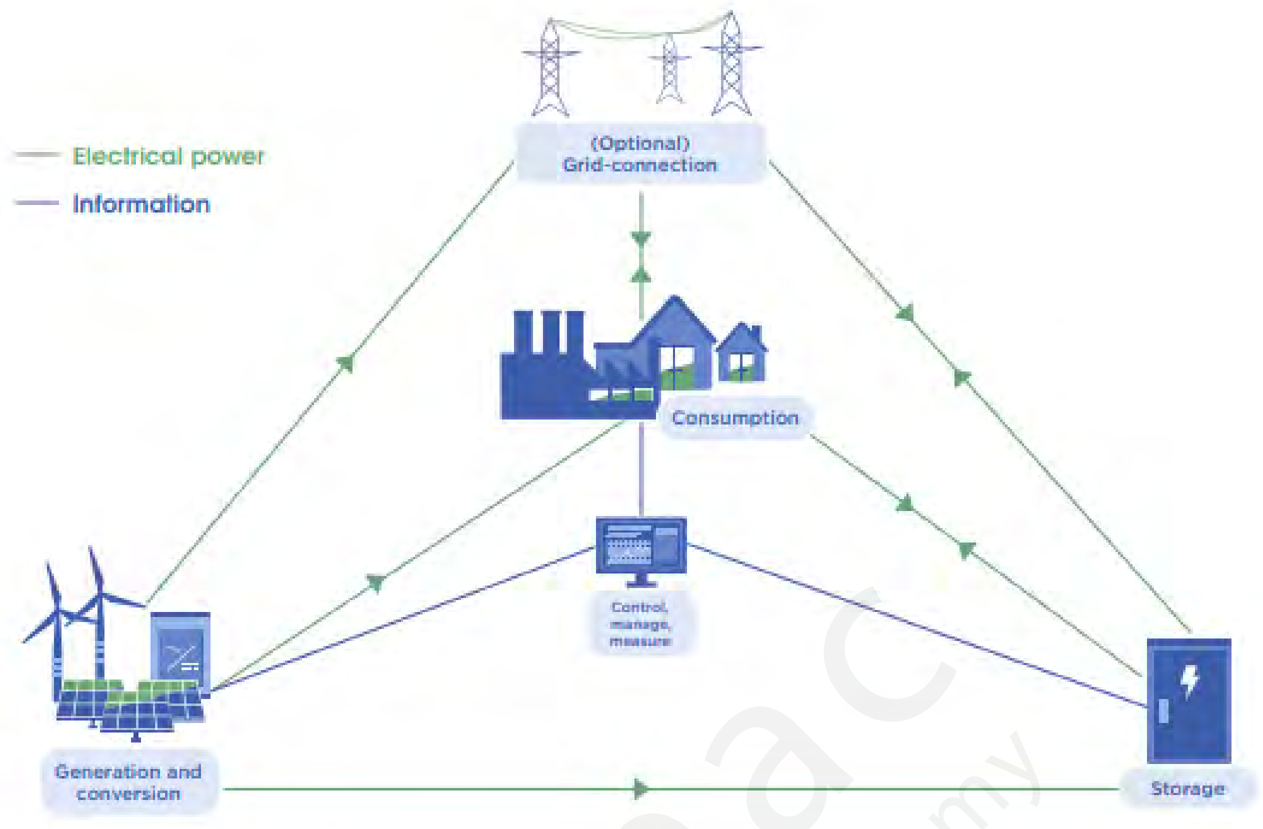

Figure 1: Renewable mini-grids of the future. From "Quality Infrastructure for Smart Mini-grids," by IRENA, p. 15. Copyright 2020 by IRENA.[5]

Mini-grids can be grid-connected, in which case their infrastructure is gridcompatible. A grid-compatible mini-grid abides by the same standards and technical guidelines as the grid. Mini-grids built within 15 km of the grid are likely to be integrated into the grid in the medium term, and it is advisable to plan for this accordingly. Electricity produced by grid-connected mini-grids or the main utility grid can be traded in case of grid integration. This integration can contribute to grid stability because mini-grids can continue to operate in isolation from the main grid if a disruption occurs („island mode"). However, most mini-grids function as isolated mini-grids.

For solar PV grids used primarily for basic energy services (e.g. lighting), DC grids can be used. In such cases, DC grids are more cost-effective due to the absence of inverters, which translates into a lower CAPEX investment and avoids conversion losses. However, the majority of mini-grids are planned as AC grids, offering both single-phase and three-phase currents for the full spectrum of residential and commercial uses.

A variety of factors have driven developers to opt for renewable-energy based power generation systems, including: a sharp decrease in the cost of RE and storage technologies in the last decade; higher oil prices around the world; the logistical challenges associated with securing a continuous diesel supply in rural areas (e.g. inaccessibility and theft); and the availability of abundant local RE endowment (e.g. solar or hydroelectric potential). Diesel generators ("gensets") may still be used for backup purposes to help meet demand peaks, but lithium-ion batteries have become cost-competitive options and offer the possibility to move towards 100% clean energy.

Most RE mini-grids are dimensioned to deliver power reliably and continuously, and performance can be measured using the Multi-Tier Framework (MTF) for energy access[6] defined by the Energy Sector Management Assistance Program (ESMAP), an initiative of the World Bank.

Economic and Financial Feasibility

Careful dimensioning (or sizing) is critical to ensuring the sustainability of a mini-grid investment and avoiding negative outcomes.

An undersized system will soon fail to deliver reliable power as consumption grows. Failure to deliver reliable power will lower consumer satisfaction, and willingness to pay may be irreversibly affected. To avoid this, load assessment and demand forecast, based on a detailed on-site demand survey, are necessary for adequate sizing.

Over-dimensioning compromises the economic viability of the investment. To avoid this risk, project developers are increasingly installing scalable and/or modular systems so that capacity can be increased as needed.

Building mini-grid infrastructure around anchor loads, such as C&I customers (e.g. telecom towers), banks, and drinking water providers, offers mutual benefits.

Anchor customers can substitute their private diesel generators with a cheaper source of energy. Additionally, their relatively predictable and substantial power consumption patterns, as well as high ability to pay, strengthen the mini-grid financially. RE mini-grids are characterised by a high upfront total CAPEX investment (typically about $1,000 per user) and relatively low running costs.

Table 1: Key facts and figures related to RE mini-grids

Lifespan	Approximately 20–25 years	Substantial CAPEX replacement needs around year 10, which includes replacing inverters and Li-ion batteries (depending on the number of effective cycles). This must be scheduled and budgeted ahead of time to ensure continuous operations.
Levelised cost of electricity (LCOE)	Typically, between $0.50 and $0.75/kWh	This depends on the technical solution used, logistical constraints, and the size of the community.
Payback period	With subsidies, private operators can expect a return on investment after about seven years, depending on the project economics.	In Zambia, the equity country risk premium is high: 16% in 2022. Therefore, investors typically expect a 16% equity risk premium plus a variable premium (at least 2%).

Benefits and Outcomes

Mini-grids often are the most affordable electrification option for many remote population centers and offer reliable power supply to their consumers. Once the required authorisations have been obtained, mini-grids can usually be constructed in less than a year. Grid-compatible mini-grids are an especially financially viable option for future grid extension due to: existing infrastructure and higher ability to pay/demand, grown organically with the mini-grid system prior to grid arrival.

Mini-grids contribute to promoting inclusive growth in several ways. They can facilitate the productive use of energy (e.g. milling and other agri-processing activities) and support other income-generating activities. For example, power generated from mini-grids can provide lighting, which allows workers to repair fishing nets at night. Beyond improved economic opportunities, access to affordable and reliable electricity is linked with an overall increase in people's quality of life quality of life (e.g. health and educational opportunities). When it comes to education, lighting can be used by children to study at night. In healthcare facilities, electricity can improve patient care. Mini-grids can also be used to enhance food security through cooling and irrigation. An important aspect of inclusive growth is gender inclusivity. Mini-grids can improve gender equality by making electric cooking (e-cooking) more accessible. Collecting wood for cooking is a gendered activity that is typically undertaken by women and girls. Through the replacement of individual gensets, RE mini-grids also save a significant amount of CO_2 emissions as well as reduce deforestation by supporting the shift away from cooking with charcoal towards e-cooking.

Constraints and Risks

- Low ability to pay in rural areas is one of the main barriers faced by the RE mini-grid market. In Zambia, willingness to pay is estimated between ZMW 70–125 ($4–$8 per month) for households and ZMW 200–460 ($12–$28) for businesses.
- Regulatory risk often arises due to the absence of clear, stable, and favourable regulation. The lack of information about potential sites and grid extension plans creates substantial uncertainty for investors. In Zambia, due to regulatory gaps, some procedures are dependent on ERB's willingness to support the sector. One major risk related to this is that the mini-grid licence, including the tariff, is only granted/confirmed by the ERB after project construction is complete. There are also risks specific to grid arrival because there are no defined procedures for interconnection or compensation mechanisms if Zesco (the utility company) takes over the mini-grid.
- Unreliability or absence of mobile phone networks may prevent the use of digital control and payment systems.
- Security risks are associated with criminal damage (or terrorism in some countries) and pose a threat to both employees and the infrastructure itself, and is reinforced by the lack of an insurance market for mini-grids in most countries.
- Lack of human capital as well as limited local resources; lack of basic skill sets; and the presence of logistical challenges can lead to serious implementation delays. As a result, the cost of setting up operations is high, especially in rural areas.
- Other risks include: political interference; foreign exchange risk; and site inaccessibility—for construction and maintenance work in remote areas, particularly during the rainy season.

Future Perspectives

Substantial subsidies and capital will be required going forward to reach universal access to electricity. In the context of highly subsidised tariffs on the grid, the subsidisation of rural electrification is also a question of equity, but subsidy schemes need to be carefully designed (e.g. reverse auctions).

Productive use of energy has an increasing role to play in accelerating socioeconomic development and strengthening mini-grids financially. ESMAP found that more than 30 types of income-generating[7] machines could have payback periods of less than 12 months when used on a mini-grid. However, adequate financing options, such as PAYGO (pay-as-you-go) or microfinance products, are missing. Operators could partner with microfinance institutions or extend consumer finance themselves with a loan repayment automatically programmed on their consumers' smart meters.

Future mini-grids are expected to include several power-to-X (PtX) systems beyond simple battery storage, which could serve as anchor loads storing energy when it is in excess; and supporting peak load management if smart technology is introduced. Power-to-X refers to different pathways for the conversion, storage, and reconversion of electric power. Examples include the production of hydrogen through electrolysers as well as e-vehicles and their spare batteries.

Digitalisation (relying on smart meters and remote-control systems) will support cost-efficient management, from load forecast and dispatch to remote monitoring and the integration of PtX systems. It will also be required for cashless and prepaid payments solutions, which improve revenue collection and cash flows, and can serve as consumer relationship management systems (e.g. for the generation of a payment history).

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