INTEGRATING MINI GRIDS INTO NATIONAL GRIDS: TECHNICAL AND ORGANIZATIONAL ASPECTS

Recommended Citation

Chris Greacen, "INTEGRATING MINI GRIDS INTO NATIONAL GRIDS: TECHNICAL AND ORGANIZATIONAL ASPECTS", NAPSNet Special Reports, September 22, 2020, https://nautilus.org/napsnet/napsnet-special-reports/integrating-mini-grids-into-national-grids-technical-and-organizational-aspects/

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SEPTEMBER 22, 2020

I. INTRODUCTION

In this Special Report, Chris Greacen describes the technical and organizational aspects of integrating mini-grids into national grids, including technical, economic, and market issues related to interconnecting mini-grids, which are increasingly important in many countries as renewable generation becomes more cost-effective and practical, into national transmission systems. Some of the potential short- and longer-term impacts of the COVID-19 pandemic on mini-grid deployment are also noted.

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This report was produced for the Regional Energy Security (RES) Project funded by the John D. and Catherine T. MacArthur Foundation and presented at the RES Working Group Meeting, Tuushin Best Western Premier Hotel, Ulaanbaatar, Mongolia, December 9-11, 2019.

Banner image: OPALCO mini-grid infrastructure, Lopez Island, Washington, USA, Orcas Power and Light Company.

II. NAPSNET SPECIAL REPORT BY CHRIS GREACEN

INTEGRATING MINI GRIDS INTO NATIONAL GRIDS: TECHNICAL AND ORGANIZATIONAL ASPECTS

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Summary

Mini grids are an essential part of a modern rural electrification toolkit, allowing rural communities to obtain reliable electricity for household and small industrial use far quicker than through conventional grid extension. But their inclusion requires addressing technical and organizational issues with how mini grids integrate with the national grid. The first key issue is coordinating and optimizing rural electrification planning (how to determine what portions of a country to prioritize mini grids and where to prioritize other rural electrification solutions). Technically this involves geo-spatial engineering economics decision-making based on population density, expected electric loads, renewable energy resources, and proximity to the expanding national grid. Organizationally this requires coordination and clear communication among institutions planning, funding, and deploying on-grid and off-grid electrification. Another key issue is the actual electrical integration of mini grid assets into the national grid when it arrives, either as generators contributing power to the national grid, or as distribution franchises reselling national grid electricity to retail customers. On the technical side are power quality and safety requirements for such integration. On the organizational side is the need for a regulatory framework and its enforcement that clearly describes the relationship between the national grid and mini grids.

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Abbreviations and definitions

AVR: automatic voltage regulator

Apparent power (symbol S): the product of root-mean-square voltage and root-mean-square current, measured in volt-ampere (VA). Apparent power is related to real power (P) and reactive power (Q), according to the formula . In an electrical distribution system, conductors, transformers, and other components must be sized according to the apparent power.

Brownout: a sustained drop in voltage on an electric supply system. The brownout can occur unintentionally as a result of disturbances to the system. Intentional brownouts may be used by utilities during emergencies as a load reduction strategy to avoid a complete system shutdown (blackout). Low voltages during brownouts can harm some loads, including motors.

Circuit breaker: a device for stopping the current in an electric circuit as a safety measure. While low voltage overcurrent breakers detect a fault from within the breaker enclosure, many types of circuit breakers discussed in this book (such as medium voltage breakers and/or those sensing conditions other than overcurrent) are tripped by an external protective relay.

Demand-side management: strategies and tools used to match electric demand to available supply, typically through customer incentives and education and automated load control technologies.

DG: distributed generation/generator

Fault: an abnormal, accidental connection or short circuit in a power system. A ground fault is an accidental connection between one of the phase conductors and the ground; a phase-to-phase fault is an accidental connection between one phase conductor and another.

Feed-in tariff: fixed electricity prices that are paid to renewable energy producers for each unit of energy produced and injected into the electricity grid

HV: high voltage, defined by IEEE Std. 100-2000 as greater than 100,000 V (100 kilovolts, or kV). As with low and medium voltage, this term can have different meanings in different contexts, even within the same country.

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers (USA/worldwide)

Induction (or asynchronous) generator: an AC generator in which the rotor current is produced by electromagnetic induction; there is no direct electrical connection to the rotor. Without a grid connection, an induction generator's output frequency is a function of both rotational speed and load. When an induction generator is connected to a power grid, the frequency is regulated by the grid. If the generator's rotational speed is greater than the synchronous speed, power is produced; if the speed drops below the synchronous speed, the generator becomes a load on the grid. An induction generator requires reactive power from the grid or from a capacitor bank to create the magnetic field that induces current in the rotor.

Inverter: A solid state device that converts electricity from direct current (DC) to alternating current (AC).

kW: kilowatt

LV: low voltage; generally, the voltage at which electricity is distributed to retail customers, typically below 1000 volts AC.

Mini grid: a low-voltage distribution grid that receives electricity from one or more small generators (usually renewable) and supplies electricity to a target group of consumers, typically including households, businesses, and public institutions. A mini grid can be fully isolated from the national grid or connected to it, but if designed to be connected to the national grid must also be able to intentionally isolate ("island") from the grid

MV: medium voltage, defined by IEEE as 1,000 V to 100,000 V

MW: Megawatt

National grid: The network of high-voltage and medium-voltage power lines connecting major power stations in a country.

PCC: point of common coupling. The point in an electrical system where utility and customer/generator assets are connected; often, but not necessarily, the location of the meter or the service transformer.

Power factor (PF or cos φ): the ratio of real power (P) to apparent power (S). If both voltage and current are sine waves, power factor is the cosine of the phase difference between the voltage and current. If voltage and current are in phase (the peaks and troughs occur at the same time), the power factor is 1 (all real power); if they are out of phase (the peak current coincides with zero voltage and vice versa), the power factor is 0 (all reactive power). Power factor can be either leading (capacitive) or lagging (inductive) depending on whether the current lags or leads the voltage.

Protective relay: an apparatus designed to detect an unacceptable operating condition on an electrical circuit and trip circuit breakers when such a condition is detected. Protective relays monitor such conditions as overcurrent, overvoltage, reverse power flow, and over- and underfrequency. A relay can also be programmed to after a specified or current-dependent time delay.

Reactive power: the component of apparent power, measured in volt-ampere reactive (var), responsible for transfer of energy between magnetic fields in generators and inductive loads such as motors and fluorescent lights. This electricity is not generated by the utility or consumed by the customer, but "sloshes" back and forth between generators (or capacitor banks) and loads with each AC cycle. By convention, inductive loads are said to "consume" reactive power and capacitive loads "produce" reactive power. Small customers are generally not billed for reactive power, but transmission and distribution system components must be sized to accommodate the increased current. The higher current also causes higher losses in the transmission and distribution system.

Real power: the component of apparent power, measured in watts (W), that performs work or generates heat or light. Small residential customers are generally billed only for real power.

SPD: small power distributor

SPP: small power producer

Synchronous generator: a generator whose frequency is a function only of rotational speed. At the moment a synchronous generator is connected to an electric grid, the generator's operator must ensure that it matches the frequency and phase of the grid power. Once the generator is operating in synchronization with the grid, the grid will regulate the rotational speed of the generator.

Synchronous speed: the speed at which an induction machine (generator or motor) neither consumes nor produces power, a function of the machine design and grid frequency. Specifically, the synchronous speed n_s of a machine is the rotational speed (in RPM) of the stator magnetic field: $\mathbf{n_s = 120 \times f/p}$, where $\mathbf{f}$ is the frequency of the AC supply current in Hz and $\mathbf{p}$ is the number of magnetic poles per phase. For example, a 4-pole machine connected to a 50 Hz grid.

Utility grid: the system maintained by an electric utility for transmission and distribution of electric power throughout the utility's service territory.

1 Introduction

Countries throughout the world are pursuing rural electrification through a two-track approach. One track is a centralized conventional grid electrification approach, primarily through extension of the existing high- and medium-voltage grid and connection of customers to this grid using conventional transformers, poles and wires. In contrast, the decentralized track is a bottom-up approach based on off-grid technologies such as mini grids or household-scale solar home systems.

This two-track approach has grown increasingly popular as the costs for renewable energy components have decreased, making renewable energy powered off-grid options increasingly competitive. Off-grid electrification has also grown in popularity as governments have struggled with the expense and time delays of electrification through conventional means, especially for remote communities. For a community that has been told it must wait 15 years for electrification by the grid, a solar mini grid that can be constructed in several months is a welcome opportunity.

This paper focuses technical and organizational issues with how mini grids integrate with national transmission and distribution networks (referred to as the “national grid”). On the technical side, key issues with this integration are coordinating and optimizing rural electrification planning (how to determine what portions of a country to prioritize mini grids and where to prioritize other rural electrification solutions), and actual electrical integration of mini grid assets into the national grid when it arrives, either as generators contributing power to the national grid, or as distribution franchises reselling national grid electricity to retail customers. On the organizational side are issues of how governments can foster technical and financial support for safe, reliable mini grids when simultaneously rolling out a conventional rural electrification program, and the need for a regulatory framework that clearly describes the relationship between the national grid and mini grids.

Section 2: Mini grids and rural electrification provides more information on mini grid technologies and contexts and provides an overview of key mini grid issues. **Section 3:**

Integrating mini grids into national rural electrification planning describes tools and planning approaches that can lead to least-cost electrification planning that deploys the national grid and mini grids where most appropriate and minimizes the conditions of overlapping service areas and conflict. **Section 4: Regulatory and process issues in integrating mini grids to the national grid** explores a range of options for mini grids when the main grid arrives and how policies and programs can be designed to facilitate a graceful integration. **Section 5: Technical aspects of integrating mini grids to the national grid** explores the technical issues of grid integration of mini grids. **Section 6: Mini grids and the national grid in Northeast Asia** focuses on the DRPK and the Northeast Asia context exploring how mini grids can serve as a tool in increasing reliability and electricity access in rural electrification, and what kinds of programs and regulatory frameworks might support a vibrant two-track approach. Finally, **Section 7: Conclusions** summarizes key drivers of mini grids and ends with suggestions regarding actions that governments might undertake to improve the climate for development of mini grids, and to assure that mini grids meet the needs of local residents and are designed for smooth eventual integration into national or regional grids.

For decision-makers interested in developing a national mini grid program, key mini grid issues of importance not included in this paper include:

- Subsidy and program design to encourage appropriate mini grid deployment;
- Technical standards to ensure safety, reliability and power quality;
- Appropriate tariffs and tariff design
- Obtaining and structuring finance for investment in mini grids

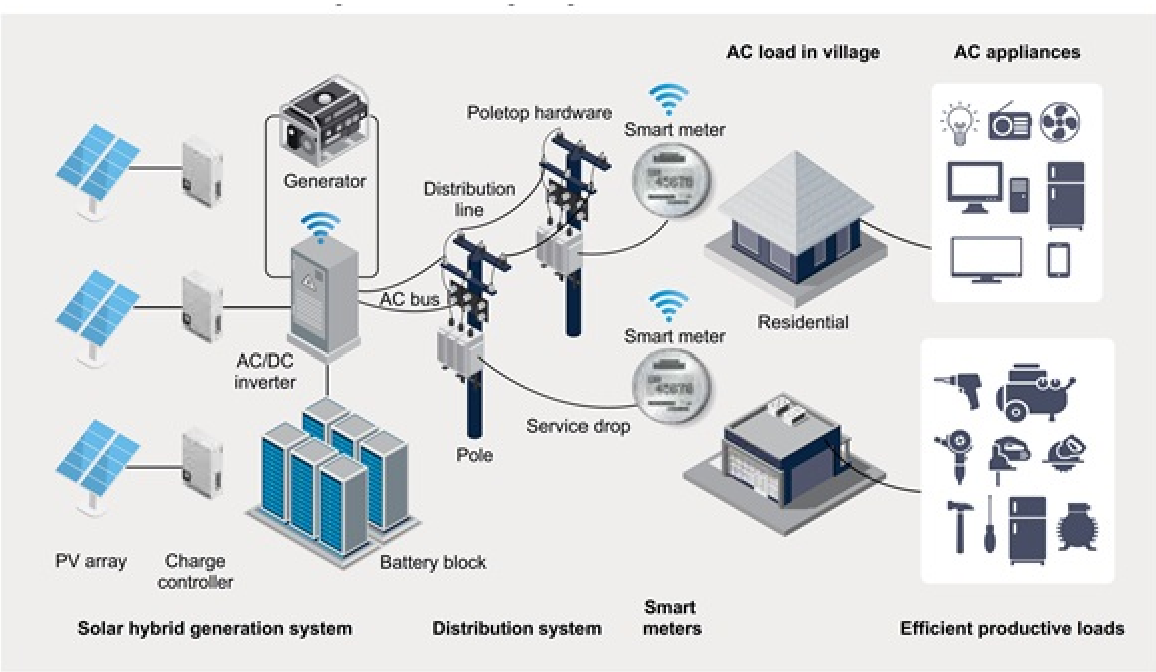
These are addressed in a variety of resources described in Annex 1.

2 Mini Grids and rural electrification

The term "mini grid" refers to small electric power generation and distribution systems that provide electricity to multiple customers. In practice this can range from providing electricity to just a few customers in a remote settlement, to bringing power to hundreds of thousands of customers in a town or city. Mini grids can be fully isolated from the main grid or connected to it but able to intentionally isolate ("island") themselves from the grid. Mini grids supply power to households, businesses, public institutions, and anchor clients such as telecommunication towers and large agricultural processing facilities.

Mini grids are powered by a variety of generation sources. The most rapidly growing energy source for mini grids is solar electricity from solar photovoltaic (PV) panels, driven by rapid declines in the cost of solar panels over the last several decades. Solar mini grids can vary in electrical capacity from “pico grids” as small as a few kilowatts (kW) up to the multi megawatt (MW) scale. Solar mini grids almost always include battery storage, allowing the sun's energy to be stored for nighttime usage as well as for cloudy periods. One or more inverters convert the direct current (DC) electricity produced by solar panels and stored in the batteries into alternating (AC) current used by households and other customers. The high cost of battery storage typically limits storage to a couple of days’ worth of energy storage or less. To provide reliable electricity during periods of particularly high usage or extended cloudy periods, solar mini grids often include diesel backup generators that can be dispatched when batteries are depleted and electricity is needed. When two or more different sources of electricity generation (such as solar and diesel) are used the mini grid is said to be a “hybrid” (see Figure 1).

Figure 1: Schematic of a solar hybrid mini grid with battery storage.



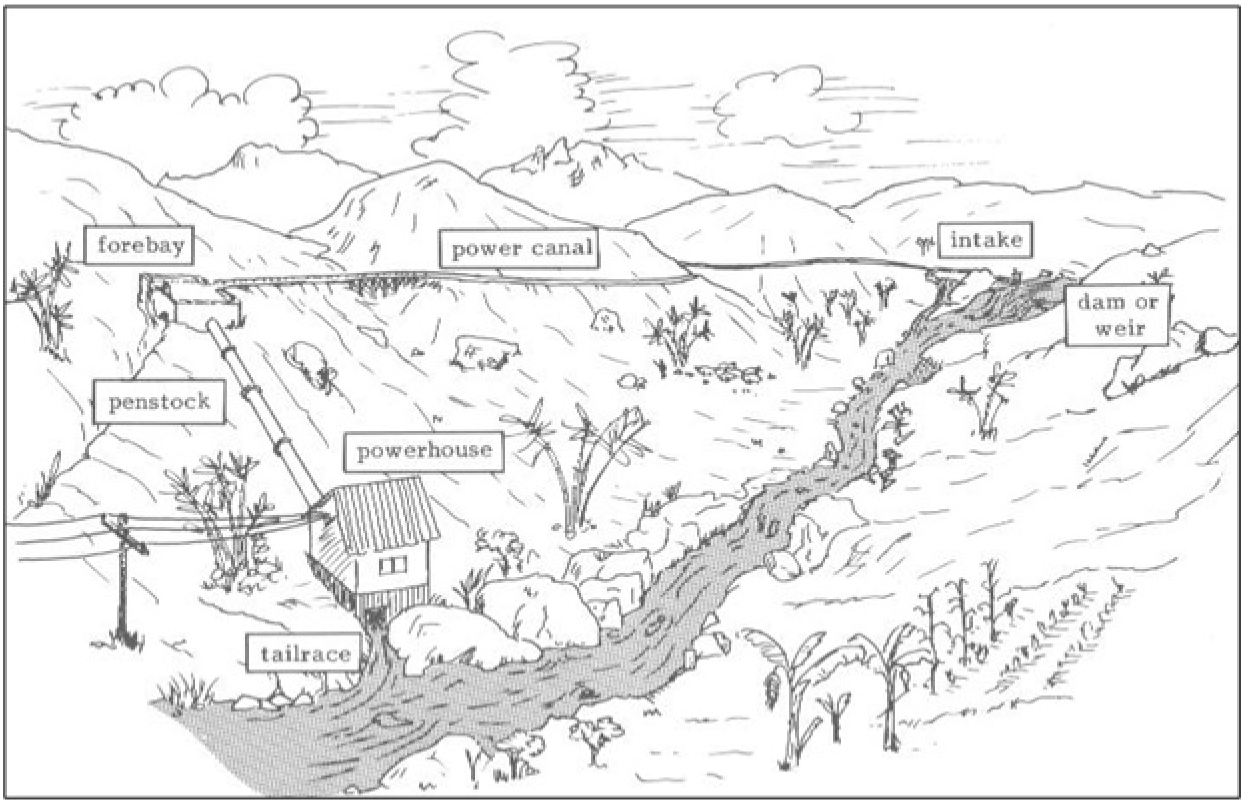
Note: AC = alternating current; DC = direct current; PV = photovoltaic.

Solar mini grids generally obtain more than 50% of their electricity from solar panels. Batteries store electricity for nighttime use and diesel generators provide backup generation. An inverter converts DC electricity stored in batteries to AC electricity distributed on poles and wires to consumers. Most modern mini grids use pre-payment meters that reduce payment collection risks and costs, often with payment via cell phone. Efficient LED lighting and household appliances provide high levels of service with low kWh usage. Image source: World Bank

Despite the recent cost reductions in solar electricity, most existing mini grids are powered by diesel generators (ESMAP 2019). Because diesel fuel is expensive, in many cases diesel mini grids only provide electricity in the evening time. With typical diesel prices, generated electricity costs at least $0.50 per kWh and often over $1 per kWh.[1] Diesel generators powering mini grids can vary from a few kW up to multi-MW scales. If diesel generators are large and of high quality, there may be opportunities to “hybridize” new or existing diesel mini grids by adding solar panels and batteries to both lower energy cost and extend hours of operation from a few hours a night to 24-hour power. Small, low-quality diesel generators have notoriously poor frequency and voltage regulation, however, which can make integration with the inverters needed in a solar electric system difficult.

Hydropower mini grids are a cost-effective option for communities located close to a source of falling water. Electrical capacities typically range from kW to multi-MW. Typical hydropower generators used in mini grids are run-of-the-river type, meaning they do not have significant water storage. Rather, a small weir is built across a stream damming up the waterflow enough for the water to enter an intake channel and ultimately flow down a pipe (sometimes called a “penstock”) to a powerhouse below. Hydropower is typically operated 24 hours a day, though there may be limitations in power output especially during the dry season. Micro-hydropower typically has no battery storage. Rather, a constant level of AC power is generated, and the portion not used is diverted to an electric heating element (see Figure 2).

Figure 2: Micro-hydropower mini grids capture the energy in falling water.



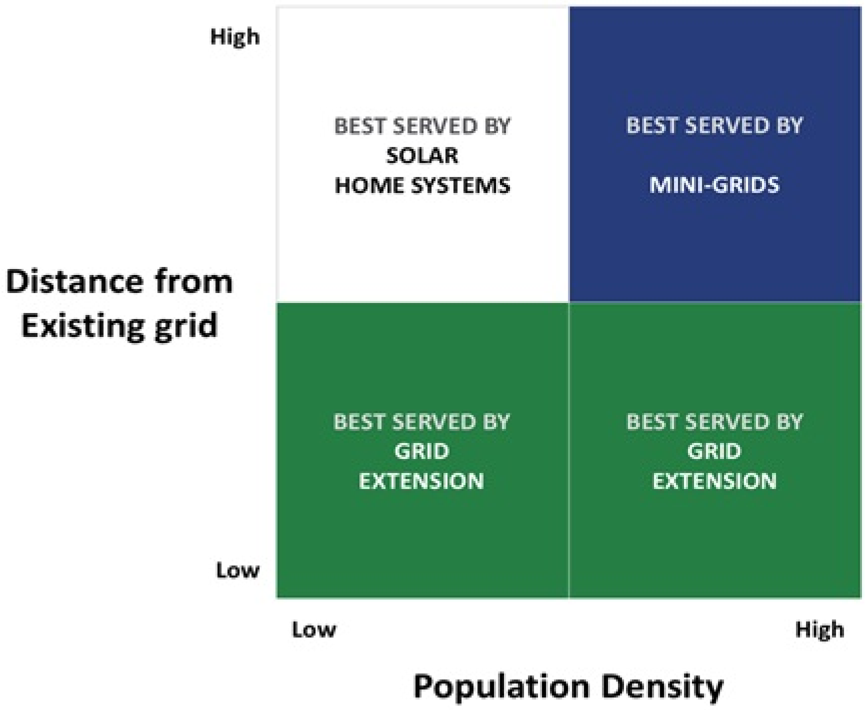
Water is diverted from a stream using a dam or weir into an intake structure and channeled to a forebay/settling tank. From there it enters a penstock pipe that delivers water under high pressure to a turbine, which spins an electrical generator. Water then returns to the stream via a tailrace. Image source: (Allen Inversin 1986)

Biomass-powered mini grids burn agricultural residues such as rice husks or sugar cane bagasse in a boiler to create high pressure steam that is piped to a steam turbine to generate electricity. Steam turbines are typically at least 500 kW in electrical capacity. Biomass-powered generators from several kW to MW scale use a gasification process, combusting biomass fuels in an oxygen-deprived environment to create a mixture of carbon monoxide and nitrogen that can be mixed with diesel fuel or burned directly in modified diesel engines that, in turn, spin alternators to generate electricity. Biogas-powered mini grids burn methane from the anaerobic digestion of animal manure and residues from agricultural processing in modified diesel engines connected to alternators. Typical electrical capacities range from tens of kW to MW-scale.

Some mini grids are powered by a mix of wind-power and diesel generation. With the low cost of solar panels, wind turbines for mini grids are found mostly in larger mini grids (hundreds of kW to multi MW) with either excellent wind resources or in regions in the high latitudes where winter sunlight is very restricted.

Mini grids are the technology of choice for rural electrification when population densities are high and distances from electrified areas are high (for example, further than 10 to 15 km). If densities are low and distances from electrified areas are high then the area is often better served by solar home systems. Areas closer than 10 to 15 km from the national grid are generally more cost-effectively served by grid extension. Figure 3 summarizes the conditions under which mini grids are typically used for electrification.

Figure 3: Areas best served by grid extension, solar home systems and mini grids.



Source: (Davies 2019)

Mini grids are widely deployed in many countries throughout Asia, Africa, Latin America and the Pacific. In general, any village or town on the planet that has potential of economic growth with the addition of electricity and that is difficult to electrify through conventional means is a good candidate for a mini grid.

3 Integrating mini grids into national rural electrification planning

Decades ago, rural electrification planners focused on how to expand the medium voltage network and low voltage poles and wires to try to provide rural population centers with electricity in a timely and affordable fashion. Unserved populations simply had to wait if the national grid was far away.

Contemporary two-track rural electrification can provide electricity to rural load centers far more quickly, but the job for rural electrification planners is more complicated. Planners must now determine which areas are best served by conventional grid extension approaches and which are better served by off-grid solutions like mini grids and solar home systems. Fortunately, technological advancements have brought a powerful set of tools to help, such as GIS (geographic information systems) mapping tools that integrate multiple layers of geospatial and satellite data including on grid locations, population densities, and renewable energy resource maps, and create new maps based on calculations using geospatial data.

Policy makers, regulators, and utility engineers also must decide how to allow for the electrical interconnection of mini grid assets in cases where the national grid arrives to an area formerly served by a mini grid. Here again, new technologies are valuable tools, including multi-function inverters and programmable relays that allow for safe and affordable interconnection to the national grid.

3.1 Geospatial least cost planning to coordinate grid expansion and mini grids

A key foundational step in integrating mini grids into a comprehensive rural electrification strategy is to conduct planning that avoids unnecessary overlap between the service areas of the main grid and mini grids. A typical best-practices least cost rural electrification plan is conducted by a Rural Energy Agency (REA) or Ministry in charge of rural electrification, with the goal of mapping the least cost electrification option for all towns and villages in a country. Practices vary from country to country and have been evolving as lessons are learned. Nigeria’s least cost rural electrification planning process has been the beneficiary of a significant recent World Bank effort and reflects a current best-practices approach (Shrestha 2019). It comprises the following steps:

1. Define all unelectrified households and enterprises.
    1. Identify the unelectrified population using geospatial maps of existing electrical grid infrastructure, databases of electrified schools and health centers, and satellite maps of the region at nighttime.
    2. Define clustered settlements in rural and urban areas.
    3. Build a GIS map layer with projected future population for each area based on existing populations and growth rates.
2.
3. Calculate demand for electricity in each cluster
    1. Estimate consumption level for all the households and businesses in each cluster on the map. This is often done using satellite imagery and requires mathematical functions that correlate the buildings’ roof size and type to expected electrical consumption. On-the-ground energy survey methods play an important role in calibrating these functions.
    2. Estimate per-customer electricity demand growth based on historic and technology evolution trends.
    3. Based on population estimates and per-customer consumption growth, project future demand growth.
4.
5. Identify renewable energy resource potentials
    1. Assemble geospatial data on renewable energy resource potential such as the World Bank’s Solar Irradiation Map or maps of hydropower potential based on hydrology and topography.
6.
7. Determine least-cost technology for each household or enterprise
    1. For each town or cluster on the map, calculate the cost of interconnecting to the national grid based on estimates of the cost of grid extension per kilometer and geospatial data in step 1 above. Generally, communities within 10 km of the national grid are most cost-effectively served with grid extension (assuming the grid is reliable).
    2. Develop capital and per-kWh cost estimates for mini grids of different types, technologies, and capacities based on renewable energy resource potential, price of diesel fuel, expected load profiles, and technology costs. Note that assumptions as to technology costs may change over time.
    3. Select the least cost technology for each settlement.
8.
9. Test sensitivities of key inputs to provide assurance that the model is logical.
10. Develop year-by-year rural least cost electrification plan
    1. Based on the inputs above, develop a year-by-year rural least cost electrification plan that

selects communities for grid electrification where these are lowest cost.

2. Include an estimate of the number of years at expected expansion rates before each community could be expected to receive electricity from the national grid.
3. Clearly map out areas that are priorities for mini grid electrification.

11.

Once the geospatial least cost rural electrification plan is finalized it is important for utilities to follow it. In many cases utilities experience political pressure to electrify areas not on the plan, or to electrify towns out of sequence. A consequence of this is that areas that were good candidates for mini grid development according to the plan suddenly experience high risk of arrival of the main grid. When the main grid arrives, customers disconnect from the mini grid and connect to the main grid, rendering the mini grid unable to earn enough money to cover costs or debt payments incurred by the individuals and organizations (developers) that invest in it. It is also important to keep the planning document up to date, with maps associated with the plan updated to reflect areas as they become electrified. Periodically (for example, every five years) the plan should be re-evaluated considering changes in costs, technology and updated status of electrification.

The least cost rural electrification plan should be provided by the government to mini grid developers for use in determining which sites to select. Underlying geospatial data sets of high value to mini grid developers include detailed geospatial satellite data on customer locations as well as estimated load curves based on household and productive use surveys extrapolated over the GIS maps of the region. Moreover, mini grid developers need up-to-date information on the national grid's year-by-year expansion plans and current expansion status.

Providing these data by the government to private sector mini grid developers lowers costs substantially. Doing so also lowers risk to developers by helping ensure that mini grids are built in priority areas that are unlikely to be electrified by national grid expansion for at least as long as it takes to earn a return on the investment and operational costs of the mini grid. Providing these data to private sector developers also can help governments make efficient use of subsidy dollars by ensuring that mini grids that are awarded subsidies are low risk and high benefit based on geospatial analysis.

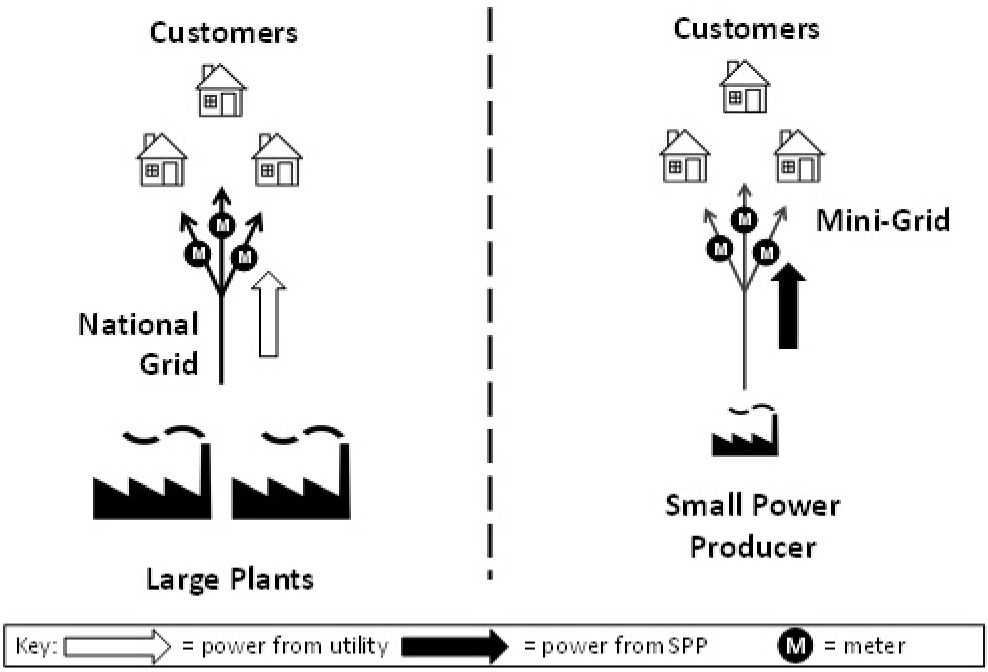
4 Regulatory and process issues in integrating mini grids to the national grid[2]

Careful planning can help reduce risks of conflicting service areas between mini grids and the main grid, as described above. But it cannot eliminate the risk to mini grid operators of main grid arrival. As the main grid expands, it inevitably grows into areas served by mini grids. If there is no clarity as to what happens when the main grid expands into an area served by mini grids, investors will be reluctant to invest in isolated mini grids to begin with.

This was a significant problem in Cambodia a fifteen years ago. The lack of a policy for what to do when the big grid connected to a mini grid led to underinvestment by hundreds of private mini grid operators. Many private sector operators of mini grids limped along with second- and third-hand diesel generators and mini grid distribution systems using undersized, non-outdoor-rated wiring often tied to trees. Investing in system upgrades made little sense to these entrepreneurs, since they would be out of business and their assets scrapped if the national utility, Electricité du Cambodge, decided to electrify their service area next.

The Cambodian regulator has addressed this problem by allowing mini grids that meet sufficient technical standards to connect to the national grid and convert themselves into small power distributors (SPDs). Figure 4 shows the situation before a mini grid is connected to the national grid. Setting a sufficient margin between the bulk purchase tariff and retail sales tariffs allows the SPDs to cover their distribution costs and earn a profit (Rekhani 2012). As of 2017, the Cambodian regulator has issued licenses for over 250 distribution utilities that were formerly isolated diesel-powered mini grids. Cambodia has been successful in pursuing the centralized and decentralized tracks in parallel, but it appears to be the exception rather than the rule among countries faced with a similar need for rural electrification.

Figure 4: Base Case: Before the Mini grid Connects to the Main Grid.



Source: (Greacen, Engel, and Quetchenbach 2013)

When private and cooperative investors are reluctant to invest in isolated mini grids, isolated villages suffer because they are denied a chance to receive electricity that they otherwise might have had and instead must wait years or decades for the national grid to arrive, if indeed it ever does. Conversely, policies like Cambodia's that allow mini grids to connect to the main grid and convert from a mini grid to an SPD can help to foster win-win-win arrangements for developers, utilities, and the public. If the right policies are in place, both the private sector and community organizations will have economic incentives to build and operate isolated mini grid systems. They can electrify villages that the national utility is reluctant to serve. This allows the national utility to concentrate on expansion of the high voltage and medium voltage grids. The national utility can also potentially benefit from the availability of power generation and end-of-line voltage support when the national grid reaches a previously isolated mini grid. Rural customers also benefit because they receive electrical service sooner and have the possibility of receiving higher-quality and lower priced electrical service when the big grid finally arrives.

To encourage investors to invest in isolated mini grids, regulations and policies should be adopted that give mini grids any of the following options when the big grid arrives:

- **Small power producer (SPP)**. The mini grid converts to a main grid–connected SPP selling wholesale electricity directly to the national grid and no longer selling to retail customers.

- **Small power distributor (SPD)**. The mini grid converts to an SPD that buys its full supply at wholesale from the main grid and sells its purchased electricity to retail customers (with or without backup generation).
- **SPP + SPD**. The mini grid continues to sell electricity to its retail customers with its own generated electricity or wholesale purchases from the main grid operator and also sells electricity to the main grid operator when a surplus is available.
- **Side-by-side but not interconnected.** The mini grid continues to serve customers even when the grid arrives, with no electrical interconnection between it and the main grid, even though both operate in the same village.
- **Compensation and exit**. The mini grid goes out of business, and the developer receives some compensation for assets taken over by the main grid operator (typically a government-owned national utility).

The first four options are co-existence options. The fifth option is a going out of business option with compensation.

A sixth outcome—abandonment—is not a recommended practice, but unfortunately has been the dominant outcome for mini grids when the main grid arrives.

4.1 The Small Power Distributor (SPD) Option

An SPD purchases electricity from a national or regional utility (typically at medium voltages such as 33 kilovolt [kV] or 11 kV), and operates a distribution network that delivers this electricity to retail customers. The SPD will usually have a legal right to sell to retail customers in one or more villagers that are specified in its license or permit.

SPDs are common in several Asian countries (Nepal, Bangladesh, Vietnam, and Cambodia) that have had major success with scaling up electrification. Sometimes these SPDs started out as mini grids and became SPDs when the grid arrived in the area, as in the case of the 250 Cambodian SPDs discussed above.

Similar considerations apply in the more common cases in which SPDs did not start out as mini grids, but were instead built to function as SPDs right from the beginning. For example, in Nepal more than 116,000 households receive their electricity service from community-owned distribution entities that purchased electricity at wholesale from the national utility and then resell it at retail. These community distribution cooperatives operate under the community electrification bylaws issued by the government in 2003. In accordance with the bylaws, communities must provide 20 percent of the total cost of constructing distribution lines, while the government contributes the remaining 80 percent. The approach has proven successful in electrifying communities more quickly than a conventional national utility-led expansion. The community owned SPDs have also substantially reduced electricity theft and improved the timeliness of bill payment by consumers (Mahato 2010).

Similarly, Bangladesh has 70 rural electric cooperatives that provide service to approximately 8.4 million customers. These cooperatives, called Palli Bidyuit Samity (PBS), have been the main mode of electrification through grid extension. PBSs purchase electricity in bulk from the Bangladesh Power Development Board and then resell this electricity at retail to members or nonmember buyers in their service areas (Palit and Chaurey 2011). They serve between 35,000 and 275,000 customers (Chowdhury 2009).

In Vietnam, about 21 percent of the country's 8,000 rural communes are served by private, community, or cooperatively owned local distribution utilities (LDUs) that purchase electricity in bulk from regional power utilities and resell the power to retail customers (Van Tien and Arizu 2011).

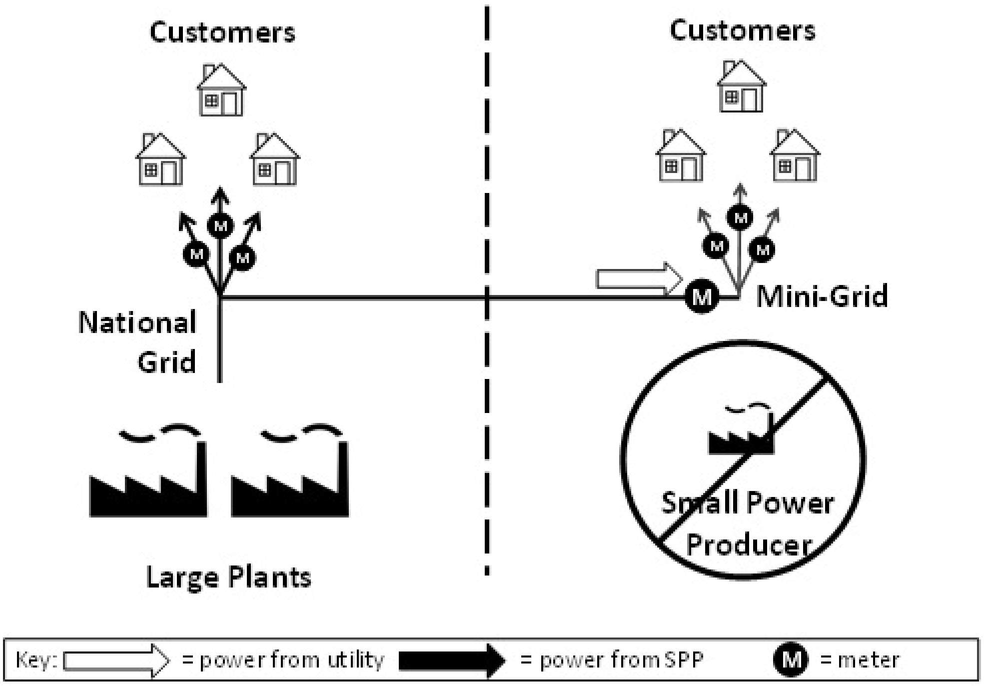
Tanzania was the first country in Africa that allowed the SPD option for mini grids upon main grid arrival. Under Tanzania's SPP rules issued by the Tanzanian Energy and Water Utilities Regulatory Authority (EWURA 2017, Section 36 (1)), mini grids that meet technical standards are explicitly allowed to apply to EWURA for the right to operate as:

- An SPP selling to the national grid
- An SPD that purchases electricity in bulk from a DNO connected to the main grid and then resells that electricity to the SPD's retail customers
- A combination of an SPP and an SPD

But the option of converting from a mini grid to an SPD, while promising on paper, will be a non-option unless the SPD has the potential to be commercially viable. Therefore, the rules state that SPDs will be allowed to charge a retail tariff that provides a sufficient margin for an efficient SPD to be commercially viable (Section 37(1) EWURA 2017). But even when this option is legally permitted, it may not be politically feasible because households in the villages now connected to the national grid will argue that they are entitled to the same low tariffs as households served by the national utility in neighboring villages or in cities. If the national utility's retail tariffs are a *de facto* cap for an SPD, then the only available option would be to subsidize the SPD's operating or power purchase costs so it can profitably sell electricity at the national utility's retail tariff. Three delivery mechanisms for such subsidies are described in Appendix 2.

The case of a mini grid converting to an SPD is shown below in Figure 5. The distribution system that had served the isolated mini grid continues to sell electricity to the same customers, but now this electricity comes from the national grid network rather than from the mini grid's isolated generator.

Figure 5: The Small Power Distributor (SPD) Option



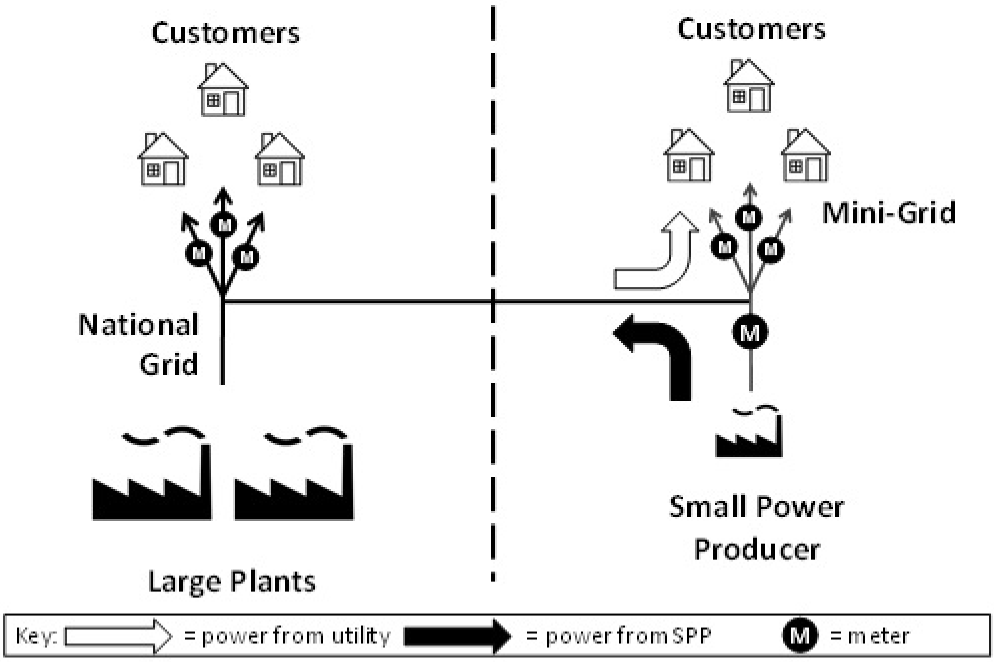
In the SPD option the mini grid system obtains bulk electricity from the national utility for local distribution. Source:(Greacen, Engel, and Quetchenbach 2013).

If regulators allow mini grids to become SPDs, care must be taken to ensure that the distribution system is built or retrofitted to a standard that can accommodate interconnection with the national grid (Jaap du Preez 2011; Moncef Aissa 2011). If the developer cuts corners to save money on the cost of installing the initial distribution system, then this system will need to be upgraded when the isolated mini grid becomes connected to the main grid. Or if upgrading is not feasible, the existing distribution system may even need to be ripped out and totally replaced when the SPP gets connected to the main grid.

4.2 Small Power Producer (SPP) Option

When the main grid arrives, some mini grids may prefer to leave the retail sales business and only sell electricity at wholesale to the national grid (see Figure 6)

Figure 6: SPP Option



The SPP generator interconnects with the main grid, becoming another power plant on the grid. The utility takes over distribution of electricity to retail customers. The arrows in this case indicate contracted power flow, not necessarily the flow of electrons. In this case, the SPP is only selling electricity at wholesale to the main grid. It may be the case that some electrons actually flow to the village customers, but this does not really matter—all that matters is that the electricity injected into the grid by the SPP offsets an equal amount that the national grid's other plants would have had to produce. Source: (Greacen, Engel, and Quetchenbach 2013).

Whether a mini grid can make the transition grid to the main grid as an SPP and remain financially viable depends crucially on three factors: the cost of electricity production by the SPP, the feed-in tariff (FIT) that the SPP now connected to the main grid will receive for sales of electricity to the national utility, and the capacity factor at which the SPP will be able to operate.

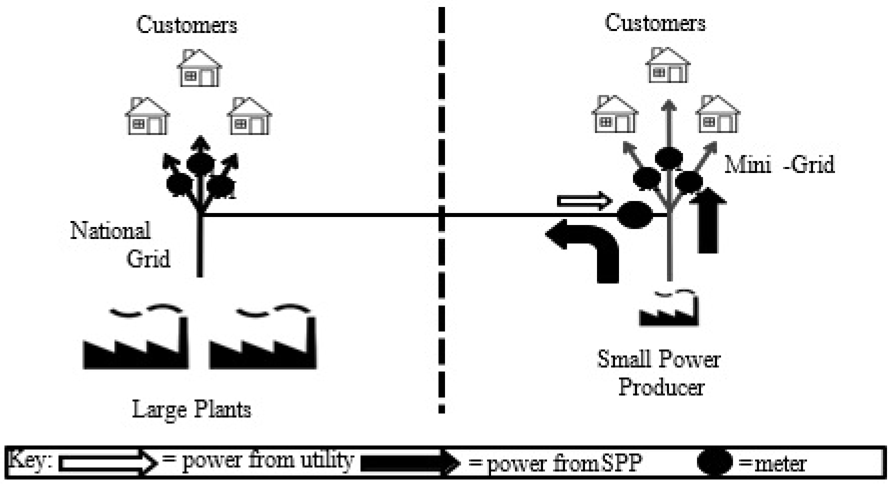
For some SPP generators such as small hydropower projects, the cost of electricity production can be sufficiently low to compete with conventional generation on the main grid, especially after the bank loans have been paid off. For example, one small hydropower project in southwestern Tanzania provides electricity to complement an existing diesel mini grid operated by Tanzania Electricity Supply Company (TANESCO). Tanzania has a dual feed-in tariff policy FIT system: a high tariff is given for sales to TANESCO on one of its existing mini grids and a lower tariff for sales to TANESCO on the main national grid. Until the national grid expanded into the area, the SPP generator received the mini grid tariff, which in 2012 was a lucrative 480 T Sh/kilowatt-hour (kWh) ($0.305/kWh) (EWURA 2012). But once the grid arrived, the project sold electricity at the much lower national tariff of about 152 T Sh/kWh ($0.097/kWh).

The issue of the capacity factor plays an important role and may mitigate lower tariffs for on-grid operation. An isolated mini grid it is only able to sell as much electricity as is being demanded by its relatively small number of customers at any moment. Typically, in the middle of the night the demand on a mini grid system is low, as most residents in the local community are asleep and their appliances are turned off. For a grid-connected SPP, however, the national grid is generally able to absorb full power output from an SPP 24 hours a day. The ability to operate at a greater capacity factor means many more kilowatt-hours are sold, helping to partially or even fully offset the impact of lower tariffs.

4.3 Combined SPP and SPD Option

In the combined SPD and SPP option (Figure 7), the SPP plays both roles discussed in the two preceding options: it sells electricity to retail customers, as well as generates electricity for sale to the national grid. This option should be encouraged in countries that face shortages of generation capacity on their main grids while also facing the challenge of extending rural electrification services to a greater portion of the population; or in areas where the local distribution grid is weak and brownouts or blackouts are common.

Figure 7: Combination SPP and SPD



The arrow indicating ‘power from utility” is drawn smaller, representing the fact that electricity purchased from the national grid is reduced (because of the power flowing directly to mini grid customers from the SPP). In some periods of the day electricity flow from the national grid may cease completely with all local customer load being covered by the SPP. Source: (Greacen, Engel, and Quetchenbach 2013).

Electricity sold to retail customers can come from either the mini grid’s generator or as electricity purchased wholesale from the national utility. In this regard, there is a wide spectrum of possibilities, and the position of a given project on the spectrum may shift over time. To take a real-world example, the 4 MW Mwenga hydropower project in Tanzania (commissioned in October 2012) generates most of its electricity for sale to the grid but also supplies essentially 100 percent of the electricity used by retail customers. As the project expanded from its initial 900 customers to include 5,600 (expected) retail customers spread over 32 villages, the portion of electricity consumed by retail customers will increase and the portion sold to the grid will decrease. This combination SPP/SPD purchases wholesale electricity from the grid only when the hydropower project is shut down for maintenance, or (more likely) for reconnection times of short duration (15 minutes or less) when a disturbance on the national utility grid forces the hydropower project to trip offline. At the other end of the spectrum, diesel generators—inexpensive to own but expensive to operate—provide backup power in villages or for crucial loads (hospitals, mobile-phone repeaters, military bases) that require very reliable electricity or that suffer from frequent grid blackouts.

4.4 Side-by-side but not interconnected

In the “side-by-side” or “co-existence” model (see Figure 8), the mini grid continues to serve customers even when the grid arrives, with no electrical interconnection between it and the main grid, even though both operate in the same village.

In 40–50 villages in Indonesia, community-owned mini grids continue to sell electricity on the mini grids' distribution systems, which remain physically separate from the national utility, PLN. These mini grids appear to have survived because their tariffs are lower than the tariffs charged by PLN or because many rural households were unwilling or unable to pay the high fees required to connect to the main grid.

In Uttar Pradesh in India the national utility has intermittent electricity (in some areas sometimes only a few hours a day), but when it is available it is inexpensive. In these villages it is not uncommon for mini grid companies to set up mini grids and households receive electricity from both sources. In some cases, certain lights and other circuits in a household are powered by the mini grid while others are powered by the national grid. In other cases, the house has a manual transfer switch that switches circuits from one source to the other.

Figure 8: Side-by-side

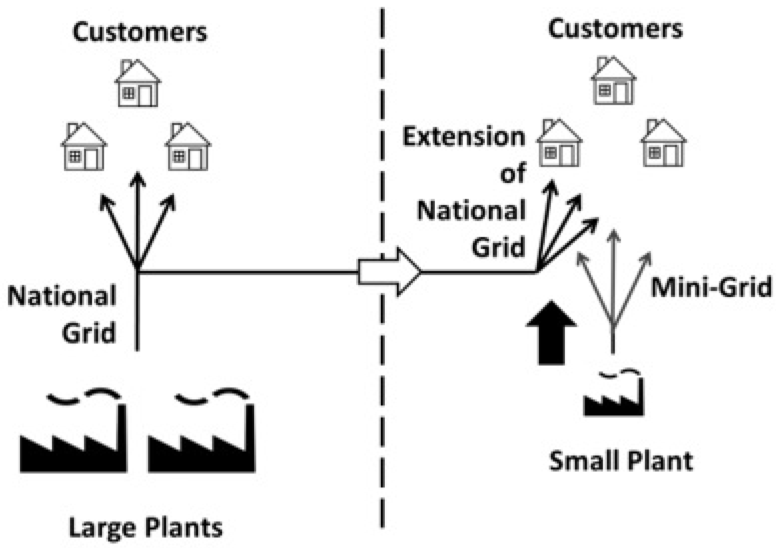


Figure 8: Side-by-side

Source: (Greacen, Engel, and Quetchenbach 2013).

Source: (Greacen, Engel, and Quetchenbach 2013).

4.5 Buyout Option

In the buyout option, the utility purchases and operates the existing mini grid distribution network and possibly the generator (see Figure 9).

Figure 9: The Buyout Option

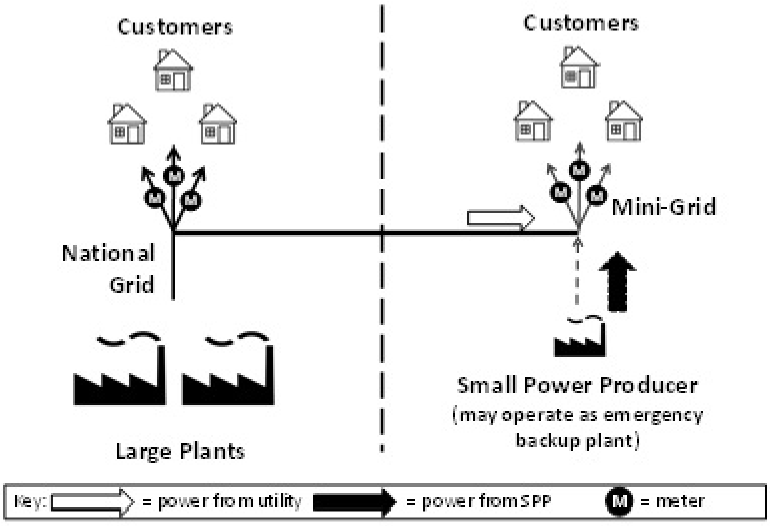


Figure 9: The Buyout Option

Source: (Greacen, Engel, and Quetchenbach 2013).

Source: (Greacen, Engel, and Quetchenbach 2013).

This option may make sense if the following criteria are met:

- The mini grid is built to engineering standards comparable to the standards used in the utility's own distribution assets
- The utility has the interest and local human resources to operate the newly acquired mini grid including bill collection, new hookups, maintenance, and dispute resolution

In the buyout option, which assets (distribution system assets only or distribution system and generator assets) are to be sold at what cost would need to be worked out on a case-by-case basis.

In Nigeria, if the main grid arrives within five years after the mini grid becomes operational and the mini grid has obtained a permit from the regulator, the developer has the right to financial compensation under a compensation formula specified by the Nigerian Electricity Regulatory Commission. The formula includes compensation for 12 months of lost revenue as well as a discounted depreciation of its generation and distribution assets.

In Tanzania, only the distribution assets (poles and wires) are eligible for compensation, assessed at the value that it would cost to replace them minus a 4% annual depreciation. Moreover, compensation is only provided for the portion of distribution capital costs that were not financed through grants.

4.6 Assets Abandoned

The final option (not likely to be attractive to the mini grid operator) is that the mini grid assets are scrapped or moved to another location and the national utility treats the area like a greenfield site, building a new distribution system (see Figure 10). If the quality of the mini grid is below standard and it is not cost-effective to upgrade it, this may be the only option available. In Thailand, for example, of 59 village-scale micro-hydropower mini grids installed after 1983, 34 were abandoned by 2004. The vast majority of these communities (31 villages) were connected to the main grid and received completely new distribution systems from the country's rural distribution utility, the

Provincial Electricity Authority (PEA) (Greacen 2004).

Figure 10: Abandonment.

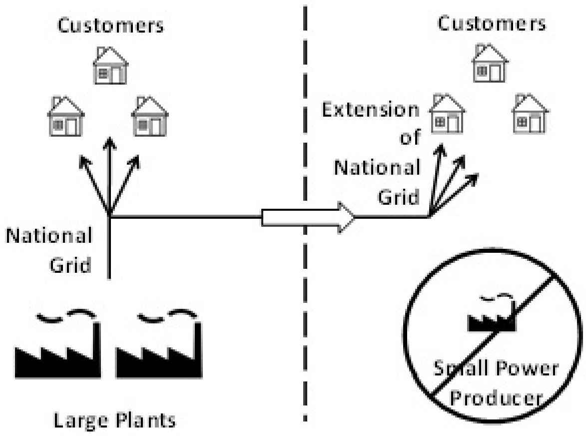


Figure 10: Abandonment.

Source: : (Greacen, Engel, and Quetchenbach 2013)..

Source: : (Greacen, Engel, and Quetchenbach 2013)

5. Technical Aspects integrating mini grids to the national grid[3]

As discussed in the previous section, a supportive mini grid regulatory framework provides one or more options when the main grid reaches its doorstep. The operator can connect its generating assets to the grid, becoming a small power producer (SPP). It can purchase electricity from the grid and resell it to consumers using the existing distribution network, becoming a small power distributor (SPD). It can do both, becoming both an SPP and an SPD. It can operate as an SPD when the main grid is operational, maintaining its generating assets only for backup use when the main grid is down. Finally, the mini grid operator can abandon all its generating and distribution assets, requiring its customers to start from scratch with the main grid.

The fate of the generator and mini grid distribution assets under each option are summarized in Table 1.

Table 1: Use of Generator and Mini grid Distribution Assets in Each Option

Option	Generator	Mini grid distribution network
Small power distributor (SPD)	Scrapped or relocated	Used by SPD to resell electricity purchased at wholesale
Small power producer (SPP)	Used to sell electricity to main grid	Either no longer used, or used by the utility to sell electricity to retail customers
SPP and SPD	Produces electricity for retail sales and to sell to the main grid and/or used as backup supply source	Used to supply electricity to the SPP's/SPD's retail customers
Side-by-side but not interconnected	Continues to produce electricity for retail sails	Continues to be used to supply electricity to retail customers
Buyout	No longer used or sold to utility	No longer used or sold to utility
Abandoned	Scrapped or relocated	Scrapped

5.1 Technical requirements for SPD or buyout option

For a rural mini grid to connect to the national grid (as an SPD, or if its assets are purchased in the buyout option) a step-down transformer will need to be installed that converts electricity from medium voltage (MV) to the low voltage (LV) distributed over the mini grid wires. This transformer and its installation will have to conform to standards employed by the national utility. In addition, the mini grid's power distribution system including poles and wires will require conformance with utility standards.

Key areas covered in relevant standards for distribution lines include consideration of:

- safety distances and protection corridors
- conductor phase and configuration (delta or wye)
- conductor size and composition
- proper insulators and line accessories
- selection of circuit breakers to accommodate increased breaking capacities
- lightning protection
- switching equipment
- poles
- pole stays
- cable cross-section
- cable layout
- cable joints and terminations
- grounding practices
- meters and boxes

An extremely helpful step that utilities can perform (perhaps requiring encouragement or a formal order from the regulator) is to maintain an updated copy of relevant rural electrification technical standards on the utility's Web site. An example of this is Vietnam's "Technical Regulations for Rural Electrification/Electric Network" (Socialist Republic of Vietnam, Ministry of Industry 2006). Making national rural electrification standards accessible to mini grid developers makes it easier for developers to elect to build distribution systems that are compliant and are suitable for interconnection or resale to the utility.

Even if interconnection with the national grid is not expected, safety and reliability concerns warrant consideration of minimum technical requirements for mini grids. Examples of these include Sri Lanka's Village Hydro Specifications (ESD/RERED Government of Sri Lanka 1999) and the International Electrotechnical Commission (IEC)'s *82-62257-9: Recommendations for Small Renewable Energy and Hybrid Systems for Rural Electrification* parts 9-1 through 9-4 (IEC 2006).

5.2 Technical requirements for connecting as an SPP

The SPP option (which involves connection of distributed electric generation resources with the grid) is technically considerably more challenging than the SPD option.

For a formerly isolated mini-grid to operate in a grid-connected mode, it must be reconfigured in ways that accomplish the following tasks:

1. Remove or disable equipment that modulates fuel supply (for example, water flow in a

hydropower project) or conducts load diversion in response to frequency variations. In systems where intentional islanding capability (see chapter 4) is desired, this equipment may be left in place with controls to allow it to be temporarily enabled during islanded operation. Change the control mode of the AVR from voltage control to power factor control, if appropriate.

2. Connect safely to the grid. (This is generally an issue of connecting at the correct frequency and phase.)
3. Inject electricity of sufficient quality (appropriate power factor and voltage, low total harmonic distortion).
4. Disconnect quickly and safely from the grid in appropriate circumstances (when a disturbance is detected on the grid) and reconnect when it is safe to do so.

With these changes, the grid-connected small power producer relies on other (generally much larger) generators in the electric power system to maintain frequency regulation. However, if frequency or voltage on the grid at the site of interconnection deviates sufficiently from agreed-upon standards, the small power producer is programmed to disconnect from the grid.

5.2.1 Frequency and voltage control in isolated and interconnected mini grids

The fundamental technical differences between isolated and grid-connected systems with local generating assets are the means of control of frequency and voltage. In an isolated mini grid, the renewable electricity generator must control both frequency and voltage. For a rotating generator, frequency is determined by the rotational speed of the generator shaft, while voltage depends on the changing magnetic flux through the generator's stator windings as the generator's rotor spins. In a stand-alone synchronous generator, frequency is kept constant by a regulator (governor) and voltage is varied by increasing or decreasing the strength of the rotor magnetic field. Typically, voltage is controlled by an automatic voltage regulator (AVR), which can be configured to maintain either constant voltage or constant power factor. In an isolated mini grid, the AVR is configured for constant voltage. In an inverter these functions are accomplished through carefully timed solid state switching of power transistors.

On the main grid, frequency is stabilized by the rotational inertia of very large generators. When connected to the grid, a small generator will spin at the grid frequency (or slightly above grid frequency if it is an induction generator). Thus, a grid-connected small generator makes no attempt to regulate frequency; it just injects current in step with the grid's frequency.

Regulation of voltage by a grid-connected distributed generator often depends on the preference of the utility's distribution engineers. A key difference is that whereas frequency is a variable that is constant across the whole utility electric power system (and thus subject to control throughout the system by a few large generators) voltage varies from node to node throughout the system depending on the distribution of loads, generation, and power factor correcting capacitor banks. In some locations, utilities may prefer that a distributed generator operate its AVR to keep a constant power factor (power factor control mode). This helps ensure that the utility's efforts at regulating voltage (often through capacitor banks, load tap changers, and voltage regulators) are not complicated by the distributed generator simultaneously adjusting its AVR to also regulate voltage. In other cases, particularly in parts of the distribution system where utilities do not have good voltage regulation, the utility may ask the distributed generator to regulate voltage (operating its AVR in voltage control mode). Utilities often make this determination on the basis of a power flow study, in which the system voltages, currents, and power flows are modeled under minimum and maximum load conditions with the addition of the proposed distributed generator.

5.2.2 Dispatchability

Due to their small size relative to other generators on the grid and the intermittent nature of most renewable energy resources, renewable energy generators are generally not considered dispatchable assets that can be taken on- or off-line or ramped up or down as needed by the utility. However, as renewable distributed generators come to make up a larger fraction of total resources on the grid, their intermittent and irregular power production profiles can contribute to grid instability. Where this is demonstrated to be an issue, small power producers and the main grid operator may make provisions for dispatchability or provide an incentive system that encourages SPPs to match utility load patterns through pricing signals. Increasingly, grid-connected solar projects in the scale of hundreds of kilowatts to tens of megawatt scale also include battery storage to allow for dispatchable power several hours after the sun has set.

5.2.3 Islanding

Islanding refers to the condition when a portion of the grid becomes temporarily isolated from the main grid but remains energized by its own distributed generation resource(s). Islanding may be unintentional or intentional. Unintentional islanding, a potentially hazardous condition, occurs when a distributed generator fails to properly shut down during a grid disturbance. However, with appropriate safety and control mechanisms, intentional islanding can be used to provide reliable service to mini-grid customers in locations where the utility grid is unreliable.

5.2.3.1 Unintentional islanding

Islanding has traditionally been seen by utilities as an undesirable condition, as it can a) present a hazard to lineworkers who might assume the lines are not energized during a failure of the central grid, b) deny central control over power quality, and c) damage utility or customer equipment at time of reconnect if not properly coordinated. Utilities' concerns about unintentional islanding have been a major impediment to the widespread adoption of distributed generation. For the most part, these concerns have been addressed through anti-islanding features in grid-interactive inverters and the provisions included in standards such as Underwriters Laboratories (UL) 1741 and IEEE 1547.

Islanding detection methods are broadly classified as passive or active. Passive islanding detection methods (used with both inverters and rotating generation) include detection of over/underfrequency, over/undervoltage, rate of change of frequency, voltage phase jump (voltage vector shift), and reverse reactive power flow (reverse VAR) (Bower and Ropp 2002; Alternate Hydro Energy Center, Indian Institute of Technology Roorkee 2008). In active methods, commonly incorporated into grid-interactive inverters, the inverter constantly attempts to drive the voltage and/or frequency outside the acceptable range using positive feedback (Bower and Ropp 2002; Ye et al. 2004). If the inverter is connected to a larger grid, it will be unable to change the grid voltage or frequency; if the system is islanded, the voltage and/or frequency will rapidly be driven outside the normal range and the inverter will shut down.

Other techniques, such as transfer trip schemes and phasor measurement units (PMUs), are available to avoid unintentional islanding. These techniques require a dedicated telecommunications link between the SPP's protective equipment and the utility, adding significant cost and complexity to the protection system. Requirements for transfer trip and related systems may present a significant barrier to grid interconnection of small rural power systems. Utilities and regulators should be encouraged not to require these methods unless there is a demonstrable need to protect utility equipment that cannot be protected using traditional protective equipment.

5.2.3.2 Intentional islanding

There are circumstances under which islanding operation may be desired. In the case of a mini-grid being integrated with a central grid that has historically shown itself to be prone to reliability problems, the mini-grid interconnection may be designed in a way that permits the mini-grid to continue operating autonomously and provide uninterrupted service to local customers (and uninterrupted revenue to the mini-grid operator) during outages on the main grid; this capability is known as intentional islanding. Policy regarding grid interconnection of previously autonomous mini grids should allow for maintaining future capability to operate autonomously, provided this can be done safely. The IEEE standard 1547.4-2011 specifically addresses power systems that include intentional islanding.

Implementing intentional islanding requires that the system perform several steps, reliably, in correct sequence and timing:

1. The distributed generator must recognize an abnormal condition on the utility grid and disconnect a circuit breaker located at an appropriate location to separate the generator and islanded mini-grid load from the main grid.
2. Upon disconnecting, the distributed generator must immediately switch from “synchronized mode” to “autonomous mode” engaging controls to regulate frequency. In the case of a hydropower project, this may mean turning on a resistive ballast load controller or other means to keep the turbine spinning at the correct speed. The generator’s automatic voltage regulator (AVR) controls may need to switch over immediately to operate in a different mode. For example, if the AVR was operated in a power factor control (pfc) mode when connected to the main grid, it will need to switch to voltage control mode. In addition to the generator configuration, the settings of various protective relays will likely need to be different in islanded mode, or separate relays employed, since small generators (particularly inverters) typically produce less fault current than large generators on the main grid and voltage or frequency tolerances may need to be broader in island mode. Similarly, inverter-based generation may need low-voltage ride-through (LVRT) and frequency ride-through (FRT) capability to continue operating during voltage disturbances due to faults or sudden load changes, especially while the grid is transitioning to islanded mode (Institute of Electrical and Electronics Engineers 2011).
3. The system must continue to sense line voltage on the main grid, and when main grid power returns to stable conditions, initiate reconnection, and return to control regimes (e.g. letting the grid control frequency) appropriate for grid-connection. Before reconnection, the mini-grid’s generation must be synchronized[4] with the main grid (Institute of Electrical and Electronics Engineers 2011).

The protective relay settings governing intentional islanding must be selected based on the local grid operating conditions and coordinated with the utility’s protective relays. Separating from the main grid at minor disturbances may lead to lost opportunities for revenue generation from selling power to the utility. On the other hand, staying online “too long” and only disconnecting at more extreme disturbances on the grid can lead to cases in which the distributed generator and mini-grid voltage and frequency sag excessively, leading to brownouts and blackouts with possible equipment damage.

Similarly, settings for what constitute “stable conditions” on the main grid for reconnection must take into account the timing and effects of reclosers, if they exist on the main grid’s feeder to which the distributed generator reconnects. When a line is disconnected after a fault, a recloser will automatically re-energize the line after a short delay. The distributed generator’s controls must (a) disconnect the generator fast enough to avoid being online when a recloser energizes the circuit; and (b) wait to resynchronize until grid voltage and frequency are stable (typically a few cycles).

5.3 Interconnection requirements for different generator types

AC electricity is typically produced from one of three types of device: induction generators, synchronous generators, or inverters. Each of these have specific characteristics that require consideration if interconnecting to a main grid. Each offers different advantages in terms of possibilities for interconnecting and islanding and each requires different protective devices to interconnect with the main grid.

5.3.1 Induction (asynchronous) generators

Induction generators are used for some wind turbines small hydropower schemes, including off-grid systems from 1 kW or less up to 100 kW or more, and grid-connected systems up to at least 1 MW (CADDET Centre for Renewable Energy 1997). Hydropower systems under 10 kW widely use re-purposed induction motors as low-cost generators, especially in Asia (Ekanayake 2002).

Induction generators are usually less expensive than synchronous machines, and there are no brushes or commutators to wear out. Grid interconnection requires simpler protective equipment, since induction generators do not need to be synchronized with the grid before being interconnected. To connect an induction generator to the grid, the generator is connected through a “soft starter” to limit inrush currents and run up to synchronous speed (Small Hydro Action for the Promotion of Efficient Solutions (SHAPES) 2008), or, for generators small enough that inrush currents won’t trip breakers, the generator is simply connected at dead standstill and grid power is used to operate the generator as a motor, bringing it up to synchronous speed. Power is transmitted to the grid as long as the generator turns faster than the synchronous speed. Below the synchronous speed, the generator acts as a motor and consumes power.

Induction generators require reactive power from the grid or from capacitors to generate a magnetic field and induce current in the generator’s rotor; thus, induction generators cannot produce electricity without an external source of current. Capacitors located near the generator reduce the reactive load on the grid. To avoid operating without a grid connection (unintentional islanding), induction generators are typically supplied with a capacitor bank smaller than would be necessary for self-excitation at grid frequency, requiring the grid to supply some reactive power, but less than would be required without capacitors (World Bank 2012). If the induction generator has a capacitor bank that is “too small,” self-excitation will still occur, but at a higher rotational speed and higher frequency. This higher frequency will trip a frequency relay, disconnecting the generator.

5.3.2 Synchronous generators

In a synchronous generator, the frequency of the output is directly related to the rotational speed of the rotor—at a given speed, the generator will always produce the same frequency. Synchronous generators are commonly used in isolated mini-grids, since they do not require a supply of reactive power from the grid and can self-start with no external supply of reactive power. Synchronous generators have an advantage over induction generators in that a synchronous generator’s AVR can directly control power factor by supplying reactive power to the grid if needed, providing additional voltage support.

Before connecting to the grid, the voltage output from a synchronous generator must be synchronized with the grid voltage. The generator frequency and the grid frequency must be the same, and the two waveforms must be in phase (the peaks must exactly line up); if the waveforms are not synchronized, large currents will flow and the generator will be severely damaged. Synchronization can be manual or automatic. Manual synchronization is rarely used with large generators (> 100 kW) and requires a skilled operator, but can at times be used as a backup to an automatic synchronization system (Institute of Electrical and Electronics Engineers 2009). The need for synchronization means that the protective relays and equipment required for interconnection of a synchronous generator are somewhat more complex than for an induction generator. For more on these details, please see (Greacen, Engel, and Quetchenbach 2013).

5.3.3 Inverters

Inverters are solid-state electronic devices that convert DC power to AC. Since solar PV modules produce DC, inverters are an essential component of these systems. Inverters are also used in some wind power systems, in which the generator coupled to the wind turbine generates power at varying frequency (depending on the wind speed), which is then converted to DC and back to AC at the grid frequency.

There are two basic types of inverters: grid-interactive (grid-tie or synchronous) and standalone (or off-grid). In grid-interactive inverters, the grid controls both frequency and voltage. These inverters are designed to export power to the utility grid and incorporate many of the functions traditionally performed by protective relays, including synchronization, over/undervoltage protection, and frequency protection. Exporting power to the utility grid requires a grid-interactive inverter; however, most grid-tie inverters cannot operate without a grid connection and will shut down if one is not present. (That is, most grid-tie inverters do not support intentional islanding.)

A standalone inverter regulates its own frequency and voltage and can operate without a grid connection. Some standalone inverters allow the grid to be used as a backup for the renewable generation (or, alternatively, allowing the renewable generation to serve as a backup when the grid is down), but the inverter cannot be paralleled with the grid: either the inverter is providing power to the AC loads, or the grid is providing power and the inverter is switched off. These inverters have separate terminals for the grid connection and for the AC loads; connecting the load terminals of a standalone inverter to the utility grid will damage the inverter. In many cases, standalone inverters with grid connection terminals allow intentional islanding of the mini grid, but do not allow the SPP to sell power to the utility.

Some inverters can operate in both standalone and grid-interactive mode, allowing both grid export and off-grid (intentionally islanded) operation.[5] These inverters offer the most flexibility, allowing both intentional islanding and power export. In addition to the main grid connection, some of these inverters (including the SMA Sunny Island) allow other inverters or small induction generators to be connected to the AC load bus; this feature allows the construction of AC-coupled mini-grids using a variety of energy sources. As with standalone inverters, these dual-function inverters generally have separate terminals for the grid connection and the AC loads, and incorrect connection will result in damage to the inverter.

With standalone inverters, including those capable of grid-interactive operation, the AC load on the mini-grid is limited by the capacity of the inverter. Multiple inverters can also be added in parallel on the AC bus to accommodate higher capacities. To accommodate multiple-phase loads in larger systems, a three-phase inverter can be used, or alternatively three single-phase inverters can be networked together with one on each phase.

When adding a grid connection to an existing inverter-based mini-grid, it is important to determine whether the existing inverter can be connected to the grid. Since standalone inverters without grid-interactive functionality cannot synchronize their output to an external voltage source, connecting the load terminals of a standalone inverter to the utility grid will damage the inverter. Standalone inverters that support grid connection generally have dedicated grid input terminals. The inverter manufacturer's specifications should be consulted to determine whether the inverter can be connected to the grid or other AC generators, and the connections should be made by a qualified installer. If the inverter is capable of on-grid operation, grid integration is literally as simple as connecting the inverter terminals to the main grid through an appropriate overcurrent-protected switch.

Unlike rotating machines (synchronous and asynchronous generators), which generate a relatively pure sine wave output using rotating magnetic fields, inverters synthesize a sine wave using solid-state electronic components. If the synthesized waveform is not exactly a true sine wave, current is introduced at frequencies that are multiples (harmonics) of 50 or 60 Hz, depending on the local utility frequency. This phenomenon is called *harmonic distortion*. Transformerless inverters may inadvertently introduce DC current into the grid, a process referred to as *DC injection*. These abnormal currents can damage utility transformers and other system components and can cause problems for other utility customers; thus, grid-tie inverters must meet strict requirements for power quality, including limits on total harmonic distortion and DC injection.

5.4 Functions of common relays used in interconnecting small generators.

Protective relays detect abnormal conditions, including short circuits and overloads, and operate circuit breakers to isolate the malfunctioning system components, preventing damage to the generator and to transmission and distribution system components. Small induction generators connecting at low voltage generally require over/undervoltage and over/underfrequency protection, while synchronous generators also need synchronizing check and over/under-current relays. The operation of protective relays for a generator must be coordinated with that of relays and reclosers in the utility's transmission and distribution system; for example, time-overcurrent relays can be used to disconnect a generator quickly when a fault occurs near the generator while allowing sufficient time for the utility's relays to disconnect a distant fault.

5.4.1 Discrete vs. multifunction relays

Originally, protective relays were electromechanical devices, and these electromechanical relays are still manufactured. These relays were discrete--each one performed a specific task, and a given installation required several different relays. Many protective relays now use solid-state electronic components controlled by microprocessors. A major advantage of the microprocessor-based design is that the functions of many discrete relays can be incorporated in a single package. Multifunction protective relays can provide most or all of the functionality needed to protect a small synchronous or induction generator for approximately US$1000-1500. For a single-phase induction generator, depending on utility requirements, a combined over/undervoltage and frequency relay may provide sufficient protection for approximately US$500.

5.4.2 Technical standards for interconnection.

Several internationally recognized standards, including several IEC standards and the IEEE 1547 family of standards, guides and recommended practices, are commonly used or referenced as part of interconnection processes in developing countries. However, implementation of such standards without modification in a developing economy may be problematic, given lack of testing facilities, equipment, and trained technicians and engineers familiar with these standards. Regulators may choose to adopt modified standards in accord with available resources, as has been done in some countries.

5.5 The Interconnection Process

Codes, standards, and utility policies regarding grid interconnection vary among countries and regions. In many countries, especially in the developing world, these norms may or may not yet be well defined. In cases where they are not, interconnections are left to be resolved on a case-by-case basis, made without official sanction, or abandoned as infeasible.

Private or state-owned utilities may be unfamiliar with engineering standards and administrative processes for making interconnections. In some cases, utilities may view small generator interconnection as burdensome or as a threat to their monopoly and actively oppose it. Standards that address such utility concerns while treating distributed generators fairly do not need to be created from scratch. Policies already in effect or proposed in countries including Tanzania, Kenya, Sri Lanka, Thailand, Rwanda, Nigeria, and Vietnam, sometimes in the form of a "grid code" or "distribution code," offer models that can be adapted. A simplified interconnection policy may be used for small power producers; such a policy should cover:

1. the application process,
2. who is responsible for analysis and approval of interconnections,
3. responsibility for payment and construction,
4. safety and protection requirements,
5. a testing and commissioning procedure, and
6. communications and data exchange between the SPP, the utility, and the regulator.

Several developing countries have created advanced policies that are helping accelerate adoption of grid-connected renewable energy, including village mini grids. Key countries with mini grid interconnection policies in various stages of development include Thailand, Tanzania, India, Kenya, Sri Lanka, and Bhutan. In addition, some policies in the industrialized world, including Japan, Europe, and the USA, may be transferable or adaptable to developing countries. Model policies for grid interconnection have been developed in the USA by several public and non-profit entities. Of the four major model policies, all or most agree on essential points: holding all technologies to a uniform standard, including all generators up to 10 MW, using nationally recognized engineering standards (i.e., IEEE and UL), and not requiring additional insurance for distributed resources.

Application for interconnection. The process of applying for interconnection should be as straightforward and transparent as possible. At the same time, the process must ensure the utility and regulatory agency are provided with sufficient information from the small power producer to ensure a safe, reliable, and accurately metered utility interconnection.

Utility approval. Utility approval processes for interconnection typically employ a series of screens, questions whose answers determine which procedural pathway the power producer must follow to interconnect its system. Failing to pass individual screens results in a progressively more rigorous and costly approval process for interconnection. One important screen found in almost all interconnection procedures is system size (generating capacity), with smaller systems qualifying for a simpler and usually speedier process.

Responsibility for implementation: utility or small power producer? In many developing countries, regulators have established renewable/distributed energy goals and guidelines requiring utilities to give small generators access to utility distribution systems, but the utilities often give this lower priority than conventional electrification strategies of expanding central generation and transmission and distribution systems. To resolve this impasse, utilities in many countries now allow small power producers to take the lead on installing all of the lines, switchgear, and transformers needed to make the interconnection.

Commissioning and testing, periodic inspection, and metering. International standards, including IEEE 1547, call for a commissioning or testing procedure to be performed by a qualified engineer once interconnection equipment is installed and ready for operation. This policy is typically echoed by regulators and utilities. Follow-up after interconnection may include an annual reporting requirement on the generator's part or a clause reserving the utility's right to perform on-site inspections as needed. Metering at the point of common coupling where utility assets meet mini grid operator's assets may use simple analog meters that are read manually, but use of digital transmitting meters is increasingly common and can help with early detection and repair of system faults.

6 Mini grids and the national grid in Northeast Asia

The electric power industry should maintain and reinforce the self-supporting power generation bases, and direct a great deal of efforts to developing new power sources. Provinces should build power generation bases to suit their local features and put power generation at the existing medium and small-sized power station on normal footing to satisfy the needs of electric power for local industry by themselves. -- Chairman Kim Jong Un, 2018 New Year Address

Source: (38 North 2019)

Mini grids and decentralized electricity generation can be part of a comprehensive rural electrification and electricity sector strengthening strategy for the Northeast Asia that increases electricity access and strengthens reliability. For rural communities that currently have no electricity, mini grids can provide electricity many years faster than conventional grid expansion. For communities that currently are connected to the national grid but have intermittent service, mini grids can provide reliable electricity for times when power is otherwise not available. This can especially be important for critical loads like hospitals where lack of electricity can mean the difference between the life and death of a patient.

Mini grids can help utilities to defer expensive upgrades in cables and substations. For example, in Mae Hang Song, Thailand, a solar mini grid with battery storage allowed the national utility to postpone upgrading a long MV line that had become insufficient for a growing population (Srithiam, Asadamonkol, and Sumranwanich 2015). In the Orcas Power and Light Cooperative (OPALCO) utility in Washington State in the USA, a grid-intertied 500 kWp solar mini grid with battery storage is used to reduce peak wholesale electricity costs and also serves as emergency backup with the ability in the future to route electricity to priority loads such as the local hospital (OPALCO 2018). Funds for the project came from 270 customer-members who bought shares in the project and whose electricity bills are offset by the solar panel power production.

Solar panels, which are available at historically low prices of \$0.25 per Wp or lower in China (PV Magazine 2019) can provide valuable and affordable electrical insurance against droughts that have historically reduced hydropower output in the DRPK and other countries around the world. During sunny dry summers when water is scarce, solar panels produce their maximum. Electricity generated by grid-connected solar panels can keep water behind the reservoir and thus available later in the season. Some jurisdictions are installing solar panels on the reservoirs themselves, where “floating solar” need not take up dry land area and also helps cover the reservoir surface, reducing evaporation (ESMAP 2018).

While a geospatial study is necessary to determine the full extent of the opportunity, it is likely that mini grids with electricity storage can provide electricity to many Northeast Asian communities that lack sufficient electricity supply. If electricity is available only during some hours of the day (e.g. in the middle of the night) mini grids connected to the national grid can combine renewable energy sources such as solar electricity together with intermittently available grid electricity to charge storage batteries that enable 24-hour electricity availability.

Rural electricity through mini grids offers opportunities for rural economic development and improving the quality of life, reducing drudgery of work, and reducing the burden on forests for fuel. Specific areas for electrification through mini grids include:

- Household, commercial and industrial lighting
- Electric powered tools for manufacturing, agricultural processing, and construction
- Heat pumps for electrical heating
- Electric powered vehicles and farm equipment reducing reliance on scarce and expensive imported diesel and petrol.

Communities that are within a kilometer of a stream with falling water[6] are possible candidates for micro-hydro powered mini grids, which can produce electricity at levelized costs even lower than solar. Once the national grid arrives, these can be connected and augment the national grid, helping reduce the need for large centralized power plants. Hydropower turbines at these scales are apparently already being installed in the DPRK (North Korean Economy Watch 2013) and also available at relatively low prices in China.

In addition to meeting existing needs, mini grids will help with the resilience of the grid to natural disasters such as floods and droughts. The ability of a mini grid to island provides for villages and towns to maintain power supply even if cut off from the national grid by broken powerlines from a winter storm or earthquake. This can minimize disruption in the towns' economy and allow for uninterrupted service especially to crucial loads like hospitals.

7 Conclusions

International experience with mini grids suggests that there are ten building blocks to increasing deployment of mini grids at scale. Not all of these have been discussed at length in this paper, but some version of all of these will play a role if mini grids are to be deployed at scale in the Northeast Asia. These ten building blocks are:

Reducing technology costs: Many key components of mini grid costs have decreased – and are still decreasing -- world-wide as parent industries scale up. Energy storage is lowering in cost as electric vehicles are deployed at exponentially increasing numbers. Solar panels have dropped in price thanks to high growth rates in installation of solar farms. Operations and maintenance costs can be decreased when mini grid developers install and use remote monitoring equipment that tracks mini grids performance on the internet in real time and allows technicians to diagnose and solve problems without a costly site visit. Clustering of sites that reduces travel requirements per site for technicians.

Geospatial portfolio planning: Geospatial least cost electrification planning provides a comprehensive answer throughout the whole country of "what is the least cost way to electrify each population center?". Use of geospatial computer tools helps developers to select promising sites based on satellite and demographic data. Satellite data on the locations of buildings in a village lowers the need for costly on-the-ground surveys for mini grid distribution design.

Income-generating uses of electricity: Productive use of electricity literally puts money in the hands of the users of mini grids, helping ensure that there are sufficient funds to pay electricity bills. And income generating sources help in other ways too: powering agricultural processing or water pumping increases the number of kWh sold, which helps spread fixed costs over larger sales. Moreover, many productive uses take place during the daytime – which is ideal because it is when solar panels are producing electricity that need not be stored in a battery.

Community engagement: Mini grids work best when they have the full support of the community – with recognition and acceptance of the tariff rates and playing roles in mini grid operation such as selling “pay as you go” cards or working as a local maintenance person. If the mini grid is owned and operated by the community, then local committees will need to be chosen comprising competent, committed leaders that can make fair and timely governance decisions regarding the mini grid.

Local and international industry: Successful scale up generally involves a link between international industry and local industry. International industry can generally help harness the finance necessary for significant mini grid deployment, and can bring new technologies to the table. Local industry understands how to get things done in country, has technology innovations adapted to the local context that are rooted in their manufacturing and installation expertise, and has the local network to find local labor needed to construct, operate, and repair mini grids.

Access to finance: Finance for mini grids comprises grants, loans, and equity investment. A key grant mechanism used in mini grids today is Results Based Financing (RBF) in which a mini grid developer is compensated a certain amount (typically $300 to $500) for each connection. Other grant subsidies focus on encouraging productive use. The money for these grants is often provided by international finance institutions like the World Bank or regional development banks. Generally local banks and investors require training to understand mini grids enough that they can feel comfortable offering loans and equity. International development banks sometimes provide low interest loans to government banks that are, in turn, on loaned to local commercial banks specifically for lending to mini grids and other off-grid energy solutions.

Training and skill development: Successful mini grid deployment requires skill development at many levels. At the village level, operators need training to ensure that the mini grid is functioning safely and efficiently, and within levels that will not lead to equipment damage or malfunction. Local companies interested in developing mini grids need training on load estimation, mini grid design engineering, construction and commissioning. Areas of particular focus that are different than conventional power systems engineering include energy storage, renewable energy technologies, and systems integration. Regulatory authorities and energy ministries require skills in mini grid evaluation and rural electrification planning that includes on-grid and off-grid solutions. Utilities require training on mini grid integration with the national grid.

Institutional framework: Full scale deployment of rural electrification has always required subsidies of some kind. An institutional framework needs to be in place that channels adequate grant funding structured on performance-based criteria.

Workable regulations: Regulatory frameworks that support mini grids need to include provisions for streamlined licensing (or registration for smaller projects -- which requires only alerting the regulatory authority but does not require permission); retail tariffs flexibility (the ability to charge retail tariffs that allow for a viable business), as well as regulatory options for when the main grid arrives that include interconnection procedures and feed-in tariffs for SPPs and wholesale tariffs for

SPDs. Beyond power sector regulation, a broader regulatory framework needs to include import duty exemptions for mini grid equipment, streamlined or clustered project environmental review, and business regulation that allows is conducive to investment.

Enabling business environment: Deployment of the quantity of mini grids needed to meet unmet energy needs for rural populations will require an investment that the World Bank estimates at $220 billion worldwide. Full scale deployment will require an environment that has an overall risk/reward balance that is attractive to the private sector. Achieving this will require progress in the nine elements described above.

8 Addendum: Mini grids and COVID-19

8.1 Increased challenges, but also new opportunities

The spread of the COVID-19 pandemic around the world has had a significant impact on the deployment of mini grids. In the short run, we are seeing a negative impact, due largely to COVID-related travel restrictions, but in the medium and long-term the role and prospects for deployment of mini grids may be enhanced by the experiences under the COVID outbreak.

In the short term, restrictions related to the COVID-19 outbreak on travel and activities deemed "non-essential" by governments have limited the ability of crews, particularly international crews, to travel to the villages and other hosts of mini-grid systems to perform surveys or install mini grid equipment and collect payments. The transport of equipment has been slowed, and manufacturing of essential mini-grid components have also been affected as factories in parts of China shut down. Companies that install and operate mini grids have seen business drop off significantly, and many are concerned about being able to remain solvent.

Mini grid operators also have grave concerns about revenues. According to an April 2020 SE4ALL survey of over 80 mini-grid companies in Africa and Asia, on average mini grid companies expect to lose 40% of their revenues in coming months. These operators expect that sales of electricity will fall, not because there is less innate demand for electricity, but because their customers have dwindling incomes. Movement restrictions restrict markets, reducing the ability of customers, many of whom are farmers and traders, to earn a living (SE4ALL 2020).

In the medium and long term, however, the outlook may be brighter, and the experience of COVID-19 may lead the villages, towns, enterprises, and others considering mini-grids to adopt and deploy mini-grids more rapidly than they would have had the pandemic not occurred. In countries where the main grid is already compromised, COVID-19 has often worsened electricity supply reliability from the main grid. In Myanmar, for example, every monsoon season electricity reliability worsens considerably due to trees falling on power lines and landslides knocking out distribution systems. COVID-19 has made keeping the lights on for rural Myanmar much more difficult because of travel restrictions and the reduced flow of materials necessary for repairs. As a result, power reliability in rural areas is even worse than usual this year. Communities that already had mini grids (and their neighbors in the dark) are seeing the reliability benefits of local, decentralized generation. Communities that have functioning mini grids are still able to process rice, keep lights turned on at night, and charge cell phones necessary for communication.

8.2 COVID-19, hospitals, and distributed generation

As it became clear that COVID-19 was spreading globally, concern focused strongly in the energy practice of the World Bank and other institutions on urgently deploying solar/hybrid power systems for medical facilities, particularly in rural areas and in cities with poor electricity grids. Many of these facilities, it is planned, will become the backbone of mini grids once the immediate COVID-related needs have passed.

The mini-grids needed to help with the COVID-19 response cover a range of types and sizes. On one end of the spectrum are power supplies that can be tens or hundreds of kilowatts for designated COVID-19 hospitals, generally in urban areas but often burdened with unreliable electricity supplies from the national grid. Oxygen concentrators and other equipment like ventilators require reliable 24/7 electricity, necessitating reliable backup power or storage. At the other end of the spectrum, rural dispensaries in unelectrified villages need power for lighting, patient monitoring, and to power communication devices, requiring only kilowatts or less of power. A robust “cold chain” needs electricity to run refrigeration to keep test samples cool from collection centers to laboratories, and also to keep vaccines cold in transit from factories through central storage and distribution to dispensaries. Factories that manufacture personal protective equipment need electricity to fabricate the materials and supplies for masks, gloves, and gowns needed for health care workers. Reliable clean water supplies are also essential for hygiene, and are often best provided by solar water pumping from wells.

In many circumstances, especially where the grid is either unreliable or is non-existent, solar power with battery storage is the most affordable way to provide the highly-reliable power needed. Development institutions like the World Bank are trying to minimize the use of diesel generators, and this has taken on greater urgency in the response to COVID-19. Diesel fuel supply chains in many countries are strained even during normal times and are expected to worsen under pandemic conditions. Hospitals with diesel generators often find it difficult to pay for diesel fuel even when it is available. Moreover, repairs to diesel generators take hours or days, often due to restrictions in availability of parts or of service technicians, during which time electricity may not be available for oxygen concentrators. Because COVID-19 is a respiratory disease, diesel smoke also makes symptoms worse and death rates higher. The appropriate role for diesel is only as a backup, with the bulk of electricity provided more affordably by solar panels or grid power where available.

Wherever possible, governments and development partners are working with local renewable energy companies to use local inventory to build these systems because it is faster and also provides a lifeline to companies hard hit by pandemic-related downturns in business. Where local inventory or capacity is inadequate, they are working with international companies that can deliver rapidly-deployable “box” solutions, often built into standard shipping containers. In some cases, the United Nations Office for Project Services (UNOPS) has been contracted to provide rapid procurement and logistics to get equipment where it is needed quickly.

Building in sustainability for these mini-grid systems is crucial, so contracts are being written to ensure operations and maintenance in the medium term and require that developers and operators of these facilities develop and implement plans that address long run sustainability, such as transitioning systems to become the backbone of financially self-sustaining community mini grids. Instead of only supplying the hospital or clinic, the poles and wires are built throughout the community and meters installed to collect revenues from electricity sales throughout the community. In many cases the solar array, conversion equipment and battery storage will need to be increased in capacity to accommodate the increased load beyond those of heath care facilities. With AC-coupled mini grids, these new capacity additions need not be located at the medical clinic facility. They can be located elsewhere on the AC network and contribute to the total energy supply. Figure 11 shows the timeline of development of a mini-grid implemented first to provide emergency power but evolving to meet community needs.

Figure 11: Timeline of Deployment of Emergency Mini-grids and Transition to Community Operation

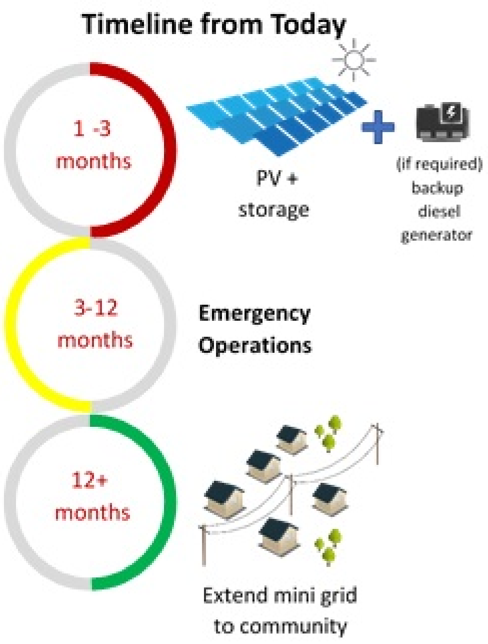


Figure 11: Timeline of Deployment of Emergency Mini-grids and Transition to Community Operation

In many cases, the town medical facility is a logical place for the heart of the mini grid anyway: the medical clinic or hospital is typically already in the middle of the community, and often has land surrounding it that is government-owned and can be made available for the solar array with minimal disruption to the community. The clinic or hospital may also be a larger building, with roof area to accommodate solar photovoltaic panels. The important role of the medical center in the community can help provide a measure of protection to the solar array from theft or vandalism.

One consequence of COVID-19 is that within the World Bank, different divisions are collaborating in unprecedented ways across the health, energy and water sectors, as well as working closely with departments of client governments. Some of the ingredients in these new responses include rapidly adapting cloud-based procurement and monitoring platforms, and using geospatial datasets of vulnerable populations to help to determine the most critical sites for system deployment. Inventories of solar panels, batteries and other components are matched with needs revealed by medical facility surveys and streamlined procurement documents and technical standards are being worked on around the clock and across the globe in a race against the pandemic.

COVID has had a dramatic short-term effect of increasing the portion of grid-connected renewable energy in the overall energy mix. This is not because there is more renewable energy being produced, but rather because with the pandemic, many commercial and industrial loads have decreased, and as a result the needs for fossil-fueled generation has declined. The World Economic Forum estimated that electricity demand in the USA in April 2020 dropped to a 16-year low (DiSavino 2020). Year-on-year declines in April electricity consumption in Germany and the UK were 11.5 and 17.2%, respectively. Less demand for electricity means that some power plants must be turned off. The decision of which to turn off hinges on the plant's marginal cost of electricity generation. Renewable energy plants have the lowest marginal costs of production because their fuel is free and are therefore generally must-run plants. The result of this is that fossil fuel plants have been turned off, and system operators have surprised the power engineering community by proving they are able to manage grids at 70% or more renewable energy penetration. During the lockdown, carbon intensity reductions varied from 15.9% in Italy to 35.9% in Germany (Hall 2020).

On the other hand, short run prices of solar panels have increased as a consequence of COVID-19.

China, which is the largest producer of PV modules, faced a number of challenges in manufacturing new modules. Production declines are expected to raise the price of solar modules by about 18% in the second quarter of 2020 as existing inventories were depleted. But this is not expected to last long. In the third and fourth quarters of 2020, most plants are expected to return to operation, bringing prices back to where they would have been (Cristina Vitale 2020) in the absence of the pandemic.

Decreases in electricity consumption during COVID-19 have reduced the spot price for electricity in many markets, increasing the expected years before an investment in renewable energy pays back. This, in turn, dampens investors' enthusiasm for new renewable energy installations. In Italy, for example 74% of solar farm operators recorded significant drops in orders for new power plants, with reductions ranging from 10 to 30% and expected to reach 50% by the summer (Cristina Vitale 2020).

In the medium term it is unclear how the interplay between decreased supply of renewable energy equipment and decreased demand for electricity will result in changes to renewable energy prices. But it seems clear that in the medium term, decreases both in supply of renewable energy equipment as well as demand for electricity will likely lead to decreases in the growth of renewable energy installed while the pandemic persists.

For decisions-makers working on rural electricity access, COVID-19 has shifted the urgency to powering medical facilities as countries race against the exponential spread of the virus. In the face of intermittent electricity supplies on national grids and constraints in diesel supply chains, COVID-19 has highlighted the singular ability of hybrid renewable energy systems to provide reliable and affordable electricity where 24/7 electricity supply is a matter of life and death.

As the pandemic wanes, emergency medical facility solar electric installations have the potential to transition to become the backbone of village renewable energy mini grids, with metered customers paying sufficient tariffs to cover costs and ensure sustainability. The transition will not necessarily be easy in every case, but it is a new modality of mini grid deployment that, with perseverance and attention to detail – can help creates a silver lining on the dark cloud of a crisis.

As electricity planners adapt planning practices during and after the pandemic, the new "medical facility-to-mini-grid" modality emerging during COVID-19 and the resiliency benefits of decentralized renewable energy will raise the profile of mini grids in national electricity planning.

At the same time, with the predicted worldwide COVID-19 economic downturn it will be more important than ever for mini grid electricity to be designed to enable productive uses that drive increased local economic activity, which, in turn, will provide the foundation for local communities to afford mini grid electricity. Traditionally these have included activities like grinding grain, carpentry tools and sewing machines, water pumping, and chilling or freezing produce, milk or meat. In the future, there are opportunities for expansion to include fueling of electric vehicles, mechanized battery-powered farm equipment, and in the future, when commercialized, the use of solid state devices to make ammonia from air, water, and electricity for use as a fuel and as a fertilizer.[7] Batteries used in larger vehicles bring the possibility of vehicle-to-grid (V2G) technologies wherein electricity can flow both ways to and from vehicles, supplementing mini grid storage when necessary.

Annex 1: Further resources

For decision-makers interested in developing a national mini grid program, key mini grid issues of importance not included in this paper include:

- Subsidy and program design to encourage appropriate mini grid deployment;
- Technical standards to ensure safety, reliability and power quality;
- Appropriate tariffs and tariff design
- Obtaining and structuring finance for investment in mini grids

There are a number of contemporary resources available on the internet for zero cost that address these issues. Here are some of the best:

- Energy Sector Management Assistance Program. 2019. *Mini Grids for Half a Billion People : Market Outlook and Handbook for Decision Makers*. ESMAP Technical Report;014/19. World Bank, Washington, DC. © World Bank. License: CC BY 3.0 IGO. https://openknowledge.worldbank.org/bitstream/handle/10986/31926/Mini-Grids-for-Half-a-Billion-People-Market-Outlook-and-Handbook-for-Decision-Makers-E-ecutive-Summary.pdf?sequence=1&isAllowed=y
- International Renewable Energy Agency. 2018. *Policies and Regulations for Renewable Energy Mini-Grids*. /publications/2018/Oct/Policies-and-regulations-for-renewable-energy-mini-grids.
- "Mini-Grids Support Toolkit | Mini-Grids Support Toolkit | Energy | U.S. Agency for International Development." 2018. February 12, 2018. https://www.usaid.gov/energy/mini-grids.
- Tenenbaum, Bernard, Chris Greacen, Tilak Siyambalapitiya, and James Knuckles. 2014. *From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa*. Directions in Development. World Bank Publications. https://openknowledge.worldbank.org/handle/10986/16571

Appendix 2: Creating a Viable SPD Option

If a regulator believes that SPDs make sense, there are important details to consider. These include consideration of technical standards for mini grids, and (if mini grids are expected to charge uniform national tariffs) the availability of subsidies and how to deliver them.

Subsidies to Implement the Small Power Distributor Option or the Combined Producer and Distributor Option

If the SPP decides to convert itself from an isolated SPP to a connected SPD or to a grid-connected combined SPD and SPP—*and* the government requires that the new SPD sell electricity to its retail customers at the uniform national tariff—the government must provide the SPD with subsidies, either directly or indirectly, so that it can provide its retail customers with the same tariff levels and structures that are given to the retail customers of the national utility.

It is common for political authorities to mandate that a national state-owned utility must charge a uniform national tariff. But a private or community-owned SPD will be able to comply with this mandate only if its business is commercially feasible. Commercial feasibility requires a sufficient inflow of money through tariff revenues and/or subsidies that will cover the SPD's costs. Without this minimum inflow of revenues, the uniform national tariff will be an unfunded mandate that cannot be achieved.

When a national utility serves poor rural customers, it has one major advantage that is not available to SPDs—it is able to subsidize the consumption of its poor rural customers through cross-subsidies from its other well-to-do residential customers or from commercial and industrial customers located elsewhere on its system. An SPD may find it more difficult to cross-subsidize the tariffs of its poor household customers from the tariffs of other customers within its service or concession area, because an SPD will have fewer customers and most of these customers are likely to be other poor households. In addition, SPDs are not likely to have many large commercial and industrial customers among their customers who could potentially subsidize poor households. Therefore, if a government requires that SPDs charge the uniform national tariff, it will have to provide subsidy funding from some outside source.

While it is relatively easy to describe subsidies, it is not easy to implement them in practice. Consider the views of the key players on providing subsidies to SPDs.

Minister of energy

Look, it is a political embarrassment for the government to have two villages near each other with widely different tariffs. You cannot have households paying the uniform national electricity rate in a village connected to the main grid while you have households in a village just a few kilometers away served by a mini grid operator who are being forced to pay a tariff to the operator that is two to three times higher than the national tariff. This is unfair and it is simply not sustainable. The only solution is to connect all these small isolated mini grids to the main grid as soon as possible and then charge them the same retail tariff regardless of whether they are supplied by the national utility or some small private or community distributor.

Managing director of the national utility

I will connect to these isolated villages if the government orders me to do so. But it is going to cost a lot of money to build lines out to these isolated communities and we do not have that money. So if this is the government's policy, then either the government or the donors will have to provide us with grants to pay for the cost of constructing these new lines. And then even after we connect the village, we are going to lose money on every kilowatt-hour that we sell to any households in these villages that are eligible to buy electricity at the lifeline tariff. If the SPP wants to become a distributor of our electricity, that's fine as long we are not asked to subsidize his tariffs. If the government wants us to subsidize these small distributors, then the government should come up with the money that allows me to do this. The government is happy to make promises, especially before an election, but is very forgetful when it is time for the government to pay for these promises.

Existing mini grid operator

The minister and the national utility seem to have very short memories. I took the risk of building a generation and distribution system in this community when no one else was interested in providing it with electricity. And I have given good service to this community for many years. Obviously, I do not want to delay the arrival of the main grid because this can lower the cost of electricity to the village and provide the village with more hours of electricity each day. But I should be allowed to continue at least as a distributor after the main grid arrives because I know my customers in this village and I can provide better service and with fewer losses than the national utility. And I can only function as a distributor if there is a workable margin between the price that I pay for the bulk power and the price that I can charge when I resell the power to my retail customers.

Customers in a village currently served by an SPP

It is not fair that we have to pay three times as much for electricity than friends and relatives in other nearby villages that are served by the national utility. They are able to buy electricity on the social tariff and we pay tariffs that are two to three times higher to the operator of the mini grid. It is also unfair that the connected villagers get electricity for many more hours than we do. We are lucky if we get electricity for 4 to 6 hours at night while they get electricity for 24 hours a day. And certainly once our village finally gets connected to the national grid, we should pay exactly the same tariffs as everyone else in the country who is connected to the national grid. The ultimate indignity would be to get connected to the national grid but still be forced to pay a private operator more for electricity than those who are served by the national utility.

If the country can afford ongoing operational subsidies for SPDs, decision makers will need to consider how to deliver these subsidies.

How to Deliver Operational Subsidies to Small Power Distributors?

There are three principal ways that a government can provide outside operational subsidies to an SPD to enable it to charge the same tariff as the national utility and also provide social or lifeline tariffs to its low-consumption customers. We consider each of these three methods in turn.

Method 1—Funding from the General Budget

Under this method the government provides subsidy funding from its general budget. The basic problem with this approach is that governments make this promise, they simply do not have the money in their budgets to provide such a subsidy on an ongoing basis. And even if the money were available, it would take time and effort to establish administrative mechanisms for delivering the subsidy funds. Moreover, subsidies agreed to by one government administration might be terminated five years later when another government is in power.

Method 2—A Separate Rural Electrification Subsidy Fund

Here the government or some other entity such as the rural electrification agency (REA) or regulator administers a subsidy fund that receives funding from the government and outside donors. Rural electrification funds (REFs) and REAs now exist in more than 15 Sub-Saharan African countries. Most of them were established, in part, to channel subsidy funding from different sources through a single organization or fund. In almost all instances, the subsidy funds have been used to provide capital cost grants to lower connection costs for households that wish to take service from isolated mini grids or from the national utility. For example, in Tanzania, the REA is willing to provide a grant of $500 for each new connection made in rural areas. Similarly, AMADER, the REA of Mali, typically provides capital cost grants for about 75 percent of the cost of a new connection—on average about $580 per new connection (Adama and Agalassou 2008)

In Peru the government offers initial capital cost subsidies to both grid and off-grid suppliers in rural areas, which is very similar to ones offered by African REAs/REFs. But the Peruvian government also provides both operational and consumption subsidies in addition to initial capital cost subsidies (see box 5.3). The government has established a fund known as FOSE that provides ongoing consumption subsidies to consumers in rural areas that consume less than 100 kWh/month. The funding for the consumption subsidies comes from all residential, commercial, and industrial customers located anywhere in the country with a monthly consumption greater than 100 kWh/month. Specifically, these consumers are required to pay a 2.5 percent surcharge on their monthly bills to fund a discounted social tariff for any residential customers that consume less than 100 kWh/month.

What is the cost of this cross-subsidy for an average residential electricity consumer in Lima? The average monthly consumption of a typical residential customer is about 200 kWh/month at a price of $0.10/kWh. Hence, the typical monthly urban residential bill without the surcharge would be approximately \$20.00, and the FOSE surcharge adds about \$0.50 to that bill. The 2.5 percent surcharge is also applied to the monthly bills of commercial and industrial customers. Overall, about 2 million Peruvian electricity consumers pay the 2.5 percent surcharge, which produces a fund of about \$36 million per year for subsidizing the monthly bills of 3 million low-consumption customers (Revolo 2009). Based on the Peruvian model, similar consumption funds have been established in Brazil, Bolivia, and Guatemala.

Method 3—Discounted Bulk-Supply Tariffs

The government or the regulator requires that the national utility sell wholesale or bulk power to the SPD at a discounted price that will allow the SPD to charge the uniform national tariff (including any social tariff components) to its retail customers and still remain commercially viable. The justification for the discounted bulk-supply tariff is the SPD will be serving many customers at nonremunerative rates under a mandatory social or lifeline tariff and that its distribution costs will be higher because its customers will typically be dispersed over a larger geographic area.

This is the most common subsidy mechanism for three reasons. First, it is administratively simple as its only administrative requirement is that the national utility lower its bulk-supply tariff for some or all wholesale customers. Second, it is a hidden subsidy and does not appear in the government budget nor does it appear as a line item on the monthly bills of other electricity consumers. Third, it does not require any direct contributions from the national government.

It does have drawbacks, however. One is that the subsidy structure does not match the cost structure of SPDs. SPDs have a low share of variable cost and a high share of fixed cost, but the subsidies are tied to sales. Under this structure, the SPD is incentivized to spread its fixed costs over sales of as many kilowatt-hours as possible, which does not work well with energy efficiency or energy conservation.

The one entity that will be most aware of the subsidy is the national utility because it is being forced to sell bulk power at a price below its actual costs. In a sense, the national government is using the national utility as an agent both to provide and deliver a subsidy. The national utility can be made whole if it is allowed to charge its other customers a higher tariff to compensate for the subsidized power that it must provide to SPDs or if it receives some explicit external payment from the government.

A government can always order the national utility to provide such a bulk power supply subsidy, but the utility could find subtle ways to sabotage the implementation of the order. Therefore, it is best to provide the national utility with positive economic incentives to comply with the directive. One way to do this is to require that the national utility periodically and publicly report on the amount of the bulk-supply subsidy that it is providing SPDs and then allow the national utility to include an automatic adjustment component in its general retail tariffs that recovers the cost of the discounts that it has been required to provide. And if the national utility is also selling electricity to retail customers on its own isolated mini grids at the uniform national tariff, these below-cost subsidies should also be reported and recovered through an automatic adjustment clause (AAC) in its general retail tariffs. This highlights the existence of the subsidies and helps to ensure that the national utility will be “made whole.”

In Thailand, where there is a long-standing policy of a uniform national retail tariff, a similar mechanism was used at a national scale. The rural Provincial Electricity Authority (PEA) was allowed to purchase electricity from the Electricity Generation Authority of Thailand (EGAT) at a bulk-supply tariff that was 30 percent lower than the tariff paid by the Metropolitan Electricity Authority (MEA), which serves the Bangkok metropolitan area (Barnes and Tuntivate 2009). This helped address the problem of the PEA’s distribution costs being much higher per unit of revenue than the MEA’s.

The Importance of the Distribution Margin

If this last subsidy method is going to be successful, it requires an adequate differential between the price at which the SPD purchases power using the bulk-supply tariff and the average price at which the SPD resells this power at retail. This differential is usually referred to as the distribution margin. It must be large enough to cover the SPD’s distribution costs (annual capital costs of its medium- and low-voltage network and operation and maintenance [O&M] costs to operate these networks) and the tariff discount provided to lifeline tariff customers (if there is no separate subsidy mechanism for these low-consumption customers). If the distribution margin is too small, the SPD will be caught in a price squeeze that may force it into commercial insolvency; if the margin is too large, the SPD will earn unnecessary high profits. Table 2 provides some preliminary estimates of distribution margins that exist in four Asian countries.

Table 2: Bulk-Supply and Retail Tariffs of Rural Distribution Entities in Asia

Table 2: Bulk-Supply and Retail Tariffs of Rural Distribution Entities in Asia

Country	Bulk-supply tariff (U.S. cents/kWh)	Retail sale price (U.S. cents/kWh)	Distribution margin (U.S. cents/kWh)
Bangladesh	3.7 (0–100 kWh)	3.94	0.24
Vietnam	2.4 (0–50 kWh)	3.4	1.0
	6.4 (51–200 kWh)	8.5	2.1
Nepal	4.9	5.5	0.6
Cambodia	13.55	28.0	14.4

Source: Authors' estimates based on van Couvering (2011), Rekhani (2011 and 2012), Van Tien and Arizu (2011) and NRECA (2012).

Source: Authors’ estimates based on van Couvering (2011), Rekhani (2011 and 2012), Van Tien and Arizu (2011) and NRECA (2012).

Case studies of SPD tariff arrangements

Bangladesh

In Bangladesh the bulk-supply price is 3.70 cents, and the average retail price allowed by the national electricity regulator is 3.94 cents for the country’s 70 rural electric cooperatives. This leads to a very small distribution margin of 0.24 cents (about one quarter of 1 cent), which reflects the fact that the regulator has decided to keep the allowed retail tariffs of the cooperatives within a relatively narrow band. But this decision fails to recognize that the cost and load characteristics of the 70 cooperatives are quite different, and the resulting average differential of less than one U.S. cent is simply too small to cover the actual distribution expenses of most of them. As a consequence, many of the 70 cooperatives are commercially insolvent (NRECA 2005; Van Couvering 2011).

Vietnam

The situation is different in Vietnam. Vietnam has proposed implementing a bulk-supply tariff system, where the tariff will vary depending on the consumption levels of retail customers served by the local distribution entity. For example, if the distribution entity is serving a low-consumption customer (that is, 0-50 kWh/month), the distribution entity will be allowed to purchase bulk power at 2.4 cents/kWh and sell it to these low-consumption customers at 3.4 cents/kWh, which allows for a distribution margin of 1 cent. If it is serving retail customers in the 51-200 kWh/month range, it will pay a higher bulk-supply tariff of 6.4 cents/kWh though the allowed retail price will also increase to 8.5 cents/kWh, which provides for a distribution margin of 2 cents. To implement such a system requires having accurate information on the composition of the distribution utility's customers (Van Thien and Arozi 2011), but it is unclear whether this proposed system will ever be implemented. There has been growing customer dissatisfaction with the performance of many existing distribution entities and growing political pressure for a uniform national tariff. As a consequence, the Vietnamese government now seems to favor takeover of distribution entities by the country's provincial power companies.

Nepal

Nepal, like Bangladesh, has a relatively small distribution margin. The 266 community-owned distribution systems buy bulk power from the Nepal Electricity Authority (NEA) at 4.9 cents and are allowed to resell it at 5.5 cents. Hence, the differential of 0.60 cents, while larger than Bangladesh's 0.24 U.S. cent differential is still relatively small. But the small differential in Nepal may be viable because of one important factual difference. The physical distribution facilities in these villages have been 80 percent funded by the government. This means, in effect, that the community-owned distribution systems are not paying the full capital costs of their distribution system; instead, they are paying a small annual lease payment. This, in turn, may allow them to be financially viable with a small distribution margin (Shrestha 2012).

Cambodia

Cambodia is unique because more than 80 of the SPDs that were functioning at the end of 2012 previously operated as SPPs before their conversion. Three features of the Cambodian tariff system have helped to achieve this successful conversion. The first is that the bulk-supply tariff at which the national utility sells power to the SPDs varies by region of the country and it appears that the bulk-supply tariffs are fully cost-reflective (that is, there is no discounting). For example, the bulk-supply tariff is higher in the northern Highlands and is lower in the rural areas surrounding the capital. A second feature of the Cambodian tariff system, which is not seen in many countries, is that retail tariffs in rural areas are generally higher than the retail tariffs in urban areas. Hence, there are regional tariff differentials and therefore no uniform national tariff. The third is that the allowed distribution margin is generous. Recent statistics from Cambodia show distribution margins of about 14 cents (Rekhani 2011 and 2012; Chanthan 2013). This is the highest margin that we have found in Asia.

Brazil and Peru

Throughout Latin America, distribution margins are routinely calculated by Latin American electricity regulators when retail tariffs are reset every four to five years for distribution companies and these numbers are publicly available. The Latin American numbers are particularly interesting because the allowed distribution margins are calculated based on the density of the distribution enterprise's service area and the composition of customers served. With the exception of Cambodia, Asian distribution margins are considerably lower than those in Brazil. Table 3 shows distribution margins for 22 SPDs in Brazil, together with data on number of customers, annual sales, and service territory area. In Brazil distribution margins vary from 1.5 cents/kWh (at an urban utility with 60,000 customers and very high sales of 1,654 gigawatt-hours (GWh)/year) to 8.5 cents/kWh at a more rural utility with only 287 GWh of sales per year.

Table 3: The Distribution Margin of Small Power Developers in Brazil, Sorted by Number of Customers

Table 3: The Distribution Margin of Small Power Developers in Brazil, Sorted by Number of Customers

Company	Area (km^2)	Customers	Sales (GWh)	Distribution margin (U.S. cents/kWh)
CAIUÁ-D, Caiuá Distribuição de Energia S/A	9,149	194,000	1,083	3.7
CLFSC, Companhia Luz e Força Santa Cruz	11,850	166,000	767	5.7
EBO, Energisa Borborema—Distribuidora de Energia S.A.	1,984	151,000	551	4.3
EDEVP, Vale de Paranapanema	11770	147,000	642	5.6
EEB, Empresa Elétrica Bragantina S/A.	3,453	110,700	568	5.9
SULGIPE, Companhia Sul Sergipana de Eletricidade	5,946	110,600	251	7.3
CNEE, Companhia Nacional de Energia Elétrica	4,500	90,300	477	5
ENF, Energisa Nova Friburgo—Distribuidora de Energia S.A.	933	86,700	287	8.5
DMEPC, Departamento Municipal de Eletricidade de Poços de Caldas	534	60,000	1,654	1.5
CFLO, Companhia Força e Luz do Oeste	1,200	45,000	239	4.2
CLFM, Companhia Luz e Força Mococa	1,844	38,000	183	6.5
COCEL, Companhia Campolarguense de Energia	1,360	34,600	186.7	5.1
CJE, Companhia Jaguari de Energia	252	29,000	505	2.4
COOPERALIANÇA, Cooperativa Aliança	569	29,000	155	4.1
IENERGIA, Iguaçu Distribuidora de Energia Elétrica Ltda	1,252	28,000	198.4	4.9
DEMEI, Departamento Municipal de Energia de Ijuí	45	26,000	96.7	6.7
HIDROPAN, Hidreletrica Panambi		14000	85.4	5
UHENPAL, Usina Hidroelétrica Nova Palma Ltda.		13,700	58.6	5.8
MUX, Energia, Muxfeldt Marin and Cia. Ltda		8,000	50	4.6
FORCEL, Força e Luz Coronel Vivida Ltda	280	5,900	33	7.3
EFLUL, Empresa Força e Luz Urussanga Ltda	237	4,800	73	3.6
EFLJC, Empresa Força e Luz Joao Cessa	253	2,300	11.1	7.2

Source: Calculations made by Pedro Antmann (World Bank) based on data available on the Web site of ANEEL (the Brazilian national electricity regulator).

Note: km^2 = square kilometers; GWh = gigawatt-hours; kWh = kilowatt-hours.

Note: km^2 = square kilometers; GWh = gigawatt-hours; kWh = kilowatt-hours.*Source:* Calculations made by Pedro Antmann (World Bank) based on data available on the Web site of ANEEL (the Brazilian national electricity regulator).

Distribution margins at these smaller SPDs (less than 10,000 customers) in Brazil vary from 3.6 cents to 7.2 cents, consistent with the rough rule of thumb that in Latin America distribution margins need to be around 4 cents/kWh for SPDs with thousands (but not tens of thousands) of customers. In Peru the necessary distribution margin for a completely rural distribution entity known as a Sector 5 entity was recently calculated as 8.4 cents. For the rural systems in this Sector 5 category, the median number of customers was 10,254 with a median density of 36.1 customers per kilometer of low-voltage lines and a median consumption of 32.3 kWh/month.

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III. ENDNOTES

[1] One liter of diesel can generate about 3 kWh of electricity in an efficient diesel generator. Thus, if diesel fuel costs $1 per liter then the fuel costs alone for diesel-generated electricity are about $0.33/kWh before any electrical losses

[2] This section is adapted from material published in Tenenbaum, Bernard, Chris Greacen, Tilak Siyambalapitiya, and James Knuckles. 2014. *From the Bottom Up : How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa*. Directions in Development. World Bank Publications. https://openknowledge.worldbank.org/handle/10986/16571

[3] This section is adapted from material published in Greacen, Chris, Richard Engel, and Thomas Quetchenbach. 2013. "A Guidebook on Grid Interconnection and Island Operation of Mini-Grid Power Systems Up to 200 KW." LBNL-6224E. Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/a_guidebook_for_minigrids-serc_lbnl_march_2013.pdf

[4] For reasons explained in the text below, if the generator is a synchronous generator, then both frequency and phase will need to be matched for resynchronization. If an induction generator is used, the prime mover is commonly used to bring the generator up to correct frequency to minimize inrush currents at the moment of interconnection.

[5] The following inverters sized for the residential market in industrialized countries (all 8 kW or smaller) were capable of both grid-tie and standalone operation: OutBack Power GS, GFX, GTFX, and GVFX series; SMA Solar Technology Sunny Island (SI) series; Schneider Electric XW series; and Princeton Power Grid-tied Inverter and Battery Controller (GTIB) 480-100.

[6] The power available from falling water is given by the formula Power = (efficiency)*(height drop)*(flow) where Power is measured in kW, height is measured in meters of vertical distance, and flow is measured in cubic meters per second.

[7] At present, ammonia can be made using hydrogen produced via electrolysis of water (which in turn can use renewable electricity as the electricity input) using the century-old Haber process, which is better suited to larger installations. Ultimately, research and development may lead to solid state cells for ammonia production that can be deployed at a scale suitable for pairing with mini- and micro-grids.

IV. NAUTILUS INVITES YOUR RESPONSE

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