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International Renewable Energy Agency

RENEWABLE MINI-GRIDS

INNOVATION LANDSCAPE BRIEF

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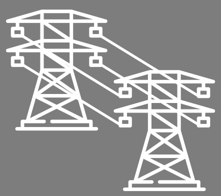
DISCLAIMER

1 BENEFITS

Renewable mini-grids operating in connection with the main grid can benefit the whole power system.



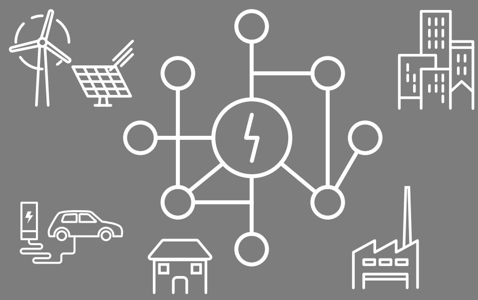
National grid

Benefits to main grid:

- Flexibility through exports/imports
- Ancillary service provision

Benefits to mini-grid consumers:

- Improved reliability of supply
- Revenues from service provision
- Electricity bill savings



Mini-grid

2 KEY ENABLING FACTORS

- Policies and regulatory structures for interconnected mini-grids
- Standardisation of renewable mini-grids
- Intelligent control systems to manage energy sources
- Access to financing

3 SNAPSHOT

➜ In the Netherlands, pilot projects with renewable mini-grids provide balancing service to the main grid

➜ In Tanzania, mini-grids achieve 98% reliability, compared with 47% for the national grid

➜ Global installed capacity for off-grid renewable mini-grids is about 4.2 GW, with high potential for grid connection

WHAT ARE MINI-GRIDS?

Integrated energy infrastructure, based on distributed power-generation, form local mini-grids. Although normally autonomous, these can also connect to the main grid.

RENEWABLE MINI-GRIDS

A grid-connected mini-grid using **renewable power sources** offers benefits to customers boosts overall **system flexibility.**
Grid connection strengthens the use of **solar PV and wind power** in the whole system.

ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS

ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of renewable energy mini-grids and explains the latest innovations in these systems, which can enable greater shares of VRE – specifically solar and wind energy – in the power sector. Although autonomous (or "off-grid") mini-grids are more widely deployed. This brief focuses mainly on renewable energy mini-grids that have become interconnected to larger grids and on the services those mini-grids can provide to the main grid.

The brief is structured as follows:

I. DESCRIPTION

Renewable energy mini-grids are a form of integrated energy infrastructure with distributed energy generation resources and loads. They provide autonomous capability to satisfy electricity demand through local generation, mainly from renewable energy sources.[1] Renewable energy mini-grid systems can also include power storage appliances; smart meters and smart devices for control, management and measurement; and power conversion equipment. Mini-grids can be either isolated and fully autonomous or connected to the main grid (IRENA, 2016).

Renewable-based mini-grids include generation capacity that can range from kilowatts (kW) to over 100 megawatts (MW). Commonly, mini-grids operate independently from the main grid, in which case they are referred to as "off-grid" or "autonomous" mini-grids. This capability makes renewable mini-grids a viable option for providing electricity to populations in remote locations where transmission lines are not economically viable because of the distance to the nearest main grid or where power supply is unreliable and unstable, with constant power outages.

Historically, most renewable mini-grids have been deployed as off-grid solutions. However, renewable mini-grids are now being tailored to different applications and are starting to be found in grid-connected areas to increase the reliability of supply for consumers, reduce electricity bills or decrease grid dependency. An interconnected renewable mini-grid can both connect to the national or neighbouring grid and operate as an autonomous unit. Leveraged by digital technologies, renewable mini-grids can further help integrate distributed energy resources (DERs), while introducing more renewables into the electricity mix.

A detailed breakdown of the types of renewable mini-grids, their relationship to the main grid and typical tiers of service are provided in Table 1.

1 The definition of a "renewable mini-grid" is adapted from IRENA (2015) and IEC (2014).

Table 1 Types of renewable mini-grids

	Service Level	
	Low	**High**
Autonomous	**Autonomous basic renewable mini-grid** **Generation sources:** PV, hydro and biomass **Service level:** Less than 24-hour power **End users:** Remote communities without major commercial or industrial activity **Added value:** • Enhanced energy access • Alternative to grid extension • Improved quality of life	**Autonomous full renewable mini-grid** **Generation sources:** PV, hydro, biomass and wind **Service level:** 24/7 power **End users:** Remote communities or islands with major commercial or industrial requirements; Industrial sites disconnected from the grid **Added value:** • Alternative to expensive, polluting imported fuels • Diversification and flexibility of supply
Interconnected	**Interconnected community renewable mini-grid** **Generation sources:** PV, wind and biomass/biogas **Service level:** High: critical/interruptible **End users:** Medium to large grid-connected communities (*e.g.* university campus) **Added value:** • Community control • Improved reliability • Response to catastrophic events	**Autonomous full renewable mini-grid** **Generation sources:** PV, hydro, biomass and wind **Service level:** 24/7 power **End users:** Remote communities or islands with major commercial or industrial requirements; Industrial sites disconnected from the grid **Added value:** • Alternative to expensive, polluting imported fuels • Diversification and flexibility of supply

Focus of this document

Note: PV = photovoltaic.

This brief focuses on renewable-based mini-grids that are grid connected, also referred to as "interconnected mini-grids", and that can provide services to increase the flexibility of the main grid for greater integration of VRE. Although interconnected renewable mini-grids are not widely implemented, and in many cases existing connected renewable mini-grids do not yet provide such services to the grid, renewable mini-grids have the potential to work in harmony with the national grid for a flexible renewable power system. Working in such a way would also improve renewable mini-grids' efficiency and cost-effectiveness.

Off-grid mini-grids have increasingly become connected to the main grid in recent years, as seen in countries like Cambodia, Indonesia, Nepal and Sri Lanka. Therefore, this brief is relevant when preparing existing and future mini-grids in isolated locations for potential interconnection to larger grids.

Table 2 provides an overview of the different interaction models between a renewable mini-grid and the main grid.

Table 2 Interaction models between renewable mini-grids and the national grid

Interconnection	Description
With export	Renewable mini-grid exports only the excess electricity generated to the main grid.
With import	Renewable mini-grid operator purchases electricity from main grid to charge its battery systems and supplies electricity to consumers.
With import and export	Renewable mini-grid exports the excess electricity generated to the main grid, and the operator can purchase from the main grid in case of low generation and high demand.
None	No electricity is imported from or exported to the main grid. These grids are referred to as “off-grid” or “autonomous” renewable mini-grids.

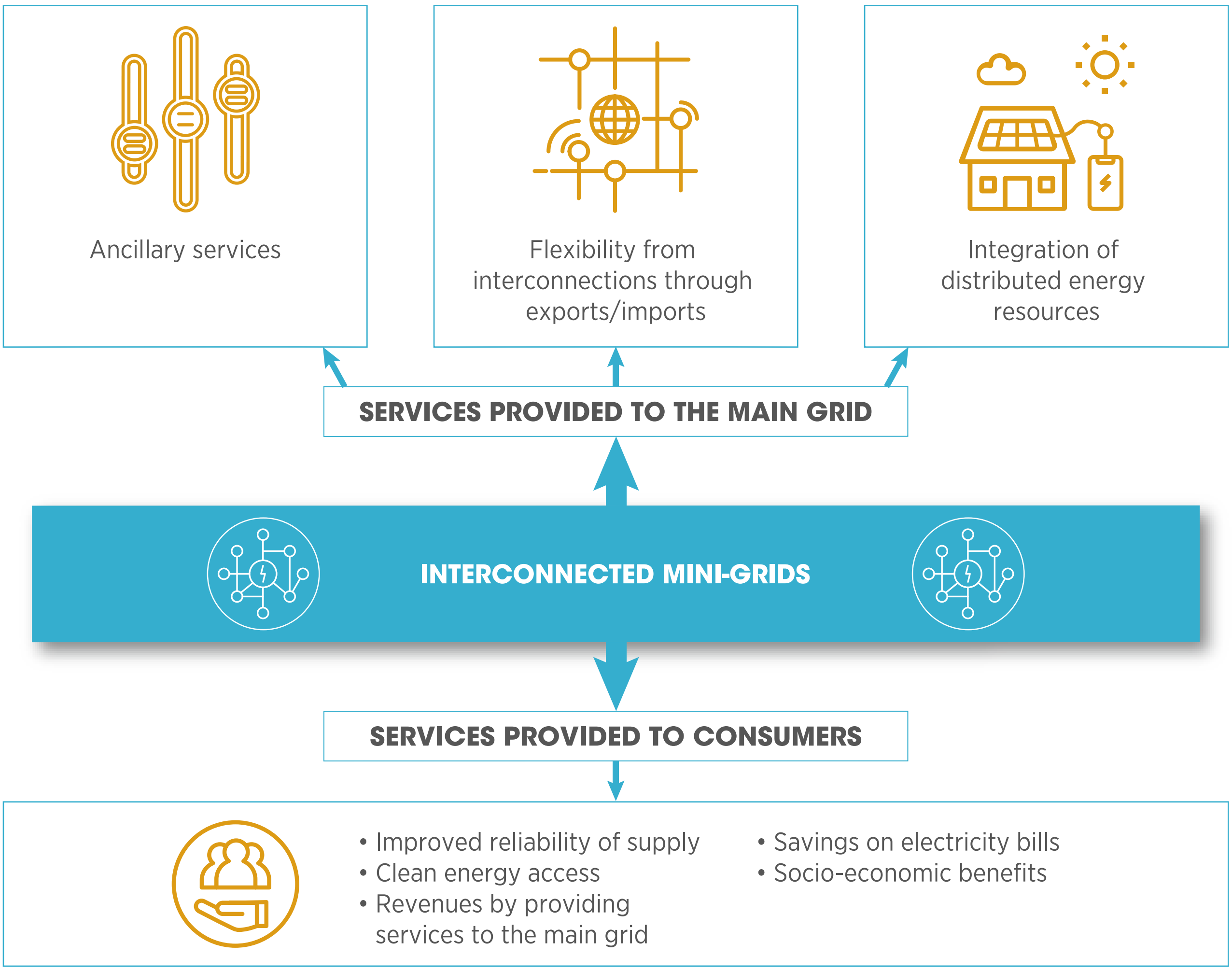
Based on Okapi (2017).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

The latest advances give renewable mini-grids an important role in the transformation of the global energy system. Besides providing electricity to consumers, renewable mini-grids can provide certain key services to the main grid.

These services and mini-grids' contributions to increasing the VRE share in the power sector are summarised in Figure 1.

Figure 1: Contribution of interconnected renewable mini-grids to the power sector



Services provided by interconnected mini-grids to the main grid

Interconnected renewable mini-grids are generally used for community applications and can be designed to sustain critical loads. They can be further optimised to provide back-up to the main grid or to provide primary power with the main grid.

Ancillary services

Renewable mini-grids are emerging as efficient ways to help balance power grids, as they incorporate critical support services such as frequency control, voltage stability congestion management, system restoration and enhanced power quality.

In some cases, larger mini-grids could serve transmission networks and smaller mini-grid systems could serve distribution networks. When the mini-grid has a grid connection, it is likely to have contracts with operators managing the distribution or transmission network. Distribution system operators (DSOs) are interested in voltage support services and transmission system operators (TSOs) in frequency regulation support (Martinez-Ramos et al., 2018).

Voltage control as an ancillary service involves maintaining the set points of the reactive power or the voltage in a network. The voltage control ancillary services include a fault ride-through capability, congestion management through load curtailment, primary voltage control, secondary voltage control and tertiary voltage control (Idoko et al., 2018). These services can be provided by the mini-grid to the DSO under (i) long-term agreements (e.g. limits on the power factor of the mini-grid at the point of common coupling) or (ii) on demand, in a similar way to load curtailment or peak-shaving provision (e.g. request to reduce reactive power consumption or to maintain a desired voltage) (Martinez-Ramos et al., 2018).

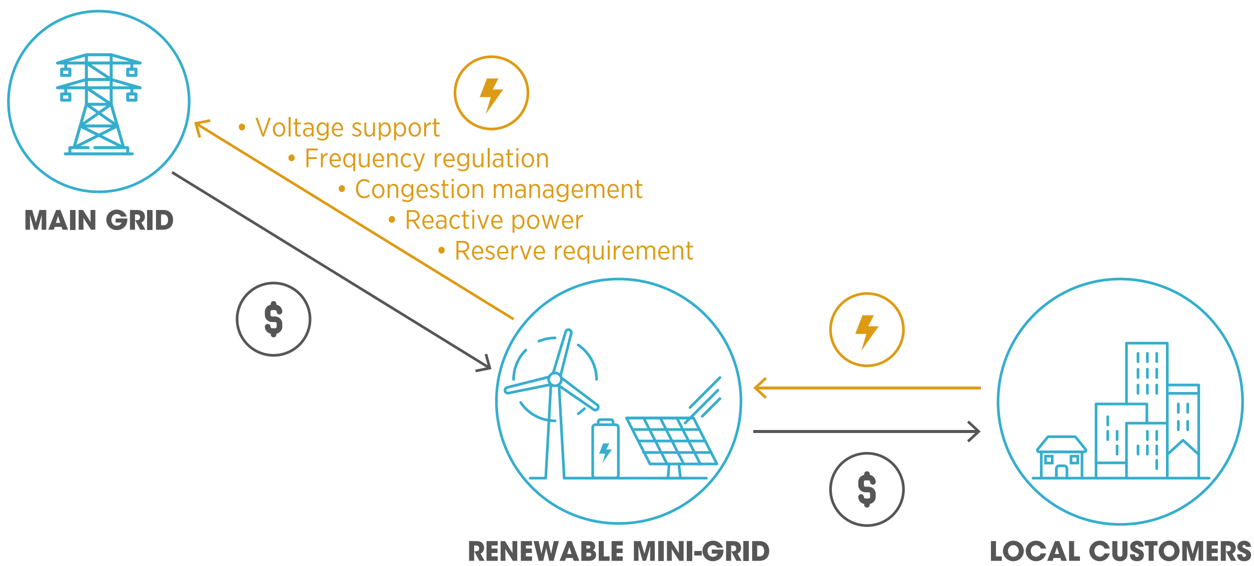
Renewable mini-grids with battery storage systems are a convenient means to assist with frequency regulation, as the storage system helps provide a high ramping rate and, through this, fast frequency response and aid in balancing the local network.

For instance, in the Netherlands, a series of pilot projects has been undertaken to build smart, integrated, decentralised energy (SIDE) systems in certain neighbourhoods. The degree of flexibility of such renewable mini-grids not only is effective at local balancing but also can be used to help balance the main grid.

Among other countries, the United States has been actively building and testing interconnected mini-grids. One example is the Stone Edge Farm mini-grid in California (US), which has in place 630 photovoltaic (PV) panels on eight buildings, generating 300 kilowatts (kWp), along with several energy storage systems and a hydrogen production station for vehicle fuel. The mini-grid can also provide ancillary services.

Figure 2 shows a summary of ancillary services provided by interconnected mini-grids.

Figure 2: Ancillary services enabled by interconnected mini-grids



Flexibility through electricity imports and exports

When the regional or national grid is available at (or near) the site of a mini-grid, interconnecting them allows any excess power produced on the mini-grid system to be fed into the large regional or national grid. This requires the mini-grid to be able to function at the frequency and voltage of the main grid. Therefore, devices enabling synchronisation between the mini-grid and the main grid, such as automatic voltage regulators (AVRs) for example, are required in such configurations.

Indonesia is currently shifting off-grid mini-grids into interconnected systems. Nine formerly isolated hydropower mini-grids, with total capacity in the range of 20–40 kW, are now connected to the main grid. They provide electricity at retail to local villagers and are selling electricity surplus to the national utility, Perusahaan Listrik Negara, under government-specified feed-in tariffs. The additional income generated has helped improve the commercial sustainability of the mini-grid operations and finance social improvement projects within the villages (World Bank, 2018).

Optimisation models and intelligent sensors can be further employed to monitor the operations of the national grid and automatically switch between using the renewable mini-grid and not. These systems may enable demand-side response by choosing to connect and supply electricity to the main grid during periods of high demand or charging excess electricity into batteries when the main grid does not need support.

SMART SENSOR SYSTEMS CAN MONITOR THE NATIONAL GRID, TAKING MORE POWER WHEN NEEDED FROM THE RENEWABLE MINI-GRID

Integration of distributed energy resources

Some mini-grids have very low capacity, and in such cases there is the opportunity to aggregate multiple small-scale mini-grids into one single unit that interacts with the main grid. The aggregation of mini-grids can support the main grid during peak loads and congestions and acts as an aggregator that can provide ancillary services to the central grid.

An example is autonomous energy grids (AEG) which are under research by the National Renewable Energy Laboratory in the United States. An AEG relies on scalable cellular blocks that are able to act similarly to mini-grids, self-optimising when islanded and participating in optimal operation when interconnected to a larger grid (NREL, 2019). In autonomous energy grids, mini-grids together with other DERs, machine learning and simulation, can help create a resilient system that does not require physical operators. Therefore, the system is able to self-organise information and intelligently control infrastructure while systematically integrating different forms of energy, including intermittent energy sources such as solar and wind (Kroposki et al., 2018).

Services provided by interconnected mini-grids to consumers

Interconnected renewable mini-grids that are established for community applications largely focus on improving the security of supply, particularly during extreme events. Renewable mini-grids can provide consumers with locally produced renewable electricity and increase resiliency by providing reliable back-up power in events of power outage of the main grid. For instance, smart meter data in Tanzania showed that the reliability of renewable mini-grid technologies was 98%, while the national grid's reliability factor stood at 47%.

Mini-grids can facilitate energy access for a wide spectrum of uses. They can provide electricity to power households and institutions such as schools, hospitals and local businesses, thereby enabling greater economic activity in the regions they serve. By 2030, nearly 267 million people are expected to get electricity access through solar PV, wind and hydro-based mini-grids (IEA, 2018). An important enabler to reaching energy access goals is the cost-competitiveness of these solutions. The levelised cost of electricity for renewable-based, grid-connected mini-grids (solar PV, wind, hydro) is between USD 250 and USD 300 per megawatt-hour (MWh), which is lower than the levelised cost for diesel-based mini-grids (IEA, 2018). Furthermore, in general, the cost of mini-grids systems varies depending on the size, the DERs deployed and the number of vendors involved.

In the United States, the California Energy Commission examined the cost of 26 mini-grids, of which 93% used solar PV and energy storage. The study found the average system cost to be USD 3 million/MW (CEC, 2018). Mini-grids costs are expected to decrease further before long, as the costs of solar PV and energy storage continue to decline (Asmus, 2018).

In addition, interconnected renewable mini-grids can earn extra revenue by selling electricity and ancillary services to the main grid. This can, in turn, reduce consumer electricity bills while enhancing the cost-competitiveness of the renewable mini-grid.

Potential impact on power sector transformation

- **Managing frequency and voltage fluctuations, Johannesburg, South Africa:**
  In the Longmeadow facility in Johannesburg, a hybrid solar mini-grid serving an industrial site has fully grid-connected and off-grid functionalities. The system includes a PowerStore battery-based grid-stabilising system to address frequency and voltage variations, enabling it to offer uninterrupted and reliable power supply. This mini-grid has helped achieve a **30% reduction in electricity bills and fossil fuel consumption** (ABB, 2018).

- **Local integrated utility, Feldheim, Germany:**
  The village of Feldheim owns and operates a local renewable mini-grid system consisting of solar, wind and biomass-based generation sources and a battery storage system. The solar farm has a yearly generation of 2 700 MWh, the biogas plant can produce 4 gigawatt-hours per year, and the wind turbines have a capacity of 74.1 MW. Excess electricity generated is fed into the national grid. Additionally, the renewable mini-grid uses its battery storage system to provide ancillary services, such as frequency control, to the main grid. As a result of the renewable mini-grid system, **electricity costs for local residents** have **fallen by over 30%** (Eid et al., 2016).

- **Selling electricity to the main grid, Indonesia:**
  Existing hydropower mini-grids in Indonesia were enabled with a grid interconnection. These nine mini-grids provide energy supply to the local villagers and sell excess generation to the national utility (Perusahaan Listrik Negara) under government-specified feed-in tariffs. **Revenues from this model** have contributed to **maintaining the mini-grid operations** and provided financing to social projects in the villages (World Bank, 2018).

- **Aggregating interconnected mini-grids, Italy:**
  A group of researchers in Italy has explored the aggregation and co-ordination of interconnected mini-grids to provide ancillary services to the main utility. A method has been proposed that considers the active power production of mini-grids on a day-ahead basis according to the daily market prices and renewable energy forecasts. Aggregation allows the system to reach **sufficient scale** to interact with the **transmission and distribution network** and provide **ancillary services** (*e.g.* power reserve[2] for frequency control) (La Bella et al., 2019).

2 Active power reserve corresponds to the power margins for increasing and decreasing the output power of generation units to compensate severe frequency deviations.

III. KEY FACTORS TO ENABLE DEPLOYMENT

Although renewable mini-grids have great potential, only a few such systems have been installed. Generally, the challenges faced by renewable mini-grid developers are not technical, but rather lie in uncertain or underdeveloped policies as well as financing and regulatory issues. While renewable mini-grids can be government or community owned, large deployment of renewable mini-grids will most likely take place through private ownership investment. However, to attract private investments, stable policies and favourable economic conditions need to be in place.

Policies and regulatory structures for interconnected renewable mini-grids

The lack of clearly defined regulations for grid-connected renewable mini-grid deployment and operation is a key challenge. An important first step is to include mini-grids in national electrification plans and strategies (IRENA, 2017a; USAID, 2017). Connecting renewable mini-grids to the national grid offers several advantages for the main grid, primarily the ability to use the mini-grid for operation support and as a flexibility provider. To realise the full potential of renewable mini-grids, Regulations are needed to guide the operation of mini-grid interconnections with the national grid.

Decisions made by mini-grid developers and operators often depend on the level of payment expected from customers. Without regulated tariffs, developers face significant uncertainty regarding the economic viability of their business model.

Additionally, without clear retail regulations, renewable mini-grid customers may be more vulnerable to price fluctuations. Setting retail regulations can provide greater certainty and security to mini-grid developers, operators and customers (USAID, 2017). Therefore, tariff policies and incentive schemes need to create fair and equitable conditions for the development of alternative grid solutions, including renewable mini-grids.

Grid connection readiness

Grid connection readiness generally refers to a mini-grid's ability to interconnect to a national grid; it can be determined from the outset or postponed until the national grid arrives (USAID, 2017). Developers and operators of mini-grids should keep up to date with the country's grid extension plans and thereby have the opportunity to respond effectively once the main grid reaches their location.

Mini-grid design has to consider, from an early stage, elements that could ease eventual grid connection. To interconnect to the main grid, mini-grids must be compatible with, among other things, the main grid's conductor characteristics, generation equipment, transformers, surge protection and switchgear (USAID, 2017). As mini-grids vary greatly in capacity, storage size, automation level, and so on, interconnection requirements will depend on each case. General considerations include dual-mode switching functionality (going from islanded to grid-connected mode and back again), cable ratings based on energy demand growth, and adequate equipment protection (Ackeby et al., 2016).

For existing systems, the interconnection can be achieved through automatic controllers. The reactive power must be controlled locally by the automatic voltage regulator for synchronous machines, by the electronic load controller for induction machines or by the electronic control unit via phase locked loop (PLL) in the case of direct current (DC) generators, such as PV panels. Furthermore, control systems used for island or grid-connected operation are different, even if they are combined in a single controller.

Technological innovations for mini-grids

Emerging technological breakthroughs are enhancing mini-grids' ability to interconnect to the main grid. These are described as follows:

- **Plug-and-play energy management systems using artificial intelligence:** A plug-and-play system is a technology that can work easily when first connected without the need for configuration or adjustments by users. Developments in optimisation model software enable plug-and-play energy management systems to intelligently use the connection to the main grid. Artificial intelligence and data analytics can be used to forecast demand as well as generation from renewable sources and can be used by the renewable mini-grid operator to accurately match supply with demand. Accurate forecasts that reduce uncertainty in VRE generation can enable renewable mini-grid operators to better balance the grid and improve the overall management of all renewable mini-grid components, including energy storage, as well as the support they can provide to the main grid. For instance, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia has developed a solar forecasting system that includes a Skycam and machine learning-based algorithms to forecast variations in solar mini-grid output based on cloud cover. In the short term, these advanced forecasting solutions could help improve accuracy while also improving the services that mini-grids can provide to the main grid. For example, the research institutes CSIRO and NREL, from Australia and the United States, respectively, are currently working together to simplify the integration of renewable mini-grid systems by creating a plug-and-play controller that can maximise the use of solar energy (NREL, 2016).

- **Low-cost battery storage technology:** Battery storage systems have a significant role to play in the cost-effectiveness of renewable mini-grid solutions. They are further crucial in balancing the variability of PV and wind and in shifting the electricity generated at times when supply exceeds demand to times when demand exceeds supply. Thus, battery storage systems help eliminate fossil fuel-based back-up systems. Historically, renewable mini-grid systems have used lead acid batteries owing to their lower cost. However, advances in research coupled with large-scale manufacturing of lithium-ion batteries have engendered steep cost reductions in this technology, making it a competitive solution for renewable mini-grids. This is particularly relevant for interconnected renewable mini-grids, as lithium-ion batteries can offer better energy density than other battery technologies and have a fast response rate. According to IRENA estimates, the cost of lithium-ion batteries could decrease in stationary applications by 54–61% by 2030, reflecting a drop in the total installed cost for lithium-ion batteries for stationary applications to as low as USD 145 per kilowatt-hour (kWh) (IRENA, 2017b). Lower costs for lithium-ion batteries will enable an increase in the deployment of mini-grid systems, which in turn will increase the share of electricity generated from VRE (specifically solar PV), further reducing dependence on conventional, polluting fossil fuels.

- **Direct Current (DC) mini-grids[3]:** Although these systems are more suitable for off-grid applications, DC mini-grids' connection to the national grid is starting to be explored and is in a very early phase of development. DC mini-grids may face challenges in the long-distance transfer of electricity at low voltages. For this, the use of solid-state transformers, which allow the mini-grid and the main grid to operate at different frequencies while isolating both systems against faults and allowing bidirectional power flows, is under study to facilitate interconnections.

- **Advanced metering infrastructure:** Smart meters can enable remote monitoring of consumption and can support the implementation of a variety of pricing schemes, such as time-of-use tariffs. In the case of off-grid systems, renewable mini-grid operators can implement prepaid tariff models using mobile payment systems and use smart meters to remotely switch customers' electricity supply on and off.

3 These systems supply low voltage DC, which can be used to power some devices, including mobile phones, electric scooters and other home appliances.

Standardisation of renewable mini-grids

To facilitate more installations of renewable-based mini-grids, there is a need to develop quality assurance mechanisms for these solutions. This can be achieved through the establishment of an institutional infrastructure known as "quality infrastructure"[4].

Work is ongoing at the International Electrotechnical Commission (IEC) to develop a comprehensive set of standards for rural electrification, the "IEC TS 62257 series on rural electrification". The Institute of Electrical and Electronics Engineers (IEEE) has also developed guidelines for the interconnection of mini-grids to the main grid, including 1 547.4 – IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems. However, there is still a lack of system-approach standardisation for renewable mini-grid systems.

This issue triggers questions on the quality and safety of every project, creating challenges in attracting investment for such systems. In 2016, the US Department of Energy, along with the National Renewable Energy Laboratory, initiated the "Quality assurance framework" to establish standards for mini-grid systems (Baring-Gould et al., 2016). IRENA is also working on this topic, looking at the quality infrastructure needed for mini-grid systems. For instance, interconnected mini-grids will require communication and control protocols determined by a clear, comprehensive set of national standards and interconnection regulations that are applicable in different cases (IRENA, forthcoming a).

In the case of DC mini-grids, the International Electrotechnical Commission (IEC) is developing globally applicable standards. Voltage levels and ranges of voltage variation should be standardised. Also, since the traditional alternating current (AC) plug and sockets cannot be used in the case of DC systems, new quality and safety standards should be established for every component in DC mini-grids.

Access to financing and business models

Access to finance and long-term investments for developing renewable mini-grids is a key challenge, especially in emerging economies where the return on investment could be uncertain owing to the large capital outlay required and the relatively low-income levels of average consumers. In such countries, financing schemes and subsidies are required to fulfil the initial capital investment requirements. Several organisations, such as the European non-profit Alliance for Rural Electrification (ARE), are working towards providing access to funding for the installation of renewable-based mini-grids in emerging economies. The alliance further acts as a platform to bring together development funding institutions and renewable mini-grid operators (ARE, 2018).

The lack of a solid business model for renewable mini-grids is also a great challenge for renewable mini-grid developers. Microgrid-as-a-service is a new financing mechanism that enables organisations to deploy microgrids without any upfront investment. This financing model allows municipal, district, institutional and commercial campuses, as well as large buildings, to stabilise long-term energy costs and upgrade critical energy infrastructure without capital outlay. In some areas, microgrids with distributed solar PV or co-generation result in less costly electricity than that from the main grid. In other cases, the savings are spent on electrical or resilience upgrades. This is the same concept as the emerging business model of energy-as-a-service. For more information, see *Innovation landscape brief: Energy-as-a-service* (IRENA, forthcoming b).

4 Quality infrastructure encompasses different, closely interrelated elements, including accreditation, certification, standards, testing, inspection, metrology and quality management systems.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Table 3 displays key indicators of the mini-grid market distribution, while Table 4 introduces different examples of mini-grids that have an interconnection to a large grid.

Table 3 Market indicators for mini-grids*

Indicator	Key facts
Regional share of mini-grid capacity	North America: 40% Latin America: 4% Asia-Pacific: 42% Europe: 10% Middle East & Africa: 4%
Mini-grid market share by segment	Remote, enabling energy access: 45% Commercial & industrial: 16% Utility distribution: 15% Community: 10% Institutions: 9% Military: 5%

* Mini-grids powered with both conventional fuels and renewables are considered

Based on Asmus (2017).

Table 4 Examples of interconnected renewable mini-grids

Example	Type of mini-grid	Location	Description	Impact
Distributed energy resources gathered in a mini-grid	**Interconnected solar powered mini-grid**	**Mooroolbark, Australia**	AusNet services, distributor serving the Mooroolbark community, in partnership with GreenSync and Power Technology Engineered Solutions are trialling a mini-grid serving households in the community. In this project, 14 of the 17 households in the community are provided with individual solar PV and 10 kWh battery storage systems which are connected by a mini-grid network. The other houses without solar panels are also connected to the mini-grid.	The mini-grid project aims to support the main grid by offering flexibility services (ReNew Australia, 2016). During the trial, the mini-grid was able to island the community from the main grid and provide electricity for 22 hours before switching back to the main grid.

Example	Type of mini-grid	Location	Description	Impact
Interconnected micro-grid for rural energy	**Grid-connected micro-grid**	**Nuwakot District, Nepal**	In January 2018, the 23 kW Syaurebhumi micro-hydroplant in Nuwakot (Nepal) was interconnected to the national grid. It was the first micro-hydroplant in the country to be interconnected, which is expected to open doors for other interconnections. This marks a very significant step towards restoring inoperative micro-hydroplants, considering the fact that there are over 3 000 micro-hydroplants with approximately 35 MW of installed capacity, of which around 5 MW is not in use.	The plant is expected to export annually a total of 178 245 kWh of electricity to the national grid, and plans are in place to interconnect another micro-hydroplant, the 40 kW Leguwa Khola plant in Dhankuta. By connecting households that were otherwise not connected to the national grid, the supply of reliable, affordable power from micro-hydroplants positively impacts the local community, including by increasing incomes as well as employment and education opportunities (UNDP Nepal, 2018).
Facilitation of electromobility through solar micro-grid	**Solar panels, electric vehicle charging stations and energy storage**	**San Diego, California, United States**	Working with Smart City San Diego, San Diego Gas & Electric installed a mini-grid at the zoo that comprises ten solar canopies that power five electric vehicle charging stations in the parking lot. They plan to deploy a 1 MW/4 MWh battery storage facility that will support the grid interconnection.	The system has bidirectional inverters, so it can source energy from the grid during off-peak hours to charge the batteries. When the batteries are fully loaded, additional electricity is fed into the grid. The storage system will also be used for some energy arbitrage by taking advantage of wholesale power price volatility.
Mini-grid with large-scale battery system	**Interconnected mini-grid using wind and solar energy**	**South Australia, Australia**	The Australian Renewable Energy Agency will be investing USD 8.7 million towards a USD 21.9 million*, 30 MW/8 MWh battery storage facility adjacent to Wattle Point wind farm. This battery system will use the local wind power and solar PV power to create a mini-grid system.	The system should provide fast response during outages in the main grid and reduce congestion on the interconnector linking South Australia with Victoria. The mini-grid can also island the local network using 90 MW of wind farm and solar PV modules.
Mini-grid selling electricity surplus	**Grid-connected mini-grid**	**New York, United States**	The Brooklyn mini-grid has been developed by LO3 Energy and Siemens. The mini-grid network connects users in a neighbourhood such that DER owners can sell electricity to other users. The users can choose between the utility grid or the mini-grid. The transactions are carried out in a secure blockchain-based system called TransActive Grid.	The local mini-grid eliminates nearly 6% in transmission and distribution losses while selling excess energy to the main grid. The mini-grid also enables buyers to choose between the best resources available.

*Converted into USD using a conversion factor of 1 AUD = 0.73 USD.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Hardware:

- Efficient renewable energy generation technologies using solar PV, wind, hydro turbines and others.
- Battery storage systems, such as lithium-ion batteries.
- Advanced metering infrastructure to enable mobile-based payments and remote monitoring of the grid system.
- Mini-grid controllers to enable the smooth operation of mini-grids.
- Grid-forming inverters capable of rapid response and sustaining safe operation during power outages.
- Plug ports compatible with DC-based mini-grid systems and household or industrial appliances that can operate on DC.
- Hardware to facilitate interconnection between the national grid and the mini-grid.

Software:

- Cloud-based software systems to enable remote monitoring and payments.
- Control systems to manage various energy sources connected to the mini-grid. When the mini-grid is connected to the national grid, control systems are required to enable switching between the two grids.

POLICIES NEEDED

- Policies for standardisation of mini-grid systems based on the quality of service provided.
- Subsidies to encourage investments in mini-grid projects.
- Policies that permit and assess the participation of interconnected mini-grids in energy markets.
- Support for the aggregation of mini-grids as a unit that can interact with the energy system.

REGULATORY REQUIREMENTS

Retail market:

- Permit interconnection and islanding of mini-grids with the national grid.
- Define tariff mechanisms for electricity from mini-grids, keeping consumers' interests in mind.
- Define compensation mechanisms for interconnection between the mini-grid and the national grid (IRENA, 2018).

STAKEHOLDER ROLES AND RESPONSIBILITIES

Mini-grid developers:

- Work with regulators and suppliers, along with system integrators, to develop standards, set system base options and obtain certification for mini-grids.
- Partner with other industry participants, such as device manufacturers, battery system providers and control system providers, to design and manufacture efficient devices compatible with DC mini-grid systems.

System operators:

- Invest in infrastructure required to enable interconnection and island mode operation of mini-grids.
- Enable mini-grid participation in markets to provide flexibility services.

Local community:

- For existing mini-grids, engage with the civic leadership as part of a consultative process for mini-grid interconnection.

ABBREVIATIONS

DC	direct current
DER	distributed energy resource
kW	kilowatt
kWh	kilowatt-hour
MW	megawatt
MWh	megawatt-hour
PV	photovoltaic
VRE	variable renewable energy

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