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INNOVATION OUTLOOK
RENEWABLE MINI-GRIDS

SUMMARY FOR POLICY MAKERS

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SUMMARY FOR POLICY MAKERS

Why renewable-based mini-grids?

Mini-grids based on renewable energy sources provide clean energy to communities in rural and remote areas that lack access to modern energy services. Mini-grids can deliver higher levels of service than solar home systems, fostering productive uses of energy, in addition to basic services such as lighting. In areas with a main grid, mini-grids can be connected to the main grid to provide a more reliable, cleaner and cost-competitive alternative, including for consumers requiring large amounts of power without any supply disruptions.

Mini-grids based on renewables, or renewable mini-grids, are hybrid mini-grids with a significant share of renewable energy used to generate the electricity they distribute. Renewable mini-grids continue to gain momentum as energy solutions in areas where energy demand is not fulfilled, and where grid extension is not a cost-effective alternative. Renewable mini-grids are reaching maturity, as shown by their improved reliability, reduced environmental impact, enabling of increased local control over energy used, and sustained cost reductions. They light remote communities, enable industry in isolated areas and provide back-up to the main grid when it fails. The mini-grids of the future will use more energy from renewable sources and will provide increasingly reliable power at an even lower cost. Ultimately, this will extend even more electricity to remote areas and support more-resilient grid-connected communities and industry.

Renewable mini-grids represent a growing market that is potentially worth more than USD 200 billion annually. Renewables can be mixed with diesel-fuelled capacity to convert between *50 and 250 gigawatts (GW) of capacity to hybrid mini-grids*. Autonomous renewable mini-grids limit the need to use poles and wires to connect communities to the main grid, and interconnected renewable mini-grids can potentially reduce the burden on, and even support, centralised utility networks. Using different types of renewable energy technologies, depending on local conditions, affects the design of a renewable mini-grid. Existing diesel mini-grids have been retrofitted to offset fuel by, predominantly, adding shares of solar photovoltaic (PV) generation integrated with storage solutions.

Small hydropower (SHP) and biomass power generation continue to be mini-grid solutions that are relatively unexploited, despite the existing 75 GW of global SHP installed capacity and more than 1 million biogas systems in rural areas. In areas with hydro and biomass resources, SHP and bioenergy can supply the base load for community energy demands without the need for short-term storage. However, seasonality in the availability of resources is an issue to consider for these two options. Small-scale wind can be integrated in mini-grids, complementing the generation patterns of PV systems. Innovation will boost the transition towards 100% renewable mini-grids, by gradually raising the penetration of renewable sources.

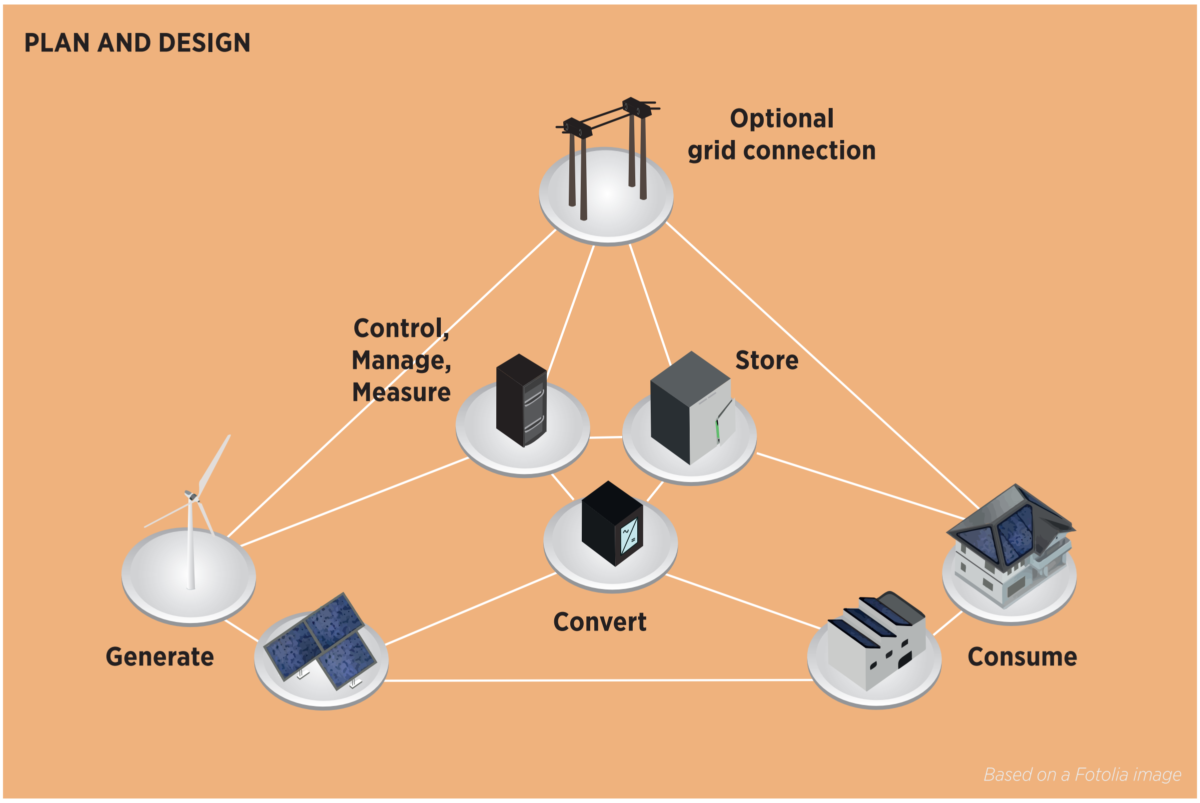
This report informs policy makers and other stakeholders in the energy sector about the technology developments in renewable mini-grids. It also discusses how these technology developments could enable faster commercialisation and large-scale deployment of renewable mini-grids. The information contained in this report helps countries to support their national objectives by expanding their renewable energy options. Policy makers will also find in this report a discussion on the effective implementation of incentive programmes and policy actions for a transition towards a sustainable energy regime.

What is a mini-grid?

Mini-grids can be designed for and can deliver power at different levels of service, tailored to demand needs.

Mini-grids are integrated energy infrastructure with loads and energy resources. The core functionalities for mini-grid technologies are: power generation; power storage; control, manage and measure (CMM); convert and consume. Figure 1 presents an example of a renewable mini-grid. Planning and designing is instrumental to connect the other five functionalities together, before construction and during operation.

Figure 1: Mini-grid functionalities



Mini-grids can be categorised based on their connection to the grid and the level of service provided. A renewable mini-grid can be interconnected to the main grid or independent from neighbouring grids, in which case it is considered autonomous. Renewable mini-grids can provide different levels of service, from basic services such as only lighting to higher levels of service, such as satisfying commercial energy demand. Table 1 provides an overview of these categories.

Deployment of mini-grids

Autonomous mini-grid systems supplying basic services are widely deployed. Interconnected mini-grids are still emerging. There is significant untapped potential for mini-grids in regions such as Africa and Latin America.

This report, *Innovation Outlook: Renewable Mini-grids*, has found that autonomous mini-grids delivering basic services are nearly mature and are being deployed globally. Autonomous renewable mini-grids delivering higher service levels are being tested in most regions of the world. There has been limited deployment of interconnected mini-grids, and most of the implemented systems are concentrated in North America and East Asia.

Table 1: Types of mini-grids

	Lower Tier of Service	Higher Tier of Service
Autonomous	**Autonomous Basic (AB mini-grids)** **Generation Sources:** PV, hydro and biomass **Tier of service:** Less than 24-hour power **End-users:** Remote community without major commercial or industrial activity **Added value:** • Enable enhanced energy access • Alternative to grid-extension • Improve quality of life • Cost savings	**Autonomous Full (AF mini-grids)** **Generation Sources:** PV, hydro and wind **Tier of service:** 24/7 power **End-users:** Remote communities with major commercial or industrial requirements; industrial sites disconnected from grid **Added value:** • Alternative to expensive polluting imported fuels • Diversification and flexibility of supply • Cost savings
Interconnected	**Interconnected Community (IC mini-grids)** **Generation Sources:** PV, wind and biomass/biogas **Tier of service:** High critical/interruptible **End-users:** Medium to large grid-connected community, such as university campus **Added value:** • Community control • Improved reliability • Response to catastrophic events • Cost savings	**Interconnected Large Industrial (ILI mini-grids)** **Generation Sources:** PV, wind and biomass/biogas **Tier of service:** Very high: Critical/uninterruptible **End-users:** Data centres, industrial processing or other critical uses **Added value:** • High reliability for critical loads • Enhance environmental performance • Resiliency

Table 2: Status of deployment for different types of mini-grids

Limited	Pilots	Emerging	Mature
● (black)	● (red)	● (yellow)	● (green)

Region	Autonomous Basic	Autonomous Full	Interconnected Community	Interconnected Large Industrial
Canada and US	Limited	Mature	Emerging	Emerging
Caribbean, Central America, Mexico	Mature	Emerging	Emerging	Limited
South America	Mature	Emerging	Limited	Limited
Europe	Mature	Pilots / Emerging / Emerging	Pilots	Pilots
North Africa	Mature	Emerging	Limited	Limited
Sub-Saharan Africa	Emerging / Mature	Emerging	Limited	Limited
Central and North Asia	Pilots / Emerging	Limited	Limited	Limited
East and South Asia	Mature	Pilots / Emerging / Mature	Emerging	Emerging
Middle East	Limited	Pilots	Limited	Limited
Oceania	Mature	Emerging / Mature	Pilots	Pilots
Antarctica		Mature		

Innovation plays a crucial role in scale-up

The renewable mini-grids of the future require technology advancements in the planning and design phases, as well as in each and every functionality of mini-grids: from generation to consumption, and across electricity storage, power conversion and CMM technologies. Each functionality needs improvement to unlock cost reductions, respond to social needs and protect environmental resources.

This report features exciting research on the ground-breaking innovations that can spearhead an accelerated deployment of mini-grids with higher shares of renewables as one of the competitive energy-supply options of the future. Research and development (R&D) and early commercialisation today are expected to produce the innovations required to make renewable mini-grids more environmentally friendly, reduce their costs and improve their reliability. These innovations are expected to result in an easier deployment of renewable mini-grids over the next two decades. The R&D innovations featured in this publication provide key approaches being taken to address the challenges faced by renewable mini-grids today.

Although not all of the research featured in this publication could lead to operational solutions by 2035, these innovations have the potential to help renewable mini-grids reach a critical mass and further a transition in which mini-grids will use only renewables for power generation. Some of the research topics and technological developments that are currently being pursued in laboratories are listed below and are thoroughly discussed in this publication:

- Innovations in planning and design reduce cost and simplify the implementation of renewable mini-grids. Current R&D in this field strives to enhance tools for designing and planning, to increase availability of load data and to lower the cost of renewable energy resource assessment.

- Innovations in CMM make the operation of renewable mini-grids easier and more reliable. Among many others, some of the identified research initiatives currently ongoing focus on making more intelligent short- and long-term controls as well as wind and solar predictions, adapting metering technologies, improving communication technologies and interoperability standards, and easing the integration of technologies.

- Innovations in storage enable increased efficiency in the use of resources and more reliable operation, yielding strong benefits across all areas of major impact. This publication discusses the research efforts to improve batteries, such as using less expensive and more abundant materials to make lithium-ion batteries, lower maintenance requirements, or storage that can handle seasonal variations in resource availability.

- Innovations in inverters, rectifiers and converters result in fewer power losses and provide a hardware platform to integrate the components of the renewable mini-grids, which can ease set-up and lower costs. The identified research in conversion includes new converter designs with high efficiencies at partial output, the combination of diverse functions into inverters or, among others, improved modularity for different renewable mini-grid markets.

- Innovations in consumption reduce the energy requirements, yielding environmental and cost benefits. This publication discusses more-efficient appliances available, particularly in remote energy access markets, the scale-up of appliances designed for direct current (DC) grids and the development of more flexible connectivity between DC lines and appliances.

Exciting innovations in the pipeline

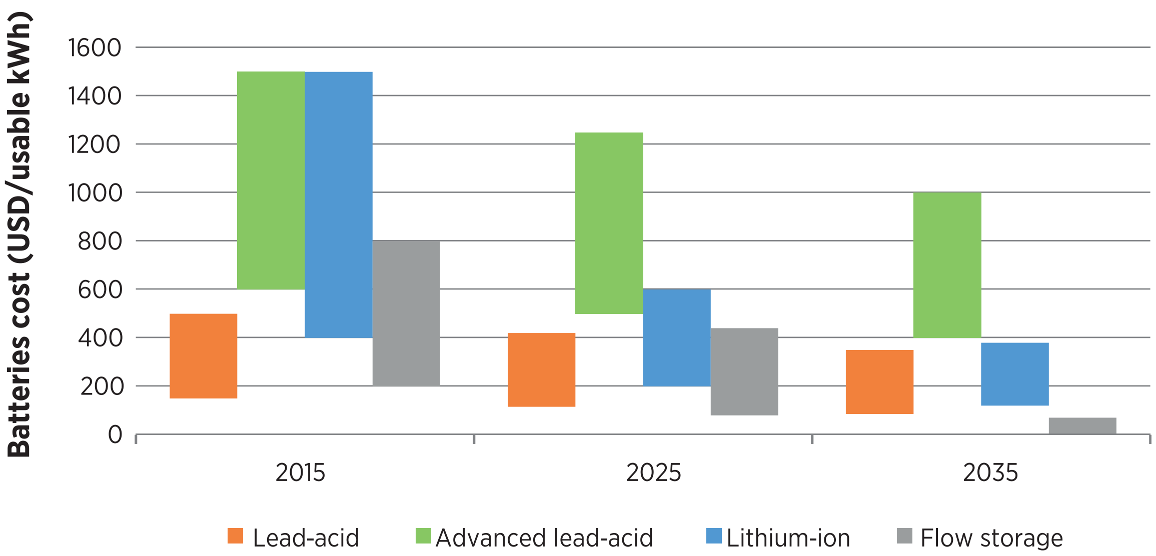
Ground-breaking improvements are under way, not only in components, but in system integration, controllability and flexibility.

In the future, innovations in renewable mini-grids will include increasingly modular solutions using off-the-shelf hardware and software. The technologies will have lower costs and increased capabilities. As the costs of renewable generation and storage drop, the importance of modularity and ease-of-use will continue to increase. Modularity and ease-of-use will be driven by the use of smarter planning and controls, improved interoperability and better scalability of designs. An overview of the technological progress expected in the functionalities of mini-grids by 2035 includes:

- Lithium-ion, organic flow and other chemistries will drive down the cost of batteries and are expected to have increased uptake in the market. Although lead-acid batteries are expected to continue to be a major storage technology in renewable mini-grids, advanced lead-acid batteries will play a larger role. Advanced lead-acid batteries are increasingly capable of handling more cycles at greater efficiencies. There will be a proliferation of other chemistries available that will create further competition to drive down prices. Innovations in phase-change materials and thermochemical materials are expected to allow for increased use of thermal storage over long periods. Supercapacitors can benefit from innovations in the use of graphene and increased capabilities for high power and long life. The impacts of technological innovation on battery costs are shown in Figure 2.

- Short-term controls with the ability to integrate more sophisticated algorithms and more accurate wind and solar predictions, accompanied by intelligent control and integration of batteries, are key for increasing the penetration of renewable energy. Research on smarter and more flexible meters

Figure 2: Expected cost reductions in lead-acid, advanced lead-acid, lithium-ion and flow storage batteries by 2015, 2025 and 2035



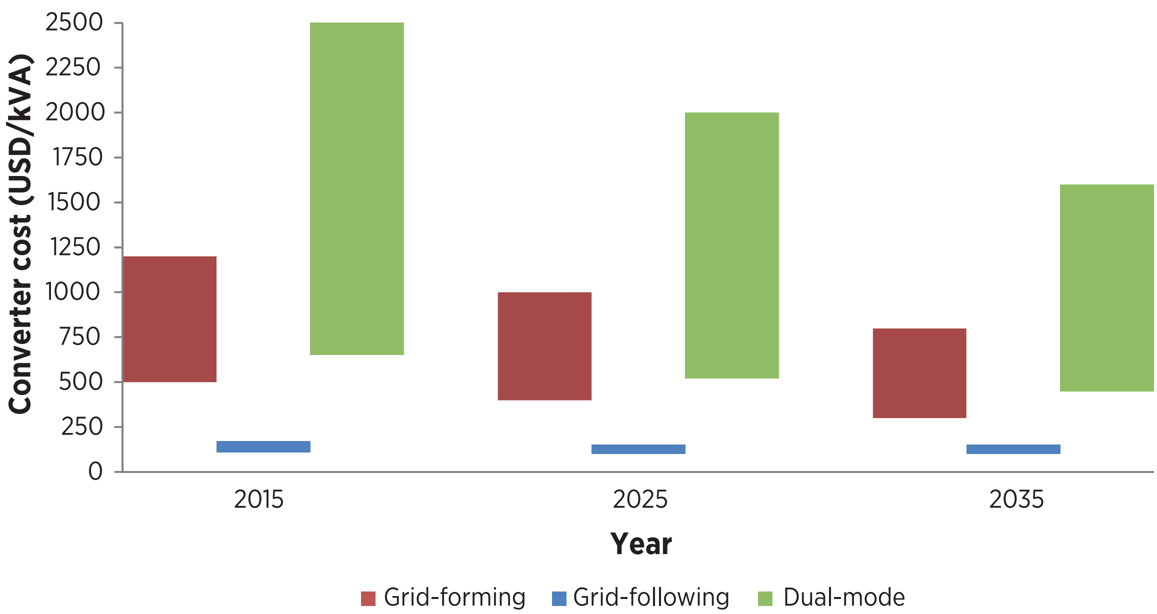
that are able to adapt to new business models, time-of-use pricing, automatic meter reading and advanced metering infrastructure are key areas of research and innovation. Modular solutions and improved communications and standards will be critical to ease the integration and interoperability of components.

- Internet of Things technologies will continue to enable more intelligent use of electricity by allowing for interconnection and intercommunication among conventional appliances. Along with cost reduction trends and the standardisation of DC lines, the use of appliances that can operate with DC and more efficient AC appliances are expected to increase in the market.

- The increasing use of DC grids and appliances will require more efficient and affordable DC-DC converters. The availability of conversion technologies in markets is expected to increase and to include larger-power battery inverters. However, most of the innovations for conversion technologies are expected to happen in transistors. These will bring costs down, increase efficiencies and reduce their size and weight. Figure 3 summarises the expected impact of innovations in cost reduction for grid-forming, grid-following and dual-mode converters by 2035.

This publication also includes a patent review and shows that innovation trends in most of the core technologies are positive. Interest in their potential to transform the energy sector is growing. In the last four years almost 12 000 patents in CMM technologies and more than 30 000 patents in storage technologies were filed in China. During the same period, 2 180 patents in converters and conversion electronics and more than 2 090 patents in the fields of energy efficiency, demand-side management and back-up technologies applied to renewable mini-grids were filed in the United States.

Figure 3: Expected cost reductions in grid-forming, grid-following and dual-mode converters in 2025 and 2035

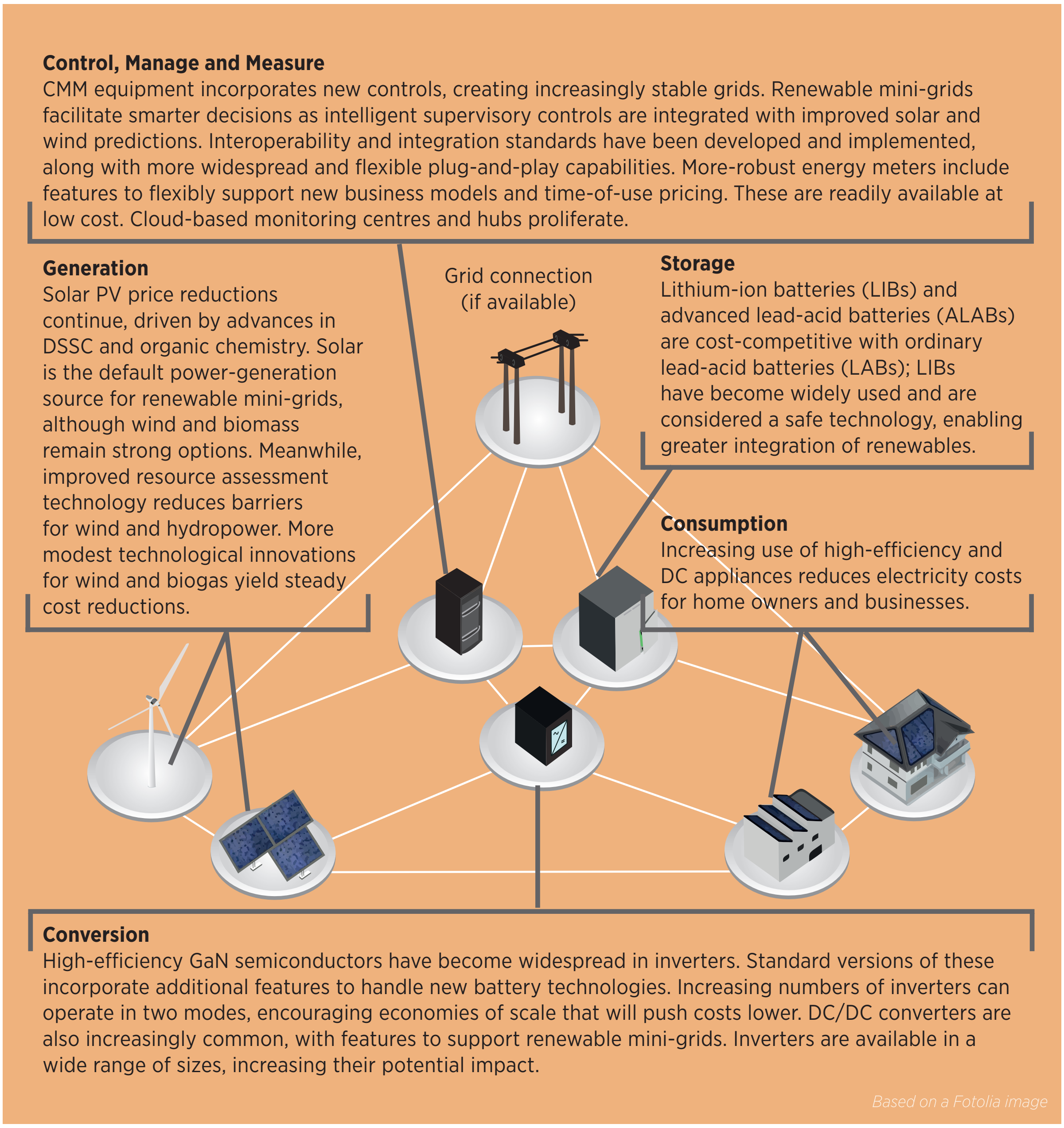


What will the mini-grid of the future look like?

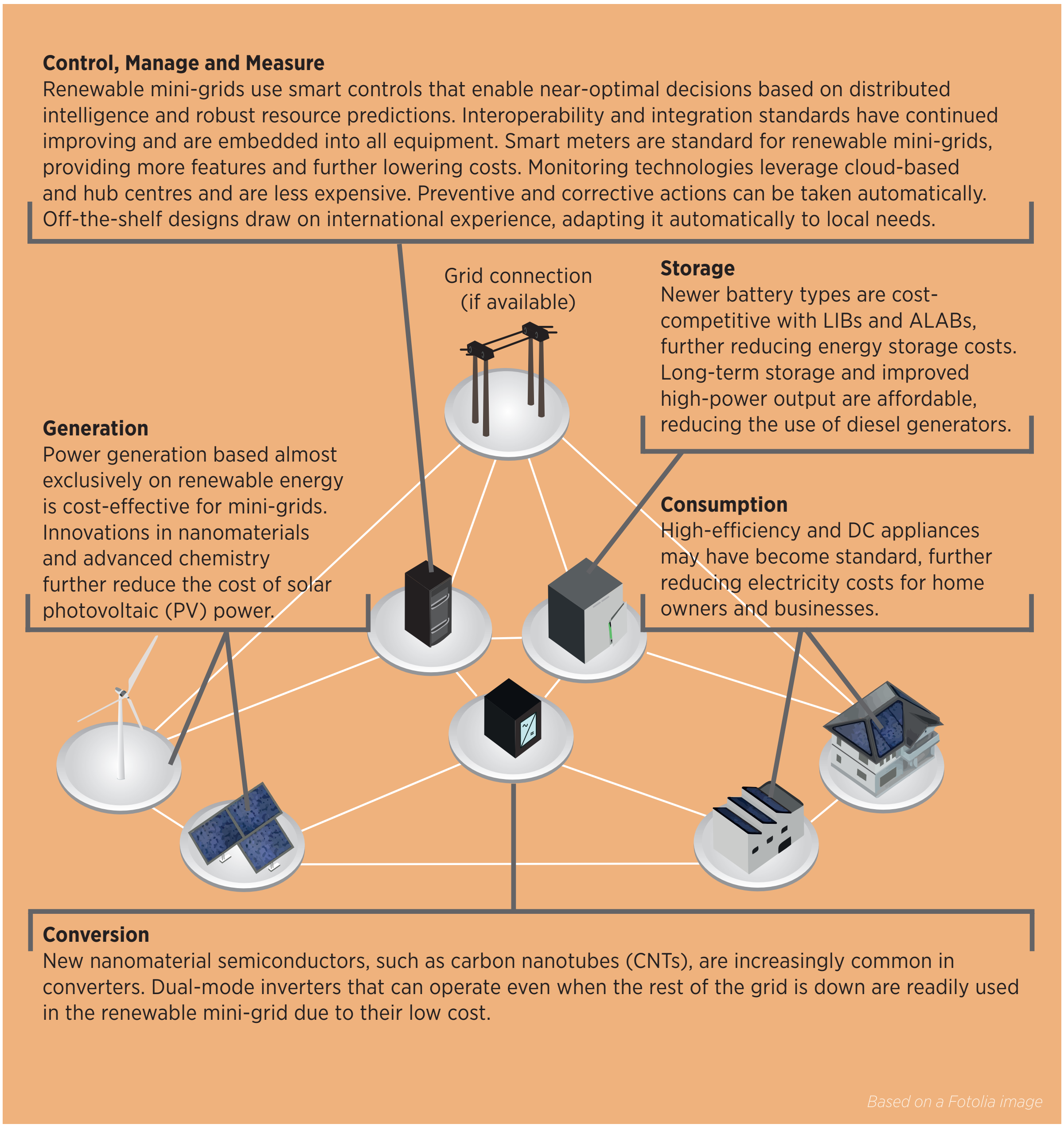
A two-part figure, shown below and on the page that follows, depicts the potential evolution of current research and technological development.

Figure 4: Potential evolution of renewable mini-grids by 2025 and 2035

The Renewable Mini-grid of 2025



The Renewable Mini-grid of 2035



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Innovation strengthens the competitiveness of mini-grids

Technology innovation, accompanied by advancements. Mini-grid power generation looks set to fall in business models and system operation, will dramatically reduce the cost of producing electricity in renewable mini-grids to one-third of its current cost in the next two decades.

Innovation will enable autonomous renewable mini-grids to provide higher service levels at a lower cost. This will lead to greater geographic reach in the coming decades, providing larger isolated communities with increasingly cleaner electricity. The levelised cost of an autonomous mini-grid using only renewable energy is expected to drop to between USD 0.30 per kilowatt-hour (kWh) to USD 0.57/kWh by 2025, and to a range of USD 0.19/kWh to USD 0.35/kWh by 2035. Current costs are between USD 0.47/kWh and USD 0.92/kWh. The primary drivers for this lower levelised cost are expected to be lower storage costs and more intelligent controls. However, innovation in the other functionalities will be necessary.

By 2025, autonomous renewable mini-grids will be able to provide both basic and high tiers of service at competitive prices, leading to massive commercialisation and deployment to remote areas globally. As the costs decline, renewable mini-grids will make more economic sense and will increasingly compete with the extension of main grids. By 2035, renewable mini-grids will be a cost-competitive option even in areas close to the main grid.

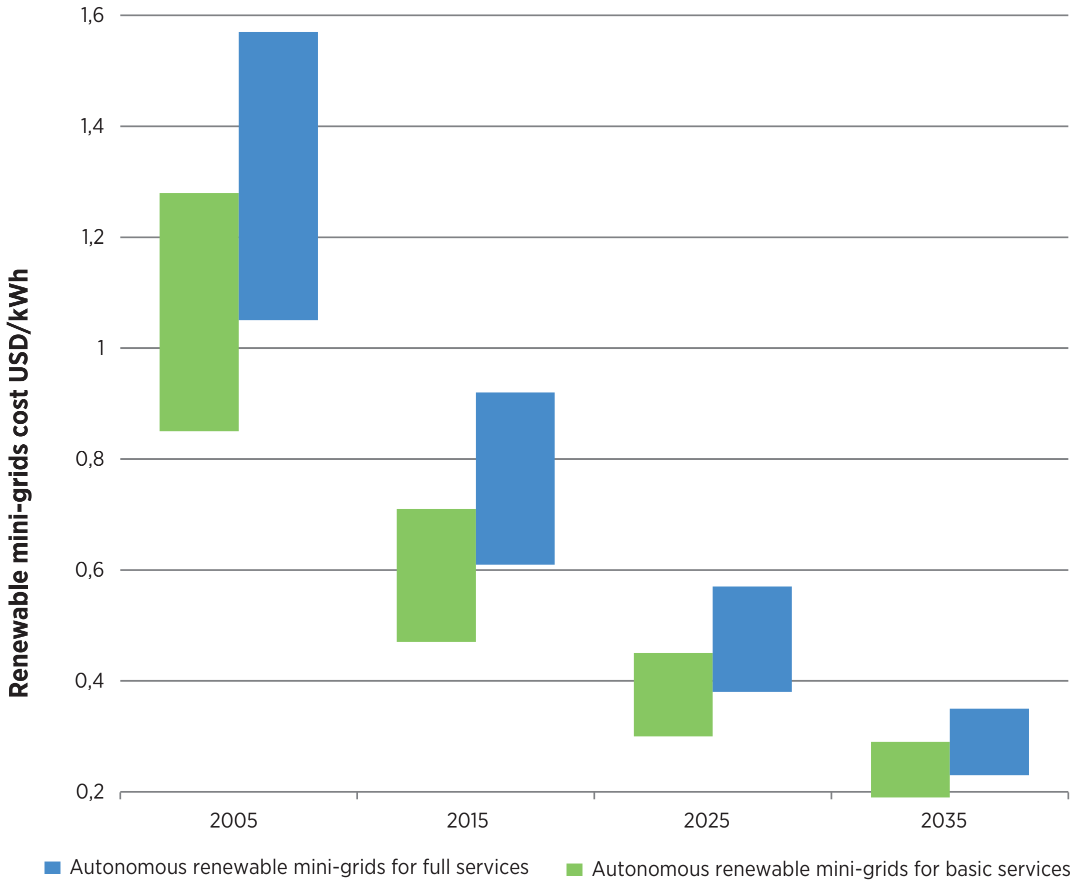
Interconnected renewable mini-grids also are evolving to become a commercially viable option. Today the business case for interconnected mini-grids is strongest for customers with critical needs and in areas with expensive main grid power. By 2025, however, innovations are expected to drive installation of renewable mini-grids to customers with less stringent load requirements, leading to a more resilient grid system. A predominant driver will be the search for better resilience and disaster-response capabilities. By 2035, broader acceptance of renewable mini-grids by utilities will further improve compatibility between renewable mini-grids and the main grid. Mini-grids that use a small or medium-sized amount of renewable energy in their generation mix are expected to be common, and the increasingly declining costs will allow communities seeking better environmental options to adopt renewables using renewable mini-grids.

Figure 5 presents the evolution of estimated costs for autonomous renewable mini-grids that draw all of their energy from renewable sources. These estimates are conservative. Combining renewables with other energy sources could offer options with even lower costs, and interconnected mini-grid costs may be able to purchase energy from their neighbouring main grid to reduce costs.

The cost reduction of interconnected renewable mini-grids will be influenced by the economics of the interconnected main grid, but the main cost trends from autonomous grids could be applied.

In the transition towards a mini-grid deploying 100% renewable energy sources, and depending on the mini-grid design, a hybrid mini-grid might have lower costs than a 100% renewable mini-grid. However, the cost of integrating renewables in mini-grids will decline thanks to technologies that enable a higher share of renewable energy, such as storage and control systems. For example, for the lowest-cost solar PV mini-grid design the optimal fraction of renewable energy may rise from 60% at less than USD 0.45/kWh in 2015, to more than 90% at around USD 0.30/kWh in 2025, to almost 100% renewable at USD 0.20/kWh in 2035.

Figure 5: Unsubsidised cost ranges for renewable mini-grids from 2005 to 2035 for a 100% renewable energy community system.



Source: Author elaboration with HOMER Pro, 2016

How can policy makers pave the way?

None of these innovations are possible without the adequate support of policy makers, the private and non-profit sectors, and academia.

Although renewable mini-grids present an exciting opportunity for re-thinking traditional energy supply models, their development and deployment require balancing of social needs, political will, economic efficiency, technological capabilities and environmental protection. To address these interlinked aspects, *Innovation Outlook: Renewable Mini-grids* offers key advice for policy makers, technology investors, project developers, the non-profit sector and academics, to help all to participate in fostering the growth of these technological options. The following are some of the options to support the deployment of renewable mini-grids discussed in the report:

Public-private partnerships and loan grants can help develop and implement projects, while public venture funds and subsidies contribute to generating and exchanging knowledge. Funding from the public and private sectors is critical to support the fundamental research activities that generate new ideas.

- Policy makers play a critical role in providing market policies to support commercialisation of renewable mini-grid equipment for a larger growth of the industry. Innovations in the final stages of renewable mini-grid development could benefit from market policies to overcome the "valley of death".

- The regulation of renewable mini-grids is still in its infancy, and, among other things, the public sector should focus on adopting new, flexible standards that encourage development and avoid standards that discourage innovation. The challenge of regulating renewable mini-grids is to keep a balanced approach between specific policy regulation for these mini-grids and a flexible regulatory framework that are applicable to a myriad of options.

- Governments have an instrumental role in building competence and disseminating knowledge through international co-operation and industry support. There also is the need for a paradigm shift to facilitate new and continuous training of electrical engineers and technicians.

- Private investors play a major role in funding fundamental research activities and pilot projects and contributing to knowledge and technology transfer. There is a need for private sector investment in new technologies and for technology holders to transfer their knowledge acquired in other contexts to the renewable mini-grid sector – such as research conducted within the automobile sector on batteries.

- Academia and universities are important for the innovation of renewable mini-grids. Beyond powering innovation with fundamental and applied research, academia can collaborate in setting research agendas and by undertaking the most demanding mini-grid experiments.

The coming decades will bring exciting perspectives for mini-grids. Renewable mini-grids are increasingly chosen as the alternative to meet the energy needs of different communities across the world. From solar PV and small wind technologies integrated in DC systems with smart batteries in remote areas, to larger community-owned PV plants integrated with electric vehicles and smart demand-side control, different applications will be enhanced by a variety of innovative solutions. In this dynamic landscape, mini-grids have enormous potential beyond their application for energy access, complementing larger systems and supporting productive uses of renewable energy. *Innovation Outlook: Renewable Mini-grids* looks ahead to the exciting developments to come in the next decades.

The mini-grids of the future will use more energy from renewable sources and will provide increasingly reliable power at an even lower cost. Ultimately, this will extend even more electricity to remote areas and support more-resilient grid-connected communities and industry.

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