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INNOVATION OUTLOOK

RENEWABLE MINI-GRIDS

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ABBREVIATIONS

AB	Autonomous Basic service, one of the four renewable mini-grid types identified in this report
AC	Alternating current
AF	Autonomous Full service, one of the four renewable mini-grid types identified in this report
ALAB	Advanced lead-acid batteries
AMI	Advanced metering infrastructure
CAES	Compressed air energy storage
CAIDI	Customer Average Interruption Duration Index
CAPEX	Capital expenditures
CEMG HIO	Clean Energy Mini-grids High-Impact Opportunity
CERTS	Consortium for Electric Reliability Technology Solutions
CF	Capacity factor
CHP	Combined heat and power
CMM	Control, manage and measure
CPC	Cooperative Patent Classification
c-Si	Crystalline silicon
CSAC	Centre for Self-Assembly and Complexity
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC	Direct current
DG	Distributed generation
DSM	Demand-side management
DSSC	Dye-sensitised solar cells
EASE	European Association for the Storage of Energy
EC	European Commission
EDLC	Electrical double-layer capacitor
EE	Energy efficiency
EEE	Energy-Efficient Ethernet
EERA	European Energy Research Alliance
EPO	European Patent Office
EV	Electric vehicle
GSM	Global System for Mobile Communication
HAWT	Horizontal-axis wind turbine
HVDC	High-voltage direct current

IC	Interconnected Community application, one of the four renewable mini-grid types identified in this report
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ILI	Interconnected Large Industrial application, one of the four renewable mini-grid types identified in this report
IoT	Internet of Things
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre of the European Commission
KI	Key indicators
kVA	Kilovolt-amp
kW	Kilowatt
kWh	Kilowatt-hour
LAB	Lead-acid battery
LBNL	Lawrence Berkeley National Laboratory (US)
LCOE	Levelised cost of electricity
LEAP	Long-range Energy Alternatives Planning System
LIB	Lithium-ion battery
LiDAR	Light detection and ranging
LVDC	Low-voltage direct current
LWT	Large wind turbine
M2M	Machine-to-machine
MG	Micro/Mini grid
MIMO	Multiple Input Multiple Output
MOSFET	Metal-oxide semiconductor field-effect transistor
MPPT	Maximum power point tracking
MV	Medium voltage
MW	Megawatt
NASA EOS	National Aeronautics and Space Administration Earth Observing System
NOCT	Nominal Operating Cell Temperature
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OSeMOSYS	Open Source Energy Modelling System
PAP	Plug-and-play
PCM	Phase-change material

PHS	Pumped hydro storage
PLC	Power line communication or Power line carrier
PoE	Power over Ethernet
PR	Performance ratio
PV	Photovoltaic
R&D	Research and development
RES	Renewable energy source
RV	Recreational vehicle
SAIDI	System Average Interruption Duration Index
SEI	Solid electrolyte interface
SGIP	Smart Grid Interoperability Panel
SHS	Solar home system(s)
SMES	Superconducting magnetic energy storage
SMS	Short Message Service
SOC	State of charge
SOEC	Solid oxide electrolyser cell
STC	Standard Test Conditions
SWERA	Solar and Wind Energy Resource Assessment
SWT	Small wind turbine
TCM	Thermochemical material
TES	Thermal energy storage
TFT	Thin-film transistor
TOC	Temperature operating conditions
UNFCCC	United Nations Framework Convention on Climate Change
UPS	Uninterruptible power supply
US DOE	United States Department of Energy
USPTO	United States Patent and Trademark Office
VAWT	Vertical-axis wind turbine
VRB	Vanadium redox battery
VRLA	Valve-regulated lead-acid
WASP	Wien Automatic System Planning Package
WAsP	Wind Atlas Analysis and Application Program
WiMAX	Worldwide Interoperability for Microwave Access
WIPO	World Intellectual Property Organization

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.

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.

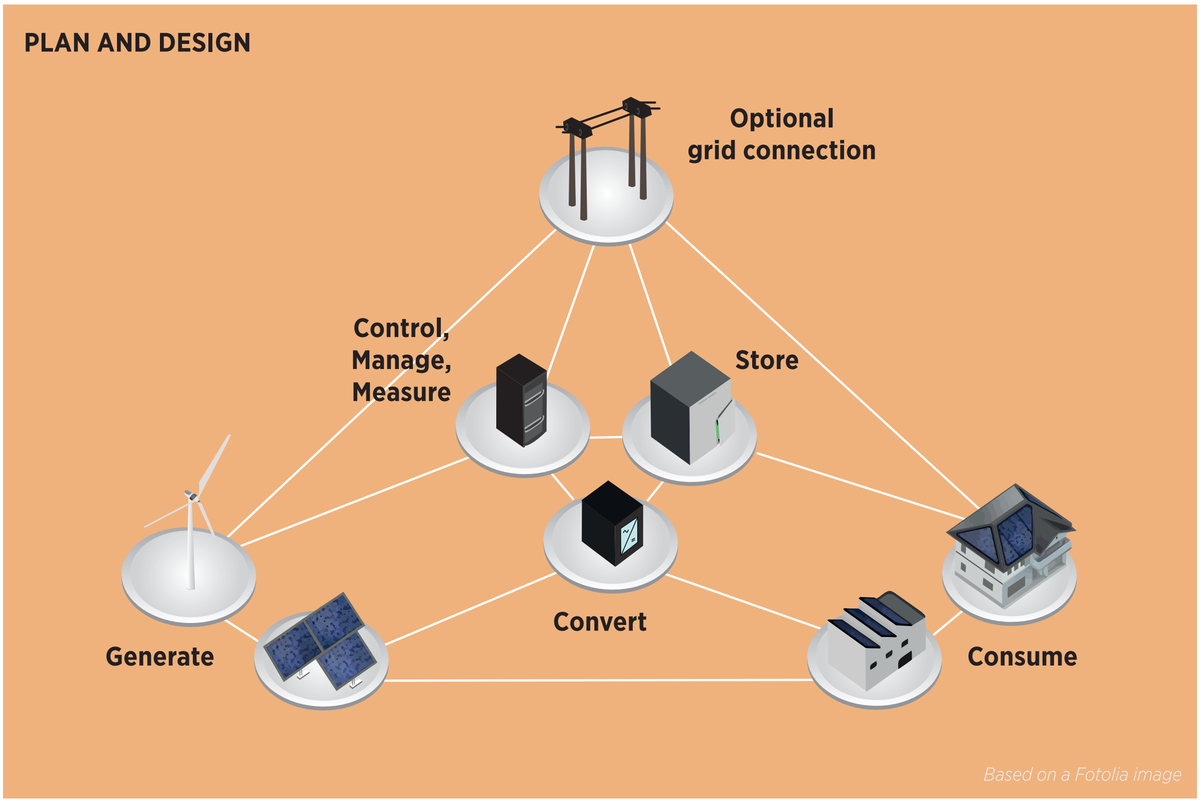
This report informs policy makers and other stakeholders in the energy sector about the technology developments in renewable mini-grids. It also discusses how these technology developments could enable faster commercialisation and large-scale deployment of renewable mini-grids. The information contained 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 S1 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 S1: 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 S1 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 S1: 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 S2: 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

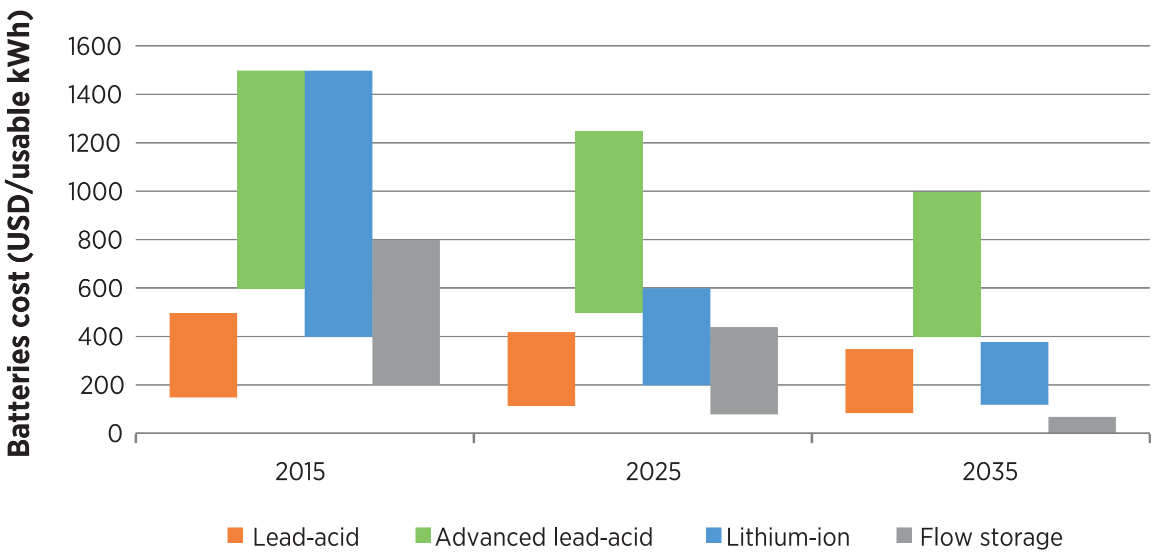
Ground-breaking improvements are under way, not only in components, but in system integration, controllability and flexibility.

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 S2.

- 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 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.

Figure S2: Expected cost reductions in lead-acid, advanced lead-acid, lithium-ion and flow storage batteries by 2015, 2025 and 2035

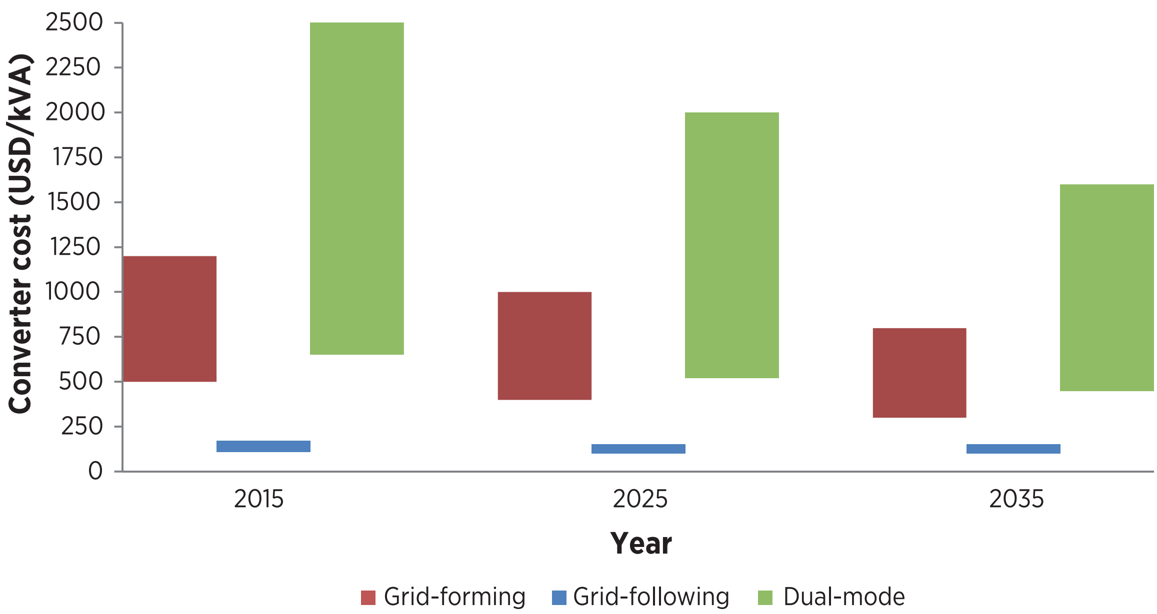


- Internet of Things technologies will continue to enable more intelligent use of electricity by allowing for interconnection and intercommunication among conventional appliances. Along with cost reduction trends and the standardisation of DC lines, the use of appliances that can operate with DC and 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 S3 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 S3: Expected cost reductions in grid-forming, grid-following and dual-mode converters in 2025 and 2035

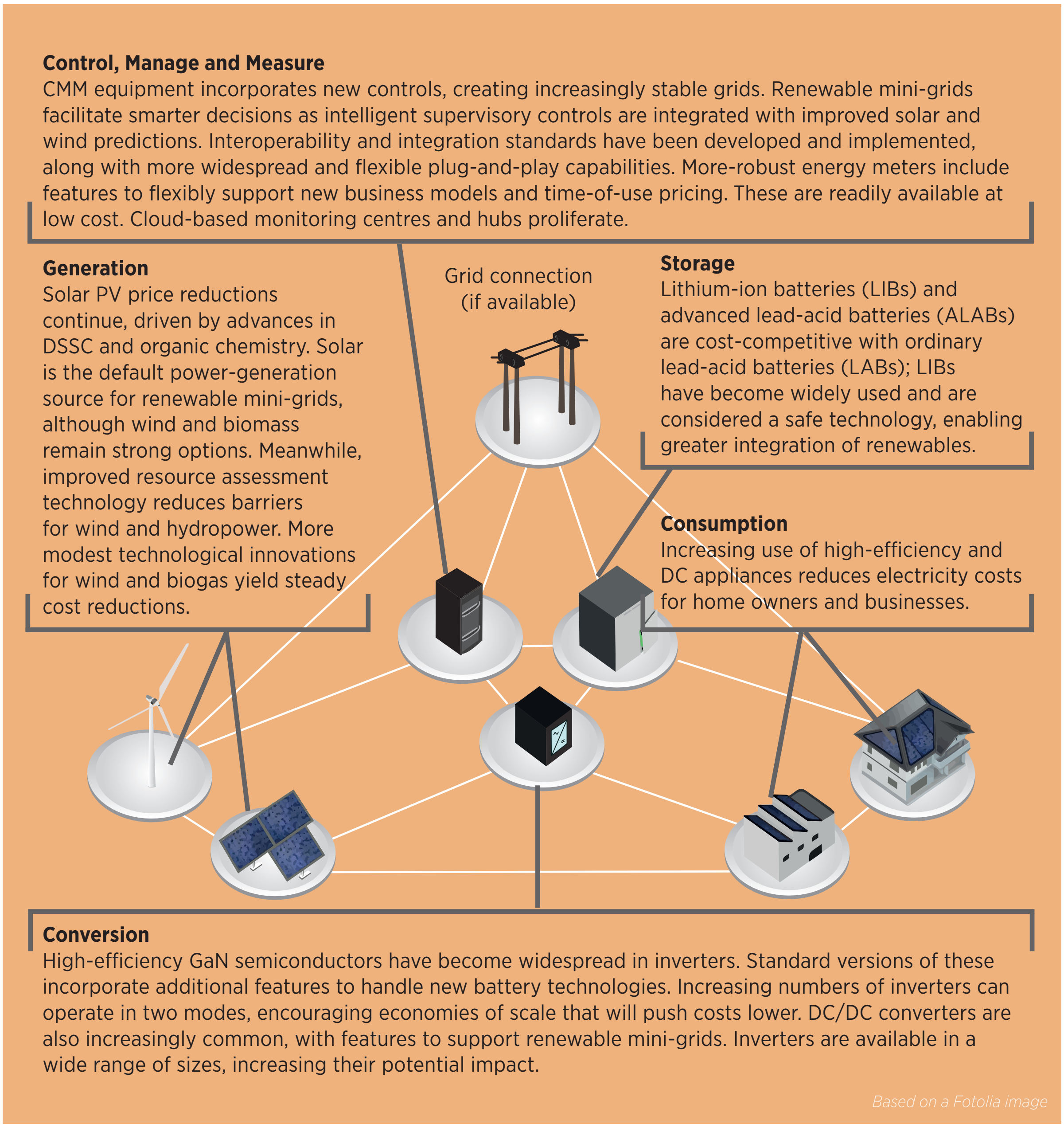


What will the mini-grid of the future look like?

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

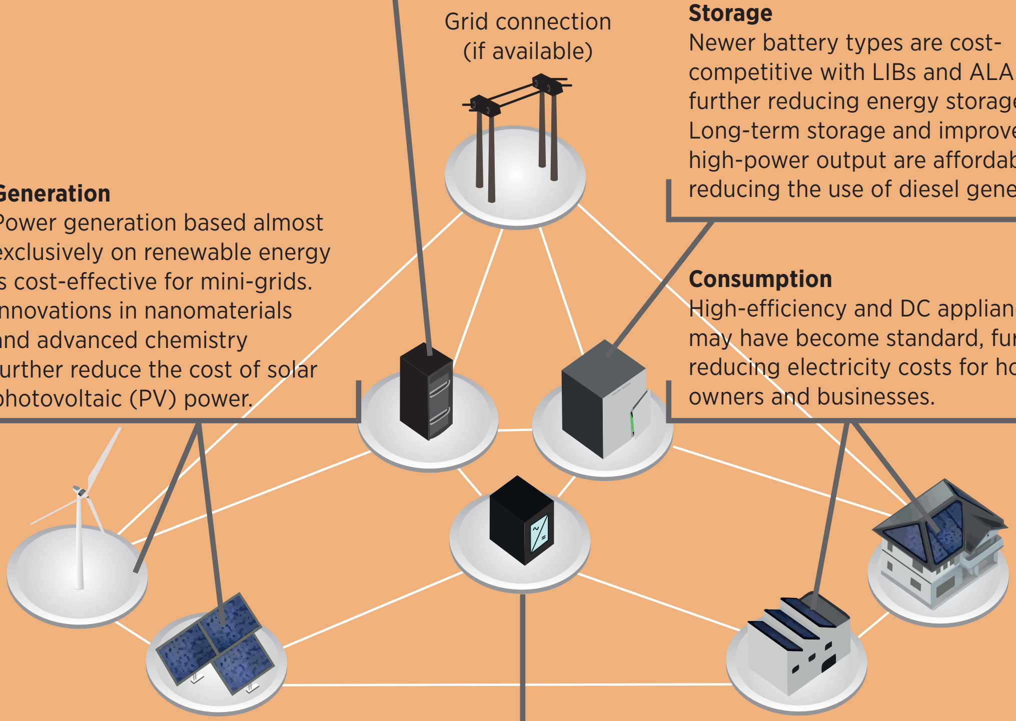
Figure S4: Potential evolution of renewable mini-grids by 2025 and 2035

The Renewable Mini-grid of 2025



The Renewable Mini-grid of 2035

Control, Manage and Measure
Renewable mini-grids use smart controls that enable near-optimal decisions based on distributed intelligence and robust resource predictions. Interoperability and integration standards have continued improving and are embedded into all equipment. Smart meters are standard for renewable mini-grids, providing more features and further lowering costs. Monitoring technologies leverage cloud-based and hub centres and are less expensive. Preventive and corrective actions can be taken automatically. Off-the-shelf designs draw on international experience, adapting it automatically to local needs.



Generation
Power generation based almost exclusively on renewable energy is cost-effective for mini-grids. Innovations in nanomaterials and advanced chemistry further reduce the cost of solar photovoltaic (PV) power.

Storage
Newer battery types are cost-competitive with LIBs and ALABs, further reducing energy storage costs. Long-term storage and improved high-power output are affordable, reducing the use of diesel generators.

Consumption
High-efficiency and DC appliances may have become standard, further reducing electricity costs for home owners and businesses.

Conversion
New nanomaterial semiconductors, such as carbon nanotubes (CNTs), are increasingly common in converters. Dual-mode inverters that can operate even when the rest of the grid is down are readily used in the renewable mini-grid due to their low cost.

Based on a Fotolia image

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.

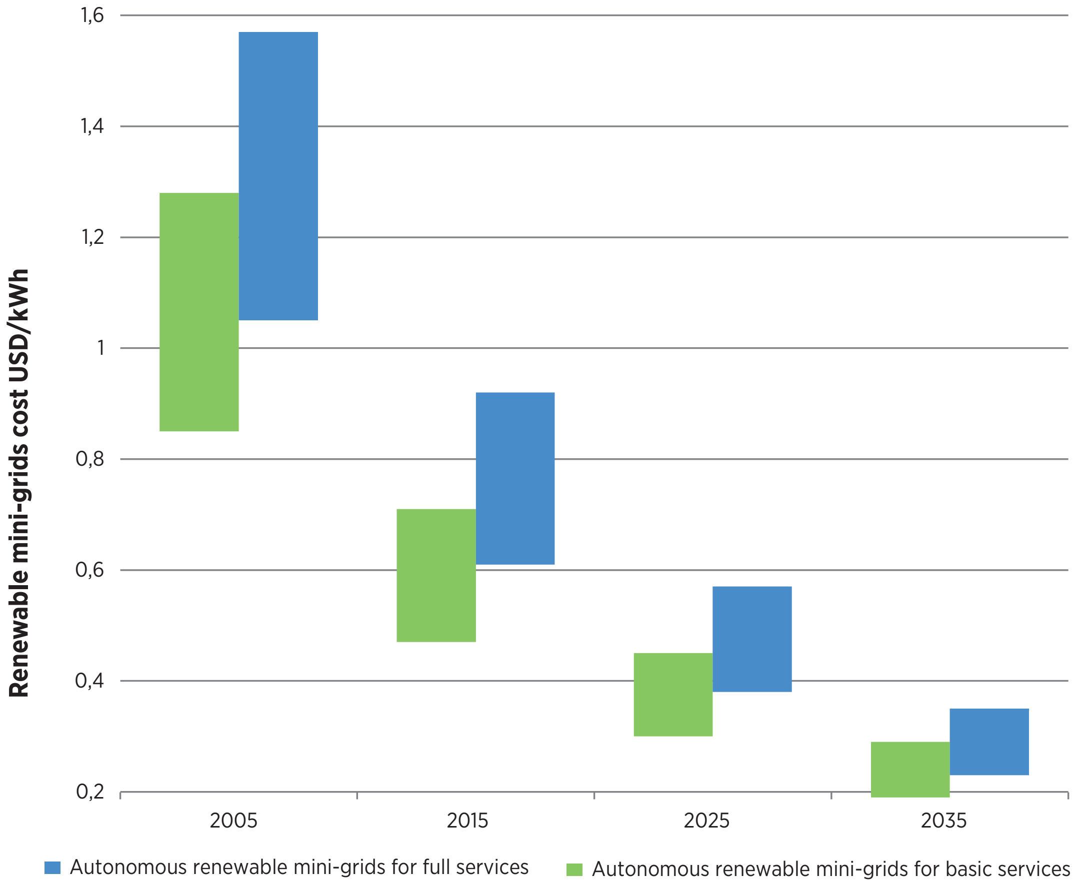
Interconnected renewable mini-grids also are evolving to become a commercially viable option. Today the business case for interconnected mini-grids is strongest for customers with critical needs and in areas with expensive main grid power. By 2025, however, innovations are expected to drive installation 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 S5 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 S5: 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.

GLOSSARY OF TERMS

Algorithm	A formula or procedure created using software to solve a repeated obstacle or problem.
Anode	The electrode by which current enters an electrolytic cell, voltaic cell or battery.
Autonomous mini-grid	A mini-grid that operates completely independently of a larger grid.
Biogasification technologies	Technologies that use an organic, carbon-based matter to produce useable fuel. If the fuel is used to produce electricity, it will be fed into an engine and generator.
Broadband ethernet	A structure that connects multiple electronic devices to create a local area network. Broadband ethernet connections are considered to be more reliable, faster and lower-cost than fibre broadband connections due to multiple copper wire transmission lines.
Capacity factor	The percentage of electricity actually generated in comparison with what could be produced at full rated power.
Cathode	The electrode by which current leaves an electrolytic cell, voltaic cell or battery.
Chronological simulation	Software that simulates chronologically the hourly commitment and dispatch of power supply equipment and allows insights to whether this equipment is physically capable of supplying the expected load.
Commercial scale-up	A mature stage of technological innovation focused on increasing the use and deployment of a technology.
Cut-in wind speed	The minimum wind velocity needed to overcome frictional forces related to the rotation of wind turbine blades to produce power.
Demand-side management	Strategies to reduce energy use during peak hours, to match demand with power/resource availability.
Distributed generation	Decentralised technologies that are located close to the electrical load that they serve. These often are installed at the distribution level and use renewable energy sources.
Drivers	Political, economic, social, environmental or technological factors that influence or advance renewable mini-grid deployment worldwide.
Droop control	A control approach for alternating current (AC) grids in which each generator adjusts its output by using the grid frequency. It enables parallel generators to share load.
Dual-mode inverter	Inverter capable of switching between grid-connected mode and autonomous operation.
Electrode	A conductor through which a current enters or leaves a non-metallic medium.
Electrolyte	A liquid or gel inside a battery that contains ions and that enables the electricity to flow between the cathode and the anode.
Feeder	Electric conductor that originates at a primary distribution centre and supplies power to one or more others.
Five nines	A term to describe very high reliability electricity, indicating that the electrical supply is available 99.999% of the time. Data centres often pursue this level of reliability at minimum.
Flexiwatts	Electric loads that demand flexibility shifts in time. Demand can be moved across the hours of a day or night according to economic or other signals.
Fouling issues	The accumulation of unwanted materials that can affect functioning.
Functionality	The core use or set of uses for a technology in a renewable mini-grid.
Graphene	An atomic-scale honeycomb lattice made of carbon atoms.
Grid-forming inverter	Because renewable energy sources generate DC or variable AC voltages, they require an inverter to interface with and help regulate or “form” the mini-grid. This type of inverter is required to regulate voltage and frequency.
Head range	A range of water-surface elevations for hydropower turbines to function.

Innovation	The development and diffusion of new or improved products, processes or services.
Integration	The process of linking together different renewable energy capabilities and components, either physically or functionally, to act as a co-ordinated whole.
Interconnected	In the context of renewable mini-grids, this describes a mini-grid that has the capability of connecting with a neighbouring grid to run as a single unit.
Interoperability	The capability of multiple components, devices, networks or applications to securely and effectively use and exchange information between entities that interact with energy storage.
Islanding mode	State of operation when a mini-grid is operating while not connected to or drawing electricity from a neighbouring (often centralised) electricity grid.
Key indicators	Significant, influential indicators for measuring technological growth and progress and comparing different technologies.
Levelised cost of electricity (LCOE)	A measure of the average cost of electricity over a project's lifetime. This measurement is calculated by taking all of the expected lifetime costs and dividing it by the lifetime expected power output for that system.
Leapfrog	Refers to the adoption of state-of-the-art technology in a specific sector without prior adoption of previous technology. An example is the use of mobile phones in a remote area where there was no previous access to landlines.
LiDAR Technology	Light detection and ranging (LiDAR) is a sensing technology to examine surfaces or measure distances. It uses light in the form of a pulsed laser.
Low-voltage ride-through	The capability of wind generators to operate during periods of lower grid voltage.
Long term evolution (LTE) LTE/4G	A technical process for achieving fourth-generation (4G) connectivity speeds. The fourth generation (4G) of data technology for cellular networks is up to 10 times faster than 3G.
Machine-to-machine communication	When multiple devices are able to connect and communicate between themselves to either collect or exchange data.
Main grid	The electric power distribution grid, which can work in parallel with a mini-grid. It often is referred to as utility grid or national grid.
Maximum power point tracker	A device embedded into the charge controller that adjusts operating parameters in wind and solar installations to maximise power output.
Micro-siting (renewable generation)	Evaluating site locations for individual renewable energy generation components such as turbines or solar arrays within a larger renewable energy siting project. For example, the location of a wind turbine must be carefully placed to ensure optimal power generation.
Mini-grid/ Microgrid	Distributed energy sources (including generators and energy storage appliances) and interconnected loads integrating an energy infrastructure, which can operate in parallel with the main grid, off-grid or in islanding mode.
Mobile money platforms	Services that offer a user access to a variety of financial services via mobile phone.
Metal-oxide semiconductor field-effect transistor	Transistor used to switch or amplify electronic signals.
Nanomaterial	Material that contains nanoparticles of approximately 1 to 100 nanometres in at least one external dimension.
Nominal power	The nameplate power capacity of a generating unit.
Peak shaving	Reducing electricity consumption on a grid during times of peak power usage. Peak shaving can reduce electrical congestion on a grid. Peak times will vary based on load demand, feeder and distributor capacity, and the availability of power from generators.

Power factor	For AC electrical power equipment, the power factor is the ratio of the useful (“real”) energy that is delivered as compared to the total (“apparent”) energy. Ideally, this ratio is 1:1. However, certain loads and generators can reduce the amount of real energy delivered.
Power quality	A measure of how closely the delivered power matches the ideal quality level, based on clean and stable power. A supply with high power quality is noise-free. For AC electricity, high power quality is a perfect sinusoidal wave shape.
Ramp rate	The ability of a generator to adjust its power output up or down based on variability from load and production from other generators. The ramp rate is a particularly important consideration for generators that are used to ensure stable operation of a grid with variable renewables.
Redox reaction	A chemical reaction that involves the transfer of electrons between species. Redox is short for “oxidation reduction”.
Remote payment scratch card	A prepaid card with a unique identification pin number that allows the user to pre-pay for services from different locations.
Run-of-river technology	A hydroelectric installation that diverts a portion of a river’s flow to electricity generation turbines and then returns the diverted flow back to the river channel. In contrast to traditional hydro technologies, run-of-river does not require significant water storage reservoir.
Self-discharge (rate)	Discharge that occurs in batteries due to an internal chemical reaction which reduces the stored charge of the battery without any connection between the electrodes.
Solid oxide electrolyser cell	A solid oxide fuel cell that produces oxygen and hydrogen gas through the electrolysis of water by running in regenerative mode.
Syngas	A fuel-gas mixture made up of mainly hydrogen and carbon monoxide.
Technology venturing	An activity at the early stage of technological innovation focused on adapting technology to the market.
Tier of service	The level (“tier”) of electricity service provided to a customer or end-user on a grid. Lower tiers of services will have electricity available for less time each day and less power available.
Uninterruptible power supply	A device that allows for the continued operation of an electrical device or machine after a loss of power, and that protects the device from power surges.
Vacuum-annealed graphene	A process to clean graphene by heating it under controlled pressure.
Worldwide Interoperability for Microwave Access	A wireless communication standard designed to provide data rates of 30 to 40 megabits per second.
ZigBee	An open global standard for wireless technology. It is used to create networks that require low data transfer rates, energy efficiency and secure networking.

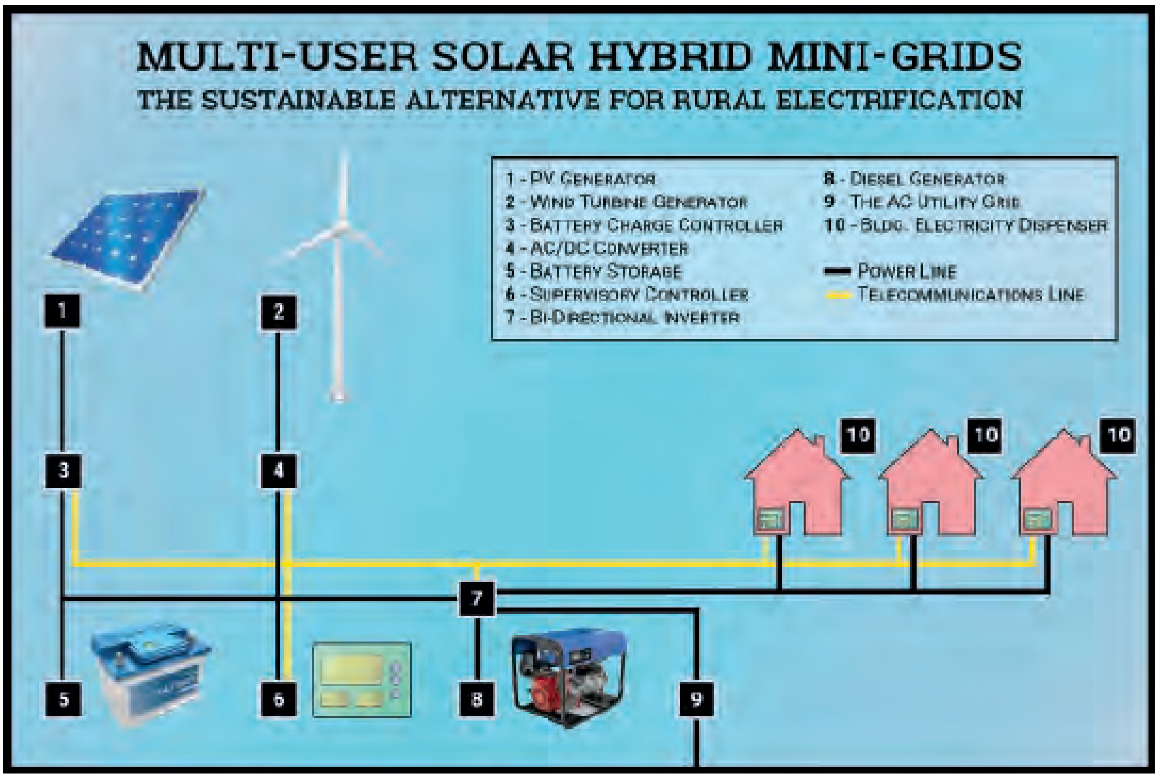
1 INTRODUCTION

Mini-grids are not new. They bring light to remote communities, enable industry in isolated areas and back up the main grid (*see* Glossary of Terms) in case of failure. However, the mini-grids of the past derived their power from costly fossil fuels and are prone to electricity back-up failures. Technological changes are providing an opportunity for mini-grids to evolve. In the future they will use increasingly more energy from renewable sources – becoming an alternative to expensive and polluting fossil fuels – and will provide increasingly reliable power. Mini-grids that use renewables in their energy mix have the potential to bring low-cost power to areas that are without it now, to support communities to improve their use of cleaner energy sources, and to increase the resiliency of industries and business. Figure 1 shows a sample renewables-based mini-grid configuration, which is commonly used in rural electrification.

Mini-grids serving remote areas with a maximum demand larger than about 1 megawatt (MW) typically are still almost entirely dependent on fossil-fuelled gensets during stand-alone operation. Smaller mini-grids in these areas often use a higher percentage of energy from renewable sources but suffer from scaling challenges and higher costs. In areas with access to the main grid, back-up systems are based almost entirely on diesel. In all cases, the cost of energy typically exceeds that of the main grid. Renewable mini-grids provide an opportunity to change this.

Renewable mini-grids are important for the increased value that they provide, not only in terms of energy cost reduction in remote areas, but also in terms of the increase in reliability that they can provide in both interconnected and autonomous areas.

Figure 1: A renewable mini-grid with DC distribution



Source: Author elaboration

Autonomous areas reliant on expensive diesel are increasingly using renewables to reduce costs. The use of renewables in these mini-grids is, generally, cost-effective today. As the costs of diesel fuel go up and the costs of renewables come down, these areas are pursuing technologies that enable them to increase the percentage of energy from renewables in their mini-grids. Innovation in mini-grid technologies is enabling these mini-grids to increase reliability, while leveraging renewables to reduce reliance on imported fuels.

In interconnected areas, mini-grids hold the tantalising potential to improve supply and, when interconnected, to strengthen the neighbouring grids to which they connect. In this way, they can provide value to the mini-grid operator, to its neighbours as well as to the main grid utility. In areas with strong utility grids, mini-grids often have a focus on high reliability and security (*e.g.*, for high-end manufacturing or data centres). In areas with weaker grids, mini-grids provide an alternative to fossil fuel back-up generators. In both instances, they provide a foundation for the integration of renewable energy.

Advancements in mini-grid technologies can reduce the challenges of integrating large amounts of renewable energy into the electrical supply, while also increasing local control and choice. The access to new generation choices provides a critical alternative to the near-monopoly that electricity from diesel traditionally has had in remote areas, and are an alternative to extending the grid to isolated areas. Mini-grids also provide an alternative to entirely independent, stand-alone systems. In contrast to electrification with very small independent systems, mini-grids give users an option to share costs and leverage the benefits of scale that come from sharing an electrical supply across different end-uses.

In interconnected areas, mini-grids provide an alternative to the exclusive use of centralised generation from the main grid. Mini-grids provide an option to commercialise preferred energy mixes locally, while also leveraging the frequently low cost of energy from the larger grid. Many interconnected communities and businesses are interested in renewable mini-grids to improve their environmental stewardship and increase local control of their energy mix. These communities and businesses are actively exploring renewable mini-grids for this purpose.

The technological innovation outlook presented in this report characterises the technological needs for increasing performance, reducing cost, mitigating environmental impacts and driving deployment of renewable mini-grids. Research on renewable energy mini-grids should be focused on lowering costs, as well as on increasing flexibility and the robustness of technologies. As the costs of renewable generation and storage continue to drop, the importance of modularity and ease-of-use will increase. Modularity and ease-of-use will be achieved by the use of smarter planning, more intelligent controls, the increased compatibility of different types of equipment ("interoperability", *see* Glossary of Terms) and the increasing scalability of designs.

Renewable mini-grids are driven by a complex web of considerations and needs. In addition to the technological innovations described here, renewable mini-grids will benefit from developments in other areas, such as socio-political innovations required for re-thinking energy regulations; new business models and new approaches to financing; and enhancements to environmental protections to increase mini-grids' use of renewable energy sources. Renewable mini-grids present an opportunity for re-thinking traditional energy supply models. However, energy technologies must balance social needs, political will, economic efficiency, technological capabilities and environmental protection in order to be effective. To address these interlinked aspects this report includes key advice for policy makers, technology investors, project developers, the non-profit sector and academics to foster the growth of this new technological option.

This report aims at informing policy makers and other energy sector stakeholders on the technology developments in mini-grid systems based on renewable energy, which would enable a faster commercialisation and a large-scale deployment of this type of power system. The information contained in this report may help countries in expanding their renewable energy options in support of their national objectives, and also in enabling a more focused and effective implementation of incentive programmes and policy actions for a transition towards a sustainable energy regime.

An overview of the different types of renewable mini-grids is presented in Section 2, explaining the renewable mini-grid ecosystem through the lens of grid connectivity and tiers of energy service. Section 3 details the current use and deployment of renewable mini-grids globally. Section 4 explains the most-current technologies at their various stages of development, categorised in the following groups: plan and design; control, manage and measure (CMM); store; convert; consume; and generate. Section 5 summarises the main technological gaps and opportunities for advancing renewable mini-grids. Section 6 details ongoing R&D and innovation prospects, providing specific examples of current research in universities, laboratories, companies and elsewhere that is expected to lead to new technological breakthroughs with promising potential for commercial application in the next two decades. Section 7 defines the potential role of key stakeholders, and particularly policy makers, in driving innovation in renewable mini-grids. Final conclusions are summarised in Section 8.

Renewable mini-grids are driven by a complex web of considerations and needs. In addition to the technological innovations described here, renewable mini-grids will benefit from developments in other areas, such as socio-political innovations required for re-thinking energy regulations; new business models and new approaches to financing; and enhancements to environmental protections.

2 TYPES OF RENEWABLES-BASED MINI-GRIDS

Mini-grids, also known as microgrids (the term mini-grids will be used in this report), can be independent of a neighbouring grid ("autonomous", *see* Glossary of Terms) or interconnected (*see* Glossary of Terms) to the main grid. Despite their commonalities, some definitions focus on autonomous mini-grids (CDM Executive Board, 2011; IEA-PVPS, 2011), others focus on interconnected mini-grids (Brucoli and O'Halloran, 2014; marketsandmarkets.com, 2014a; US DOE, 2012a) and others include both types (Carl, 2013; Office of the Federal Register and NARA, 2007).

While there are differences in all of these definitions, they all have in common that mini-grids are integrated energy infrastructure with loads and energy resources, including generators powered by energy sources such as solar PV and wind turbines; energy storage devices such as lead-acid batteries; power-conversion equipment such as inverters; and CMM equipment, including battery supervisors, and meters, among others. These loads and energy resources are interconnected with users via a distribution grid (see Figure 1). This report focuses on renewable mini-grids: those that derive a majority of their primary energy from renewable sources to generate electricity.

In addition to a connection to neighbouring grids, this report uses tiers of service to differentiate mini-grids. In contrast to traditional users of the main grids, which all share the same quality of electricity service, mini-grids provide the option for differing electricity service quality. The Global Tracking Framework's tiers of service (*see* Glossary of Terms) for autonomous electrification range from low service (Tier 1) to high service (Tier 5) (Angelou *et al*., 2013). For example, a solar lantern would provide low-quality service, as per Tier 1 (outside the scope of the present report). Renewable mini-grids are most typically used for providing power at Tier 3 and higher.

The US Department of Energy (DOE) has created a different tier framework for interconnected mini-grids (US DOE, 2012a). The primary difference between these frameworks is that expectations of service differ. This stems from the expectation that service quality traditionally has been higher when interconnected to the main grid. In this report, grid connectivity and tiers of service have been combined to create four renewable mini-grid types. A detailed breakdown of the types, their relationship to a main grid and typical tiers of service are provided in Table 1:

Table 1: Types of renewable mini-grids

	Lower Tier of Service	Higher Tier of Service
Autonomous	**AB (Autonomous Basic service)** Typical generation sources are solar PV, hydro and biomass, with diesel as possible back-up. Storage is limited, to reduce costs. Power is supplied for less than 24 hours and may be turned off when there is insufficient renewable energy to meet load. Design for energy provision for lighting and communication is basic, with limited support for motors and large loads. **Tier of service:** Tier 3-4 (less than 24-hour power) **Socio-economic considerations:** The target is low-income communities with limited funds and capacity to pay. The focus is on providing basic access to energy services to meet rural development goals. **Typical consumers:** Remote community without major commercial or industrial activity. **Sample loads:** Power for lighting, radio, mobile phone, fridge, TV, limited minor productive uses (*e.g.*, chilling drinks, hair dressing, small livestock, water pumping for small farms).	**AF (Autonomous Full service)** Typical generation sources are solar PV, hydro and wind, with diesel generators as a back-up. Larger amounts of storage and more reliable service compared with AB. **Tier of service:** Tier 5 (24-hour power) typically **Socio-economic considerations:** AF requires higher capacity to pay for power. The size of the grid is typically larger, enabling economies of scale and allowing increased energy demand. The service may include larger commercial and industrial users that require higher reliability and use motors. **Typical consumers:** Remote communities, islands, consumers with major commercial or industrial requirements; industrial sites disconnected from grid. **Sample loads:** Power for all AB loads plus major productive uses (*e.g.*, air-conditioned hotels, industrial manufacturing, commercial refrigeration).
Interconnected	**IC (Interconnected Community application)** There are few community mini-grids today, although mini-grids with limited renewables and combined heat and power (CHP) are common. The typical renewable generation options are solar PV, wind turbines and sometimes biomass/biogas technologies. These types of mini-grids may be used as a back-up to the main grid, designed to sustain only the most critical loads, or could be used to provide primary power, with the main grid as a back-up. In each situation they are designed to ensure close to 100% reliability. The design depends, among other factors, on the cost-effectiveness of renewables during typical operation. **Tier of service:** Tier 5+ (high critical/ interruptible) **Socio-economic considerations:** Focused on improving the availability of community services, particularly during outages or extreme events. There is typically high ability to pay among stakeholders, particularly when costs are shared across communities. **Typical consumers:** Medium to large grid-connected communities, such as university campuses. **Sample loads:** Critical uses such as priority loads for clinics, communication and other emergency response.	**ILI (Interconnected Large Industrial application)** There are few industrial mini-grids today, although mini-grids with limited renewables and CHP are common. The main renewable generation options are solar PV, wind turbines and limited biomass technologies. Built to ensure 99.999% reliability ("five nines", *see* Glossary of Terms) even during major utility outage events. Facilities will spend substantial resources for additional reliability and resiliency. **Tier of service:** Tier 5++ (very high: critical/ uninterruptible) **Socio-economic considerations:** The end-uses are often industrial and will suffer substantial penalties if the electrical supply fails. Examples include precision manufacturing and data centres where reliability is key for successful business. **Typical consumers:** Data centres, industrial processing or other critical uses. **Sample uses:** High-tech loads that require consistent power (uninterruptible).

Source: Debajit, 2012; Deshmukh, 2014; US DOE, 2012a; SE4All, 2015; author elaboration

3 DEPLOYMENT STATUS AND COSTS

Renewable mini-grids face competition from two main technologies: individual solutions and the main grid. At the small end of the spectrum, individual solutions such as solar home systems (SHS) and productive applications such as solar water pumps are enabling customers to set up their own renewable energy supply with low-tier service. Grid extensions traditionally have been the first option considered for electrification. Mini-grids are an opportunity that is able to balance having a local solution with the benefits of load aggregation.

Interconnected renewable mini-grids can add value to each of these applications, in terms of improving the reliability and resiliency of the supply while simultaneously allowing renewable energy sources to contribute a significant portion of the portfolio. There has been strong market growth in off-grid areas, particularly in difficult-to-access or very remote areas such as rural Africa. Due to the potential benefits there is active exploration of renewable mini-grids through pilot and demonstration projects in preparation for the technology to mature.

3.1 Deployment of renewable mini-grids

When considering deployment of renewable mini-grids, it is important to put them in the context of mini-grid deployment worldwide. In remote areas, the vast majority of these autonomous installations are 100% reliant on diesel fuel, which is both costly and environmentally damaging. According to IRENA (2015a), the market for diesel mini-grid hybridisation is between 50 GW and 250 GW, a large part of which is on islands. In terms of quantity, there are nearly 100 GW of gensets smaller than 0.5 MW worldwide (IRENA, 2015a).

Renewables can cost-effectively be retrofitted into these grids today, although further technological innovation is needed to enable wide-scale conversion to renewable mini-grids. In autonomous areas there are nearly 75 GW of small hydropower installations and about 7.5 MW of autonomous small wind turbines (IRENA, 2015a). There is some small-scale biomass generation, totalling fewer than 5 MW. Finally, solar PV is very common, but precise numbers are not available.

Box 3.1 – Saving fuel with solar in diesel grids

Increasingly, there is a push to reduce the use of diesel in mini-grids by replacing it with solar energy. These "fuel-saving" solar installations are helping grid operators use renewable energy to diversify their energy mix. Diversification reduces the impact of volatile fuel prices on generation costs. Often, these systems use low penetrations of solar energy that do not require storage, reducing capital costs. In general, fuel-saving solar systems are used in larger AF-type mini-grids to offset fuel, and often as retrofits to existing diesel grids. These systems can derive, at most, 20% to 30% of their energy from renewable energy; storage is required for higher savings. Importantly, these installations prepare the mini-grid for future upgrades to increase the use of renewable energy technologies by enhancing the controls infrastructure. For larger projects, there is strong interest in fuel savers because they allow a third-party operator to own the solar PV and sell into the grid. Common providers of the fuel-saver systems include SMA, Schneider, ABB, NRG, OPS, General Electric and Leonics.

Some examples of fuel-saving projects without the use of batteries are Cronimet's Zwartkop Chrome mine in in South Africa, the hospital of Gonaives in Haiti developed by TTA, or several pilot projects in Lebanon within the fourth phase of the UNDP-CEDRO Project, including two large factories.

Despite the potential, renewable mini-grids today represent a much smaller segment of the market. They have been installed in most regions worldwide, although the type and technologies used vary. Table 2 includes a summary of the hotspots within each region. The table includes a quick assessment of the maturity of the market, ranging from very few (limited), to isolated exploration (pilots), to developing market (emerging) to active deployment today (mature). Mature renewable mini-grids are mostly limited to smaller grids (AB type) in rural areas of Guatemala, Nepal, Nicaragua and other places with appropriate river resources for hydropower and for isolated PV mini-grids. Notable example projects from each region are presented in Annex 3.

Latin America and the Caribbean have high electrification rates, due in large part to grid extensions that provide

Table 2: Renewable mini-grid deployment by region

Region	High concentration of hot spots	Autonomous Basic service	Autonomous Full service	Interconnected Community application	Interconnected Large Industrial application
Canada and US	Canada (*e.g.,* Newfoundland), US (*e.g.,* remote areas in Alaska, California, Hawaii and the Northeast)	Limited	Mature	Emerging	Emerging
Caribbean and Central America, Mexico	Cuba, Dominican Republic, Guatemala, Mexico (*e.g.*, Baja California, Durango) Nicaragua	Mature	Emerging	Emerging	Limited
South America	Bolivia, Brazil (*e.g.*, Amazon), Ecuador (*e.g.*, Galapagos Islands), Peru	Mature	Emerging	Limited	Limited
Europe	Canary Islands, Denmark, Germany, Greek islands, Italy, Spain, some UK islands (*e.g.*, Isle of Eigg)	Mature	Mature Emerging, Pilots	Pilots	Pilots
North Africa	Algeria, Morocco, Tunisia	Mature	Emerging	Limited	Limited
Sub-Saharan Africa	Burundi, Cameroon, Cape Verde, Chad, Ghana, Guinea Bissau, Kenya, Liberia, Mali, Mozambique, Nigeria, Rwanda, Senegal, Uganda, United Republic of Tanzania	Emerging, Mature	Emerging	Limited	Limited
Central and North Asia	Russian Federation	Emerging, Pilot Project	Limited	Limited	Limited
East and South Asia	Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Nepal, Philippines, Republic of Korea, Singapore, Sri Lanka,	Mature	Mature, Emerging, Pilot Project	Emerging	Emerging
Middle East	Egypt, Palestine, UAE	Limited	Pilot	Limited	Limited
Oceania	Australian remote communities, Pacific islands (*e.g.*, the Cook Islands, Tokelau, Tonga)	Mature	Mature, Emerging	Pilots	Pilots
Antarctica	Research stations	N/A	Mature	N/A	N/A

Source: Deshmukh, 2014; IRENA, 2015a; Marnay et al., 2015; Tenenbaum et al., 2014

Box 3.2 – Renewable energy for energy access

Place: Pediatorkope, Volta Delta, Ghana

The community mini-grid of Pediatrokope in Ghana was commissioned in 2016. It consists of a 39 kWp solar PV plant and a small 11 kW wind plant to serve up to 146 connections. The system includes a diesel generator for occasional back-up; the mini-grid is designed to use lead-acid battery storage to enable the grid to obtain 95% of the electricity from renewables. The robustness of the mini-grid is ensured by Circutor's Electricity Dispensers. They use an Energy Daily Allowance approach to limit energy consumption and power draws, and users are charged a monthly fixed fee to keep tariffs simple and to ensure financial sustainability. The mini-grid is one of five in Ghana designed, implemented and managed by a consortium of local companies in collaboration with European experts.

access to most rural communities. There is a market for switching hundreds of MW of off-grid diesel mini-grids to use renewable sources, most notably in Bolivia, Brazil, Colombia and Peru.

In South and East Asia there have been some pilot demonstrations of PV-diesel grids (AB, AF), although growing industrial powerhouse India has started to deploy interconnected mini-grids for resilience and renewable energy integration (*see* Glossary of Terms) for industry (IC, ILI), despite low reliability of the main grid. China, in particular, is exploring the use of rural mini-grids (AB, AF) to complement stand-alone and grid extension programmes, and is rapidly deploying grid-connected diesel-based and hydro-based mini-grids (IC, ILI). There is significant research and initial pilot projects for improved resilience (IC, ILI) in Asian technology giants Japan and the Republic of Korea. Interestingly, the interconnected mini-grids (IC, ILI) in these areas differ in their focus based on the capabilities of the main grid. Countries like India are driven by establishing basic, reliable grid service for communities and businesses, whereas Japan and the Republic of Korea are trying to achieve even higher reliability for their industries.

Africa has the highest potential for AB and AF, although deployment faces many barriers including other investment needs, the need for grid extension, and challenges to maintain and operate the systems in the long term. Islands are considered viable currently, although the traditional grid extension approach is delaying deployment in many continental areas.

In the United States there are several interconnected renewable mini-grids being deployed in the east in response to emergency disasters, while in the west the focus is driven by a need to prepare the grid to handle increased amounts of renewable energy in the future. The United States is leading the way in research and innovation. In Europe, there has been some important work but less focus than in Japan, the Republic of Korea and the United States.

3.2 Innovation beyond technology: New business models

Scaling up the deployment of mini-grid systems requires systemic innovation along with technology innovation. Systemic innovations include those for business models, financing schemes, regulations and system integration. For newly electrified, low-income, rural areas (where many *autonomous* renewable mini-grids with basic service are used), a number of companies are offering mini-grid solutions. Although these typically require financial support to make the power affordable to customers, many are being deployed today. The business models operate on very tight operating budgets, so the technology needs to be scalable and modular to meet the dynamic energy requirements of these areas (Bardouille and Muench, 2014). Many of these business models leverage the inherent flexibility of the renewable mini-grid technology and provide basic service today with the hope of higher service in the future as demand grows.

A number of small businesses are piloting the use of these modular technologies. In India, these include DESI Power, Mera Gao, Husk Power, Minda Nexgen, Naturetech and OMC Power. African mini-grid providers include Devergy, Enersa, Persistent Energy, Powerhive, Trama TecnoAmbiental and Rift Valley Energy. None of these pioneers have sufficient customers to be profitable today without grant funding, but they have the potential to achieve profitability if they reach sufficient scale. Bardouille and Muench (2014) estimate that these organisations need to scale up to at least 250 000 customers to reach profitability, and require other forms of cross-subsidising or other means to maintain the operability of the service. They further estimate that many off-grid renewable mini-grid providers typically start with, at most, a few thousand customers, and the time required to scale, for example, could take about five years and nearly USD 75 million in investment (Bardouille and Muench, 2014). Still, the R&D that these start-up companies are leading today will need to continue to improve over the next 10 years for these businesses to succeed (Bardouille and Muench, 2014). Some of the technologies used in these mini-grids today, particularly for DC-based mini-grids, require specialised equipment to interconnect. If these grids are privately operated, the success of the grid is tied to the success of the operator.

Interconnected back-up, with less frequent operation and a focus on resiliency, adds even more potential revenue to the mini-grid market. However, the relatively low power price of main-grid electricity during on-grid operation creates a barrier for renewable mini-grids, which typically have slightly higher prices. The proliferation of distributed solar PV has created an opportunity for conversion into resilient mini-grids. Nevertheless, there is still a limited uptake of mini-grid technologies that use significant renewables, except in pilot applications and in end-uses with high costs for loss of electrical supply (*e.g.*, data centres) or in places that place high value on environmental protection. However, as the costs of renewable mini-grids decline and as the technology improves, the uptake will increase.

3.3 Costs of renewable mini-grids

The costs of renewable mini-grids, and mini-grids in general, have declined consistently over the past decade. As of 2016 the costs have fallen low enough that the technology is gaining interest as an alternative to traditional approaches. The cost will be dependent on the amount of energy from renewable sources; using the proper amount of renewable energy can minimise overall energy costs. The costs also will depend on local factors and requirements, as well as on international market conditions. Factors include the location, access to financing, technology used, regulatory environment, reliability requirements and electrical demand. Despite the range of diverse factors, observations and predictions can be made based on a typical system.

A limited number of publications have analysed the cost of renewable mini-grids. In general, these publications analyse autonomous renewable mini-grids. A World Bank study from 2005 found that the levelised costs of energy (LCOE, *see* Glossary of Terms) for mini-grid generation ranged widely, from USD 0.43/kWh to USD 0.63 USD/kWh for a 25 kW_p solar PV mini-grid. Wind and hydropower often had lower costs, but were limited to areas with a strong resource (World Bank Group, 2006). A more recent study found that in sub-Saharan Africa, the LCOE of a solar PV-diesel mini-grid that serves 100 users can vary from USD 0.46/kWh to USD 0.74/kWh, while a 100% solar PV mini-grid will vary from USD 0.467/kWh to USD 0.714/kWh (Norplan, 2013). A 2014 project in India found that a 100 kW_p solar PV mini-grid had an LCOE of USD 0.50/kWh (Islam, 2014).

Larger autonomous renewable mini-grids with greater than 1 MW of peak power demand are uncommon – although there are numerous mini-grids based on diesel – and increasingly are integrating low penetrations of renewables (see Box 3.1 for a description of these fuel-saver mini-grids). A 2015 study from the Frankfurt School of Business assessed the LCOE of diesel grids with greater than 1 MW of peak power demand and 30% of their energy from solar PV. The study estimated the generation costs of seven different large-scale diesel mini-grids and found that the LCOE varied between USD 0.34/kWh and USD 0.51/kWh (Frankfurt School, 2015).

The costs of interconnected systems will vary greatly based on utility grid costs in a region. From a cost perspective, a well-designed interconnected renewable mini-grid will use energy from the lowest-cost source, whether the main grid or the mini-grid. Therefore,

Table 3: Table of unsubsidised cost ranges for renewable mini-grids from 2005 to 2015 for a 100% renewable energy community system

USD/kWh for 100% RE	2005	2015
AB	USD 0.85–1.28	USD 0.47–0.71
AF	USD 1.05–1.57	USD 0.61–0.92

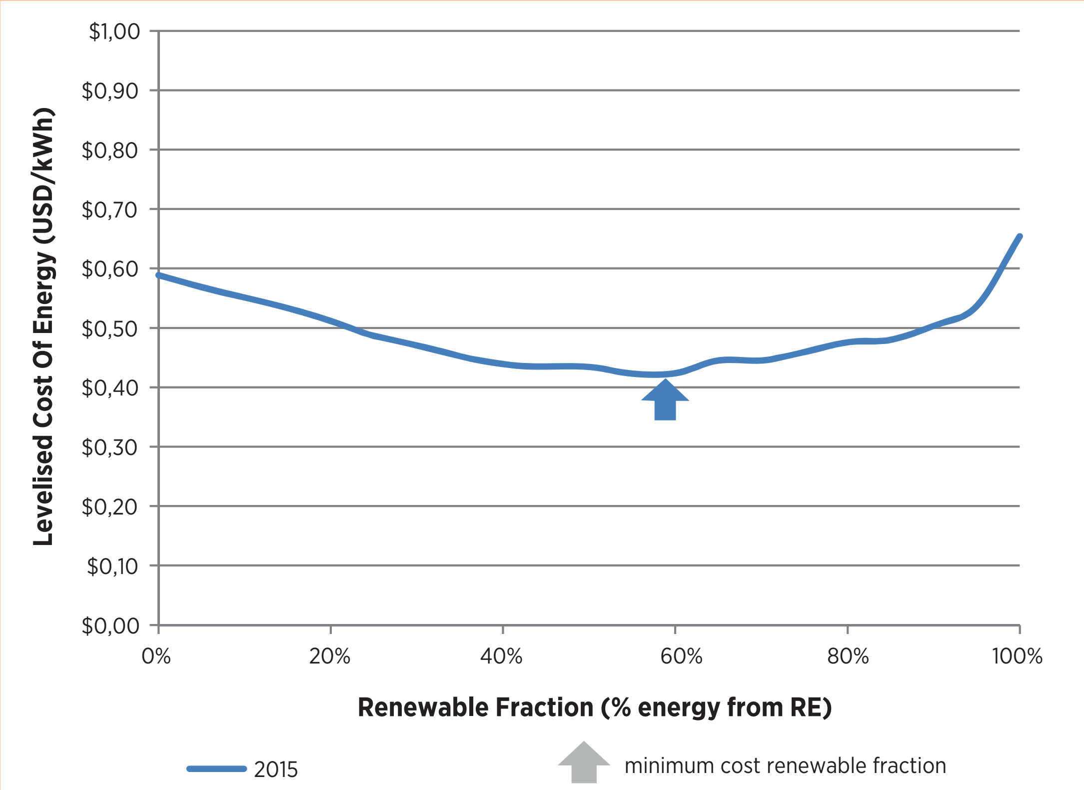
Source: Author elaboration with HOMER Pro, 2016

costs for the autonomous AF systems can be viewed as an upper threshold for the interconnected ILI and IC renewable mini-grid systems. Similar to previous studies, this report modelled autonomous renewable mini-grids to predict the effects of innovation on the cost of renewable mini-grids. The findings for a 100% solar PV energy-based mini-grid is summarised in Table 3. It is noteworthy to mention that a mini-grid that uses other sources (including wind, hydro or non-renewable sources) may have lower costs than those described here.

Box 3.3 – Cost of integrating renewables in mini-grids

If the amount of renewables (or storage) is too high or too low, the price will be higher. Additionally, a renewable mini-grid that includes a diesel generator will have lower costs than a renewable mini-grid that gets 100% of its power from renewable sources. This concept is shown in Figure 2 below, which shows the total LCOE from the lowest-cost solar PV renewable mini-grid design in 2015. Each point on the lines represents a system with varying percentages of energy from renewable sources (solar, in this example).

Figure 2: Plot of renewable fraction vs. levelised cost of energy for 2015



Source: Author elaboration with HOMER Pro, 2016

In addition to the expected cost varying with the amount of energy from renewable sources, the cost is expected to decrease with technological innovation over time. The R&D efforts are expected to not only lower the cost of electricity from renewable mini-grids, but also increase the economically optimal percentage of energy derived from renewable sources.

A list of the assumptions and modelling techniques used is provided in Annex 7.

3.4 Benefits of renewable mini-grids

Renewable mini-grids are important for the value they can offer. Many of the benefits stem from the local nature of renewable grids. They enable local choice and control of the energy supply, while allowing business and communities to use local resources for their energy. Different communities and businesses will have different needs, but the technology platform can provide a range of values. Renewable mini-grids are important for the increased value that they provide, not only in terms of energy cost reduction in remote areas, but also in terms of the increase in reliability that they can provide in both interconnected and autonomous areas. In all areas they provide a technologically viable pathway to increasing the use of renewable energy. Some of the key benefits of renewable mini-grids are summarised in Table 4.

A strength of renewable mini-grid technologies is that they provide a platform that can respond to the needs of different areas. The following sections provide some insights into how the key benefits are shaping the use of renewable mini-grids in each of the four renewable mini-grid types presented in Section 2.

Table 4: Key benefits that renewable mini-grids provide

Benefit	Description and detail
Reduced energy imports and stabilised energy costs	Enable the use of renewables, which can reduce the need for imported fuels that fluctuate in price. This stabilises energy prices.
Reduced cost of energy	Autonomous mini-grids can provide the lowest-cost energy option in remote areas.
Increased reliability and resiliency	Enable the use of robust, local generation which can be used to increase reliability and improve response to catastrophic events. If developed with the support of the main grid utility, they can provide reliability and resiliency support to the main grid.
Improved environmental outcomes	Provide a platform for renewables that offers a clear technological pathway to high use of renewable energy.
Greater energy choice	Allow energy options that may otherwise be difficult through main grid utilities, and enable communities and businesses to have control of their energy supply. Mini-grid operators can opt for more renewable energy and higher reliability. In areas with weak or poor regulatory environments, renewable mini-grids provide a technological alternative to improving energy.
Increased local energy	Create opportunities for energy supplies built around local resources and local need.
Diversification	Provide an alternative to the main grid in interconnected areas. In remote areas they provide an alternative to extending the main grid and stand-alone systems. They also enable commercialisation of technologies and generation that may be overlooked in main grids.

Benefits of AB (Autonomous Basic) service

For smaller and less prosperous areas, renewable mini-grids can enable enhanced energy access. For some areas, this is the transition towards modern energy access. This includes improving access to electricity while reducing energy costs. Renewable mini-grid technologies provide new fuel supply options (diversification). Whether a region is entirely dependent on the burning of local biomass for energy, has sparsely distributed stand-alone systems, or has a part-time diesel grid, renewable mini-grids provide new flexibility. They also provide an alternative to extending the main grid, which can be costly to install and maintain — particularly for very isolated areas. Renewable mini-grids provide a technological option for improving quality of life and lowering energy costs.

The target of renewable mini-grids in these areas is modest reliability, which even though modest provides a huge shift in the quality of life and ability of business to thrive. There often is a focus on ensuring viability even when consumers have limited ability to pay. The mini-grids in these areas, driven by innovations in metering technologies and efficient appliances/lighting, increasingly are enabling more services for less. They also are enabling users to buy only what they need and can afford.

Benefits of AF (Autonomous Full service)

In remote, isolated areas currently reliant on diesel for electricity, renewable mini-grids enable alternatives to burning expensive, dirty imported fuels. Mini-grid technologies provide an option to diversify the energy supply, which can reduce fuel imports and stabilise energy costs. The high cost of electricity from diesel fuel has pushed many of these areas towards renewable energy. This is, arguably, the single most important driver for these areas. The use of at least some renewable energy in these mini-grids is often cost-effective today. As technology improves, more and more renewables can be added cost-effectively.

The addition of renewable energy to the supply provides diversification, which increases reliability and resiliency to fuel supply disruptions. The near-monopoly that diesel generation historically has had in many isolated areas has made the cost of electricity fluctuate with international energy markets. Having no alternative to diesel has had negative ramifications in these areas. Supply disruptions can cause significant spikes in the cost of energy. This is a key reason that remote co-operative grids in Alaska increasingly have added wind to their mini-grids. The challenge of supplying fuel over frozen rivers and ice roads has made wind generation a preferred option in the region.

Many remote areas will be disproportionately affected in the face of climate change. This reality has led many islands to make aggressive international commitments to greatly reduce the use of fossil fuels and increase the use of renewable energy.

Benefits of IC (Interconnected Community) application

The benefits that lead a community to use mini-grid technology are as diverse as the communities themselves. Renewable mini-grids represent an

Box 3.4 – University mini-grids: living research to interconnect neighbours

Place: Chicago, IL, US

The Illinois Institute of Technology in Chicago, IL, US has been slowly expanding its mini-grid since development began in 2008. The campus mini-grid was completed in 2013 and includes batteries, solar, wind and a natural gas generator, all with smart controls. It provides critical back-up and can power the campus completely during grid outages. The utility provider ComEd has partnered with Illinois Tech, Argonne National Laboratory and the US DOE, which has provided funding, to link the campus with a neighbouring mini-grid in Chicago's Bronzeville neighbourhood. Adjustments in regulations and innovations in grid interconnections are creating a living testbed and critical infrastructure back-up to enable solar and storage to power increasingly interconnected areas of Chicago (Marotti, 2016).

opportunity for communities to have control of their energy, as well as direct investment in ways that meet their local needs.

Many communities are exploring mini-grids as a way to increase the amount of renewable energy in their supply. Renewable mini-grids provide an alternative to the exclusive use of centralised generation sources common in the main grid. The technology enables community choice, while maintaining the option of using low-cost energy from the main grid. A strength of this approach is that it provides a hedge against potential increasing utility rates. It also provides a flexible and technologically viable platform for increasing the amount of renewable energy.

Reliability is a key consideration for communities exploring the use of renewable mini-grids. Mini-grids can enable communities to improve their response to catastrophic events. For example, many communities in the north-eastern United States are investing in mini-grids to "harden" their emergency centres to better respond to events like Superstorm Sandy. In areas with less-reliable grids, the value of renewable mini-grids is even higher. Many grids globally have daily outages. Renewable mini-grids can provide a near-seamless transition after a main grid outage to a functional local energy supply. As the frequency and duration of main grid outages increase, so does the value provided to the community. For all of these communities, renewable mini-grid technologies provide an increasingly viable alternative to fossil fuel back-up generators.

Community renewable mini-grids hold the tantalising potential to improve the local supply and, when interconnected with neighbouring grids, yield an even more resilient supply. In this way, they can provide value to the mini-grid operator, to its neighbours as well as to the main grid utility.

Benefits of ILI (Interconnected Large Industrial) application

Many industries require reliable and stable electricity to be successful. Supply disruptions can create significant costs. This is particularly true for high-tech manufacturers such as silicon wafer producers, or for data centres that can have expensive data losses if power is lost. Loss of power at strategic facilities, such as military bases and campuses, can, in some cases, lead to personal damages. In areas with less reliable grids, frequent disruptions make business more difficult. Businesses are exploring renewable mini-grid technologies to increase reliability. In areas with strong utility grids, mini-grids often have a focus on ultra-high reliability and security, such as for high-end manufacturing or data centres. In areas with weaker grids, businesses that traditionally may have required a back-up diesel genset for reliable power can use renewable mini-grid technology instead.

Some businesses also are interested in their environmental performance and have used renewable mini-grids as a platform to use renewable energy to power their business. Renewable mini-grids also provide a hedge against potential increasing utility rates.

As with community renewable mini-grids, large industrial mini-grids hold the tantalising potential to improve the local supply and, when interconnected with neighbouring grids, yield an even more resilient supply. In this way, they can provide value to the mini-grid operator, to its neighbours as well as to the main grid utility.

4 STATE-OF-THE-ART TECHNOLOGIES

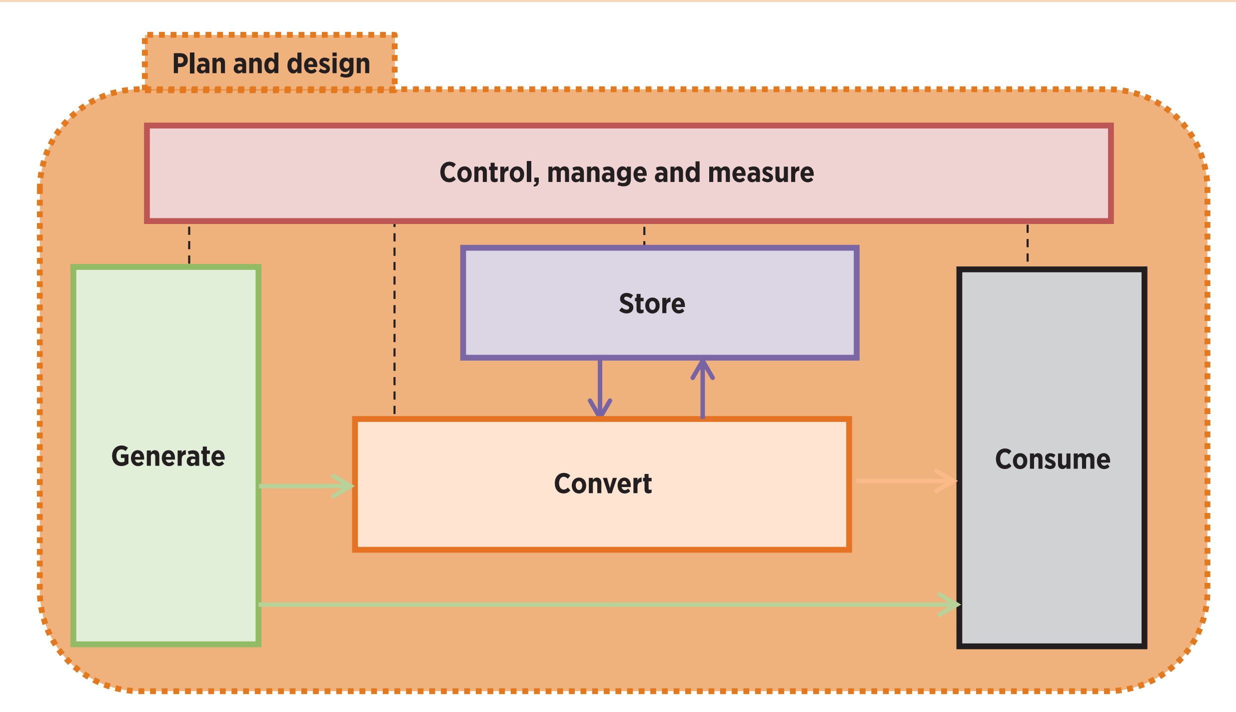
This section provides an overview of the current state of the art for technologies used in renewable mini-grids, including where technology stands in terms of development, and what is already commercially available. These are classified by their functionality and category.

Functionalities refer to the core capability that a mini-grid technology provides to a renewable mini-grid. The core functionalities include **plan and design; store; control, manage and measure (CMM); convert; consume;** and **generate,** as depicted in Figure 3:

The **plan-and-design** functionality is presented first because it precedes the other five. The remaining functionalities are presented in order based on the need for renewable mini-grid-specific developments, balanced with the value of the expected innovation to the renewable mini-grid technology in the coming decades. **CMM** technologies are expected to evolve significantly and to facilitate larger, more intelligent and more modular renewable mini-grids. These include technologies that form the brain and sensory system, and require significant tailoring for renewable mini-grids. New **storage** technologies under development and their commercialisation are expected to enable the use of increased amounts of renewables at an affordable price. The **convert** functionality comes next because of the need for specialised equipment to convert electricity between the functionalities. **Consume** follows because although many experts have identified it as having the greatest potential impact on costs, most of the innovation is less technical and will not be specific to renewable mini-grids. Cost declines for solar PV already have dropped to levels that will spur deployment of renewable mini-grids, for example. Further research on the outlook for generation can be found in Annex 6 and in other IRENA reports (IEA-ETSAP and IRENA, 2015a, 2015b; IRENA, 2012a, 2012b, 2012c, 2015b).

The **plan and design**, **CMM** and **consume** functionalities include a set of **key attributes** to summarise their current status, at the end of the subsection. For the **store**, **convert** and **generation** functionalities, key indicators are defined to enable the reader to compare technologies within each functionality.

Figure 3: Renewable mini-grid functionalities



Box 4.1 – Mini-grid design optimisation

The HOMER software, originally developed at the US National Renewable Energy Laboratory (NREL), is the standard software for evaluating the techno-economic design of mini-grids. It is used to optimise design in all sectors around the globe, from village power and island utilities to grid-connected campuses and military bases (HOMER Energy, 2015).

4.1 Plan and design

Plan and design is the glue that holds the other five functionalities together, before construction and during operation. The process includes preliminary modelling, business model development, resource planning and project engineering. Plan and design can be considered to be at a higher level than the other functionalities. GIZ has developed a catalogue that provides an introduction to the tools currently available (GIZ, 2015). Some of the commonly used tools are summarised below.

Mini-grid design

The design of a mini-grid sits at the intersection of a number of disciplines, including economics, sociology, policy, regulation and multiple engineering specialties. Large-scale utility models require similar considerations, but the complexity of the utility network at that size exceeds the needs of mini-grids. The design process typically is split into higher-level techno-economic evaluation tools focused on long-term issues and into technical evaluation tools for design details focused on the shorter term. There also is a need for broader energy planning that incorporates mini-grids. Much of the state of the art comprises utility-scale tools adapted to the needs of mini-grids. However, there are applications that have been developed specifically for the mini-grid market. A major planning challenge for renewable mini-grids is the need to balance centralised planning, such as national electrification programmes, with local needs and desires.

A number of tools have been developed over the past few decades to assist designers and planners for technical and economic evaluation of mini-grids. Natural Resources Canada's RETScreen is often used for analysing energy projects, but does not include a chronological simulation (*see* Glossary of Terms), which is critical for mini-grids. Some commercial design tools have been developed by equipment manufacturers, such as SMA's off-grid configurator tool. Other targeted design tools exist, but they are limited to specific markets (often non-commercial), for example the Lawrence Berkeley National Laboratory (LBNL) DER-CAM or EnergyPRO from EMD. These tools provide a low-cost initial design that can be refined later by a sector specialist.

Traditional utility planning tools such as Energy Examplar's PLEXOS, ABB's ProSym or SYMBAD are often much more complex than is appropriate for all but the largest of mini-grids. Power system analysis and simulation tools such as Siemens PSS E, ETAP®, DNV GL's Synergi and PowerFactory for DIgSILENT can be used for evaluations, but their cost and complexity may make them unsuitable for use in planning and designing smaller renewable mini-grids. There also are tools available for broader sector planning, such as

Table 5: Selection of tools for mini-grid design

Application	Tool
High-level technical and economic evaluation	DER-CAM, EnergyPRO, HOMER Pro, SMA Off-grid
Technical evaluation tools	ASIM, GIZ Mini-grid Builder, Paladin Only for large mini-grids: PLEXOS, ProSym, SYMBAD PSS E, ETAP, Synergi, PowerFactory
Broader Planning	GeoSim, RE^{2}nAF, LAP, Network Planner

Table 6: Selection of tools for resource planning

Application	Tool
Resource assessment	Private: 3TIER, AWS Truepower, Digital Engineering, Meteonorm, SolarGIS and Windlogic Public: Solar and Wind Energy Resource Assessment (SWERA), IRENA Global Atlas, National Aeronautics and Space Administration Earth Observing System (NASA EOS) Web, Joint Research Centre (JRC) of the European Commission
PV design	PVSyst, PVWatts, PV Sol and PVPlanner
Wind design	AWS Truepower's Windographer, Wind Atlas Analysis and Application Program (WAsP) from Risø National Laboratory, WindSim

GEOSIM, Network planner, LAP, ASIM from PowerWater, and GIZ Mini-grid Builder, which can help policy makers understand the role that renewable mini-grids can play in regional electrification plans, and how to capture some of the potential socio-economic benefits.

Resource planning

Planning requires an assessment of the renewable resources available, for which there are various private providers of resource assessments, as well as public resource tools, some of which are listed in Table 6: Other tools include those for solar PV design, where much of the focus is on financial mechanisms for deployment. There is a particularly wide range of options for interpreting wind resource data. The Wind Atlas Analysis and Application Program (WAsP), created in Denmark, predicts how wind flows over terrain using a potential-flow model. AWS Truepower's Windographer is a software tool for predicting turbine production from wind data. WindSim is a similar application that instead uses computational fluid dynamics calculations, which can be more accurate in complex terrain. Wind projects require on-site measurements prior to significant investment, whereas solar resource data are much less site-specific. There also are efforts to quantify resource availability and properties from the bottom up. For example, Practical Action uses GIS tools to create a catalogue of hydro sources based on local measurements.

Load planning

Understanding load data for renewable mini-grids is also a critical consideration. GEOSIM's Demand Analyst has tools available, and significant public data are available. For example OpenEI has useful data on modelled loads in the United States. However, load planning is further complicated because loads often change over the course of a project, as customers become more accustomed to having reliable electricity.

Key attributes

Table 7 summarises the key attributes for plan-and-design technologies in accordance with the descriptions above.

4.2 Control, manage and measure (CMM)

The CMM functionality is at the centre of renewable mini-grids. Measuring, managing and controlling

Table 7: Key attributes for plan-and-design technologies

Application	Tool
Need for specialised engineering	Requires renewable mini-grid specialist for all stages of design, including conceptual design.
Resource data (solar, wind, water)	General solar resource data are of sufficient quality; however, wind and hydro require on-site measurements to validate, and data can be costly.
Load planning	Based on *ad hoc* and site-specific approaches for estimating loads.

components allow mini-grids to operate within a network of interconnected devices while optimising the energy performance of the whole structure.

Many of the components utilised within mini-grids have been repurposed from other industries, such as telecommunications and manufacturing (Yan *et al.*, 2013). There is no clear trend regarding the type of company that dominates across all mini-grid markets. The CMM services of interconnected mini-grids are dominated by large, traditional utility service providers. These include ABB, Power Analytics, S&C, Siemens, Honeywell, LSIS and Toshiba, among others. However, the growing use of information technology is allowing major technology companies, such as Google, to participate. Utilities, such as KEPCO, ComEd, Hydro Tasmania, State Grid Corporation of China, China Southern Power Grid and SDG&E also are exploring mini-grids. The following subsections describe the different applications of CMM technologies.

Controls

Controls include protection strategies and intelligent decision making, whether by specific devices or by multiple devices working together. They can ensure the optimum integration of renewable energy technologies, ensure operational transparency and economic reliability, and maximise the mini-grid's energy efficiency (Hooshmand *et al.*, 2012; Mao *et al.*, 2014; Olivares *et al.*, 2014; Yan *et al.*, 2013). Controls can be divided into short-term controls, to ensure a stable grid, and long-term controls that can make strategic management decisions for the mini-grid. The cost and responsibility for controls is distributed among the converter components and dedicated controllers.

Mini-grid management hardware and software act as the interface between energy generation and consumption by enabling communication between the devices providing these services (Sandia National Laboratories, 2014). Intelligent dispatch must consider dynamic ramp rates and power-factor control (*see* Glossary of Terms), and often is constrained by technical requirements rather than by economic and performance trends (Deng *et al.*, 2015; McLarty *et al.*, 2015; Seal *et al.*, 2012). Controls often are split across different types of equipment in an incoherent manner, and there is not a comprehensive set of standards for designing renewable mini-grids. Manufacturers often use proprietary approaches, limiting competition and making it difficult for users of their technologies to switch to others (Palizban *et al.*, 2014; Smart Inverter Working Group, 2014; Yoo *et al.*, 2011).

The key long-term objectives of controllers are to provide reliable and economic operations of mini-grids for optimal renewable energy production and usage (Mao *et al.*, 2014). Some of the management functions that these devices provide are demand and priority load management, generator overload protection, peak shaving (*see* Glossary of Terms), energy storage management and feeder management (*see* Glossary of Terms). These objectives must be accomplished without compromising the protection hardware. In many cases the objective is to connect the network of various components and to automate the communications among them. A focus of controller development in

Box 4.2 – Solar/diesel mini-grids for mining

Place: Remote mines

The mining industry worldwide is increasingly retrofitting existing diesel mini-grids to use solar energy.

In Australia, for example, the first phase of Rio Tinto's Weipa Solar Photovoltaic Project uses 1.7 MWp of thin-film First Solar modules. In Canada, the 1 MWp SunMine solar facility in Kimberley was commissioned in 2015. An example of a wind-powered mini-grid serving a mine can be found at the Mount Cattlin lithium mine in Australia, which was retrofitted with a 110 kWp solar array and 6.4 kW of wind power.

Currently, a fuel-saver configuration is most common (see Box 3.1). Under this approach, up to 30% of energy can come from solar, with reduced need for new controls for the mini-grid or storage capacity. Future developments can use more solar, both with storage and as mini-grid controls improve and decline in cost.

2015 was to integrate and stabilise renewable energy generation in mini-grids (ABB, 2013). A number of companies offer controls that can provide economic dispatch for renewable mini-grids, including Eaton, GE, Siemens, ABB, Optimal Power Systems, SMA and Princeton Power. However, the economic optimisation approach varies among all of the controllers, and they mostly require certain specifications to interact with each other appropriately.

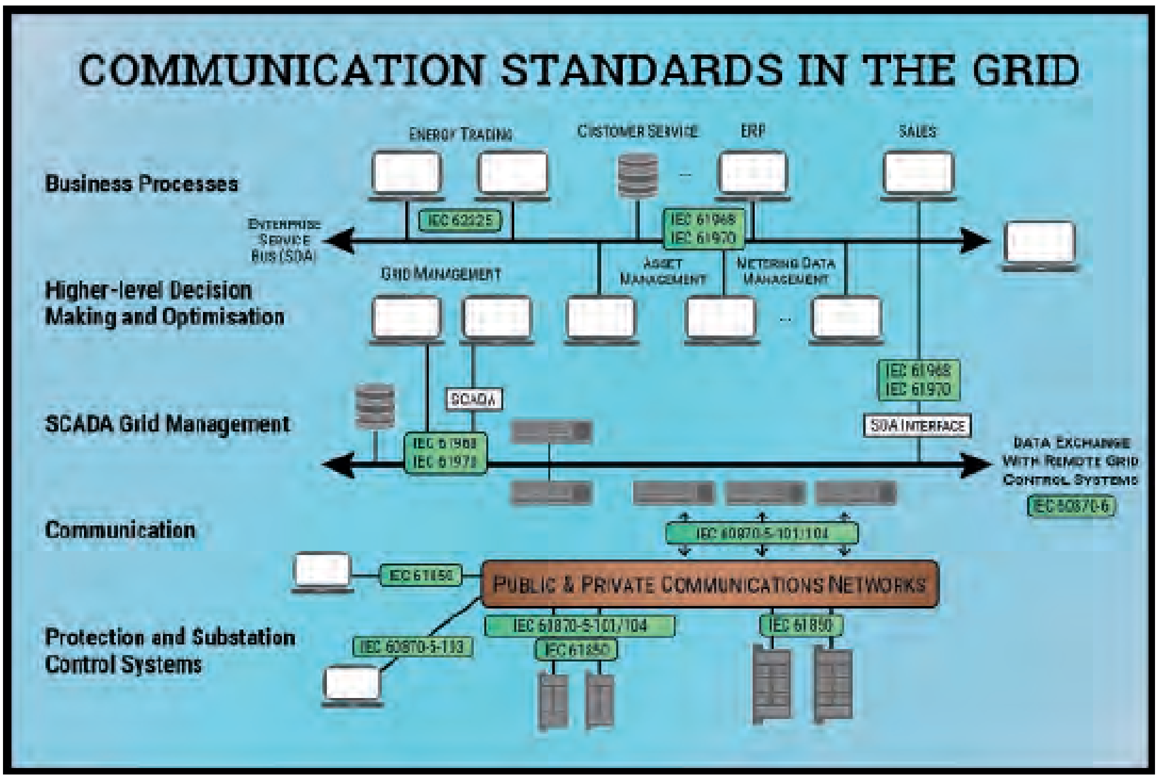
When making control decisions it is helpful to have an accurate prediction of future weather and load demand. Uncertainty and incorrect predictions increase the need for storage and for more conservative operation of the mini-grid, leading to overly complicated design as compared to the optimal (Colson and Nehrir, 2009). The ability to accurately predict electricity demand, resource availability (solar, wind, hydro) and market pricing enables smarter decision making, particularly to estimate storage needs. Current best practice has reasonably accurate predictions for one to two hours, although unpredicted variations still can occur within this window (McLarty *et al.*, 2015 and Parisio *et al.*, 2014).

Data communication and standards

Data communication is crucial for renewable mini-grids. Data communication includes capturing data gathered by sensors, transmitting the data to controllers, and then transmitting the commands generated by the controllers to the actuators in the automated systems (Setiawan *et al.*, 2014).

Data transfers within the renewable mini-grid and outside it can be carried out in either wired or wireless environments (Bani-Ahmed *et al.*, 2014; Chung *et al.*, 2013). Wireless technologies are found mainly in smaller projects and are increasingly popular because of their low installation costs and their ability to function well in remote locations (Setiawan *et al.*, 2014). Growth in cellular and other wireless infrastructure worldwide is increasing reliability and improving the performance of wireless technologies (Parikh *et al.*, 2010). Wired

Figure 4: Communication standards within the electricity supply



Source: Adapted from Appelrath et al., 2012 communication technologies have greater bandwidth and higher data-transfer capabilities, but also larger upfront costs (Setiawan *et al.*, 2014).

Manufacturers offer user-friendly tools to calculate basic performance indicators for a robust remote monitoring of the system (Kayastha *et al.*, 2014). Such indicators include renewable energy yield, performance ratio (PR) and the state of charge (SOC) of batteries. For example, Studer's Xtender analysis tool uses Excel to calculate data, which is retrieved by the online Xcom interface or manually, directly from the inverters and battery management device.

Current remote measurement and control requires significant on-site expertise to help mini-grid experts monitor, evaluate and improve the control of an operating renewable mini-grid. This improves performance and costs, and is particularly beneficial in remote areas (AB, AF) that may have less local technical expertise. However, the use of these types of technologies today remains limited.

Interoperability and standards are critical for easily integrating the diverse equipment required in a renewable mini-grid. Currently these standards are evolving, but a range of them address needs across the grid. A further challenge is that the choice of a control supplier often is tied with the inverter company. Because of a lack of standardisation, and as there is no dominant communication and control approach, it can be difficult to source various components from different manufacturers. This leads to reduced interoperability in the system. The interrelationships remain complex (see Figure 4).

Many data transfer solutions are most easily implemented with converters from the same manufacturer, although open-source compliant solutions reduce hurdles and can work across platforms. Some companies build in interoperability and are able to communicate easily with different manufacturers. Still, the number of such companies is limited.

Overall, fast and accurate transmission between devices enables intelligent controlling and monitoring between the generation and consumption functions of a mini-grid. As mobile technologies deploy, continual advances in data communication and transfer technologies will be observed (Padilla *et al.*, 2014).

Metering and monitoring

Next-generation energy meters go beyond simply measuring end-users' energy consumption. In renewable mini-grids they are critical for demand-side management (DSM). A wide range of meters is found in the market, with different functionalities and payment methods: prepaid or pay-as-you-go, post-paid, service-based, and those accompanied or unaccompanied by software. There also is a variety of non-flat tariff schemes (energy-based or power-based) that these new meters can support. Advanced tariffs often used in mini-grids can vary with the time of use, and include block rates that provide an initial amount of energy at a different rate than subsequent amounts of energy within a period of time.

Meters may be equipped with power and, optionally, energy limits set by the manufacturer. They also can be configurable by the operator to help manage customers' use of energy. Most hydroelectric mini-grids are based on constantly flowing rivers that can continuously supply the customers with energy, but the power demand is limited by the power of the turbines. In such cases, the meters can help to limit power peaks to prevent grid overloads.

Box 4.3 – Meters help supply match demand

Circutor's Electricity Dispenser BII incorporates an algorithm that limits daily energy consumption and power based on the Energy Daily Allowance (EDA) concept, which has been evolving for more than 15 years (Graillot *et al.*, 2012). The EDA is not pre-fixed, but all parameters can be modified according to the necessities of the user through a radio-frequency identification (RFID) card. The price of electricity in an EDA system can be flat or modified through a price signal that the dispenser detects, through frequency variation, MODBUS communication or a time schedule. There are more than 2 000 Dispensers installed in 10 different countries, most of them using an EDA with a service-based tariff.

Limiting clients' energy consumption is not as important in hydroelectric grids as it is for solar- or wind-based mini-grids. In solar- and wind-based mini-grids the energy production is stochastic and finite, and availability depends on storage capacity. Some meters can perform load-shedding, dividing the loads into critical and non-critical categories. This can be done by the usage of an auxiliary relay for non-priority loads, dispatchable under specific conditions (Harper, 2013). Meters start to incorporate Global System for Mobile Communications (GSM) technologies for lower-cost and easier remote monitoring communications, supported through the use of cloud-based applications.

Besides supporting non-flat tariff schemes some advanced smart meters are capable of limiting energy consumption of the consumers and are considered optimum for mini-grids dependent on storage (Harper, 2013). The Micro Power Smart Meter of INENSUS also limits energy consumption by trading energy blocks that can be consumed within a limited time. Powerhive uses a cloud-based pre-payment solution that alerts customers when their credit is low (Powerhive, 2015). Similarly, Earthspark International has developed the SparkMeter, which is being tested in Haiti and includes a "quality kWhs" concept of service levels. This involves providing real-time monitoring through a cloud-based operator interface (Buevich *et al.*, 2014). The solutions from Circutor, Powerhive, Sparkmeter and INENSUS can receive pricing signals that reflect the real-time status of a mini-grid through frequency variation. By receiving such signals when power availability is limited, the mini-grids can gradually disconnect clients (Circutor, 2015; INENSUS, 2011; Powerhive, 2015).

Some meters can perform load-shedding, dividing the loads into critical and noncritical ones. This can be done through the use of an auxiliary relay for non-priority loads, dispatchable under specific conditions (Harper, 2013). In addition, user feedback is recognised as important, and there is growing use of intelligent user feedback in main grids that could cross over to renewable mini-grids. There are some status tools that are used in communal renewable mini-grids.

Other approaches are moving towards the use of pay-as-you-go meters, following the trend in mobile phone technology in which users can buy energy credits before use. This is in contrast to traditional utility energy tariff schemes, where users pay for energy after they have used it. Remote payment is possible using scratch cards or mobile money platforms (*see* Glossary of Terms) (Harper, 2013).

Next-generation meters that monitor power quality (*see* Glossary of Terms) are necessary when sensitive data should be protected, and usually are equipped with uninterruptible power supplies (UPS) thanks to their large memory, processing speed and accuracy. These are common in data centres or financial institutions. In addition to monitoring current, voltage and power factors, power quality meters can record very rapidly switching transients (short periods of surge voltage usually caused by the sudden stop or start of large currents from motors). This is an added value of power quality meters over normal ones. In order to capture those events, next-generation power quality meters record voltage samples frequently (EATON, 2006).

Connections with equipment (interoperability) and other grids (interconnection)

Plug-and-play (PAP) technologies improve interoperability, which greatly increases the ease of connecting together diverse equipment, including both hardware and software. Ideally, this would include the ability to rapidly switch out any of the equipment including the battery, generator and all major components of the mini-grid. PAP allows for design and expansion with minimum engineering cost (IEEE, 2014). PAP includes the use of a common plug shape, ensures that the data produced can be used by all connected equipment, and that the controls can intelligently use the connected equipment. PAP requires the use of a common communication medium such as broadband ethernet, LTE/4G, machine-to-machine communication protocols (*see* Glossary of Terms) (Appelrath *et al.*, 2012) or communication through the power lines.

Utility meters and interconnections are used to connect renewable mini-grids to neighbouring grids. Interconnection considerations are split into three major types: protection; arbitrage and economic decision making; and interfacing with and support of utility services. To date these challenges have been addressed through standards and tools that enable mini-grids to quickly synchronise with the existing grid. In addition, there is a significant gap in regulatory aspects (Villareal *et al.*, 2014).

Box 4.4 – Standards for interconnection of renewable mini-grids to the main grid

In the Americas, interconnected renewable mini-grid requirements are based on the Institute of Electric and Electronic Engineers (IEEE) 1547 standards. IEEE 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems" regulations ensure that renewable mini-grids operate safely, and prevent exporting power into a distribution grid when there are line workers (IEEE, 2003). IEEE 1547 also enables devices that support a wide range of tariffing mechanisms (Basso and DeBlasio, 2004). The International Electrotechnical Commission (IEC) standard 62116 of 2014, titled "Utility-interconnected Photovoltaic Inverters – Test Procedure of Islanding Prevention Measures", provides safety requirements that are commonly used internationally for mini-grids.

Mini-grid integration has many benefits for utilities. Renewable mini-grids provide support services to the utility, such as control of voltage and reactive power along the distribution. Although its capability is technically possible, fast switching between islanded and on-grid operation is limited to high-performance mini-grids due to high cost. A key value proposition that grid-connected renewable mini-grids offer utilities is the ability to quickly and automatically reduce demand when the utility grid is congested. If the quality of power from the grid falls below certain specific standards, renewable mini-grids may disconnect intentionally. However, softer disconnects would be preferable if the utility regulatory environment encourages it.

Currently, standardisation of protocols that enable adaptability between grids is limited (Mazumder and Chang, 2014). Limited interoperability increases the costs for changing the architecture when upgrades are necessary. Working across platforms from different manufacturers can be challenging. Additionally, there are challenges from a utility standpoint with adapting the substantial existing infrastructure to interact with renewable mini-grids, although efforts are under way to remove this barrier.

In order to mitigate challenges with the interconnection of mini-grids, inverters can incorporate various advanced functions with simple software updates. The under/over frequency or voltage ride-through function prevents inverters from disconnecting immediately after voltage or frequency variations to avoid larger grid instabilities (Smart Inverter Working Group, 2014).

Other inverter functions to enhance grid stability with a large penetration of distributed generation is the soft-start method, which ensures the smooth reconnection of inverters after a shutdown (NREL, 2014). The main barriers to scaling up and increasing modularity are due to the limited standardisation of protocols to enable adaptability between grids, limited interoperability increasing costs for changing the architecture when upgrades are necessary, and the challenge of working across platforms from different manufacturers (Wang *et al.*, 2014). Some mini-grids for rural electrification require a converter to interconnect

Table 8: Key attributes for CMM technologies

Key attributes	Status as of 2015
Cost of controls	Specialised and expensive controls
Control intelligence	Non-economic and non-predictive
Plug-and-play capability	Moderate
Utility acceptance of renewable mini-grids in grid	High interest, but limited to pilot projects
Communication and standardisation	Numerous competing standards
Metering and monitoring	Some pricing and power controls. Increasing support for non-traditional payment approaches such as pay-as-you-go
Prediction of renewable resources	One to two hours with high accuracy

with other grids, especially mini-grids that use DC distribution. This consideration should be included in rural electrification efforts if future main grid or interconnection is desired.

Key attributes

Table 8 summarises the key attributes for CMM technologies in accordance with the descriptions in the subsections and, in particular, with the key factors detailed above.

4.3 Store

Storage allows a renewable mini-grid to use power at a different time than it is produced. Electrical storage is a critical functionality for increasing the amount of renewable energy that can be used. Additional benefits include an increase in the share of energy from renewable sources, the ability to provide continuous power, reducing demand for power during peak times, ramping and smoothing load and generation, and a lessening of the impact of long-term and short-term fluctuation of renewable energy (US DOE, 2013).

Currently storage represents a significant portion of the costs associated with deployment and operation of renewable mini-grids (IRENA, 2015c), due to the high upfront costs and replacement needs, which vary with each storage option. This cost can represent between 20% and 40% of the cost of a renewable mini-grid today.

To date there is no single storage technology that covers all of the needs of renewable energy generation (EASE/EERA, 2013). A shortfall was found in storage for renewable generation, as shown in Table 9: The US DOE has a database of different storage technologies projects deployed worldwide (US DOE, 2015a).

Box 4.5 – Wind-diesel mini-grid

Place: Kodiak, Alaska, US

In 2009, the Kodiak Electric Association set a goal to obtain 95% of Kodiak Island's electricity from renewable energy sources by 2020. They have already met this challenge, now deriving 99.7% of their electricity from wind and hydropower. The grid includes 9 MW of wind and 30 MW of hydro capacity to meet the annual demand, which peaked at 26 MW in 2011. The key innovation of this project is the successful mix of storage technologies, including 2 megawatt-hours (MWh) of gel lead-acid batteries and two 1 MW flywheels. The storage helps to stabilise grid frequency and voltage, as well as to provide ride-through capabilities for load fluctuations to support local industry (RMI and Carbon War Room, 2015).

Table 9: Summary of state-of the-art storage technologies and suitability in different applications

Technologies aggregate in focus	Conventional generation	Renewable generation	Renewable mini-grids	Transmission	Distribution	Customer services
PSH	Suitable	Evolving	Unsuitable	Suitable	Evolving	Unsuitable
CAES	Suitable	Evolving	Unsuitable	Suitable	Evolving	Unsuitable
Electrochemical	Evolving	Evolving	Evolving	Suitable	Suitable	Suitable
Chemical	Evolving	Evolving	Evolving	Evolving	Unsuitable	Evolving
Electromagnetic	Unsuitable	Evolving	Evolving	Suitable	Suitable	Unsuitable
Thermal	Suitable	Evolving	Evolving	Evolving	Evolving	Suitable

* *The data presented here are for guidance only and are based on typical usage and on the assumption of batteries with typical balance-of-system costs (including wires and racking). The costs may deviate significantly when climate control is required or if delivered to a particularly remote area. Actual costs and performance may vary based on the specific requirements of each renewable mini-grid.*

*Source: Adapted from EASE/EERA, 2013, with additional author elaboration**

Electrochemical storage

Lead-acid batteries (LABs) have been the predominant technology for electrochemical storage for decades. Lithium-ion batteries (LIBs) now provide competition, and their market share is expected to increase in the coming decades (IRENA, 2015c). Other alternatives are improving rapidly, including advanced lead-acid batteries (ALAB), flow batteries and sodium-ion technologies.

Lead-acid batteries (LABs)

The positive electrode (*see* Glossary of Terms) in LABs is made out of lead dioxide, and the negative electrode is formed from metallic lead. There are two main classes of LABs: those with wet cells and valve-regulated (VRLA) batteries. Wet cells are also known as flooded (unsealed), while VRLAs can use gel or absorbed glass mat (AGM) sealed battery banks. The performance of gel batteries is preferred for applications with higher ambient temperatures or when slow discharge rates are required. AGM batteries are superior for their high charging rates. Flooded, unsealed technology is the cheaper option but requires some maintenance. Although most batteries have a limited range of operation, LABs have strong limitations (between 40% and 80% of the rated capacity). For this reason, and throughout this report, "usable kWh" is the unit used in the indicators for installed costs. The lifetime of LABs depends strongly on operating temperatures, as well as on the cycling depth of the batteries. Table 10 depicts the main indicators for LABs.

Table 10: Summary of state of the art for lead-acid storage technologies

Indicators	Typical values
KI 1a: Installed cost (USD/usable kWh)	150–1 500
KI 1b: Installed cost (USD/kW)	300–2 000
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.15–0.35
KI 2: Round-trip efficiency	> 70–90%
KI 3: Life cycle (cycles) with moderate discharge	1 000–3 000
KI 4: Self-discharge rate (% per month)	3–12

Source: ARE, 2013; Fuchs et al., 2012; Hoppecke, 2013; IEC, 2011; IRENA, 2015c, 2012d; authors estimates

Cost

The main cost challenge for LABs is the price volatility of lead in the market (London Metal Exchange, 2015), as it makes up 49% of the manufacturing cost (FMI, 2014).

Technology

There is considerable room for technical improvements in LABs. The round-trip efficiency is a major consideration since, during the storage process, stored energy drops by between 10% and 30%. The usable energy density (Watt-hours/kg) is low compared to many other electrochemical-storage technologies (ARE, 2013). Finally, performance and durability are impacted if the temperature in which the battery operates is too hot or too cold (IRENA, 2015c). This can increase costs for controlling the room temperature at which batteries are installed.

Commercialised innovations (*see* Glossary of Terms) in LABs include the development of ALABs. Development of ALABs has been supported by the Advanced Lead Acid Battery Consortium since 1992 (McKeon *et al.*, 2014). Adding carbon to LAB electrodes reduces the accumulation of deposits and hence provides better performance and lifetime, increased charging rate and reduced maintenance requirements (Shiomi *et al.*, 1997; US DOE, 2012b). This advanced technology allows manufacturers to overcome performance drawbacks found in conventional LABs (IRENA, 2015c). Axion Power uses a purely carbon electrode that claims to achieve four times the lifetime of a LAB, and Firefly International uses a carbon foam substrate which has achieved four times more cycles than a conventional VRLA (McKeon *et al.*, 2014). DataSafe® HX+ batteries from Enersys use a thin plate of pure lead, which can perform better at higher ambient temperatures, offer higher power density and a longer working life, and are virtually maintenance-free (Enersys, 2014). These batteries already have been used commercially at a number of specific sites, but they still are not yet fully commercialised in the market (McKeon *et al.*, 2014).

Social and environmental considerations

Regulations and standards on lead emissions during manufacturing have become more common. There are increasing concerns about LAB manufacturing

Box 4.6 – Advanced lead-acid: next-generation lead-acid batteries

There are some commercially available ALABs such as the Ultrabattery® by Ecoult, developed in Australia by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The Ecoult battery combines the fast charging rate and longevity of an ultracapacitor with the storage potential of traditional LABs. This provides high efficiency, between 92% and 95%, and high cycle endurance, outperforming common LABs significantly (McKeon *et al.*, 2014). Ecoult was acquired by the long-established and US-based East Penn Manufacturing Company Inc. in 2010, further expanding the distribution of the technology.

facilities in which high lead exposure has been found in workers and community neighbours. LABs are designed to be 100% recyclable (Battery Council International, 2012), but the actual amount recovered from them is typically lower. For example it has been estimated that China, the largest manufacturer of LABs (mainly for the automotive sector) has a recycling rate for LABs of only 31% through official channels. Small-scale recyclers and aftermarket recycling help to increase this to up to 62% (Zhang, 2013). Logistics and proper disposal of batteries are challenges in remote areas. The automotive sectors in many countries have tackled this issue by returning a deposit or requiring an exchange to get a battery.

Lithium-ion batteries (LIBs)

Lithium-ion batteries (LIBs) can be found in portable electronic applications, the automotive industry and the energy storage sector. The LIB has a positive electrode made of lithiated metal oxides and a negative electrode built from carbon. The electrolyte (*see* Glossary of Terms) within the battery contains lithium salts dissolved in organic carbonates (SAFT, 2014). LIBs excel in applications requiring short discharge durations and high power performance, such as frequency regulation (IRENA, 2015c). A list of indicators is summarised in Table 11:

Table 11: Summary of state of the art for lithium-ion storage technologies

Indicators	Typical values
KI 1a: Installed cost (USD/usable kWh)	400–2 000
KI 1b: Installed cost (USD/kW)	400–1 000
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.25–0.40
KI 2: Round-trip efficiency	> 85%
KI 3: Life cycle (cycles) with moderate discharge	1 000–5 000
KI 4: Self-discharge rate (% per month)	> 5

Source: Akhil et al., 2013; ARE, 2013; Fuchs et al., 2012; IEC, 2011; IRENA, 2015c, 2012d; Jaffe, 2014

Cost

Considerable price drops have brought LIBs close to being cost-competitive with LABs. The wider range of operation across the range of SOC also benefits their lifetime kWh costs. The costs of LIBs can be high due to special packaging, expensive materials such as cobalt in the cathode, manufacturing processes and overcharge protection circuits (Daniel, 2015; IEC, 2011; Nitta *et al.*, 2015; Wood *et al.*, 2015). Massive production of LIBs for mobile applications has led to increased

Box 4.7 – The rise of lithium-ion batteries

There are a significant number of LIB manufacturers, particularly in China, Japan, the Republic of Korea and the United States. LIB manufacturers include Samsung (19% market share), Panasonic (20%), LG Chem (15%), Toshiba, Sony, BYD and ATL. Notable entrants include Tesla, which announced its Powerwall (7 to 10 kWh) at a low cost of USD 350/kWh and its Powerpack (100 kWh) at only USD 250/kWh (Tesla Motors, 2015). Tesla will use Panasonic cells inside its batteries, with the significant cost reductions driven by the scale of production. These innovations have generated considerable interest in the technology and have shaken up the market for major manufacturers.

scales and standardisation in the market. This trend will continue and may lead to further standardisation of the technology and applications, benefiting the off-grid market.

Technology

Depending on the material of the cathode, an LIB's life typically ranges from 1 000 to 5 000 cycles. The discharge rate is flexible, varying from seconds to weeks. LIBs have the benefit of being able to operate continuously at partial states of charge with no need to be fully recharged (equalised). This is very beneficial, since batteries may not be fully charged for extended periods during operation. Challenges include a low range for operating temperature, so storage control rooms are required to have ambient conditioning to ensure a stable temperature for an efficient and safe operation.

Social and environmental considerations

Recycling LIBs is more complicated than recycling LABs, due to their large number of components and variety of materials (Gaines, 2014). The recycling of LIBs is not regulated (Ibid.). Their current cumulative recycling efficiency rate is 5% to 25%. Lab efficiencies are between 40% and 70%. The highest known laboratory recycling rate is 89% to 95% (Wang, 2014).

The use of cobalt is a concern due to its toxicity, which presents risks to the environment and human health. It also is costly. Some manufacturers are making progress, such as the SuperPolymer battery 2.0 from Electrovaya, which has eliminated the use of N-Metal Pyrrolidone (which is hazardous to human health). It also offers greater fire resistance and can tolerate wider temperature ranges (Electrovaya, 2012; Frost & Sullivan, 2014).

Another concern is the availability and reserves of lithium worldwide. The US Geological Survey estimates that there are over 13.5 million tons of lithium reserves and nearly 40 million tonnes of resources (USGS, 2015), with almost 70% of this located in Argentina, Bolivia and Chile (Gaines, 2014). Lithium consumption reached 36 000 tonnes in 2014, a 40% increase from 2007 (Jaskula *et al.*, 2013; USGS, 2015). A 10% annual average rate of increase is expected for all lithium applications, and up to 21.3% in batteries for grid applications (Fox-Davies, 2013). Nevertheless, some see no threat to lithium availability and consider that existing resources will be enough to meet projected demand, taking into account new mining techniques (Gruber *et al.*, 2011; Speirs *et al.*, 2014).

Flow batteries

Flow batteries work by storing electricity in liquid electrolytes. These electrolytes flow through cells or electrodes to complete redox reactions (see Glossary of Terms) and energy conversion. A membrane or separator that allows for ion transport separates the electrolytes on the cathode side (catholyte) and the anode side (anolyte) (see Glossary for the terms "anode" and "cathode"), completing the electrical circuit (Nexight Group, 2010). Flow batteries are flexible and can be fully discharged across their full range without damage. Their self-discharge (see Glossary of Terms) can be high due to the use of pumps for moving electrolytes. Table 12 summarises the main characteristics of flow batteries.

Cost

Membranes for flow batteries have very high manufacturing costs. For example, they can represent up to 40% of the battery's cost for 250 kWh vanadium redox batteries (VRBs) (Viswanathan *et al.*, 2012). However, because of its longevity the cost per kWh over the lifetime of the battery is low. In larger batteries of up to 4 MWh the main cost comes from the chemicals used, which is more than 40% (Ibid.).

Table 12: Summary of state of the art for flow-storage technologies

Indicators	Typical values
KI 1a: Installed cost (USD/usable kWh)	350–800
KI 1b: Installed cost (USD/kW)	1 200–2 000
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.08–0.40
KI 2: Round-trip efficiency	65–85
KI 3: Life cycle (cycles) with moderate discharge	3 000–15 000 (cell stack)
KI 4: Self-discharge rate (% per month)	3–12

Source: Akhil et al., 2013; ARE, 2013; Fuchs et al., 2012; IEC, 2011; IRENA, 2015c, 2012d

Box 4.8 – The history of flow batteries

There are several types of flow batteries, among them vanadium redox batteries (VRBs), zinc-bromine batteries (ZRB), zinc-iron, iron-chromium, polysulphide bromide (PSB) and organic flow batteries (OFB), characterised by the type of electrolyte used. Many flow batteries today use VRB, but new chemistries such as zinc-chloride, zinc-iron and zinc-bromide also are increasingly used. VRBs were invented in Australia by the University of New South Wales in 1986 and have resulted in some commercial success. Since then there have been a wide range of chemistries beyond VRBs that have been used successfully in flow batteries. Major companies that offer flow batteries include Gildemeister, Red Flow, Red T, Imergy, ZBB, UniEnergy Technologies and ViZn.

Technology

Flow batteries still have lower efficiencies than LIBs, but this efficiency can be controlled in accordance with the usage of each stack, either for short-duration applications or for energy-intensive applications (Akhil *et al.*, 2013). Pumping and shunt losses have a considerable impact on overall battery losses, affecting their round-trip efficiency. They are expected to last 10 to 20 years. VRB appear to be limited by calendar years rather than cycles (Akhil *et al.*, 2013). Flow batteries have an advantage in that they do not self-discharge. Their energy density is low, although this is not an important issue for stationary applications.

Other promising electrochemical technologies

There are a range of technologies that could overtake the more dominant technologies discussed above.

Sodium-ion (Na-ion) chemistries are over two centuries old. They offer a low-cost solution and are fully commercial, but they have shortcomings in requiring extremely high temperature (up to 700 °C) to operate and have a high self-discharging rate. Research is focusing on low-temperature batteries.

Mechanical storage

Flywheels are a high-performance and efficient technology and are considered as an alternative to high-power batteries. Flywheels transform electric energy and store it as kinetic energy. When excess energy is produced, flywheels increase their rotor speed in order to store this surplus energy. They then convert the kinetic energy back to electric energy by decelerating their rotor speed. Flywheels can smooth outputs from wind turbines and other renewables to improve grid stability and allow higher renewable energy penetration, such as in a wind-diesel hybrid mini-grid used in the

Table 13: Summary of state of the art for flywheel storage technologies

Indicators	Typical values
KI 1a: Installed cost (USD/usable kWh)	1 500–3 000
KI 1b: Installed cost (USD/kW)	1 000–4 000
KI 1c: Installed cost ($USD/kWh_{lifetime}$)	0.06–0.10
KI 2: Round-trip efficiency	85–95
KI 3: Life cycle (cycles) with moderate discharge	> 100 000 (full discharge)
KI 4: Self-discharge rate (% per month)	5–15

Source: Akhil et al., 2013; Fuchs et al., 2012; IRENA, 2012d, 2012e; Nexight Group, 2010; Viswanathan et al., 2012

Box 4.9 – Cradle to Cradle® storage

Innovations in sodium-ion technology have been achieved by the Aquion Battery aqueous (saltwater) hybrid ion which contains non-toxic materials and can be discharged completely (100%), while delivering well over 3 000 cycles. The battery's key innovation is the use of saltwater. It already is being piloted in several sites and has started to be commercialised. Thanks to its high environmentally friendly performance, it has become the first battery in the world to obtain a Cradle to Cradle® certification, which evaluates manufacturers' ongoing commitment to sustainability and to their communities.

Box 4.10 – Storage without batteries

Place: El Hierro, Canary Islands, Spain

The El Hierro grid uses pumped hydropower for storage instead of electrochemical storage. It was commissioned in 2014 and became fully operational in 2015. When there is excess wind energy from the 11.5 MW wind farm, water is pumped up into a lined volcano crater in the middle of the island. The system is backed up with diesel generators. Beyond achieving a large percentage of energy from renewables, the design is built to be replicable. The El Hierro grid has reached a technical milestone, in that the diesel generators can be shut down and power can be generated by renewables, helped by hydroelectric storage, for periods of time in which the energy supplied is 100% renewable (ITC, 2016). The Red Eléctrica de España provides real-time monitoring of the system, promoting transparency and replicability (REE, 2016)

Azores Islands. Flywheels usually come in sizes of 100 kW to 1 650 kW (Akhil *et al.*, 2013), but they also can reach 10 MW of power output (IRENA, 2012e). Their main indicators are included in Table 13:

Pumped hydro storage is another form of electromechanical storage suitable where terrain and geology allow. It is, largely, a mature technology that is based on pumping water to an elevated reservoir, and then recovering the energy through turbines when power is needed. The suitability of pumped hydro is highly site-specific, as are the costs. However, it is an option that can be considered and can be used if local conditions allow.

Cost

Even if upfront costs are high, flywheel technologies have a long lifetime and are quite modular. Flywheels offer a competitive cost of power for short-term fast-response power needs but have achieved limited commercial progress (DTU, 2013). Most work on flywheels has been in the United States, in particular by Beacon Power and other companies such as Tribology Systems, Velkless Flywheels, Amber Kinetics, Piller Power Systems, the research centre CIEMAT, Zigor Corporation and Centre for Concepts in Mechatronics (DTU, 2013; EASE/EERA, 2013; Viswanathan *et al.*, 2013).

Technology

Flywheels have relatively high standby losses, meaning that energy is expended in order to maintain their rotation. Overall efficiency is higher when they are cycled in short time scales. They have a 100% depth of discharge capacity but have a very high self-discharge rate of 5-15% per hour (Fuchs *et al.*, 2012).

Flywheels are used mainly as UPS (*see* Glossary of Terms), for frequency regulation, and for power quality. High-power flywheels are commonly used, whereas long-duration ones are still in the R&D phase. High-power flywheels are capable of releasing large amounts of power in a short period, of about one minute. Flywheels are most commonly high-power and low-speed applications. Rotors are made mainly of steel or graphite fibre composites.

Social and environmental considerations

Most of the materials used in flywheels – namely steel, copper and aluminium – are recyclable. There are some power electronics that contain hazardous materials that need to be disposed of adequately. The composite rotor materials have limited recycling possibility, with techniques still under development. The main operational risk is fatigue failure of the rotor, which releases heat and debris and could be catastrophic if not contained adequately (Kaldellis, 2010).

Box 4.11 – Carbon fibre flywheels

Beacon Power has developed a modular (100 kW up to several MW) carbon fibre rim, and a near frictionless vacuum-sealed rotor flywheel, that can reach up to 175 000 full-depth charge and discharge cycles.

Figure 5: Relationship between grid-following, grid-forming and dual-mode inverters

Other storage

Thermal storage enables the use of otherwise excess electricity by using it for heating or cooling. In general, thermal storage is less costly than electrical storage, but its applicability is largely limited to distributed solar water heaters. Thermal storage and a heat grid can increase the flexibility of heat pumps and renewable energy generation (Easy Smart Grid GmbH, 2015). Some projects are incorporating thermal storage and are being tested. For example, in Portugal's Azores Islands a domestic hot water electric back-up based on solar thermal energy is used to optimise electricity dispatch (Neves and Silva, 2015).

Chemical storage also has seen limited use in renewable mini-grids to date. The main focus of research on chemical storage technologies has been on the use of hydrogen as an energy carrier. Research is ongoing in the use of water electrolysis to produce hydrogen in periods of excess generation of renewable energy. However, even if electrolysis is a mature process it still suffers from high costs, has a production efficiency of 70%, and only 4% of hydrogen production is done through water electrolysis (Mazloomi *et al.*, 2012). Other chemical storage applications include power to gas, biofuels, methane and some metals. Research also is under way on the production of syngas (*see Glossary* of Terms) through gasification, which can later be combusted to generate electricity (DTU, 2013). The Catalysis for Sustainable Energy Initiative in Denmark has focused on using catalytic processes for energy storage.

Electrical storage technologies include electrical double-layer capacitors (EDLC) and superconducting magnetic energy storage (SMES). Due to their immaturity their costs are unknown as limited pilots have been conducted.

4.4 Convert

Conversion allows a renewable mini-grid to move energy around between various parts of the mini-grid. Power conversion between the different types of electric charge can be classified according to the input and output currents as converters (DC-to-DC, AC-to-AC), rectifiers (DC-to-AC) and inverters (AC-to-DC). Power inverter technologies included in this section are **grid-following**, **grid-forming** and **dual-mode** inverters (*see* Glossary of Terms). Grid-following inverters are the most common, due in large part to their use in most rooftop solar PV units. If the AC grid fails, these inverters no longer work until AC grid power is restored. Grid-forming inverters are capable of creating an AC grid in autonomous renewable mini-grids. Dual-mode inverters combine the benefits of both and are the interconnection point to the main grid, but are more costly.

Inverters can be single-phase or three-phase, depending on the distribution line and the loads. An important factor when connecting motors is the surge power of the inverter, or the capacity to supply higher than its nominal power (*see* Glossary of Terms) for a few seconds or minutes (Meral and Dinçer, 2011). DC-DC converters also are covered to a lesser extent. Power-conversion technologies are typically considered mature. They are widely available and highly efficient, in particular grid-following inverters and DC-DC converters. Grid-forming and dual-mode inverters are in the commercial scale-up phase and are the most important for renewable mini-grids.

Converters have shorter lifespans than generation technologies, requiring replacement every 5 to 15 years, depending on their quality and robustness.

Grid-following inverters

The main function of grid-following (or grid-tied or grid-dependent or solar) inverters is to convert the DC output of the PV arrays to AC electricity to feed into the grid. There are several types. They can work with a transformer or without one, and in a single single-phase or in three depending on the grid type. There are central inverters, string inverters and module inverters. They automatically switch off when the grid formed by an AC source is down, to avoid islanding (*see* Glossary of Terms) or when they surpass the grid voltage or frequency (Vallvé, 2012). Those inverters also are used in AC coupled installations, equipped with a maximum power point tracker (MPPT). Grid-following inverters operate under real and reactive power set-points (Mueller-Stoffels *et al.*, 2013). Table 14 summarises their main indicators.

Micro-inverters are a small but growing segment of the grid-following inverter market. Under this approach, most common with solar PV, many smaller inverters are used. This can reduce some of the impacts of PV panel mismatch, and enables PV to interact through the AC bus. The latter consideration can be particularly beneficial since many electricians are more familiar with designing and building AC grids. However, to store PV energy, it must be inverted then rectified, which can increase losses. Enphase Energy is the major manufacturer of these, producing almost 90% of the micro-inverters for PV installations.

Costs

Prices of grid-connected inverters vary according to their size, quality and features. Large inverters with power above 100 kW have higher prices per kilovolt-amp (kVA) than smaller inverters. Inverter prices normally decline due to improved power semiconductors and circuits, and generally follow price drops from PV modules. Inverter price is closely correlated to the prices of metals such as copper, aluminium and steel. Grid-following inverters are considered a mature technology, but cost reductions still can be achieved with the use of SiC and GaN semiconductors (Schwarzer *et al.*, 2014).

Table 14: Summary of state of the art for grid-following inverters

Indicators	Grid-following
KI 1: Cost (USD/kVA)	110 – 170
KI 2: Efficiency at rated power DC to AC (%)	93 – 98
KI 3: Efficiency at rated power AC to DC (%)	N/A
KI 4: Lifetime (years)	5 – 10

Source: Fraunhofer ISE, 2014; Fraunhofer ISE, 2015a

Technology

The efficiency of grid-connected inverters is also not linear. In low partial loads the efficiency is low and increases logarithmically up to a partial load of around 30% where it reaches its highest values. New improvements are being sought to increase the low partial load efficiency of inverters (*e.g.*, Fronius MIX™ concept). Transformerless AC-DC inverters usually achieve the highest efficiencies up to 98% at full load, followed by high-frequency, and low-frequency ones with efficiencies as low as 90% (US EPA, 2013). Grid-connected inverters are incorporating a series of advanced features through the use of standardised communications to enhance grid stability (US EPA, 2013). Maximum power capacity ranges from a few kW to 2-3 MW (IEA-ETSAP and IRENA, 2013).

Grid-forming inverters

Grid-forming inverters (a.k.a. autonomous or voltage source or battery inverters) create an AC grid by producing the alternating current and controlling the AC voltage. These inverters are designed only for off-grid operation, since they cannot operate in parallel with most other AC generation sources like diesel generators. In interconnected renewable mini-grids battery inverters can be used as back-up for critical loads when the grid fails. When they have formed a grid, they often are used

Table 15: Summary of state of the art for grid-forming inverters

Indicators	Grid-following
KI 1: Cost (USD/kVA)	500 – 1 200
KI 2: Efficiency at rated power DC to AC (%)	85 – 90
KI 3: Efficiency at rated power AC to DC (%)	90 – 95
KI 4: Lifetime (years)	5 – 10

Source: Appert and al-Mukdad, 2013; Mueller-Stoffels et al., 2013; proprietary manufacturer quotes, 2015 to stabilise grid frequency and voltage, and can provide re-active power support (Mueller-Stoffels *et al.*, 2013).

Many inverter manufacturers include a grid-forming inverter option in their product lines. Companies selling grid-forming large-scale inverters include Optimal Power Solutions, Leonics, Apollo, Princeton Power Systems, Emerson, Alstom and Siemens. Smaller-scale battery inverters are offered by Outback, SMA, Studer, Darfon, Magnum Energy, Victron and Schneider, among many others. Large battery inverters with nominal power higher than 200 kW are uncommon.

Grid-forming inverters are critical for renewable mini-grids, since they enable variable renewables, such as wind or solar, in conjunction with storage to power loads without other generation sources on the grid. Table 15 depicts the key indicators for grid-forming inverters.

Costs

Grid-forming inverters can cost up to five times more per kW than grid-following ones (Proprietary manufacturer quotes, 2015), although the cost premium can be as low as 30% higher. Cost variations are due to the capabilities, size and quality of the inverter. In order to compete in the market, some manufacturers launch product lines at lower prices by offering discounted basic inverters while keeping the advanced functions and extra features as technology upgrades (Meinhardt *et al.*, 2003).

Technology

Grid-forming inverters can use standard AC grid control techniques such as droop control (*see* Glossary of Terms). For example, when batteries are fully charged, the battery inverters will increase grid frequency in order to communicate to grid-following PV inverters, which respond by lowering the power output (Mitra *et al.*, 2008).

Table 16: Summary of state of the art for dual-mode inverters

Indicators	Grid-following
KI 1: Cost (USD/kVA)	650–2 500
KI 2: Efficiency at rated power DC to AC (%)	93–96
KI 3: Efficiency at rated power AC to DC (%)	90
KI 4: Lifetime (years)	5–10

Source: Manufacturer's specification sheets

The inverter efficiency will drop considerably from rated efficiency at partial loads (<30%). Several factors need to be considered during installation, such as temperature conditions, air moisture content, dirt and dust vulnerability, audible noise level of the inverter, and the applicable regulations for power quality (or electro-magnetic compatibility) (Meral and Dinçer, 2011). In order to achieve high efficiency manufacturers mainly use standard silicon-based MOSFET technologies (*see* Glossary of Terms).

Dual-mode inverters

A dual-mode inverter, also known as a grid-supporting inverter, is the electronic component permitting the mini-grid to operate in grid-connected or islanding mode. When the mini-grid is interconnected it operates as a grid-following inverter (current source inverter) when the grid formed by an AC source is on. When the grid is down it operates as an autonomous inverter (voltage source inverter). The connection to and disconnection from the grid is done with an internal or external transfer/synchronisation switch (UNDP, 2013).

Box 4.12 – Hybrid Power Conditioners (HPC) are enabling large-scale renewables in remote areas

Australian company Optimal Power Solutions has been at the forefront of large-scale autonomous hybrid power conditioners (HPC). The HPC makes it easy to integrate and optimise remote-area power sources such as solar PV arrays, wind turbines, battery banks and diesel gensets. The use of the HPC can achieve diesel costs savings on average 60% over the course of the mini-grid lifespan, extensive operating flexibility, increased energy harvesting and superior power quality. The macro HPC has been implemented in projects ranging from 1 to 2 MW in Malaysia and Indonesia.

Table 16 summarises the main indicators of dual-mode inverters.

Costs

Costs for dual-mode inverters are the highest of the three converter types. They are typically 6 to 20 times more expensive than grid-following inverters, and twice as much as grid-forming inverters. This is due mainly to their wider functionalities to work in both modes (voltage source and current source), and because of lower market share. There are a limited number of manufacturers offering dual-mode inverters, but their use is becoming more common for mini-grids and also in unstable low-quality grids.

Manufacturers of dual-mode inverters include Schneider Xantrex, SMA Studer, Leonics Victron Energy, Outback, HiQ and others. There also are devices that already integrate power conversion and storage in one single product, such as Socomec's SUNSYS PCS2, a modular solution that can perform demand response, peak shaving, active and reactive power provision, and load shifting, among others (SOCOMEC, 2015). Larger equipment, for power demands higher than 100 kW, are increasingly available from manufacturers, such as Princeton Power Systems' BIGI model.

Technology

The switch between modes is done automatically and lasts from 15 to 20 milliseconds. Nevertheless, the reliability of bundled inverters that can transition quickly and smoothly between grid-following and grid-forming AC grids is still a challenge since power quality is not always reliable and protection issues are still not fully resolved (Soshinskaya *et al.*, 2014).

Dual-mode inverters also can perform demand response, peak shaving, active and reactive power provision and load-shifting capabilities. Efficiency at rated power is slightly lower in comparison to grid-following inverters, and drops at partial loads as with other inverter types. Other technical features from grid-forming and grid-following inverters apply, as dual-mode inverters combine features from both, and innovations in both will be shared with dual-mode inverters.

DC step-up and step-down (DC-to-DC conversion)

DC-to-DC converters are used to step up (boost) or step down (buck) voltage in DC. DC-to-DC converters are used on their own in DC grids (*e.g.*, SHS or recreational vehicles), are found in many portable electronic devices such as laptops and mobile phones, and also are used as power optimisers or MPPT in PV modules and wind turbines. The most common type of DC-to-DC converters are switched-mode converters that can reach better efficiencies, between 70% and 95%. Still, this efficiency varies in accordance to output-input current and frequency of operation (Lidow and Strydom, 2012). The use of DC-to-DC converters in mini-grids is key for energy saving, in particular for data and telecommunications centres (Hayashi and Matsumoto, 2013).

4.5 Consume

Providing energy to end-users is the ultimate goal of any renewable mini-grid. Consumption includes the technologies that make this process more flexible and efficient.

DC appliances and DC grids

The majority of appliances today are designed to operate in AC, and most electricity delivered by utilities is AC. DC mini-grids can provide "unprecedented design and space flexibility, greater energy efficiency and improved sustainability" (EMerge Alliance, 2015). DC mini-grids are promising for several loads in data centres and commercial buildings due to improved power quality, increased energy efficiency and lower engineering costs (Backhaus *et al.*, 2015). DC distribution is favourable due to reduced conversion losses and less heat generation from conversions (Marnay *et al.*, 2012a). It has been demonstrated that by shifting from distribution in AC to distribution in DC in grids with distributed generation (*see* Glossary of Terms), at least 3% higher efficiency can be achieved (Willems *et al.*, 2013).

The use of DC grids also is recommended for low-tier service solar PV-based grids which tend to be more efficient and economical, but limit the appliances that can be used (Pittet, 2012). PV is generated in DC which must be converted to AC and then back to DC for

Box 4.13 – University mini-grids: living research on DC mini-grids

Place: Xiamen, China

The mini-grid of the new Xiang An Campus at Xiamen University is based on a DC distribution line of 380 V and consists of a 150 kWp solar PV array and lead-acid batteries. It powers a commercial-type building on the campus, including LED lighting, office appliances and air conditioning. The mini-grid is planned to eventually power a data centre and an electric vehicle charger; all loads use DC energy (Zhang, 2015). Various international companies have been involved in the implementation of this mini-grid including Nextek, People Power, Intel, LBNL and Canadian Solar (Marnay *et al.*, 2012b).

AC grids, adding even more inefficiency (Justo *et al.*, 2013). The use of DC 12-volt LED light bulbs powered directly by PV has provided savings of up to 30% in electricity consumption by diminishing the operation of inverters at inefficient partial load and eliminating the unnecessary DC-AC-DC conversion (Graillot, 2013). A 2015 study found that super-efficient DC appliances can lower total costs by as much as 50% (Phadke *et al.*, 2015). Even though DC appliances have long been available, their costs remain higher than AC ones due mainly to the economies of scale of the latter (Nordman and Christensen, 2015; Rajaraman *et al.*, 2015).

DC-powered devices have been used mainly in industrial power distribution, telecommunications and point-to-point transmissions, with increasing interest in low-voltage DC (LVDC) grids (Justo *et al.*, 2013). DC appliances are common in the recreational vehicle sector, but increasingly are being adopted for stationary energy in remote areas. There are a number of common appliances for DC, such as LED TVs, LED lighting, media players and refrigerators, such as SunFrost and SunDanzer. These are becoming more popular but are still more expensive. DC motors also have started to flourish, such as DC water pumps (*e.g.,* Grundfos, Lorentz) and air conditioners (*e.g.,* Hotspot Energy, Dantherm) designed for autonomous solar PV installations. Power electronics such as laptops and mobile phones are very common DC-powered devices, but usually include a converter from AC electricity to the native DC, which adds inefficiency.

There are several DC mini-grid demonstration projects, including an IBM centre in Sweden, NTT Group in Japan, New Zealand Telecom and US Intel Corp. (Justo *et al.*, 2013).

The distribution of DC is not yet standardised. Some LVDC grids use USB, which allows various appliances to connect to a single plug with a maximum of 100 watts of power (Willems *et al.*, 2013). Power over Ethernet (PoE) is an IEEE standard that can be used for DC distribution as well. Other LVDC options include UPAMD and HDBaseT. The power that LVDC technologies can handle is low and not interoperable with other standards, which limits their applications. Data centres, on the other hand, usually operate with higher voltages (Backhaus *et al.*, 2015) which can increase efficiency and power delivery potential.

Interconnecting DC grids with AC grids requires a converter to manage the energy flow, which requires

Box 4.14 – DC microgrids

Schneider Electric India is offering a small-scale DC mini-grid solution of 0.5 kW to 10 kW (Schneider Electric India, 2015). Other solution providers available in the market include Pika Energy (Pika Energy, 2015), and Specialized Solar Systems from South Africa. Their renewable autonomous mini-grid solutions for basic services provide an alternative for electrification that balances low costs with the need for basic, productive energy in rural areas.

different characteristics than the connection required for non-DC mini-grid, and might result in additional investment costs. This is a critical consideration that should be included in electrification planning and design. For remote mini-grids based entirely on DC distribution, there is uncertainty on how they will use appliances if the AC main grid is extended eventually. Some of the main challenges include equipment grounding and interaction between power converters. Project integrators operating in these areas, and particularly in the context of energy access, recognise the issue (Schnitzer, 2015). Further research and innovations are thus required (Backhaus *et al.*, 2015; Justo *et al.*, 2013). The EMerge Alliance and the REbus Alliance are open industry associations promoting the safe use of DC power distribution (EMerge Alliance, 2015; REbus Alliance, 2015).

The importance of demand-side management

Demand-side management (DSM, *see* Glossary of Terms) for renewable mini-grids is focused on adjusting demand for electricity based on the generation from renewable sources. DSM encourages users to adjust usage based on the availability of electricity. Harper (2013) presents a list of strategies including the use of efficient appliances, commercial load scheduling, restriction to residential uses, price incentives and community involvement. With regard to technologies, current limiters, distributed intelligent controllers, GridShare, conventional meters, pre-paid meters and advanced metering devices with centralised communication are described (Ibid.). Future strategies and technologies are crucial for renewable mini-grids, with a vast potential for improving the integrated energy efficacy.

Smart appliances can improve the flexibility of the load to match renewable generation. Smart appliances include the capability to communicate with the grid and accordingly adjust their operation. Major appliance manufacturers such as LG, GE, Samsung, Whirlpool and others are already offering several smart products. Whirlpool uses Nest Learning Thermostat® in its washing machines to make better choices depending on fabrics, and also to save energy with longer drying cycles and auto-delay washing, to avoid peak energy prices (Whirlpool, 2015). LG has introduced the interface HomeChat to communicate with appliances through mobile phones and easily control them. Smart ThinQ technology enables the operation of appliances during lower energy rate periods (LG, 2015). Nevertheless, the use of these appliances and functions is still limited due to their high cost and limited applicability in areas without smart-grid technologies.

Table 17: Key attributes for consumption technologies

Indicators	Status as of 2015
Availability of DC appliances in regular marketplaces	Limited to LEDs; refrigerators, TVs, media appliances and others for RV and off-grid markets
Internet of Things in appliances	Limited to high-end appliances with smart grid access
Appliance efficiency	Baseline

The importance of energy efficiency

There has been a large body of research and progress in developing more efficient appliances. For example, the average energy required for televisions dropped by 76% from 2008 to 2012 (Blumstein and Taylor, 2013). As well, according to the American Council for an Energy-Efficient Economy, the prices for most appliances, refrigerators, washers and dishwashers have decreased by up to 45% from 1987 to 2010 (ACEEE, 2013). This progress has an enormous benefit for renewable mini-grids where energy efficiency is even more critical. The key benefit for energy efficiency is to lower the overall cost of providing services using energy, without reducing the benefit to end-users. It enables a mini-grid to provide more value per unit of energy.

Key attributes

Table 17 summarises the main indicators for consumption technologies.

4.6 Options for policy makers and developers

Autonomous basic renewable mini-grids historically have been mainly small hydropower projects, since small hydro mini-grids provide a low-cost solution with limited need for storage. Small hydro projects are site-specific. As solar PV costs are dropping, this option also is becoming a cost-effective one and a mature technology up to hundreds of kW. There also has been interest in biomass gasification, but most such projects are still in a pilot phase.

Mini-grids focused on energy access are being deployed worldwide with public funding, notably in Asia, Africa and some countries in Latin America. Most autonomous mini-grids to date are demonstration or infrastructure projects funded by development agencies and governments; there are still many issues to be addressed in order to be commercially viable without external funding or cross subsidies. Some pioneer companies are seeking to commercialise and provide access to energy in remote areas using AB renewable mini-grids, but they still depend on other forms of subsidies or funding support. ***Technology innovation must go hand-in-hand with innovation in business models, finance and regulation (systemic innovation) to scale up the deployment of mini-grids.***

Many countries and communities seek to shift diesel generation to hybrid power plants. Autonomous diesel mini-grids with higher reliability needs are increasingly cost-effective in displacing diesel generation with renewable energy generation. Large diesel-based mini-grids with loads above a few hundred kW, in general, are now incorporating renewables, at a low penetration rate. Autonomous diesel mini-grids with higher reliability needs at sizes above approximately 1 MW are still limited, with only a few examples. One is the King Island Renewable Energy Project can successfully derives a majority of its power from wind and solar sources. The island of Tokelau gets a majority of its energy from solar as well. There are other larger systems with local hydro resources, notably Kodiak Island and El Hierro Island, which have been able to use hydropower to obtain higher amounts of renewables.

Table 18: State of the art of renewable mini-grids

Technologies	Current status
Mini-grids	Most AF and AB mini-grids in the market are small-scale.
	Most IC and ILI mini-grids can operate no longer than one day in islanded mode.
Plan and design	Requires renewable mini-grid specialist for all stages of design, including conceptual design.
	Solar resource data is generally of sufficient of sufficient quality; however, wind and hydro data require on-site measurements to validate, and data can be costly.
	Load planning is based on *ad hoc* and site-specific approaches for estimating loads.
CMM	Monitoring technologies are starting to be able to communicate through lower-cost GSM.
	Interconnection meters are still limited in the market.
	Meters that are able to handle different business models, provide user feedback, and have DSM capabilities are flourishing mainly for autonomous mini-grids.
Storage	Most mini-grids are still using LABs as the main storage technology.
	An increasing number of pilot projects of mini-grids are starting to incorporate other storage technologies such as LIBs, flow batteries and flywheels.
Convert	Grid-following inverters have achieved considerable price drops in the past decade.
	Dual-mode inverters are starting to become common for interconnected mini-grids, as they are coming into the main grid market for distributed generation in unstable grids that can operate interconnected or islanded.
Consume	Mini-grids are currently feeding mostly AC loads.
	The use of DC power is increasingly being explored, primarily in commercial buildings and in AB mini-grids as most appliances today have embedded power AC/DC conversion.
Generation	Low-cost silicon-based polycrystalline solar PV modules are the main technology being used for generation.
	Small wind is being used less, due in large part to competition from solar PV and to the high cost of resource assessment.
	There are some new small hydropower turbines for low-head (*see* Glossary of Terms) and low-flow applications.
	Biomass gasification that is able to handle more feedstock is increasingly available, although it is plagued with maintenance issues.

Interconnected mini-grids are being commercialised mainly in the United States, where they are being used for emergency response and to boost disaster resilience. Although they often encompassing renewable sources, they are not based exclusively on renewable energy. Combined heat and power (CHP) has been successfully used in these areas for decades.

The state of the art of renewable mini-grids today may be summarised as follows:

Renewables-based mini-grids provide an alternative to grid extension that can in some cases be less costly, more demand-driven, and environmentally friendlier. Policy makers and developers should be aware that renewable mini-grid technologies today can provide access to electricity in remote areas. Still, the technology continues to develop and improve. Renewable mini-grids have the potential to enable users to leapfrog (*see* Glossary of Terms) traditional electrification efforts such as the extension of unreliable or carbon-intensive grids. They also have the potential to provide high power for remote industry, which is difficult with autonomous power provision (such as SHS or PV for productive uses).

Mini-grids offer a viable median option between solar home systems and full-scale grid expansion. Consequently, there is an important market for mini-grid development to bolster electricity security and expand modern energy access in many countries.

Interconnected renewable mini-grids can enhance emergency response, particularly in natural disaster-prone areas. Interest is high in interconnected, resilient and high-penetration mini-grids, but the renewable portion today is driven by economics during typical grid-connected operation. They also can provide interconnected communities the possibility to decide what resources to use to generate electricity, to be less dependent on centralised utilities, and to improve their environmental stewardship. Interconnected renewable mini-grids are primarily for customers with high needs for reliability.

5 TECHNOLOGY GAPS AND OPPORTUNITIES FOR INNOVATION

Technology innovation can be split into technology venturing (*see* Glossary of Terms) and drivers (*see* Glossary of Terms) that increase use and deployment ("commercial scale-up", *see* Glossary of Terms) (IRENA, 2013). A detailed summary of the drivers for renewable mini-grids today can be found in Annex 1. This section focuses on the technology needs that need to be addressed to create the renewable mini-grids of the future.

The mini-grid market is diverse, and different types of mini-grids will have innovation requirements that can drive uptake. The uptake of different types of renewable mini-grids is based on their energy costs, social needs and environmental awareness.

There is a need to make renewable mini-grids a more competitive alternative by reducing the **cost** (*e.g.,* making them cost-effective), improving the **reliability** (*e.g.,* improving performance), increasing the **ease** of deployment (*e.g.,* making them simpler to integrate and design) and making them more **environmentally** friendly. No single innovation is required, but rather a range of technology advances and non-technology innovations is needed to enhance the uptake of the renewable mini-grids, including policy, regulation and business innovations.

Technology innovations in each of the six functionalities provide benefits across all four major impact areas. However, the impact is not equal. Innovations at the plan-and-design stage can have dramatic benefits for reducing cost and making the implementation of renewable mini-grids simpler. Innovations in CMM primarily make the operation of renewable mini-grids easier and more reliable. Innovations in storage enable more efficient use of resources and more reliable operation, yielding strong benefits across all four impact areas. Innovations in conversion enable fewer losses and provide a hardware platform for integrating the components of the renewable mini-grids together, which can ease set-up and lower costs. Innovations at the consume stage reduce the energy requirements, yielding environmental and cost benefits. Generation innovation provides low-cost, low-environmental impact benefits, yielding a savings of costs and reducing negative effects on the environment.

Table 19 summarises the identified priority gaps and the needs addressed by innovation and technological R&D. It includes a qualitative assessment of the impact of addressing the gap in terms of the cost, reliability, ease of implementation and environmental stewardship metrics. The qualitative assessment ranges from one star (⁎) for limited positive impacts to four stars (⁎⁎⁎⁎) if a gap is addressed. The priority gaps were identified and expanded based on high-level findings from the literature review, interviews with key experts, development of the key indicators in Section 4, the key indicator projections in Section 6, and the authors' professional experience with mini-grid technologies.

Table 19: Priorities to address for each mini-grid functionality

		Impact			
PLAN AND DESIGN		**Cost**	**Reliability**	**Ease**	**Environmental**
1	Standardised planning and design	****	**	****	**
CONTROL, MANAGE, MEASURE (CMM)					
1	More intelligent controls	***	****	****	**
2	Improved communications and standards	**	****	****	*
3	Improved metering and monitoring	**	***	****	***
4	Simplify connecting equipment together	**	*	****	*
STORE					
1	Use less expensive, more abundant and less resource-intensive materials	****	**	*	***
2	More robust, lower-maintenance technologies to reduce life-cycle costs for storage	***	****	***	**
3	Improvements in long-term storage capability	**	**	**	****
4	Improvements in high power output capability	**	***	**	***
CONVERT					
1	Lower capital costs of converters	****	*	**	*
2	Combine diverse function into inverters	**	**	****	*
3	Improve efficiency, particularly at partial load	**	**	*	***
4	More converter options for diverse renewable mini-grid markets	**	**	****	*
CONSUME					
1	Increased commercial availability of efficient end-uses	****	*	**	****
2	Better user tools for adapting consumption to energy supply (DSM)	****	**	***	****
GENERATE					
1	Lower capital costs for generation	****	*	*	**
2	Reduce maintenance needs	**	***	****	**
3	Improved efficiency and increased energy capture	***	*	*	****

6 PROSPECTS FOR TECHNOLOGY INNOVATION

New technological developments are expected in all six core functionalities. Research and development initiatives in the laboratory and in early commercialisation development today may overcome the 18 identified priority gaps over the next two decades. The impacts of this R&D will cut across market, technological, social and environmental factors. Where possible, active research from today is featured to provide an example of the ground-breaking innovations that potentially could unlock renewable mini-grids as the energy supply of the future (although not all research presented in this section might result in commercialised products, and the endeavours presented are only a sample of the numerous R&D efforts carried out currently by different institutions). Not all technological advancements must be achieved, but a critical mass is necessary to create a future with ubiquitous renewable mini-grids. From this perspective, many of these innovations require support from policy makers, investors and academia, as described in Section 7.

This section provides the reader with an introduction to the set of challenges, with several promising R&D solutions, and with a summary of the benefits of robust investment in renewable mini-grid technologies. The presentation of findings mirrors that of Section 4 and proceeds functionality-by-functionality. Within each of the six core functionalities the following analysis is done:

- Priority gaps are described and converted into a need that innovation can address,
- Several promising R&D initiatives that are striving to fulfil this need are then described,
- The expected high-level benefits of investment in these R&D initiatives are provided.

The information related to generation functionality is contained in Annex 6 of the report.

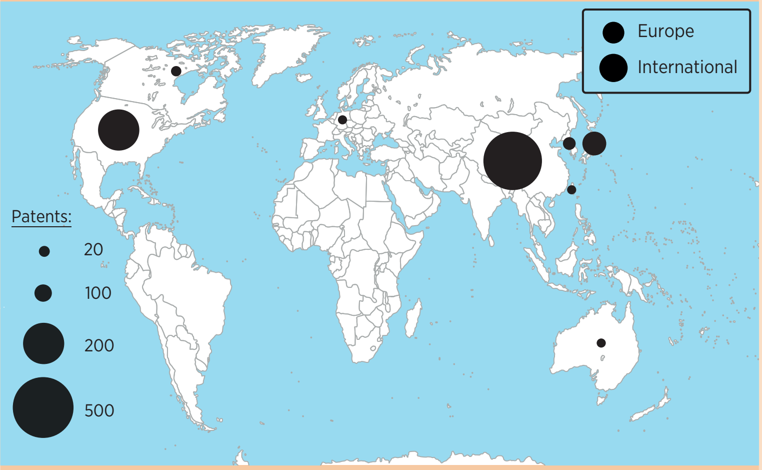
This analysis is supported by a thorough literature review, several interviews with experts, and patent data searched and presented for each of the functionalities. The patent data search gives an indication of the specific topics in which active, near-commercial R&D is happening, as well as the top countries and institutions in the number of patents filed. The results presented in the patent reviews that follow demonstrate an increasing interest in most mini-grid technologies and identify industries that hold intellectual property, which can be adapted for mini-grids. These patent reviews have provided clarity to illustrate the prospects for development of renewable mini-grids.

6.1 Plan and design

An optimally planned and designed mini-grid can dramatically reduce the overall cost, as well as reduce the complexity of integration. Innovation prospects of the technologies and software required for planning and designing mini-grid systems are presented as follows.

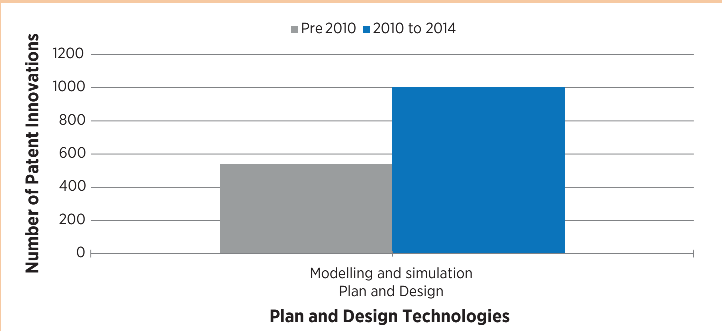
Planning and Design Technologies: Patent Review

Figure 6: Top 10 countries for modelling and simulation patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Figure 7: Number of patents for plan-and-design technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Top institutions patenting plan-and-design technologies, 2010-2014

- State Grid Corporation of China
- China Electric Power Research Institute
- General Electric
- IBM
- Siemens AG
- Toshiba
- North China Electric Power University
- China Southern Power Grid Company
- ABB Research Ltd.
- University of Tsinghua

The plan-and-design patent review focused on tools for modelling and simulation.

The most trending technology modelling and simulation is for computer-aided design (CAD).

Further patent details are provided in Annex 4.

Priority Gap 1 – Standardised planning and design

Despite the tremendous potential of mini-grids, access to financing and planning for mini-grids are more difficult than for larger renewable projects. Part of the challenge lies with regulations and existing approaches for evaluating the risk of mini-grids due to their new and novel nature. However, technology has a role to play in reducing the perceived risk. Key approaches that can help to unlock financing are using a proven technology, having a good buyer for the power, having a solid local partner and making the mini-grid as big as possible (Whittaker, 2013). Technology can help reduce the barriers to projects through bundled approaches to decrease transaction costs, and by using industry tools for evaluating the renewable mini-grids.

Need: Standardising and improving modelling for planning, financing and design

Applying traditional energy sector evaluations to renewable mini-grids can yield a perception of increased risk. The perceived risk can come from lack of familiarity with how to evaluate data uncertainty, data unavailability or evaluation techniques that are too costly for application at a small scale. All of these risks can be managed with design technology to reduce upfront costs and improve access to financing. For example, current state of the art for wind siting is at least one year of on-site measurements with an anemometer, which typically can increase the cost of deploying a 100 kW wind turbine by 5-20%, depending on the number of sites that are measured. Improved resource methods can greatly reduce this cost. As the available information increases and as tools improve, development costs could be cut by as much as 10-20%. These tools also can assist in aligning local initiatives with national goals, resulting in more effective planning and better outcomes.

- **R&D 1: Enhance tools for designing and planning**
  These tools enable projects to have a transparent and complete allocation of costs, which can improve future estimates and designs. Given the large number of pilots being financed with public funding, this information would dramatically improve technological deployment (JRC, 2013). For example, Westeva in Colombia is developing a database of renewable resources for very high-level planning and siting of mini-grids (Westrick, 2014). HOMER software is consistently updating its software to provide low-cost evaluations across all mini-grid market segments (HOMER Energy, 2015). However, there is a need to validate initial planning with actual project outcomes. Spain's Carlos III University, together with Denmark's Aalborg University, developed a grid simulator to test the power quality of mini-grids (Eloy-García *et al.*, 2013). The grid simulator was capable of the compensation algorithm (*see* Glossary of Terms) of distributed generation units in a mini-grid and used to test power quality issues of multi components such as low-voltage ride-through (*see* Glossary of Terms) and unbalanced voltage compensation (Eloy-García *et al.*, 2013).

- **R&D 2: Increase availability of load data**
  Predicting load data for a project development is difficult and is compounded by the fact that publicly available data on load usage can be limited, especially in rural, non-industrialised communities. Accurate load estimates are critical for creating efficient designs, since imbalances between the energy production from variable renewable sources and load requires expensive storage and additional intelligent controls. A number of initiatives are addressing the gap in load data.

  An example of innovations in load forecasting was carried out by the Hawaiian Electric Company and its technology partners: AWS Truepower, Siemens, Alstom, Referentia Systems Inc. and DNV GL. This collaboration created a customised renewable energy forecasting tool, the Solar and Wind Integrated Forecasting Tool (SWIFT), which deployed a local sensor network to gather solar and wind resource information, as well as an improved physics-based numerical weather prediction that addresses Hawaii's unique terrain and tropical marine environments. Now deployed, SWIFT is able to provide to developers and planners with continuous, near real-time, load data and will create a seamless integration of forecasting information into operational tools (IEI, 2014).

- **R&D 3: Lower cost of renewable energy resource assessments**
  Although solar resource assessments today are relatively more accurate than in the past, wind

Box 6.1 – Using Artificial Neural Networks to predict loads

Research at CIEMAT has been carried out for short-term load forecasting based on Artificial Neural Networks for mini-grids (Hernandez *et al.*, 2013). This work has demonstrated the close relationship between forecast errors and the number of training patterns, and applicability of load forecasting and ANN tools to mini-grids, with small errors of 3% compared to real load curves (Hernandez *et al.*, 2013).

resource assessment is more difficult due to micro-siting challenges (*see* Glossary of Terms). More accurate wind resource assessments which factor in the micro-siting impacts that plague wind installations can remove these costs. Research on these smaller-scale impacts is being undertaken by NREL and the Danish Technical University. New techniques based on LiDAR technology (*see* Glossary of Terms) and improved fluid modelling over the next two decades are expected to dramatically reduce the uncertainty of wind resource assessments. Several individual countries in Latin America, with international support, are developing publicly available solar resource maps to facilitate the use of renewable energy (Solano-Peralta, 2015). The Joint Research Centre is improving its solar radiation maps for Africa and Europe and generating expanded tools and capabilities through its Renewable Energy Rural Electrification Africa (RE2nAF) tool (JRC, 2013). IRENA's Global Atlas is continually adding data sources and tools (IRENA, 2015d).

Indicators and summary of innovation impact

Table 20 summarises the expected impact of the innovations on the 2025 and 2035 key indicators for plan and design.

6.2 Control, manage and measure (CMM)

The capabilities within this functionality include the technologies most specific to the improvement of renewable mini-grids. These technologies sit at the intersection of advanced power semiconductor devices, power electronics and information technologies (Huang *et al.*, 2013). As noted in Section 4, many of the

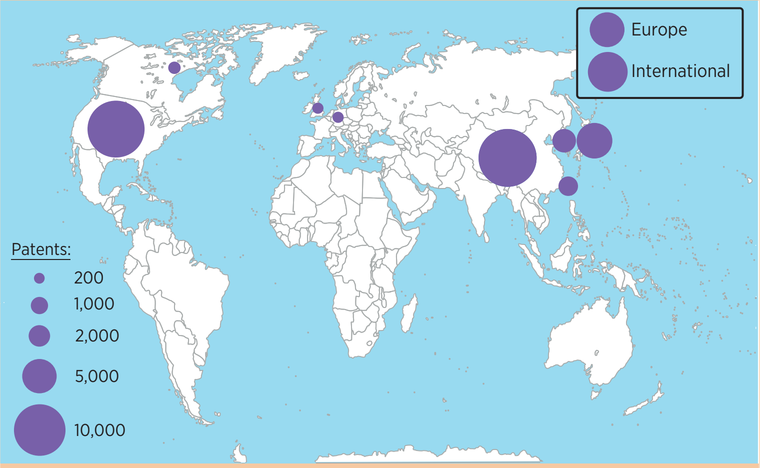
Table 20: Plan-and-design indicators

Indicators	2015	2025	2035
Need for specialised engineering	Requires renewable mini-grid specialist for all stages of design, including conceptual design.	Increasing availability of off-the-shelf components and more user-friendly, proven design tools.	Early-stage design of renewable mini-grids does not require a specialist, and robust tools exist for a complete design, based on proven off-the-shelf components.
Resource data (solar, wind, water)	General solar resource data are of sufficient quality; however, wind and hydro require on-site measurements to validate, and data can be costly.	Increasingly high-quality resource data are available.	Resource planning is supported by robust tools that accurately predict resources without on-site validation. Detailed, local resource data are affordable and readily available.
Load planning	Based on *ad hoc* and site-specific approaches for estimating loads	Increasingly intelligent load planning; however, load planning still requires frequent updating and validation.	Smart load planning tools provide accurate, proven estimates on expected load based on readily available data at a site.

Source: Author elaboration

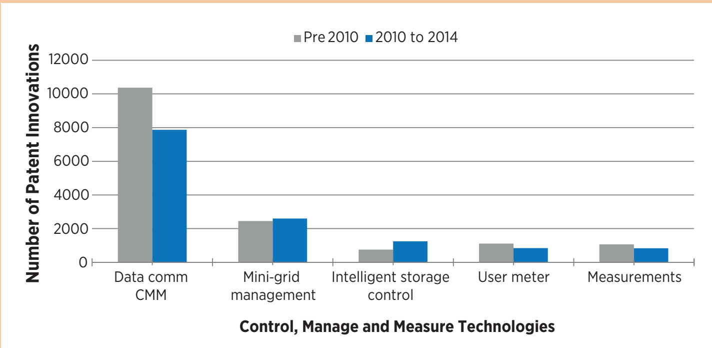
CMM Technologies: Patent Review

Figure 8: Top 10 countries for all CMM technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Figure 9: Number of patents for CMM technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Top institutions patenting CMM technologies, 2010-2014

- Toyota Motors
- Bosch GMBH
- Honda Motor Company Ltd.
- Nissan Motor
- Toyota Motor Corporation
- GM Global Technology Operations Inc.
- General Electric
- Ford Global Technology LLC
- Hyundai Motor Company Ltd.
- Panasonic Corporation

Most of the main patent holders are auto companies, due in large part to the need for intelligent power management in cars. Appliance manufacturers are also pushing innovation through, for example, the Internet of Things to enable appliances to benefit from smart grids. Many, but not all, of these technologies could be transferred to renewable mini-grids.

Further patent details are provided in Annex 4.

Trending topics on patents:

- Data communication technologies: power network operations, communications and information technologies, distribution or generation.
- Mini-grid management: technologies for reduction of losses (e.g., zero current switching or soft switching converters, zero voltage switching or non-dissipative snubbers).
- Intelligent storage control: uninterruptible or back-up power supplies integrating with renewable energy.
- User meters: utility meters which are networked together (*e.g.*, interconnection within a single building)
- Measurements: equipment characterised by state monitoring, *e.g.*, fault, temperature monitoring, insulator monitoring, and corona discharge.

components utilised within mini-grids are technologies that have been repurposed from other industries (*e.g.,* telecommunications and manufacturing) to suit mini-grids (Yan *et al.*, 2013). This trend is expected to continue, if such technologies continue to be strategically adopted.

Critically, improvements in CMM technologies will enable deployments to easily scale up and improve integration of the diverse equipment and resources required to power mini-grids with renewable energy. The authors estimate that CMM costs typically account for about 10% of a mini-grid's total cost, although this number will vary significantly across individual installations. This section presents several innovations that could reduce their cost and improve their capabilities. The cross-cutting value potential of CMM is likely to exceed the benefit from reduced costs for the CMM technologies themselves.

Priority Gap 1 – More-intelligent controls

Controllers are key for functional mini-grids (Klemun, 2014). There is significant research into how renewable mini-grids should make decisions about how to manage loads, use storage and use dispatchable generation such as diesel back-up or biomass. Decision making can be either centralised or distributed. Distributing control decisions helps to reduce the burden on a centralised controller. For example, a battery controller might decide the optimal voltage for charging a battery, while a central controller might make a decision about how quickly to charge the battery.

Benefits of intelligent controls include increased contributions from renewable energy, improved stability, high quality of service, and maintaining good efficiency levels of gensets, among others. For example, artificial intelligence and the ability to predict load demand or meteorological conditions can result in more effective load management or higher renewable energy usage. The speed of responsiveness to events such as overloads or data communication speed are indicators to evaluate the quality of controllers. Various indicators exist for evaluating the quality of service provided, such as those from other electrification infrastructure including the System Average Interruption Duration Index (SAIDI) and the Customer Average Interruption Duration Index (CAIDI).

Need: Making controls more intelligent and affordable

Research can help to determine which control strategy is preferred and under what conditions. There is significant research into how to make these decisions and what decisions are preferred:

- **R&D 1: Improve short-term control for more stable grids**
  Clusters of mini-grids are expected to be developed in the near future. Each mini-grid can have a number of energy services which could be of mutual interest among mini-grids, such as storage capability, active/reactive power demand/generation and so on. Thus multi-agents could negotiate the interchange of energy between mini-grids or mini-grid clusters. Research trends in mini-grids show that technologies for communication systems are becoming important, particularly multi-agents and hierarchical control (Guerrero *et al.*, 2013). Also, there is a need for developing robust control algorithms that use an appropriate mixture of centralised/hierarchical and distributed control to handle a wide range of architectures (Guerrero *et al.*, 2013).
  Singapore's Nanyang University and Denmark's Aalborg University have proposed an interlinking droop scheme for tying mini-grids at different frequencies and voltages to reinforce active and reactive power in their operation (Nutkani *et al.*,

Box 6.2 – Short-term stability control

Place: King Island, Tasmania, Australia

The King Island Renewable Energy Integration Project has helped the King Island grid push the limits of 100% renewable energy projects at increasingly large scales. Using its novel controls for stability, the King Island grid is currently capable of operating for periods on 100% wind and solar energy in a 1 MW+ grid (Hydro Tasmania, 2015). It is one of the few electrical systems of this scale globally to achieve this technical milestone.

2012). In the private sector, Sustainable Power is a small business developing integrated, novel solutions for high-penetration mini-grids around the globe (Sustainable Power Systems, 2015). The FREEDM System from North Carolina State University and its "energy internet" concept researches the role of power semiconductor technology, power electronics and information technology to enhance operations applicable to clusters of mini-grids (Huang *et al.*, 2011).

- **R&D 2: Improve long-term intelligent supervisory control and management**

As information technology becomes more central to the smart grid, it will benefit the renewable mini-grid market by allowing more intelligent decisions. For example, in interconnected renewable mini-grids, Causam/Power Analytics' software has a robust platform that can help with real-time decision making based on real-time equipment failures and resource availability (Power Analytics, 2015). The University of Aalborg, in partnership with the Universidad Distrital Francisco Jose de Caldas, Universidad de Puerto Rico and Universitat Politècnica de Catalunya, is conducting fundamental research into control algorithms that balance economically optimal decision making and prioritising the use of renewable energy (Luna *et al.*, 2015). The Power Systems Integration lab at the Alaska Center for Energy and Power in Fairbanks is pioneering the optimal use of renewable energy in remote mini-grids (Mueller-Stoffels, 2015).

R&D 3: Improve wind and solar forecasting

Today, hundreds of millions of dollars is at stake as renewable energy continues to play a larger role in the main grid. Private organisations such as 3TIER, AWS Truepower and Windlogic are all actively exploring meteorological tools to better create day-ahead and four-hour-ahead predictions of wind and solar outputs from renewable energy farms. Government organisations such as the US National Center for Atmospheric Research and NREL are active, along with meteorological bureaus worldwide, in researching methods for more accurate short-term estimations. These predications are run in centralised supercomputing facilities that distribute their predictions to utility dispatch centres and energy market investors.

Markets will build off of this innovation by using new tools for communication as well as data centralisation tools to distribute centralised information all over the globe. The improved predictions will enable controls to manage the use of batteries more optimally, reducing wasted electricity and enabling projects to use fewer batteries.

Priority Gap 2 – Improved communications and standards

There has been significant applied research and integration of control equipment into standards such as IEEE Standard 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems" (Basso and DeBlasio, 2004) and IEC 62116 "Utility-interconnected Photovoltaic Inverters – Test Procedure of Islanding Prevention Measures" (IEC, 2014). These standards reduce uncertainty for interconnected mini-grids. In Europe, research efforts to standardise such equipment are being driven by the Smart Energy Systems group at the European Institute of Innovation and Technology through enhancements to IEC standards 60870 "Telecontrol Equipment and Systems" and 61850 "Power Utility Automation". Meanwhile, information on technology-focused standards is being developed in parallel.

Box 6.3 – Public-private alliances to enhance interoperability

Industry-accepted standards underpin much of the increasing ease of connecting together diverse hardware and software. Groups in North America include the Smart Grid Interoperability Panel (SGIP) and the Smartgrid Alliance. Similar organisations exist in Europe (Smart Grid Coordination Group), the Republic of Korea (Korea Smart Grid Association), India (India Smart Grid Forum) and Japan (Japan Smart Grid Alliance). These organisations bring together diverse stakeholders with a common goal of facilitating the intelligent use of information in the electrical sector.

Need: Better communication devices

Communications platforms require cost-effective architecture, real-time communications (two-way link), security mechanisms, standards to ensure interoperability, scalability and field upgradability, as well as strong industry support (Vigneron and Razazian, 2012). There are two key needs for improving compatibility and enhancing communications:

- **R&D 1: Improved interoperability standards**
  There are also numerous groups that are developing the PAP standards. IEEE is developing Standard P2030.7 for the Specification of Microgrid Controllers (IEEE, 2015). A group of organisations under the Industrial Internet Consortium is testing standards at their Communication and Control Testbed for Microgrid Applications with a goal of producing industry-accepted standards, including the next phase of piloting the standards in a live mini-grid (Industrial Internet Consortium, 2015). Another effort for standardisation and facilitating plug-and-play interoperability between distributed energy resource components and smart grid applications is the SunSpec Alliance.
  As these standards improve, manufacturer "lock-in" will be reduced, enabling more robust and resilient designs. Policy support is critical for ensuring that these standards are adopted and used.

- **R&D 2: Better integration and standardisation of communication technologies**
  For DC mini-grids, researchers have found that strategic communication using the DC bus as a communication link can achieve lower-cost communication. One field of research includes the use of energy storage to change the voltage level of the DC bus to transmit messages. For example, the converter can use the DC bus to communicate the SOC of the batteries (Zubieta, 2015). Other research is done in distributed control amongst the converters, linked by the DC bus with a low bandwidth external communication link or DC bus signaling control methods (Lin *et al*., 2015 and Zhengyu *et al.,* 2015). For AC appliances, there is analogous research into power line communication (PLC). However, communications through the power line carrier, whether DC or AC, must be used strategically because the communication speed is limited. In many cases, power line communication can be used in combination with other communication channels.

Cellular wireless wide area network (WAN) communications is a mature technology where the utility can take advantage of the existing mobile infrastructure and decrease the grid's costs, without having to share the costs of operation and maintenance (O&M) or upgrading of the network (Pauzet, 2011). To avoid cyber-attacks and protect financial transactions, encryption protocols are necessary such as the Secure Sockets Layer (SSL) or Transport Layer Security (TLS).

Continued investment in mobile telecommunication infrastructure will improve the ability of renewable mini-grids to share data with external experts and managers. There are second-generation (2G), third-generation (3G) and fourth-generation (4G) wireless communication technologies. The CDMA 1xRTT and GSM/GSRM networks are 2G solutions where the meters can incorporate a SIM card (*see* Glossary of Terms) and transfer data by sending SMS messages, although with questionable reliability in terms of timing and failures. An evolution of GPRS is the EDGE (Enhanced Data Rates for GSM Evolution), characterised by higher bandwidth and connection speeds than GPRS (Pauzet, 2011). 3G networks include Wideband CDMA (W-CDMA), High-Speed Downlink Packet Access (HSDPA) and Evolution-Data Optimized (EVDO) Revision A. For DC grids, the IEEE-standardised Power over Ethernet (PoE) or Energy Efficient Ethernet (EEE) are helping to standardise the power usage of ethernet lines, which can enable communication and low-power energy over the same cable.

Priority Gap 3 – Improved metering and monitoring

There are several technical requirements and improvements for smart metering that are key areas of research. Metering needs include increased reliability, low maintenance needs, interoperability, scalability, real-time communication, cost-effectiveness, low installation costs, low power consumption, order and security (Khalifa *et al*., 2010; Pauzet, 2011). There are specific gaps that benefit mini-grids, mainly technological advancements that use metering to improve the support capabilities for distributed resources and autonomous mini-grids.

Need: More flexible, robust and adaptable metering technologies

Flexible metering technologies are necessary to support diverse business models based on local needs. Traditionally, user meters have focused only on measuring users' energy consumption. However, the proliferation of distributed energy resources that can feed back into the grid, as well as new business models such as time-of-use pricing, are driving new smart meter technology.

- **R&D 1: Improve communication technologies**
  Research on smart meters aims to replace communication conducted through serial ports (RS232 and RS485, for example) or wirelessly (infrared and radio frequency) with automatic meter reading (AMR) technologies (Khalifa *et al*., 2010). PLC communication can utilise existing cables to transmit data along with electricity. Other wireless communication technologies include radio frequencies such as satellite, WiMAX, Bluetooth, WiFi or ZigBee (*see* Glossary of Terms). Due to their short-distance coverage, the latter technologies serve mostly small home clusters (*Bari et al*., 2014).

- **R&D 2: Adapt metering technologies to be more flexible**
  Companies such as Circutor, Inensus and Eaton have been adapting their metering technologies to offer more flexible solutions. Circutor in collaboration with Trama TecnoAmbiental is currently working on a new meter technology with a universal approach. Its algorithm incorporates various business models and control strategies and allows the operators to assign different tariffs to users of the same mini-grid. Through software, the operator can activate or deactivate the available functionalities and create tailor-made tariffs depending on the needs of the mini-grid: for example, power-based tariffs and power control for hydro mini-grids, and energy control and real-time pricing schemes for solar and/or wind mini-grids. Developers of the meters also are designing a low-cost option with less functionality and flexibility that would decrease costs by 30%.

- **R&D 3: Improve remote monitoring capabilities**
  Research is looking at remote monitoring in advanced metering infrastructure (AMI) and two-way communication between the utility and the meters. The principal drive for research into innovative communication technologies is "the need to improve utility efficiency and customer service level" (marketsandmarkets.com, 2014b). At Purdue University research is ongoing to determine what required data and information can be collected through AMI in smart meters, tailored for both smart and mini-grids. The research seeks to provide data to enable accurate and smooth control over transitions in mini-grids and their individual sources (Purdue Polytechnic, 2015).

Need: Connecting local capacity with technology experts for O&M

Box 6.4 – Cloud-based monitoring

In order to provide complete mini-grid operation services, some manufacturers are starting to integrate communication hardware into meters that sends recorded data to monitoring platforms housed on cloud servers. In this way, operators can remotely monitor a user's consumption, detect theft or control cash flows. For example, Earthspark's monitoring solution consists of end-user smart meters that transmit consumption data to the signal forwarders located at the utility poles and the central gateway that collects all information and uploads it to the cloud. Similarly, Powerhive gathers all data to the Honeycomb, its cloud-based platform. Honeycomb also can map the data and ease the detection of malfunctioning and operation of the mini-grids.

Local capacity is critical; however, the advanced technologies required can benefit from the involvement of external experts. Technology can be used to bridge this gap. On a larger scale, similar technologies have been used by large-scale solar PV and wind developers to help utilities identify problems.

- **R&D 1: Improve cloud-based monitoring.** A number of companies are pioneering approaches to enable international support for local projects. SteamaCo microgrids "use an innovative cloud-based remote metering and payments system that monitors energy use, lets people pay for power using their mobile phones, and quickly troubleshoots any problems". (Ashden Awards, 2015).
- **R&D 2: Create monitoring hubs.** At Beihang University in China, researchers have developed a new monitoring system that is based on 485 communication interfaces and provides real-time running status of all equipment (Zhao and Liu, 2013). In another example, the monitoring company Draker provides solar PV monitoring solutions through the use of energy and environmental sensors, data acquisition hardware, data communications and networking technologies. Draker combines these elements to create a range of solar PV monitoring solutions that can be optimised for commercial and utility-scale projects of different sizes and needs of data management. Finally, Smart Resources Labs is an innovative monitoring company which has a test facility that looks into different mini-grid technologies to find solutions for renewable mini-grid communities.

Priority Gap 4 – Simplify connecting equipment together

The "cost for design, engineering, and modelling to develop the required specifications for a microgrid can vary widely from USD 10 000 to USD 1 000 000 or more for a large, complex system" (DNV KEMA, 2014). From a relative cost perspective, this can be estimated to be between 5% and 15% of the installed cost. The precise percentage varies greatly depending on the project scale: larger projects have economies of scale that lower the design requirements relative to project costs. The contribution of these design costs also can be reduced if there are multiple similar, smaller projects that can be replicated to achieve economies of scale. In addition, many developers underestimate the challenge of expanding existing systems (Zimmermann, 2015), and research is ongoing to reduce such challenges.

Need: Ease integration of technologies and plug-and-play (PAP)

There is significant research on simplifying technologies and making them more flexible to changing needs. PAP in interconnected mini-grids is expected to ease the incorporation of new devices and the switching to islanding mode to reduce outages (Soshinskaya *et al.*, 2014). As the shares from renewable sources and storage increase, the need for modularity and easy of connections also will increase. The active research that will drive innovation for easier integration includes:

- **R&D 1: Develop more modular and flexible hardware and software solutions to fulfil local needs**
  The smaller scale of renewable mini-grids relative to traditional large, centralised generation facilities (such as nuclear, coal, large-scale hydro or natural gas) increases the importance of

Box 6.5 – Flexible controls

The Consortium for Electric Reliability Technology Solutions (CERTS) has developed PAP schemes to overcome the need for specialised communication. CERTS uses devices that balance power locally, with strategic operational decisions taken by the supervisory central controller. This control structure reduces the need to redevelop the controls when new devices are added, and improves reliability by distributing control across multiple devices. CERTS controls have been used in American Electric Power's test bed in Ohio and deployed in the mini-grid at Alameda County's Santa Rita Jail (Klemun, 2014).

solutions that can be rapidly deployed and easily scaled up. This includes the development of more "off-the-shelf" products to spread product costs and achieve economies of scale. Modular designs, if appropriate, also can be expanded easily to allow the system to evolve with the energy needs of the served populations.

The Intelligent Power & Energy Research Corporation, through its GridMaster mini-grid control system, is actively researching how distributed computers can interact together to control mini-grids. The company's palm-size computers constantly talk and respond to each other and use distributed decision making to determine the best way to operate the mini-grid as a whole (Wood, 2015a). Modular architecture mini-grids have been proposed to ensure reliability, expansibility and controlled cost in power industries through the use of PAP, multi-level users, unified dispatching and hierarchical management within a limited cost increase (Lin *et al*., 2014).

There is significant research into intelligent software algorithms that can handle new equipment automatically. Academic leaders in developing these algorithms include researchers at the Automatic Control Laboratory at ETH Zurich (Dörfler, 2014), Aalborg University within its Intelligent MicroGrid Lab and the University of California at Santa Barbara. At Aalborg University's Intelligent MicroGrid Lab, researchers have been developing a central controller and control implementation for experimentation purposes (Meng *et al*., 2015).

Furthermore, the National Technical University of Athens has developed the Multi-Agent Intelligent Control (MAGIC) and implemented it in a pilot mini-grid consisting of 170 cottages. MAGIC is a Java-based software that implements intelligent agents that are installed in various households and able to control and monitor appliances. In case of an overload, the individual MAGIC controllers co-ordinate with the Microgrid Central Controllers to curtail individual loads and resolve the problem (Dimeas *et al*., 2014).

- **R&D 2: Demonstrate compliance with and benefits for utility interconnections in interconnected renewable mini-grids**

In many ways, the needs for IC and ILI are intertwined with policy and regulations, as well as smart grid developments in the utilities. Prospective AB and AF installations also should consider utility interconnection for future-proofing and grid extensions. Technological innovation to better measure the operations of the main grid using intelligent sensors – tools for utilities to make more robust control and dispatch decisions – will help utilities use the potential of IC and ILI. The most critical barriers for utility interconnections are on the regulatory and policy side, since interconnected renewable mini-grids must interface with an existing utility and the main grid infrastructure. Dependency on utility regulations drives many current research endeavours.

There is significant research demonstrating the benefits and capabilities for utilities that are traditionally resistant to change. Many research groups in the United States have developed test beds to ensure that the points of common coupling between the renewable mini-grid and utility interconnections are safe. The Grid Interconnection System Evaluator at NREL (Lundstrom *et al*., 2013), the CERTS Microgrid platform (Lasseter, 2007), the Galvin

Box 6.6 – DERLab test bed

In Europe, DERLab is a consortium of leading laboratories and research institutes for evaluating distributed energy and mini-grid technologies. The mini-grid testing laboratories in DERLab's Smart Grid International Research Facility Network include Fraunhofer Institute for Wind Energy and Energy System Technology, ICCS at the National Technical University of Athens, Greece's Centre for Renewable Energy Sources and Saving, and the InstEE at the University of Strathclyde in Glasgow (DERlab, 2015).

Center's smart mini-grid hub at the Illinois Institute of Technology (IIT, 2015) and the Microgrid Communication and Control Testbed under development in California (Industrial Internet Consortium, 2015) all seek to improve the connections between larger utilities and interconnected mini-grids.

In China, the Intelligent DC Living Microgrid Lab collaboration between Aalborg University and North China Electric Power University includes testing for DC mini-grids (IDMLL, 2015). Xiamen University, in collaboration with a range of Chinese and US-based companies and LBNL, is actively researching the benefits of the first DC-based mini-grid at a commercial facility (PPC, 2012).

These research efforts are working to establish interconnected mini-grids as technologically proven and safe alternatives to traditional grid development. In addition to research organisations and companies, many utilities are pursuing research into how to "harden" the grid to enhance a utility's ability to provide reliable power. Under the leadership of PJM and CAISO, utilities are expanding the market recognition of services beyond energy and demand sales. Meanwhile, smaller firms, such as Colorado-based Spirae, have been actively building, testing and deploying interconnected mini-grids that can seamlessly connect with and support the main grid.

Schneider Electric's mini-grid controller dispatches distributed energy technologies by combining information about weather forecasts, energy consumption patterns and pricing signals with the objective to minimise costs. Schneider Electric's products, together with S&C's PureWave Community Energy Storage System, are demonstrated in a pilot interconnected Oncor mini-grid in Texas. This pilot mini-grid will serve as a demonstration project for utilities to investigate the technical and economic advantages of mini-grids and boost their deployment (Wood, 2015b).

One ambitious effort that seeks to dramatically transform the sector is the use of big data in electrical networks. Over the past decade, electricity information has moved away from TDMA ("leased line") data exchange mediums and towards technologies more like the Internet sector. (Meagher, 2015). The transition from a niche information channel towards information technology (IT) practices is allowing information companies, such as Amazon and Google, to compete in developing new tools for managing and distributing data to make smarter energy choices.

Many utility grids today have limited control capabilities available at the low-voltage distribution level where mini-grids could interconnect. This has created problems in grids in Hawaii, where the 51 000 grid-connected, individual solar plant owners are exceeding the

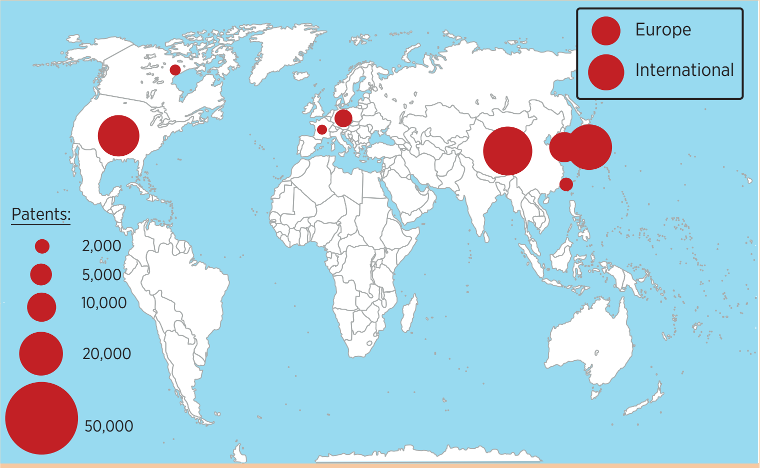
Table 21: CMM indicators

Indicators	2015	2025	2035
Cost of controls	Specialised and expensive controls	Increasingly modular, lower-cost controls	Low-cost modular controls
Control intelligence	Non-economic, non-predictive	Economic-based controls	Economic and predictive controls
Plug-and-play capability	Moderate	Increasingly modular	Seamless
Utility acceptance of renewable mini-grids in grid	High interest, but limited to pilot projects	Increasing number of commercial projects	Standard interconnection terms
Communication and standardisation	Numerous competing standards	Increasingly standardised	Common, open-source
Forecasting of renewable resources	One to two hours with high accuracy	Several hours with high accuracy	Day-ahead with high accuracy

Source: Author elaboration

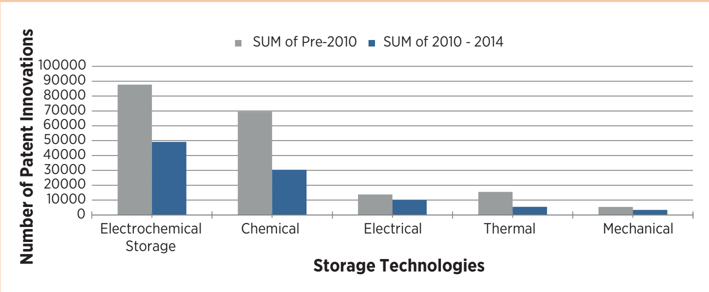
Storage Technologies: Patent Review

Figure 10: Top 10 countries for all storage technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Figure 11: Number of patents for storage technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Top institutions patenting storage technologies, 2010-2014

- Toyota Motor Company Ltd.
- Toyota Motor Corporation
- LG Chemical Ltd.
- Honda Motor Company Ltd.
- Samsung SDI Company Ltd.
- Panasonic Corporation
- Nissan Motor
- Bosch GMBH
- GM Global Technology Operations Inc.
- Sanyo Electric Company

Most of the major patent holders are auto companies, due in large part to the push for storage in electric cars. Small goods manufacturers are also pushing innovation, since portable storage is critical for portability. Many, but not all, of these technologies could be transferred to renewable mini-grids.

Further patent details are provided in Annex 4.

Trending topics on patents:

- Electrochemical: lithium-ion batteries and lead-acid batteries in the past five years. Lithium technologies and flow batteries are the most cited and published. Most patents for sodium-sulphur and LABs are old (Mueller et al., 2015).
- Chemical: proton exchange membrane cuel Cells and hydrogen technologies (liquefied, solidified or compressed)
- Electrical: ultracapacitors, supercapacitors and double-layer capacitors
- Thermal: research is focused primarily on sensible and latent heat storage
- Mechanical: research in pressurised fluid storage, internal combustion engines and fluidic energy storage (*e.g.*, pressure accumulators).

capability of the traditional grid (Trabish, 2015). However, as the utilities are expected to adopt the necessary smart grid technologies over the next two decades, large utilities will increasingly look to renewable mini-grids to manage the high level of renewables. Vendors including Siemens AG, GE, PSI, BTC, ABB and KISTERS are all active in applied research to increase the capability of the grid to handle variable renewables (Appelrath *et al.*, 2012).

Indicators and summary of innovation impact

Table 21 summarises the expected impact of the innovations on the key indicators for CMM for 2025 and 2035.

6.3 Store

Storage is one of the key functionalities for renewable mini-grids that require significant technological innovations. The main aspects that storage technologies need to address are robustness, low cost and reliability. The rapid growth of lithium-ion batteries is expected to reduce reliance on lead-acid batteries for stationary energy storage over the next two decades. Also, new technologies and chemistries will play an increasing role, via complementing LABs (*e.g.*, a renewable mini-grid with batteries and flywheels), the next evolution of LABs (*e.g.*, LABs with supercapacitors) and direct replacement of LABs (*e.g.*, with LIBs).

Priority Gap 1 – Use less expensive, more abundant and less resource-intensive materials to lower capital costs

Storage in most mini-grids today is expensive and is based on heavy metals. The use of new and alternative technologies to reduce the material needs and costs is expected to increase over the next two decades. Lead, since it is the most widely used battery type, has recycling available in many areas, although remote areas still lack recycling facilities. Regardless, the ability to recycle storage technology can help with reducing resource intensity.

Need: Use of less material and alternate chemistries to lower lithium-ion battery (LIB) costs

Materials for electrodes can represent up to 44% of LIB costs, and cathodes typically cost twice as much as anodes (Xu *et al.*, 2013). This is due to the use of costly materials, such as cobalt and nickel, for cathodes. Manufacturing costs can represent up to 20% of LIBs (Wood *et al.*, 2015) due to the time required. Innovations are expected to bring LIB costs down to USD 200-500/usable kWh by 2025 and below USD 200/usable kWh by 2030-2035 (Akhil *et al.*, 2013; Fuchs *et al.*, 2012; IRENA, 2015c; Jaffe, 2014; Nykvist and Nilsson, 2015; RMI *et al.*, 2014). LIB improvements are expected to yield higher rate and charging capacity, lower costs, and a less toxic battery. New materials for electrodes will be used in the next decade. More structural changes for developing new lithium chemistries still require further research. Lithium-sulphur, lithium-air batteries and eventually the use of alternative materials to lithium are expected to happen in the next two decades.

Some major innovations that are expected to lower costs for LIBs are:

- **R&D 1: Lower the cost of cathodes**
  Today, the two major types of cathodes used in LIBs are intercalation and conversion cathodes. In general, intercalation cathodes are more stable and more common commercially, but the conversion types have the potential for lower long-term costs. Common intercalation

Box 6.7– All-solid-state organic battery

At the Key Laboratory of Advanced Energy Materials Chemistry in China, researchers prepared an organic pillar quinone cathode using a poly(methacrylate)/poly(ethylene glycol)-based gel polymer electrolyte, revealing a promising future for an all-solid-state lithium-ion battery (Zhu *et al.*, 2014). The all-solid-state organic battery benefits from using abundant and lower cost materials that can provide twice the energy density compared to intercalation compounds.

cathodes involve inserting a metal into a lithium oxide substrate. Commercial intercalation LIB examples today include $LiFePO_4$, $LiCoO_2$ and $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$, among others.
Promising R&D in intercalation cathodes is targeted mainly at transition metal oxides such as layered compounds, the use of different stoichiometric compositions, polyanion compounds based on manganese, tsavorites like iron, and single metal fluorides like chlorine and sulphur, which can cost a fraction of cobalt (Nitta *et al.*, 2015). NREL and the University of Toledo are working along these lines and in 2012 achieved improved conductivity through the use of silicon co-doping (NREL, 2012). In Japan the National Institute of Advanced Industrial Science and Technology together with NEC Corporation have been working on the development of an iron-substituted manganese oxide cathode which is expected to be commercialised by 2020 (Sekisui Chemical Co. Ltd., 2013).

New research at the US Brookhaven National Laboratory has found that using ternary solid solutions (*e.g.*, where copper partly substitutes iron in the iron FeF_2) allows full oxidation of copper, improves electrochemical performance and has low hysteresis; its intrinsic high voltage and capacity shows promising potential to use in next-generation batteries (Wang *et al.*, 2015). Other companies such as LG Chem, NEC Corporation in Japan and Sonnenbatterie are also key research players in new innovations on LIBs.

- **R&D 2: Lower the cost of manufacturing**

Current efforts to reduce manufacturing costs include the elimination of N-methylpyrrolidone and reduction of the electrolyte wetting and solid electrolyte interface (SEI) layer formation, according to research being carried out at the US DOE's Oak Ridge National Laboratory (Daniel, 2015; Wood *et al.*, 2015). The use of an aqueous electrode can bring processing times down by 60-75%, reducing costs and energy consumption by more than 20% (Wood *et al.*, 2015). Reduced wetting and SEI-layer formation also can reduce processing time, which currently takes 1.5-3 weeks, by using an additive for the electrolyte and investigating charging steps at higher rates, among other techniques (Wood *et al.*, 2015). A spinoff from the Massachusetts Institute of Technology (MIT), 24M with support from the US DOE and venture capitalists, has claimed to be able to reduce LIB manufacturing costs by half through improved manufacturing (LeVine, 2015). 24M is aiming to manufacture LIBs by eliminating the drying process completely, injecting the electrolyte from the start and using thicker electrodes, creating a semi-solid battery (Duduta *et al.*, 2011; Wei *et al.*, 2015).

- **R&D 3: Explore use of new electrode materials**

Lithium air electrodes are particularly promising for electric vehicles due to their high energy density potential (Xu *et al.*, 2014). Nevertheless, lithium air batteries are expected to have lower manufacturing costs due to their need for fewer components. The US Pacific Northwest National Laboratory has been working on developing a new lithium-air battery concept that uses oxygen from the environment as the working cathode (PNNL, 2012). The battery energy density can reach up to 11 000 Wh/kg (close to gasoline). Given the potential low costs, USD 70-200/kWh (Gallagher *et al.*, 2014), lithium-air batteries are very promising.

At Argonne National Laboratory research is ongoing into the magnetic properties of lithium peroxide, the development of an air-breathing cathode, and electrolyte decomposition, to improve the performance of lithium-air batteries (Lu and Amine, 2013). At the University of Waterloo researchers are looking to replace expensive platinum with alternative materials for lithium-air batteries, such as a Perovskite oxide phase nanoparticle-based nitrogen-doped CNT composite which presented superior electrochemical durability (Park *et al.*, 2015). Lithium-air batteries are still limited to the laboratory level, and much work is required to ensure stability and to overcome low round-trip efficiency, low discharge capacity and low practical energy density. Their performance can be enhanced with further research on cathode materials, optimisation of the composition/decomposition of Li_2O2, and the weight ratio of the electrolyte as well as further understanding of the mechanical properties of the lithium-air battery (Ma *et al.*, 2015).

Need: Continued exploration of chemistries beyond lithium-ion

Despite the interest and promise of LIBs, concerns remain regarding lithium availability, safety, recyclability, toxicity, performance and control. The European Association for the Storage of Energy (EASE) and the European Energy Research Alliance (EERA) suggested intensive materials research for achieving substantial breakthrough on flow batteries, advanced lead-acid, aluminium-based, nickel-based, zinc-based, magnesium-based and sodium-based technologies and other new electrochemical couples (EASE/EERA, 2013).

Flow battery costs are expected to drop to USD 100-200/usable kWh by 2035 (Fuchs *et al.*, 2012). Research into new redox pair chemistries that use lower-cost materials will benefit flow battery technologies. Sodium-based technology costs are expected to decrease to USD 120-250/usable kWh (Fuchs *et al.*, 2012) and have a great potential to deliver more environmentally friendly batteries, but their high temperature dependence still poses a challenge.

- **R&D 1: Reduce costs for advanced lead-acid batteries**
  Traditional LABs are expected to achieve slight cost decreases (IRENA, 2015c), in large part due to their status as the main player in the battery market. LAB projected cost reductions of up to 20% due to learning curves as LAB manufacturing continues to increase these cost reductions will continue over the next two decades (Matteson and Williams, 2015). Due to the long experience with LAB, cost reductions for the short and medium term, down to USD 50-150/usable kWh, are achievable in the next decade (EASE/EERA, 2013). More extensive cost reductions are expected for new ALABs as their production scales up. The lower cost expectation is, in large part, due to their longer cycle life and the ability to leverage the manufacturing technologies developed for traditional lead acid.

- **R&D 2: Explore new materials in flow batteries**
  Chemicals in flow batteries are expensive and difficult to maintain. Harvard University has received funding to continue its research on organic flow batteries which use organic molecules found in plants, carbon-based quinones, which are low cost, naturally abundant, can be synthesised, are non-toxic, and are able to cycle efficiently. The researchers have been able to prove that this metal-free aqueous flow battery can retain over 99% storage retention capacity per cycle, and the materials used can cost one-third of the cost of common chemicals in vanadium flow batteries (Huskinson *et al.*, 2014a, 2014b, 2014c).

The University of Malay in Malaysia has been leading research on the use of deep eutectic solvents (DESs) for electrolytes, *e.g.*, ferrocene, which is low cost, manufactured from raw materials and biodegradable, as an alternative to ionic liquids (molten salts) which cost 20 to 50 times more (Chakrabarti *et al.*, 2014). MIT researchers have taken a different path and are instead focusing on getting rid of the membrane, in order to cut down costs and material use and avoiding reliability issues (Braff, 2014). The researchers have found that by maintaining liquids at low enough speeds the electrolytes do not mix. The flow battery uses hydrogen bromine due to its high power density and is able to maintain a round-trip efficiency above 90% (Braff *et al.*, 2013). At the Korea Institute of Energy Research work is ongoing towards a metal-free all-organic flow battery which achieved a 60.9%

Box 6.8 – Aqueous water-based electrolyte flow battery

The ambipolar zinc-polyiodide redox flow battery being researched at the US Pacific Northwest National Laboratory has received a lot of attention due to the outstanding higher energy density achieved (170 W per litre of electrolyte). This flow battery contains no toxic materials, has fire safety and has a significant potential for lower cost membrane (Li *et al.*, 2015). The use of an aqueous water-based electrolyte reduces the need for expensive chemicals required to withstand the corrosive nature inherent in other flow battery chemistries. Finally, the battery can operate at a wider temperature range, from -20 °C to 50 °C (Li *et al.*, 2015).

efficiency by using polythiophene microparticles (Oh *et al.*, 2014).

- **R&D 3: Continue exploring other novel battery chemistries**

  There is ongoing fundamental research into novel materials that could revolutionise the electrochemical storage industry. These include metal-air technologies, liquid batteries, magnesium-based, fluoride-ion, chloride-ion, other conversion-based technologies, and battery cells with higher voltages (EASE/EERA, 2013). For example, metal-air chemistries have the potential to achieve exceptional improvements in technical performance (up to three times those of lithium-ion) and high cost reduction associated with cheaper and more abundant raw materials (EASE/EERA, 2013). This is due to fewer pieces and the use of abundant oxygen as the electrolyser. These are still in early research stages, with commercial potential projected in about 20 years.

  Research today is seeking to overcome performance degradation during long-term operation, and extending the operational lifetime. Metals being researched for metal-air batteries include aluminium, lithium, nickel, sodium, magnesium and zinc. For example, C-Tech Innovation and a series of partners in the UK-based PowerAir Project are researching the promise of combined large zinc-air flow batteries that operate at high current densities (POWAIR, 2015). Zinc-air batteries offer the advantage of using low-cost, benign and abundant materials (C-Tech Innovation Ltd, 2014). Generally, metal-air technology costs are expected to be high in 2030 at USD 330-550/usable kWh, but have the potential to drop to USD 100/usable kWh by 2050 (EASE/EERA, 2013). New, novel storage technologies are not limited to metal-air batteries, but fundamental research into new chemistries can lead to similar innovations for the next generation of storage.

  Alkaline nickel-based batteries (nickel-cadmium, nickel-metal hydride, nickel-hydrogen and nickel-zinc) have been used in off-grid rural electrification applications due to their robustness and resistance in extreme weather conditions (operating temperatures of between -40 ºC and 60 ºC). There are a variety of types specialised for floating, cycling or engine starting (EUROBAT, 2013a, 2013b). Installation costs range between USD 280 and 1 130 USD/kWh, and their efficiency exceeds 90%.

Priority Gap 2 – More robust, lower maintenance technologies to reduce life-cycle costs for storage

Critical maintenance requirements and risk of catastrophic failure to capital-intensive storage devices are a primary challenge for wider use of storage. There is significant research today to reduce the requirements and reduce the risk of failure, while ensuring that the technology can be reused or recycled at the end of its life.

Need: Research into more resilient, safer designs for lithium-ion batteries

LIBs currently offer low thermal stability – that is, the recoverable power and capacity suffer significantly at temperatures above 50 °C or below -10 °C (Bandhauer *et al.*, 2011). Research is currently looking at alternative electrolytes and materials to cope with thermal runway in LIBs (Underwriters Laboratories, 2014). It is expected that by 2030 LIBs will have an operating temperature of -20 °C to 70 °C (EASE/EERA, 2013) and even will be capable of operating at temperatures as high as 200 °C (Wong *et al.*, 2014).

Box 6.9 – Solid electrolyte LIBs

At the Centre for Self-Assembly and Complexity (CSAC) at Pohang University in the Republic of Korea researchers have developed the first example of a highly thermally stable organic molecular porous material-based lithium-ion conducting material. CSAC developed a LIB that used a solid electrolyte based on an organic porous cucurbituril that provides great conductivity and resists temperatures up to 99.85 °C without signals of thermal runaway (Park *et al.*, 2015).

- **R&D 1: Research into thermal management strategies to control LIB temperature**
  Research is ongoing into thermal management devices capable of ensuring that temperature is maintained uniformly in all of the battery cells in a pack (temperature cell to cell balance), counteract rapid temperature rise, and hence avoid thermal runaway (Bandhauer *et al*., 2011). At Lancaster University in the UK, scientists are researching the use of paraffin/porous graphite for a phase-change material (PCM) cooling strategy, which has proven to improve battery safety (Greco *et al*., 2015). AllCell Technologies, an active LIB manufacturer, has patented the use of PCMs to prevent thermal runaway propagation and is already offering solutions commercially.

  Innovations are expected to occur particularly with control equipment to manage and monitor their operation. Improved controls for managing the SOC of the batteries will enable more complete use of the available storage capacity. They also can increase safety by limiting the risk of over discharging the batteries which can lead to thermal runaway and damage the batteries (IEC, 2011).

- **R&D 2: Research alternative electrolytes that withstand high temperatures**
  Electrolytes are commonly either liquid, polymer or solid-state. Most have low boiling points and are flammable (Daniel, 2008; Wood *et al*., 2015). The DeSimone Research group has been working on alternative non-flammable electrolytes made up of perfluoropolyethers which can withstand thermal stability up to 200 °C while retaining conductivity and transference properties (Wong *et al*., 2014). Other research is being developed by Leyden Energy, through the use of lithium imide-based electrolytes to minimise the thermal expansion of the battery (Frost and Sullivan, 2014; Sapru, 2014).

Need: Innovative, advanced designs for LABs

Innovations in integration are expected to achieve improved operational performance while lowering the cost.

- **R&D 1: Carbon enhancement**
  The Advanced Lead Acid Battery Consortium is supporting research on carbon-enhanced design electrodes, composition of carbon-types, degradation of carbon and possible new failure modes, among others, to extend the cycling life and enhance performance of LABs. A main focus of research is on operating in the partial state of charge required for solar PV through optimised charging algorithms and battery design (ALABC, 2015; McKeon *et al*., 2014). Results from their PV project demonstrated the possibility of achieving 17 years of cycle life while retaining 90% of the initial capacity (ALABC, 2015). Institutions such as the Centre for Applied Electrochemistry at Fraunhofer ISC and the International Lead and Zinc Research Organisation, among many industries, are key and active players supporting R&D activities that are becoming a reality in the short term or are already being commercialised.

Priority Gap 3 – Improvements in long-term storage capability

Another high priority for improvement is the ability to store variable renewable energy when the resource is available.

Need: Long-term storage (months/years) to handle seasonal resource availability (*e.g.*, wind doldrums, ebb of rivers)

Long-term storage enables variable renewable technologies (solar, wind, biomass and hydro) to be used year-round, despite electrical production that can vary seasonally.

- **R&D 1: Research seasonal thermal energy storage**
  Research into seasonal storage technology is in its initial stages. To date most work has been done through the use of sensible heat in water tanks. Research is ongoing on the use of phase-change materials such as zeolites, salt hydrates and composite materials for storing solar energy seasonally, but they still need to be tested in the laboratory (van Helden and Rommel, 2015). Another focus of research has been on thermochemical materials with potentially high energy density (SAIC Canada and Wim van Helden Renewable Heat B.V., 2013).

Box 6.10 – Academic research on renewable liquid "solar fuels"

The Solar Fuels Institute is a university-based global consortium seeking to make solar fuels a key part of the energy sector (SOFI, 2016). In contrast to biofuels like biodiesel and ethanol, solar fuels use air with heat or electricity to make fuel. This next generation of renewable liquid fuels avoids competition with farm and croplands.

Thermochemical materials store heat through the separation of two different substances. There is no known testing in laboratories, which was expected to start in 2015-2016 followed by field testing (SAIC Canada and Wim van Helden Renewable Heat B.V., 2013). R&D activities are still in their infancy; hence thermochemical materials face many challenges, and innovation is needed before they become a viable option.

- **R&D 2: Continue to develop storage in non-fossil fuels**

  Research is required into fuels that are easily created with low losses from electrical energy, allowing variable generation sources to convert into easily storable fuel when there is no immediate use for the electricity. By transforming electrical energy into chemical energy carriers with electrolysis is supposed to have a huge potential over the next 20 years. However, research is necessary to decrease costs, increase efficiencies and scale it up for large applications (EASE/EERA, 2013). This can be achieved through R&D on cost and quality of material used for membranes and electrodes and higher pressure in the processes, among others. Hydrogen is the most researched so far as an energy carrier, but it has received reduced attention in the past decade due to its limited round-trip efficiency potential (Bossel, 2006). Germany has invested extensively in gaseous storage, often called Power-to-Gas.

  Solid oxide electrolyser cells (SOEC, *see* Glossary of Terms) are still under research but are relatively untested, and operate at very high temperatures. SOEC can achieve high efficiencies but suffer from high costs and limited availability of renewable high-grade heat and electricity in the same location (Ibid.). There are a significant number of pilot project demonstrations such as wind-hydrogen in Utsira, Norway, a solar PV-hydrogen mini-grid on the Island of Corsica by AREVA, Honda's solar-hydrogen recharging station in Japan, and a wind-hydrogen community grid in Prenzlau, Germany, among many others (Fuel Cell Today, 2013).

- **R&D 3: Continue to research energy storage through non-fossil liquid fuels**

  Affordable and renewable liquid fuels have tremendous value to mini-grids, because they can easily be used in the global fleet of reciprocating machines that dominate remote and back-up energy markets. They are also stable for longer periods than many other storage technologies. Key hurdles for the research include reducing the cost of the catalysts by finding alternatives to expensive gold, increasing the efficiency of the process and lowering the high temperatures required (Service, 2015; SOFI, 2016).

Priority Gap 4 – Improvements in high-power output capability

Power demands in electrical grids can be very high for very short periods, both for meeting high power electrical demands and for grid safety/protection. Renewable energy needs alternative technologies to provide these short-term high-power requirements.

Need: Research storage that has higher power outputs and inputs for longer time periods

Technologies that can provide high power at low cost reduces the need for fossil fuel generators. Innovations to strengthen and enhance renewable mini-grids include:

- **R&D 1: Explore the use of graphene electrodes in super capacitors**

  One approach for improving the robustness of electrochemical technologies is through the inclusion of graphene in supercapacitors' electrodes. Supercapacitors with graphene result in high power capability that is 10 to 100 times more in than most batteries, as well as in high operating voltage range. They can deliver sudden surges in power in a very small time, and can withstand tens of thousands of charge and discharge cycles without diminishing performance.

However, most supercapacitors today use electrodes from carbon, which do not achieve the same level of performance (Ho, 2015). The Institute of Science and Technology in the Republic of Korea is developing a supercapacitor that uses a graphene powder electrode. Their vacuum-annealed graphene (*see* Glossary of Terms) approach improves the electrical capacity and conductivity beyond traditional carbon-based supercapacitors. Vacuum-annealed graphene cells provide a higher energy density (131 Wh/kg) and a power density of 19.03 kW/kg, which is the highest ever reported (Yang *et al.*, 2015). More importantly the supercapacitor was able to withstand tens of thousands of charge/discharge cycles at high current.

- **R&D 2: Continue to develop flywheels**
  Research into technological advances in flywheels include new flywheel disc materials, enhanced electrical components to increase responsiveness, new bearings to reduce friction and increase lifetimes, more robust power converters and novel control strategies (EASE/EERA, 2013). Although steel is the most common rotor material today, in the future carbon nanotubes (CNT) could be used to increase their energy density by an order of magnitude (Viswanathan *et al.*, 2013). New, advanced materials are required to achieve higher energy density (NEXIGHT GROUP, 2010; Viswanathan *et al.*, 2013).

  Future innovations with a horizon to 2030 will be aimed at increasing storage efficiency, reducing generation costs, and improving safety and reliability (DTU, 2013). Technological developments will tend towards increasing the storage capacity of flywheels by increasing the rotation speed of the rotor.

  Flywheel future targets for 2030 include reduction of friction to reduce energy losses,

Figure 12: Storage technology cost ranges in 2015, 2025 and 2035 depicted in USD/kW vs. USD/kWh

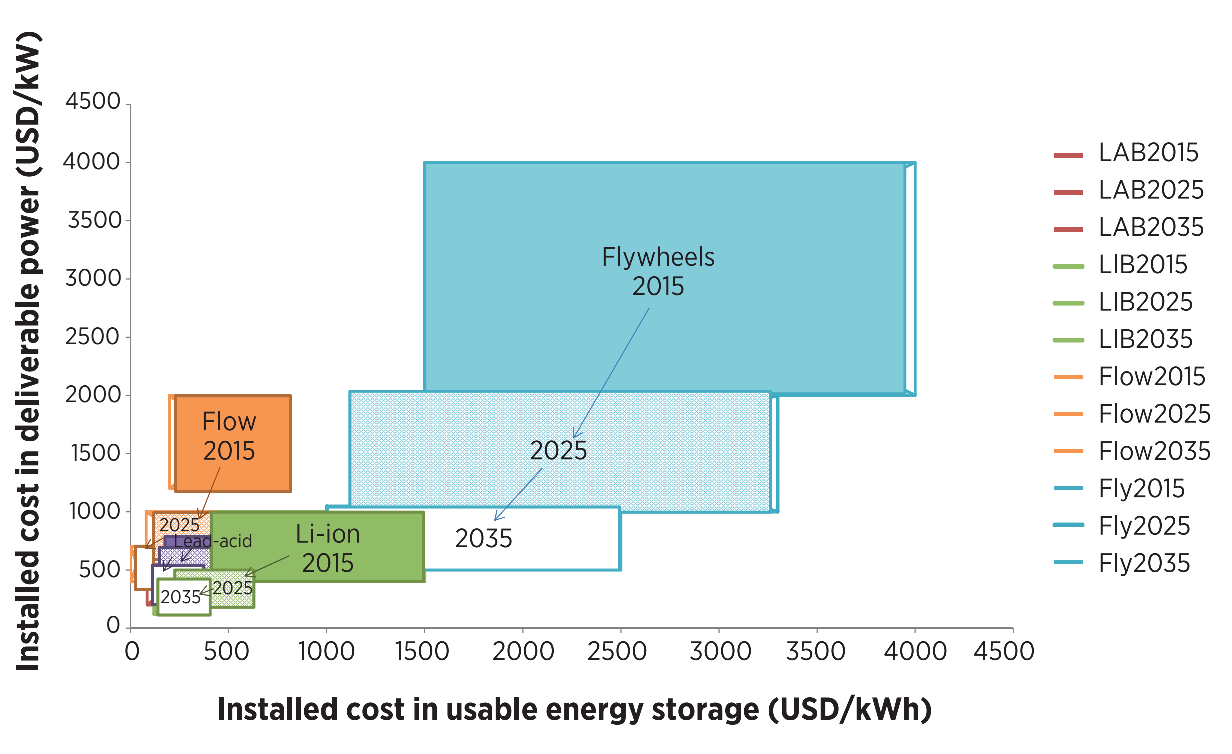


Table 22: Lead-acid storage technology indicators

Indicators	2015	2025 (EASE/EERA, 2013; Fuchs *et al.*, 2012; IRENA, 2015c, 2015e)	2035 (linear extrapolation estimate)
KI 1a: Installed cost (USD/usable kWh)	150–500	115–420	85–350
KI 1b: Installed cost (USD/kW)	300–800	250–700	200–550
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.15–0.35	0.12–0.20	0.10–0.15
KI 2: Round-trip efficiency	> 75%–85%	78%–90%	> 90%
KI 3: Life cycle (cycles)	500–2 000	1 200–4 000	1 800–6 000
KI 4: Self-discharge rate (%/day)	0.1%–0.4% per day	0.07%–0.27% per day	0.04%–0.15% per day

Table 23: Advanced lead-acid storage technology indicators

Indicators	2015	2025 (IRENA, 2015c, 2015e; Sugumaran *et al.*, 2015)	2035 (linear extrapolation estimate)
KI 1a: Installed cost (USD/usable kWh)	600–1 500 (estimate)	500–1 250	400–1 000
KI 1b: Installed cost (USD/kW)	No data	No data	No data
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.15–0.25	0.12–0.20	0.08–0.15
KI 2: Round-trip efficiency	86%–95%	> 90%	> 95%
KI 3: Life cycle (cycles)	> 4 000	> 6 400	> 8 000
KI 4: Discharge rate (hours)	Quicker than lead-acid	No data	No data

Table 24: Lithium-ion storage technology indicators

Indicators	2015	2025 (EASE/EERA, 2013; Fuchs *et al.*, 2012; IRENA, 2015c, 2015e; Jaffe, 2014; RMI *et al.*, 2014; Viswanathan *et al.*, 2013)	2035 (EASE/EERA, 2013; Fuchs *et al.*, 2012; IRENA, 2015c, 2015e; RMI *et al.*, 2014)
KI 1a: Installed cost (USD/usable kWh)	400–1 500	200–600	120–380
KI 1b: Installed cost (USD/kW)	400–1 000	200–500	120–400
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.25–0.40	0.05–0.11	0.03–0.09
KI 2: Round-trip efficiency	95%–98%	> 95%–98%	> 95%–98%
KI 3: Life cycle (cycles)	1 000–5 000	No data	No data
KI 4: Self-discharge rate (% per month)	5% per month	2.5% per month	< 1% per month

Table 25: Flow storage technology indicators

Indicators	2015	2025 (EASE/EERA, 2013; Fuchs *et al.*, 2012; IRENA, 2015c, 2015e; Viswanathan *et al.*, 2013)	2035 (EASE/EERA, 2013; Fuchs *et al.*, 2012; Viswanathan *et al.*, 2013)
KI 1a: Installed cost (USD/usable kWh)	200–800	80–440	< 70
KI 1b: Installed cost (USD/kW)	1 200–2 000	600–1 000	400–700
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.08–0.40	0.04–0.10	0.02–0.07
KI 2: Round-trip efficiency (%)	75%–85%	> 75%–85%	> 75%–85%
KI 3: Life cycle (cycles)	3 000–15 000 (cell stack)	> 10 000	> 10 000
KI 4: Self-discharge rate (%/day)	0.1%–0.4% per day	0.07%–0.27% per day	0.04%–0.15% per day

Table 26: Flywheels storage technology indicators

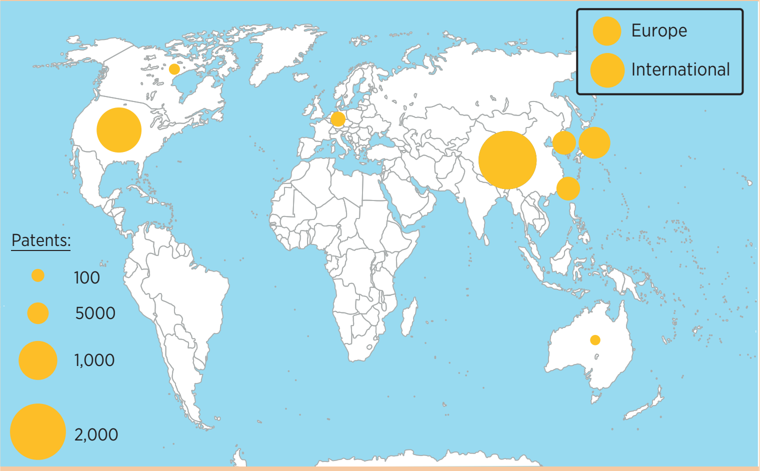
Indicators	2015	2025 (EASE/EERA, 2013; Viswanathan *et al.*, 2013)	2035 ((EASE/EERA, 2013); linear extrapolation estimate)
KI 1a: Installed cost (USD/usable kWh)	1 500–4 000	1 200–3300	1 000–2 500
KI 1b: Installed cost (USD/kW)	2 000–4 000	1 000–2 000	500–1 000
KI 1c: Installed cost (USD/$kWh_{lifetime}$)	0.06–0.10	0.03–0.05	< 0.05
KI 2: Round-trip efficiency	85%–95%	> 85%–95%	> 85%–95%
KI 3: Life cycle (cycles)	> 100 000	> 100 000	> 100 000
KI 4: Self-discharge rate (%/hour)	5%–15% per hour	≤ 5%–15% per hour	≤ 5%–10% per hour

and materials with stronger components to handle more power. According to the US Pacific Northwest National Laboratory, capital costs of flywheels are expected to drop by half between 2011 and 2020, to USD 88-173/kWh (Akhil *et al.*, 2013).

- **R&D 3: Improve and lower the cost of superconducting magnetic energy storage (SMES)**
  SMES has the potential for high-power, fast-response energy storage. SMES uses low temperature magnets to efficiently store energy. Research is ongoing to reduce the amount of power needed for cryogenic cooling to keep the coils at low temperatures, and to reduce the high costs of the superconducting materials themselves. In addition, research is looking at ways to extend the duration of cyclic periods, since it currently has a high self-discharge ratio and overall mechanical stability issues (Low Carbon Future, 2013). Innovative research includes the use of thin-films of ceramic superconducting materials to improve the mechanical properties of high-temperature superconductors and reduce the cost of manufacturing (DTU, 2013). In 2014, scientists at the Max Planck Institute demonstrated room-temperature conductivity for very short time periods (Mankowsky et al., 2014). If the duration of this behaviour can be extended, this will greatly increase the usefulness of SMES.

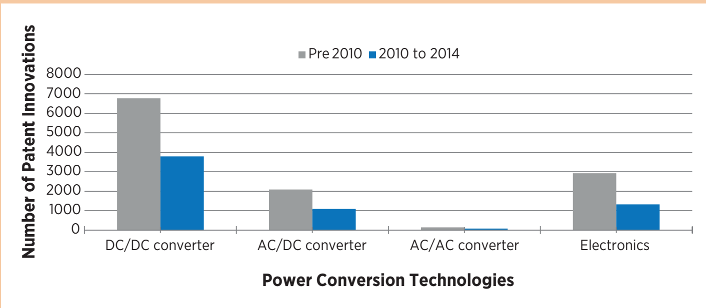
Conversion Technologies: Patent Review

Figure 13: Top 10 countries for all conversion technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Figure 14: Number of patents for power conversion technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Top institutions patenting conversion technologies, 2010-2014

- Bosch GMBH
- Honda Motor Company Ltd.
- Nissan Motor
- Toyota Motor Corporation
- GM Global Technology Operations Inc.
- General Electric
- Ford Global Technology LLC
- Hyundai Motor Company Ltd.
- Panasonic Corporation

Conversion technologies have seen a significant decrease in research interest over the past five years.

Most of the major patent holders are auto companies, due in large part to the need for intelligent power management in cars.

Appliance manufacturers are also pushing innovation, since enhancements in these technologies can improve the performance and cost of appliances in the marketplace.

Further patent details are provided in Annex 4.

Trending topics on patents:

- DC-to-DC conversion: galvanically and non-galvanically isolated DC/DC converters in the past five years. Most focus is on low-power applications, which has some applicability to renewable mini-grids.
- Conversion between AC and DC: DC/AC or AC/DC conversion technologies which use wide band gap-based power semiconductors, *i.e.*, power converters integrating silicon carbide, gallium arsenide, gallium nitride or diamond power switches.
- AC-to-AC conversion: AC/AC converters.

Indicators and summary of innovation impact

Figure 12 summarises the expected impact of innovations in cost reductions from 2015 to 2035 for flywheel, flow, LAB and LIB technologies, depicting their cost range in USD/kWh versus USD/kW.

The following tables present more detail on the expected impact of the innovations on the key indicators for 2025 and 2035 for storage.

6.4 Convert

Power conversion technologies have a critical constraint in limiting the size for autonomous applications. The main innovations required are expected to address **modularity, availability, low maintenance, low cost** and **higher efficiencies** (Ozpineci *et al.*, 2011), with expected price drops and more intelligent and embedded technologies in the coming decades. A particular concern for utilities is the possibility for islanded mini-grids which are grid-connected to operate safely in island mode during blackouts (Carey and Miller, 2012; Laaksonen, 2010) with ongoing research to address this issue. In addition, another R&D need for inverters is their improved operation on intermittent or weak grids.

Priority Gap 1 – Lower capital costs of converters

Grid-following inverter deployments have scaled up with solar PV and followed cost reductions in the PV market (IEA, 2014). Costs of grid-following inverters are expected to decrease 18% by 2025 and 35% by 2035, under projections from Fraunhofer ISE (2015a). Deutsche Bank suggests a continuous price drop in the future equal to 10-15% per year, driven by cost reductions of components, increases in efficiency and other advances (Shah and Booream-Phelps, 2015). It is expected that the grid-forming and dual-mode inverters can benefit from these trends as their use increases; battery inverters usually follow the advances of grid-following inverters, due to the wider deployment of the latter. The following R&D activities portray some potential cost reduction innovations to power electronics in the coming decades. This research also will benefit future interconnection of isolation mini-grids that use DC distribution.

Need: Use more abundant, lower-cost materials in grid-forming (battery) inverters

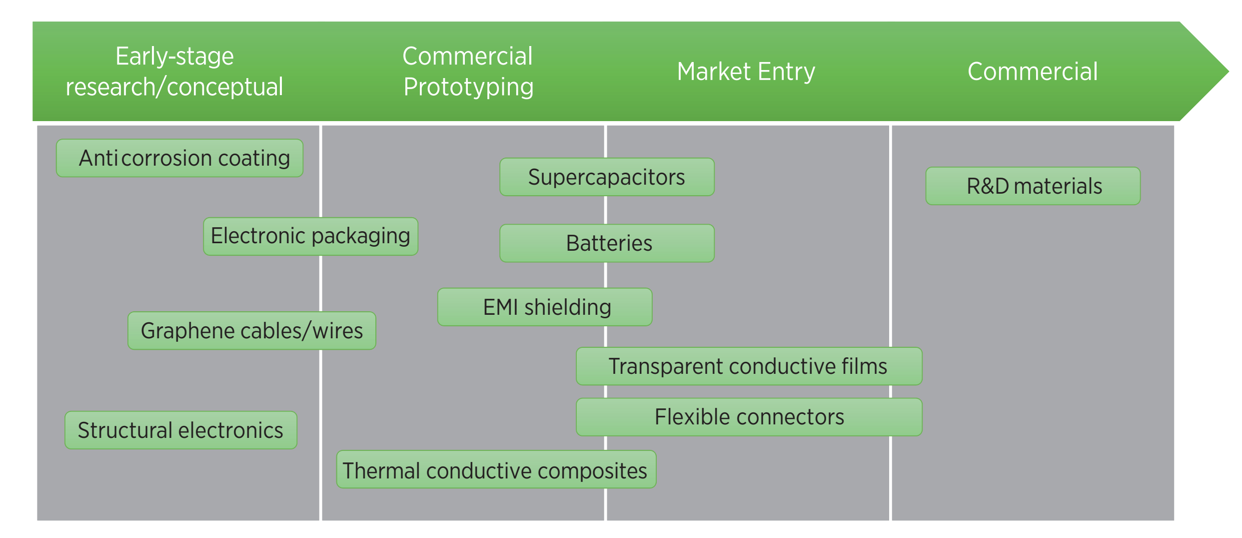
Research is ongoing to reduce the costs of inverters through the use of lower-cost materials that are more abundant. The trend during the last decade and for the years to come will be to reduce the weight of the

Box 6.11 – Alternative wide bandgap semiconductors

GaN: A **40**% volume reduction has been achieved by replacing silicon semiconductors with gallium nitride, which has been commercialised by Yaskawa. With this substitution, no cooling fans are needed, reducing the necessary volume of the inverter. Princeton Power Systems also is testing the use of GaN for its 60 kW inverter in order to reduce costs by 20% (Hoffmann, 2014). The wide rollout of GaN products is still limited due to their requirements of increased decomposition pressures and high melting point (US DOE, 2011). Also, research is required on the reliability, service lifetime and costs of GaN applications (Infineon Technologies, 2014).

SiC: Besides GaN, various experts point to the benefits of silicon carbide in the manufacturing of inverters and battery converters. Overall costs for solar inverters can be cut by **20**% due to the higher switching frequency and power density of SiC (Schwarzer et al., 2014), with major benefits of increased efficiency and reducing weight (Wilhelm *et al.*, 2010). Researchers at Aalborg University demonstrated that the wide bandgap semiconductors' capabilities of fast switching, increased power density and high efficiency also can benefit bidirectional battery converters (Pham *et al.*, 2013). SiC deployment barriers include density control and material availability (US DOE, 2011). The results of the German-funded project NeuLand showed that more effort is required to lower the cost of SiC components.

Figure 15: Commercialisation stage of various graphene-based applications



Source: Author elaboration based on Das, 2015

inverters by improving semiconductors and through advances in circuit topologies (Fraunhofer ISE, 2015a).

- **R&D 1: Explore the commercial potential of wide bandgap semiconductors**
  Inverters can benefit greatly by replacing traditionally used silicon modules with wide bandgap semiconductors like gallium nitride (GaN) and silicon carbide (SiC). Although not cost-effective today, they potentially can reduce prices by more than half (Madakasira, 2013). Their superior performance has been investigated and successfully demonstrated in inverters, rectifiers and DC-DC converters in a variety of applications, including data centres (Zhang *et al.*, 2015). Wide bandgap semiconductors respond to the market's needs for smaller, lighter, cheaper and higher-power-density electronic products that can handle high operating temperatures (Esquivel, 2014; US DOE, 2011). They also have the potential to increase efficiency due to lower switching losses.

- **R&D 2: Continue to research the potential of nanomaterials**
  Due to the fact that they are conductive and strong, nanomaterial (*see* Glossary of Terms) transistors based on carbon nanotubes or two-dimensional graphene will eventually compete with silicon. The integration of graphene transistors in inverters was demonstrated successfully in 2009 (Traversi *et al.*, 2009). Other attempts to fabricate graphene-based circuits resulted in bypassing the issue of doping variations, such as achieving voltage gain at physical gate lengths below 100 nm (Schall *et al.*, 2013). For graphene to be produced at a large scale, there is a need for techniques that will scale it up from the laboratories to circuit (Traversi *et al.*, 2009).

Figure 15 shows the commercialisation stage of various graphene-based applications. It is foreseen that graphene transistors have more than a 10-year horizon (Das, 2015). The Graphene Institute in Manchester, UK is working on substituting the use of silicon oxides with graphene-based photodetectors which are expected to be of lower cost and to reduce the sizes of power electronics (Yang *et al.*, 2014). At Sungkyunkwan University in the Republic of Korea researchers have been working on the use of graphene based thin-film transistors, which will move forward smaller applications of printable, flexible, transparent electronics at a low cost (Chae and Lee, 2014; Kim *et al.*, 2012). At Pohang University in the Republic of Korea work is ongoing on using organic field-effect transistors and graphene electrodes which can achieve lower costs, light weight, flexible and low-temperature processing for organic complementary inverters (Jeong *et al.*, 2014).

Priority Gap 2 – Combine diverse functions in inverters

There is a need for varying kinds of software development to model and control battery technologies and thus facilitate the integration of electrochemical storage devices into the electricity grid (EASE/EERA, 2013).

Need: Improved operation of battery inverters

Battery inverters are incorporating new features that improve their performance and that are able to better interact with other components.

- **R&D 1: Bundle additional features**
  Manufacturers, as discussed in Section 4, are already offering products with new features. Additional innovation is under research: for example, State Grid Hebei Electric Power Research Institute in China, together with Shandong Zhiyang Electric Company, are working on the addition of a discharge battery inspection method through the use of a sinusoidal pulse width modulation technology to improve performance (Li *et al.*, 2013). Optimal Power Solutions in Australia has been working on the development of new high-capacity, parallel power inverters than can provide greater power stability (OPS, 2015).

- **R&D 2: Enhance dual-mode switching capabilities**
  Research is looking at the capability of dual-mode inverters to shift smoothly from grid to island mode in black start and seamless forms (Soshinskaya *et al.*, 2014). To address this issue, the use of an innovative droop control is a viable solution under research but still requires further development (Tao *et al.*, 2011). For example, at North China University a droop controller was proposed to ensure a smooth switch between island and grid mode (Wen *et al.*, 2015). At Shanghai University work is ongoing on the use of a new switchover method based on controller state following to avoid the transient fluctuation of voltage and frequency and to reduce the influence of transient process on the power grid for a smoother and more reliable switchover (Fu *et al.*, 2015). Other groups driving innovations to lower the cost and increase the market share for dual-mode inverters include Princeton Power Systems, Schneider, Siemens, Studer and Aalborg University.

- **R&D 3: Make battery management more intelligent**
  Intelligent battery management is becoming more necessary due to the proliferation of new, advanced battery technologies. Optimal Power Solutions has been carrying out research on control and integration through new algorithms and strategies for their inverters to allow for the highest penetration of renewables and the use of new battery technologies that are coming into the market (OPS, 2015). Outback Power has been exploring new features, including its Advanced Battery Charge profile, to ensure compatibility and co-ordinate specific charging profiles with new battery chemistries such as lithium-ion, aqueous-ion, flow, fuel cell and others (Outback Power, 2013).

Priority Gap 3 – Improve efficiency, particularly at partial load

In the next decade, as grid-forming inverters are used more widely, it is expected that their efficiencies will follow the increase that grid-following inverters have seen, in particular for DC-to-AC conversion.

Need: New converter designs with high efficiencies at partial output

New converter designs are focusing on higher efficiencies, particularly at partial load output which can drop to 30-40% when the load is less than 20%.

- **R&D 1: Explore the potential for transformerless DC-AC converters**
  A transformerless DC-AC converter is an emerging technology for PV. Considerable research is taking place on increasing outputs and efficiencies, and reducing the costs, weight and sizes of grid-connected transformerless inverters (Blaabjerg and Ionel, 2015; Koutroulis and Blaabjerg, 2011; Mohan and Rajan, 2015; Shen *et al.*, 2012). One proposed modification

Box 6.12 – Pushing inverter efficiency to its limits

Future Energy Electronics and Jiangsu University were able to achieve high efficiencies of 99.1% and 98.8% using super junction MOSFETs and SiC diodes in a transformerless inverter (Chen *et al.*, 2015).

Princeton Power Systems also has demonstrated a 30 kW grid-connected bi-directional converter achieving 99% conversion efficiency. The SiC transistors are superior to the silicon transistors due to their faster switch and abilities to handle higher voltages, currents and temperatures. By 2016 the company will have a 30 kW and 100 kW version commercialised (Marketwired, 2015).

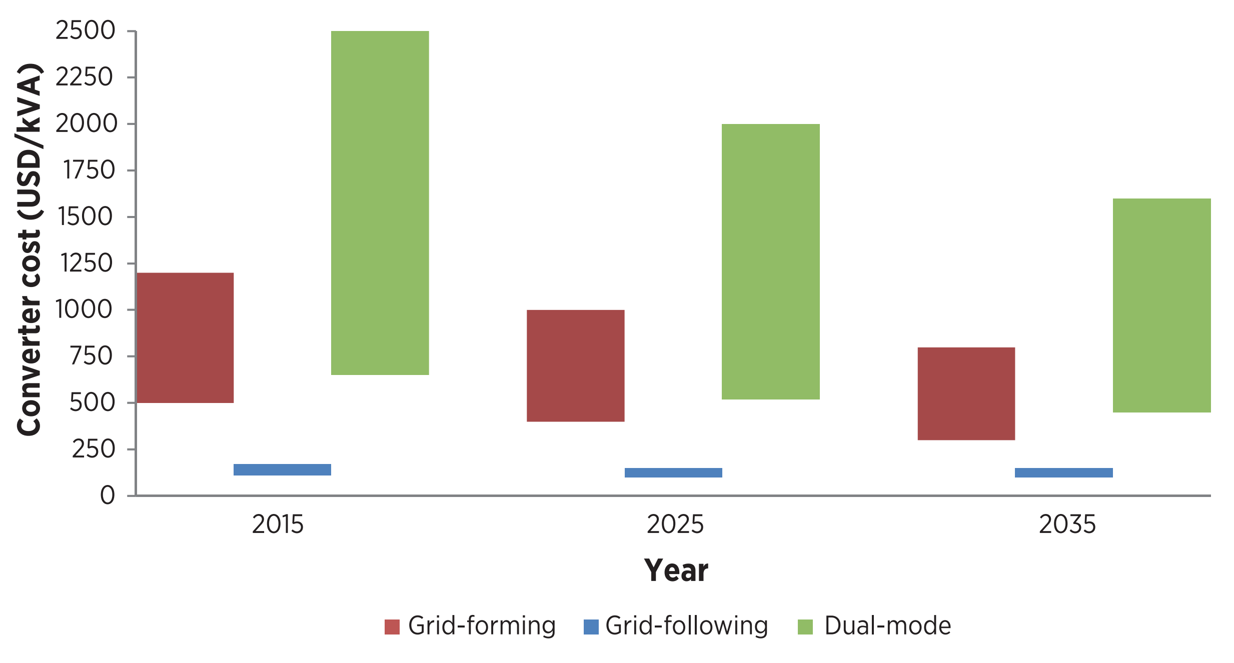
includes the connection of the transformerless converter's negative terminal directly to the ground to reduce ground leakage of current, which increases the efficiency of solar power plants, especially those using thin-film modules (Shen *et al.*, 2012).

Another solution is to keep the common-mode voltage of the output of the inverter constant, in order to limit the ground leakage of current. A prototype transformerless configuration of a CD-Boost bipolar SPWM H-Bridge converter lowered the ground leakage of current and increased efficiency by 3% compared to a conventional transformerless AC/DC converter (Azri *et al.*, 2014). Finally, the performance of another transformerless inverter has been examined with a buck-boost DC-AC converter with two switching cells instead of a transformer, including two switches, two diodes, one inductor and one capacitor in each one. The step-up/step-down is achieved without any intermediate power stage or transformers (Mohan and Rajan, 2015). Work is being carried out at the Institute for Power Generation and Storage Systems at RWTH Aachen University on optimising the efficiency of grid-following inverters, particularly at partial loads (RWTH Aachen University, 2015).

- **R&D 2: Improve DC-DC converter designs**
The use of a power switch, soft switching and voltage clamping have been proposed to achieve a maximum efficiency of above 95% and average efficiency up to 91% for a single-input multiple-output DC-DC boost converter (Sridhar and Arulkumar, 2014). A boost converter for high-voltage applications has been proposed which is based on a three-state switching cell, improving diode and capacitor design, which demonstrated an efficiency of 92% for an entire load range (Saravanan and PonGomathi, 2014). At the University of Colorado research is ongoing into DC-DC converters for data centres to improve efficiency and high conversion ratio (Costinett, 2013). Researchers from National Chen Kung University in Chinese Taipei achieved step-up and step-down conversion efficiencies of 96.3% and 95.6%, respectively, through the use of synchronous rectifiers and antiparallel diodes (Liang and Lee, 2015). At MIT a resistance compression network was proposed and achieved over 95% efficiency across a voltage range of 25-40 volts (Inam *et al.*, 2014). The RCN and an ON/OFF control narrowband frequency control are capable of doing zero-voltage switching over a wide input voltage (Ibid.).

- **R&D 3: Use new materials to improve efficiency**
Most transistors are made from silicon. Wide bandgap semiconductors such as GaN and SiC are also able to deliver higher efficiencies. The current edition of a GaN-based inverter has a nominal power of 4.5 kW, which is expected to increase in the future, and its efficiency exceeds 98% (Transphorm, 2015). Replacing traditionally used Si with SiC semiconductor modules also improves the inverter's efficiency in partial loads and reaches 98.8% (Deboy *et al.*, 2011). The Cree SiC-based three-phase string inverter is half the size of a traditional Si inverter and one-third of its weight, and its operation does not derate at high temperatures (Esquivel, 2014). Fraunhofer ISE developed a small inverter of 10 kW using SiC which enables an efficiency of 98.7% for use in UPS devices, expected to influence similar future innovations to other inverter types (Fraunhofer ISE, 2015b).

Figure 16: Converter technology cost ranges in 2015, 2025 and 2035



Note: The total global renewable energy use of the original 26 REmap countries represents 75% of global final energy consumption.

Table 27: Grid-forming converter indicators

Indicators	2015	2025	2035
KI 1: Cost (USD/kVA)	500–1 200	400–1 000	300–800
KI 2: Efficiency at rated power DC to AC (%)	85–90	87–93	90–95
KI 3: Efficiency at rated power AC to DC (%)	90–95	92–97	95–98
KI 4: Lifetime (years)	5–10	7–12	10–15

Source: Appert and al-Mukdad, 2013; Mueller-Stoffels et al., 2013); proprietary manufacturer quotes, 2015; projections based on authors' estimates

Table 28: Grid-following converter indicators

Indicators	2015	2025	2035
KI 1: Cost (USD/kVA)	110–170	100–150	100–150
KI 2: Efficiency at rated power DC to AC (%)	95–98	95–98	95–98
KI 3: Efficiency at rated power AC to DC (%)	N/A	N/A	N/A
KI 4: Lifetime (years)	5–10	7–12	10–15

Source: Fraunhofer ISE, 2014; Fraunhofer ISE, 2015a; projections based on authors' estimates

Table 29: Dual-mode converter indicators

Indicators	2015	2025	2035
KI 1: Cost (USD/kVA)	650–2 500	520–2 000	450–1 600
KI 2: Efficiency at rated power DC to AC (%)	93–96	94–97	95–98
KI 3: Efficiency at rated power AC to DC (%)	87–92	91–95	95–98
KI 4: Lifetime (years)	5–10	7–12	10–15

Source: Manufacturer's proprietary specification sheets; projections based on authors' estimates

Priority Gap 4 – More converter options for diverse renewable mini-grid markets

Converter technologies also need to adapt to new applications that are flourishing. In particular battery inverters, dual-mode inverters and DC-DC converters should be able to handle wider applications.

Need: Improved converter modularity and availability at larger sizes

Large-scale battery inverters are offered by a very limited amount of manufacturers.

- **R&D 1: Research on large battery inverters for bigger applications**
  A few manufacturers, such as S&C and Siemens AG, are offering large-scale inverters for renewable mini-grid interconnection, and plenty of research is ongoing. The M5BAT pilot installation combines various battery technologies in a 5 MW storage management installation for grid stabilisation. The project will investigate, among others, the performance of large inverters ranging between 0.5 MW and 1 MW with the main grid (SMA, 2014; Thien *et al*., 2015). In Canada, Schneider inaugurated its MicroGrid Lab in 2014 to carry out research on new large-scale (up to 2 MW) inverter technologies and a three-phase central inverter platform (Hales, 2014).

Need: Bidirectional DC-DC converters that can handle multiple input and output voltages

As DC appliances become more popular, DC-DC converters must adapt and be able to handle multiple inputs to ease their use for consumers.

- **R&D 1: Create more flexible DC-DC converters**
  Simpler DC mini-grid architectures with fewer components could result in more efficient and lower-cost energy conversion. One design that has potential is multiple-input multiple-output (MIMO) converters. Instead of many converters, a MIMO converter bundles conversion capabilities into a more reliable and compact solution. They have the potential to centralise control and reduce communication needs (Kathiravan and Govindaraju, 2015). For DC mini-grids to become a reality, MIMO converters should be bidirectional to allow integration of renewables and storage technologies. This helps to resolve safety issues from, for example, lightning strikes or equipment surges (Whaite *et al*., 2015).

Indicators and summary of innovation impact

Figure 16 summarises the expected impact of innovations in cost reductions from 2015 to 2035 for grid-forming, grid-following and dual-mode converters.

Tables 27-29 summarise the expected impact of the innovations on the expected values for 2025 and 2035 key indicators for converters.

6.5 Consume

Reduced and strategic consumption of electricity can significantly lower costs. Energy efficiency and demand-side management (DSM) are very broad areas of research in energy. This section provides some brief examples of technologies that can be used to improve mini-grid deployment, with a focus on the attributes of innovation critical to mini-grids.

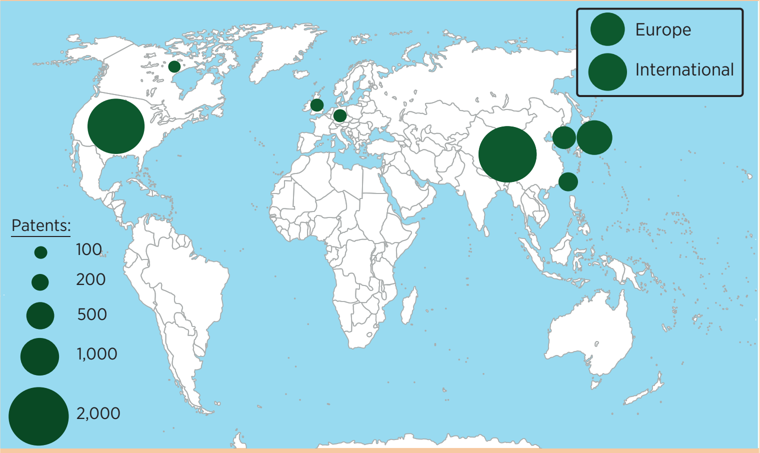
The local nature of mini-grids — supply and use are usually located near each other — provides an opportunity for innovative approaches in these areas. Flexible loads are beneficial in renewable-based mini-grids, since this allows the load demand to better match production from variable renewable generation. This can reduce the need for expensive storage. DC-focused end-uses can help to reduce the conversion costs and reduce conversion efficiency losses. Innovation in how energy is consumed is critical to provide low-cost, high-reliability energy services to energy end-users.

Priority Gap 1 – Increased commercial availability of efficient end-uses

Integrated resource planning stems from the idea that reduced consumption can have the same value as increased generation and supply. This approach led the Rocky Mountain Institute (RMI) to coin the term negawatts. Negawatts are "a theoretical unit of power measuring energy saved" (Lovins, 1990). Innovation in energy-efficient appliances is an ongoing trend of research applicable to all electricity sectors. Programs such as Energy Star in the United States have set targets

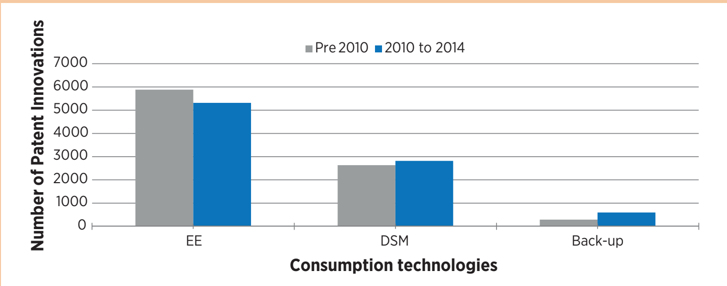
Consumption Technologies: Patent Review

Figure 17: Top 10 countries for all consumption /consume-function technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Figure 18: Number of patents for consumption / consume-function technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Top institutions patenting consumption / consume-function technologies, 2010-2014

- General Electric
- Panasonic Corporation
- LG Electronics Inc.
- State Grid Corporation of China
- Samsung Electronics Company Ltd.
- Toshiba
- Siemens AG
- Sony Corporation
- Hitachi Limited
- BSH – Bosch Siemens Hausergate

Most of these are appliance manufacturers, which could be major contributors to innovation in renewable mini-grids since their products will consume a major portion of the energy in renewable mini-grids as well.

Backup technologies have seen a twofold increase in research focus.

Further patent details are provided in Annex 4.

Trending topics on patents:

- Energy efficiency: elements or equipment involving protection devices and home appliances involving heating, ventilation or air conditioning units.
- Demand-side management: energy-saving modes or efficient standby (*e.g.*, detecting absence of load or auto-off), and demand response devices (*e.g.*, load shedding and peak shaving).
- Backup: elements or equipment involving energy storage, UPS equipment or standby emergency generators involved in the last stages of power distribution.

for appliances that are driving manufacturers to design appliances that lower energy needs, and have created technological innovation.

Need: More efficient appliances, particularly for remote energy access markets

A 2013 study from the ACEEE estimated that there is a savings potential of up to 27% of electricity by 2030 in the United States through programme designs, technologies and customer markets, and as high as 65% for residential lighting technologies (York *et al.*, 2013).

- **R&D 1: Increase commercial scale-up of efficient appliances**
  Various emerging innovations are being investigated in research centres and companies in the United States, Europe and Asia regarding household appliances including refrigerators, tumble dryers, clothes washing machines and cooking appliances (Goetzler *et al.*, 2014). For example in refrigerators advanced compressors are expected to achieve a 20% higher efficiency in the coming decade. Research is being carried out on linear and electrochemical compressors to substitute currently used reciprocating and rotary ones. In the longer term magnetic refrigeration is expected to lower energy consumption by 20-50%, with ongoing research at Oak Ridge National Laboratory, General Electric and many others. One of the main challenges that the industry faces with innovative technologies is to achieve similar performance as conventional ones with reduced costs.

- **R&D 2: Integrate diverse energy end uses through integrated energy services planning**
  The design of appliances that serve energy end-uses in an integrated manner can increase effectiveness. For example, a kitchen design where the excess water and heat of one appliance is captured to be used by another reduces the overall energy need. A prototype kitchen by Whirlpool is estimated to increase energy and water efficiency by 70% (Goetzler *et al.*, 2014). Another research concept is the ZEHcor Interior Utility Wall, a pre-fabricated wall with an external heat exchanger that feeds kitchen, laundry and bathroom appliances. Due to its clever fabrication in an external, protected environment, distribution losses are minimised. Both of these examples significantly reduce the need for primary electrical energy supply, while increasing the usefulness of energy provided to customers. These types of appliances are foreseen to be commercially available within 10 years (Goetzler *et al.*, 2014).

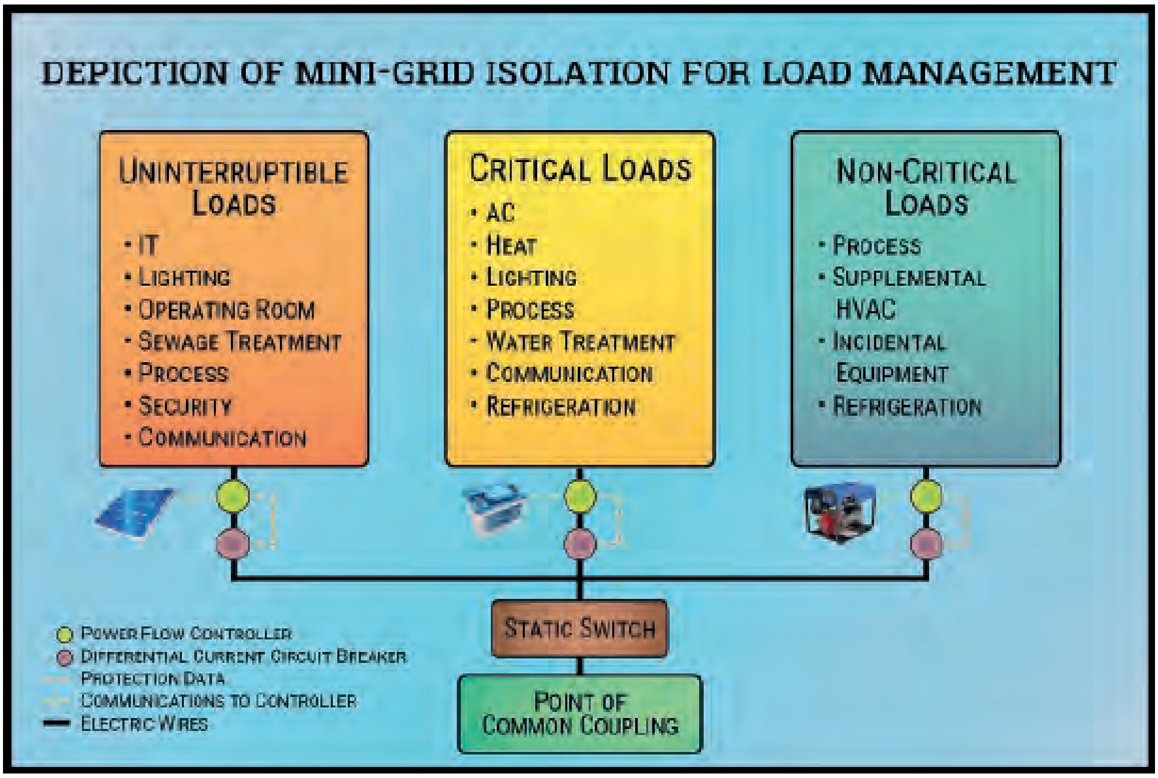
Need: Increased alignment between DC renewable mini-grids and connected equipment

Most research effort on DC distribution has been done for data centres and telecom facilities where IT and telecom equipment, as well as necessary storage technologies such as batteries or flywheels, are in DC (Murrill and Sonnenberg, 2010; Nordman and Christensen, 2015). However, the residential market has a large body of knowledge as well. "DC appliances have served niche markets for decades, offering proof of their capacity to deliver energy services for all major electricity end-uses." (Garbesi *et al.*, 2011).

- **R&D 1: Increase commercial scale-up of appliances designed for DC grids**
  A 2011 LBNL study found that "DC-based design increases the efficiency of all major residential and small commercial end-uses, including cooling, lighting, space and water heating, clothes washing, and dishwashing" (Garbesi *et al.*, 2011). In the United States, electronics will be responsible for more than 20% of a building's energy consumption by 2030, and for around 40% by 2050 (Marnay *et al.*, 2012a), providing a strategic entry point for DC appliances. DC appliances need to increase in the marketplace to achieve economies of scale and drive down costs. For example, although DC refrigerators are more efficient than Energy Star AC refrigerators, they can cost about 3-4 times more (Garbesi *et al.*, 2011). This is due in large part to the much smaller number of DC refrigerators currently produced. Research into the use of DC appliances is ongoing at Aalborg University through their Intelligent DC Microgrid Living Lab, at NTT Facilities in Japan (Noritake *et al.*, 2014) and at Xiamen University in China (Zhang *et al.*, 2015), among many others.

- **R&D 2: Develop more flexible connectivity between DC line and appliances**

Figure 19: Conceptualisation of a mini-grid based on load requirements



Source: DNV KEMA, 2014.

Increased supply voltage has gained popularity among research groups worldwide for DC data centres. From traditional 48 volt DC (VDC) standardised mini-grids, the involved groups have proposed various supply voltages between 300 VDC and 550 VDC, with 380 VDC being internationally standardised since 2009. However, others are opposing the choice of 380 VDC and proposing 350 VDC due to its scalability towards the 1 500 VDC high voltage (Willems *et al.*, 2013). There is an increased availability of appliances that can be charged through USB. Ongoing research is seeking to increase the power delivery from USBs to further allow more appliances to be charged in such a way. Another focus of research has been to increase and make more flexible the voltage range of appliances to ease their use.

Priority Gap 2 – Better tools for adapting consumption to energy supply (DSM)

A 2015 RMI study created the term flexiwatts to describe those "electric loads that demand flexibly

Box 6.13 – Internet of Things (IoT)

IoT is penetrating more and more in conventional appliances. The main technological drivers are increasingly low-cost wireless hardware, the proliferation of smartphones and expanding mobile networks (GSMA, 2015). It is estimated that by 2030, the number of connected devices worldwide will reach 100 billion (KPMG, 2015). Even though the exchange of information between appliances and users is already widespread, the communication between the devices alone with IoT is supposed to gain momentum and give the responsibility to the smart meters to take decisions.

Table 30: Consume indicators

Indicators	2015	2025	2035
Availability of DC appliances in regular marketplaces	Limited to LEDs; refrigerators, TVs, media appliances and others for RV and off-grid markets	Expands to include DC power supplies for natively DC technologies including laptops and digital TVs	Expands to include DC appliances for heavy energy uses
Internet of Things in appliances	Limited to high-end appliances	High energy use and heavily used appliances	All appliances
Appliance efficiency	Baseline	10% reduction	20% reduction

Source: Author elaboration

shifts in time" (Bronski *et al*., 2015) (*see* Glossary of Terms). Flexiwatts can provide services such as reducing a grid's peak load, shifting consumption in relation to pricing times, and matching load profiles to renewable energy generation (Bronski *et al*., 2015). It is important to identify loads that can have this flexibility. Loads can be divided, according to their importance, into uninterruptable, critical and noncritical ones to properly manage the demand and decide which ones are more flexible (see Figure 19). Intelligent controls can use load flexibility to strategically reduce the need for, primarily, storage.

Need: Better tools for managing the allowed end-uses and appliances

The use of communication technologies to improve energy consumption patterns is an ever increasing area of research focus.

- **R&D 1: Increase commercial scale-up of smart appliances based on the Internet of Things and the connected home**
  The interconnection and intercommunication among household appliances and cars can create savings for the users and increase security. For example, a car could control remotely the devices of the house depending on the location of the owner (for example, turn off heating when owners are travelling). Also, in the context of integrating other functionalities to the appliances besides consumption, many appliances are now incorporating storage and function wireless. Such loads can act as deferrable ones if plugged in when not used.
  Major investors are opting for it and are announcing their plans for actions for the following decade. Samsung envisions that by 2020 all of its devices will be open and connected to the Internet. Google also has shown interest in Internet-enabled devices as well as smart meters by partnering with various market players, whereas Apple is creating iOS applications to communicate and control appliances. In order to enhance the development of appliance connectivity and boost economies of scale, there is a need to reduce technological fragmentation and focus on the connectivity between devices and the cloud by supporting the initiatives of machine-to-machine (M2M) alliances and standardise the sector. For this, GSMA has created the GSMA Connected Living programme to converge M2M and smartphones/tablets. It is believed that the entrance in the market of connected homes of companies like Apple and Google will rapidly boost the compatibility of products.

- **R&D 2: Explore new and smarter end-use control**
  By constantly recording and communicating real-time capacity needs and use of the devices and by distributing prices signals and forecasts, appliances can communicate with a centralised controller to manage their energy use (Nordman and Christensen, 2015). By most intelligently controlling the use of electricity, the need for expensive storage is reduced. The need to oversize wires and the use of circuit breakers for energy management also will be reduced, although this impact will be smaller.

Indicators and summary of innovation impact

The following tables summarise the expected impact of the innovations on the expected values for 2025 and 2035 key indicators for consume.

6.6 The renewable mini-grid of the future

More modular solutions and off-the-shelf hardware and software are being developed with an expected increase of options that can allow for lower costs and increased functionalities. Short-term controls with the ability to integrate more sophisticated algorithms and more accurate wind and solar predictions are key for increasing the penetration of renewable energy. Research on smarter and more flexible meters that are able to adapt to new business models, time-of-use pricing, AMR and AMI are key areas of research and innovation to improve current metering technologies.

Already LIBs and other chemistries such as organic flow batteries are showing signals of driving costs down and uptake in the market. Still, LABs are expected to continue to be a major storage technology in renewable mini-grids, with new more robust ALAB being capable of handling more cycles at greater efficiencies. STES are still at an early stage of research, innovations in PCMs and TCMs are expected to allow for an increased used of

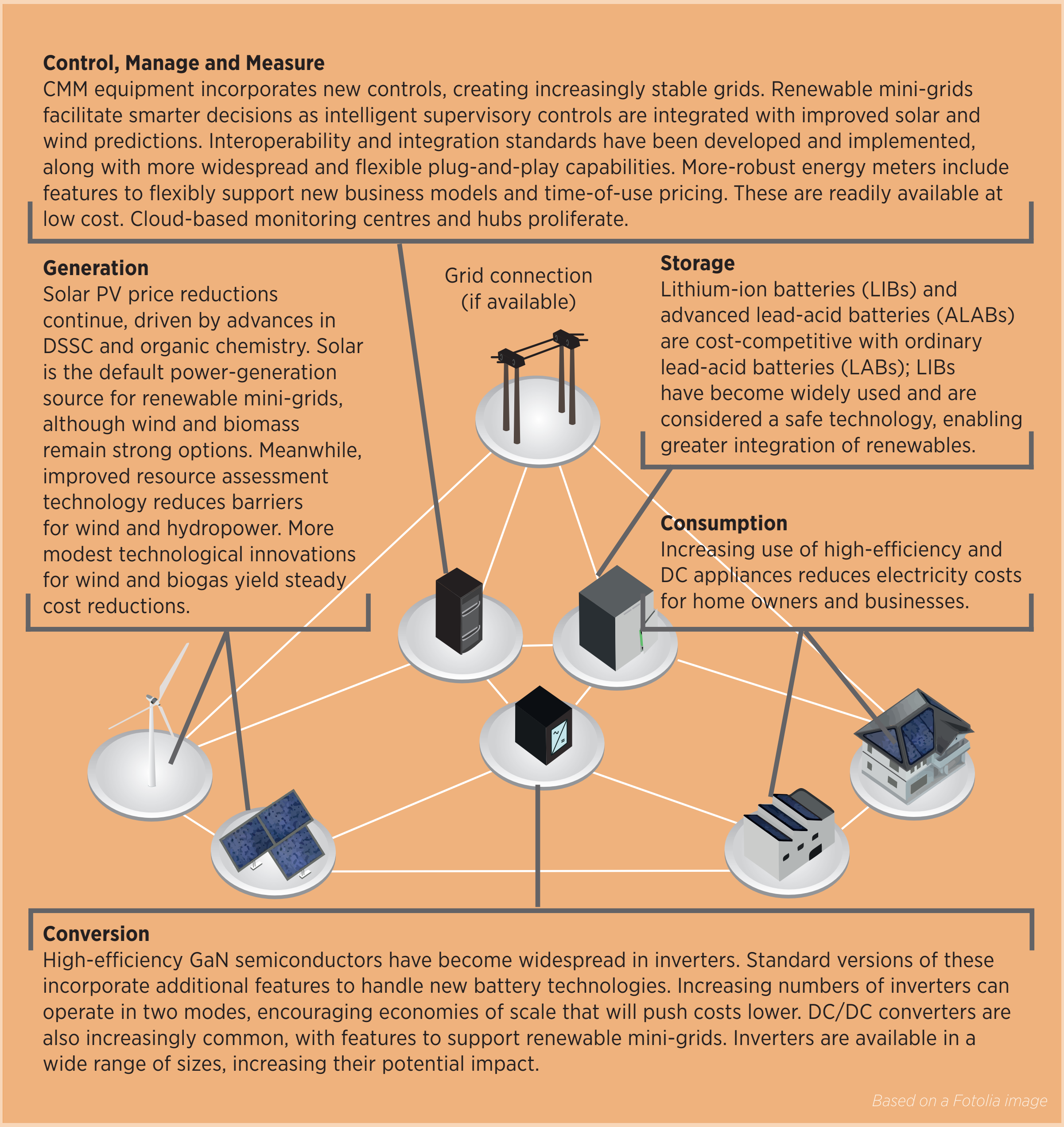
Table 31: Summary of support required for R&D opportunities

Needs fundamental research (in technology venture phase)	Needs commercialisation support (in commercial scale-up phase)
• **Storage:** Lowering the cost of storage technologies. • **Storage**: Reducing maintenance and increasing robustness of storage. • **Storage:** Research into technologies that can efficiently store energy for long periods (*e.g.*, liquid fuel from renewables). • **Storage:** New and novel technologies, *e.g.*, chemistries that use more abundant and environmentally friendly materials that are easier to recycle at the end of their lifetime. • **CMM:** Supporting applied research into interoperability between components of a mini-grid. • **CMM:** Central mini-grid control versus distributed control. • **CMM**: Improving wind, solar resource predictions. • **Convert**: Improving materials that increase efficiency at partial load and lower costs, size and weight. • **Convert**: Power interface between mini-grid and main grid and clusters of mini-grids. • **Consume:** Integration of functionalities into appliances. • **Consume:** High tolerance to quality and range of power supply. • **Consume:** DC and AC compatibility. • **Generation:** New and novel technologies, *e.g.*, PV cells that use more abundant and environmentally friendly materials. • **Generation:** Lower costs, *e.g.*, less expensive, novel PV materials that require less-intensive manufacturing.	• **CMM**: Integrated and bundled controls. • **CMM**: Support for more modular deployments that allow renewable mini-grids to scale up as needs and costs change. • **Storage:** Providing support to other chemistries that provide specific storage services critical to productive uses, *e.g.*, instant high-power demand • **Consume:** Providing support for efficient DC appliances to achieve scale. • **Consume:** Providing support to advanced features and tolerance of appliances. • **Convert:** Providing support to encourage dual-mode converters (combined grid-forming and grid-following converters). • **Convert:** Providing support to increase the available size of inverters for larger renewable mini-grids. • **Generation:** Reducing costs, improving efficiencies and energy capture capability, and lowering maintenance needs. • **Renewable mini-grid:** Providing incentives for the use of renewable mini-grids to obtain high-resilience from final users and reduce redundancy needs from utilities. • **Renewable mini-grid:** Promoting the use of autonomous grids as an alternative for rural electrification.

thermal storage over long periods. Supercapacitors are a robust technology which can benefit from innovations in the use of grapheme and be capable of delivering high power and an extensive life.

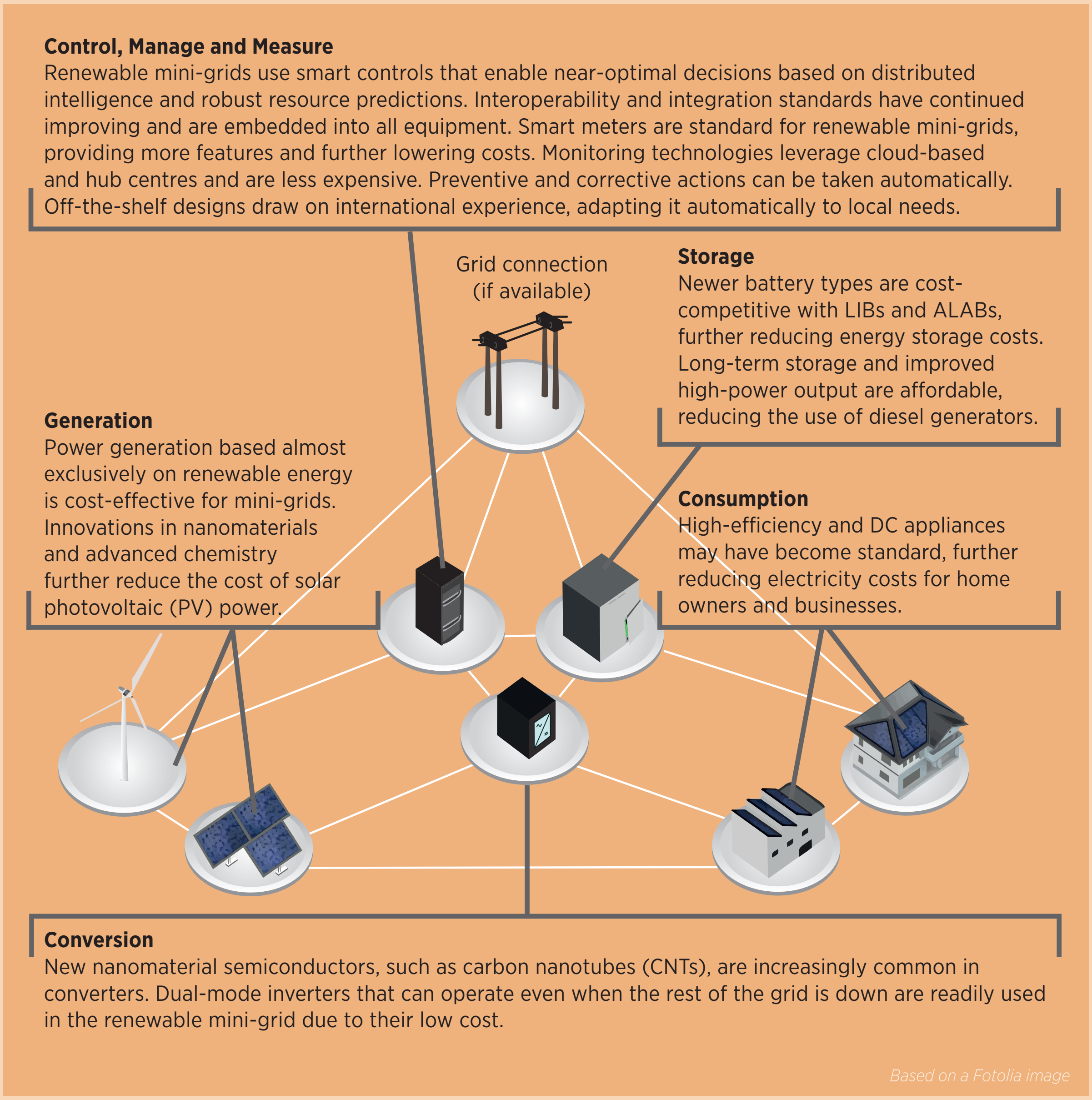
The increased use of GaN and SiC are the most expected innovations to happen in transistors for conversion technologies to bring costs down, increase efficiencies, and reduce size and weight. Conversion technologies also are expected to increase their features, *e.g.*, be able to handle and communicate better with new storage technologies. The increasing use of DC grids and appliances is also driving the need for more efficient and lower-cost DC-DC converters. Finally, the market availability of conversion technologies is expected to increase and to include larger-power battery inverters.

Figure 20: The renewable mini-grid of 2025



Source: Author elaboration, graphics from ©chesky/Fotolia

Figure 21: The renewable mini-grid of 2035



Source: Author elaboration, graphics from ©chesky/Fotolia

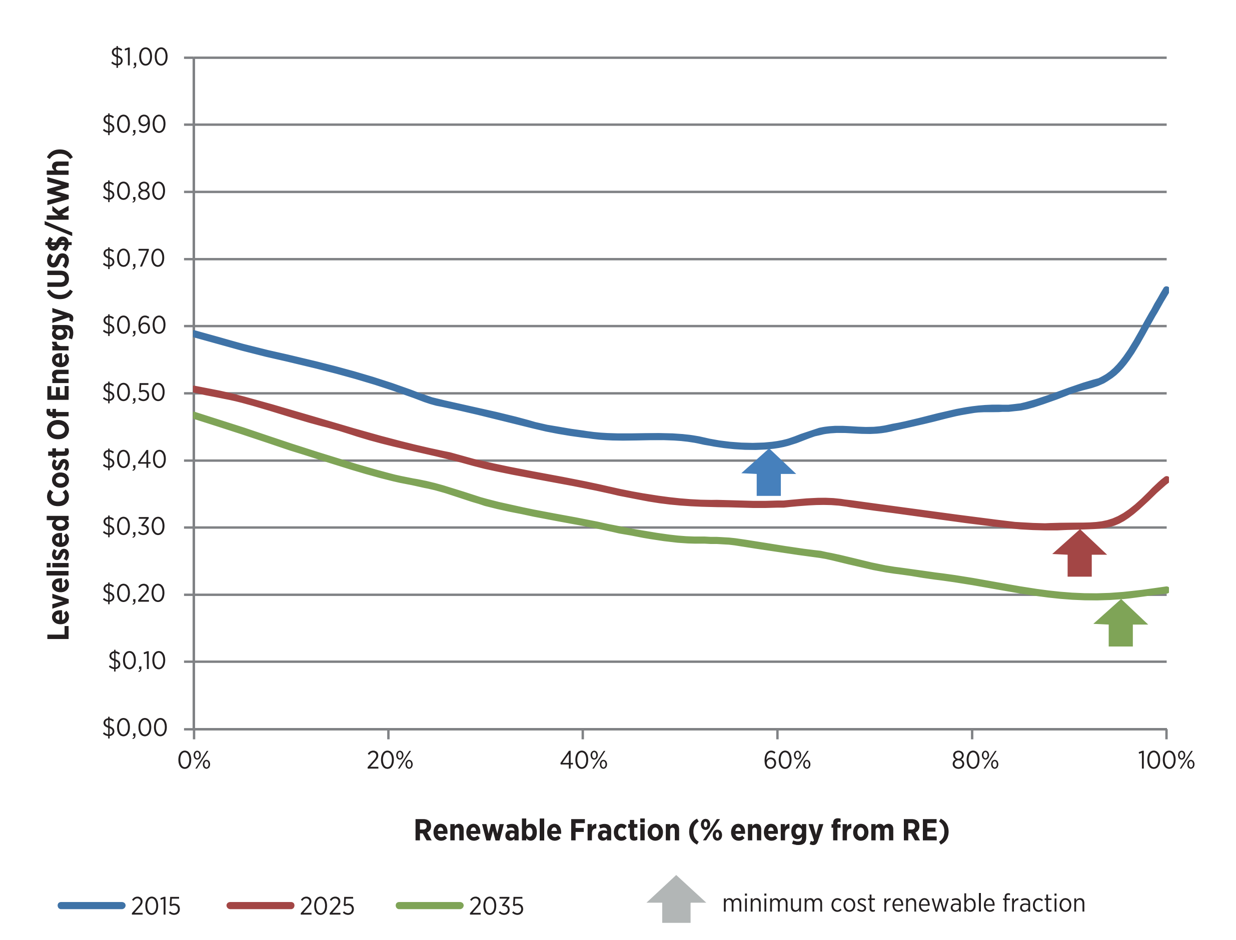
Table 32: Table of unsubsidised cost ranges in real USD for renewable mini-grids from 2005 to 2035 for a 100% renewable energy community system

USD/kWh for 100% RE	2005	2015	2025	2035
AB	USD 0.85–1.28	USD 0.47–0.71	USD 0.30–0.45	USD 0.19–0.29
AF	USD 1.05–1.57	USD 0.61–0.92	USD 0.38–0.57	USD 0.23–0.35

Source: Author elaboration with HOMER Pro, 2016

Progress in the efficiency of appliances already has been a key area of research with significant improvements to date. Still, more efficient appliances are expected to make their way on to the market, *e.g.*, magnetic refrigeration is expected to be 20-50% more efficient. The use of appliances that can operate with DC input is expected to increase significantly, along with cost reduction trends and standardisation of the DC line. One

Figure 22: Plot of renewable fraction vs. real levelised cost of energy for 2015, 2025 and 2035



Source: Author elaboration with HOMER Pro, 2016

of the key breakthroughs taking place is through IoT into conventional appliances that allows for interconnection and intercommunication for a more intelligent use of electricity.

It is expected that PV silicon-based module prices, despite significant price drops since 2005, will continue to decline up to 60% by 2035 (IEA, 2014). This will be driven by thinner wafers and improved manufacturing, among others. Next (third)-generation PV technologies such as DSSC and organic cells are expected to start coming on to the market, with Perovskite cells being among the most promising. Maintenance needs for wind turbines are expected to go down due to better designs and to the use of high-tech sensors that are able to monitor blades and complement new preventive maintenance strategies. Gasifiers are expected to be able to handle a wider amount of feedstocks, and to better handle slagging and soot to lower their maintenance needs. Wind and hydro turbine generators are expected to be able to harness a wider range of wind speeds and flow rates, respectively, through better designs, materials and embedded electronics.

The key innovations required can be split into those that require fundamental research to support technology venturing and those that require support for commercial scale-up. These are summarised in Table 31:

All of these innovations and more are expected to enable ubiquitous uptake of renewable mini-grids. It also enables project developers and planners to use renewable mini-grids to have better-matched options for the energy supply of the future. Ultimately, these developments can lead to improved access to electricity in unelectrified areas and to more resilient grid-connected communities and industry.

Visualising the renewable mini-grid of the future

The expected technological advancement of the renewable mini-grid technologies through 2025 and 2035 are summarised in Figure 20 and Figure 21:

6.7 Innovation leads to cost reduction of renewables-based mini-grids

Technological innovations are expected to dramatically reduce the costs of renewable mini-grids. Table 32 summarises the projected evolution of costs for renewable mini-grids that draw 100% of their energy from renewable sources.

It should be noted that many of the renewable mini-grids installed will not draw all of their energy from renewable sources. If the amount of renewables (or storage) is too high or too low, the price will be higher. Additionally, a renewable mini-grid that includes a diesel generator often can have lower costs than a renewable mini-grid that gets 100% of its power from renewable sources. This concept is show in Figure 22, which shows the total LCOE from the lowest-cost solar PV mini-grid design. Each point on the lines represents a system with varying percentages of energy from renewable sources (solar, in this example). The optimal fraction of energy for the low-cost renewable mini-grid increases; as innovation occurs, the renewable mini-grids are driven to use more and more renewable energy. This improves their environmental performance while reducing costs.

Refer to Section 3.1 for more background on the cost calculations, and Annex 7 for the input assumptions and modelling approaches.

7 THE ROLE OF KEY PLAYERS IN DRIVING INNOVATION

Readiness for large-scale market deployment can be accelerated. This section includes a menu of options for the public as well as the private sector. Some can accelerate development such as provision of funds to support research and innovation, while others can provide momentum such as private sector investment in new innovations. Most importantly academia may play an important role in generating new concept ideas and challenging the traditional state of the art among new generations of decision makers. The following subsections portray some options for different stakeholders to promote such new technological innovations.

7.1 The role of policy makers

IRENA has developed a range of policy tools for innovation. These have been adapted for renewable mini-grids, as shown in Table 33:

Innovations start with initial provision of funding for R&D activities that can support universities, research centres and public-private partnerships for fundamental research. Once a concept has been proven in the laboratory, policy makers can encourage pilots and tests for the technology. In this step, it is critical to provide support through grants that can allow demonstration projects to happen. Once technologies have been successfully piloted, market incentives can support early market adoption for new technologies. In parallel, training, information dissemination and creating an appropriate regulatory framework are necessary for successful deployment and adoption of new technologies.

Portfolio of policy instruments

Figure 23 depicts, at a high level, how IRENA recommends that technology innovations in general be funded across different stages of development.

Creating and sharing knowledge through funds and subsidies for supporting fundamental research and demonstration projects

There is a need for funding for fundamental research that will most benefit innovations. Key priorities for technologies that require fundamental research are summarised in Section 6.

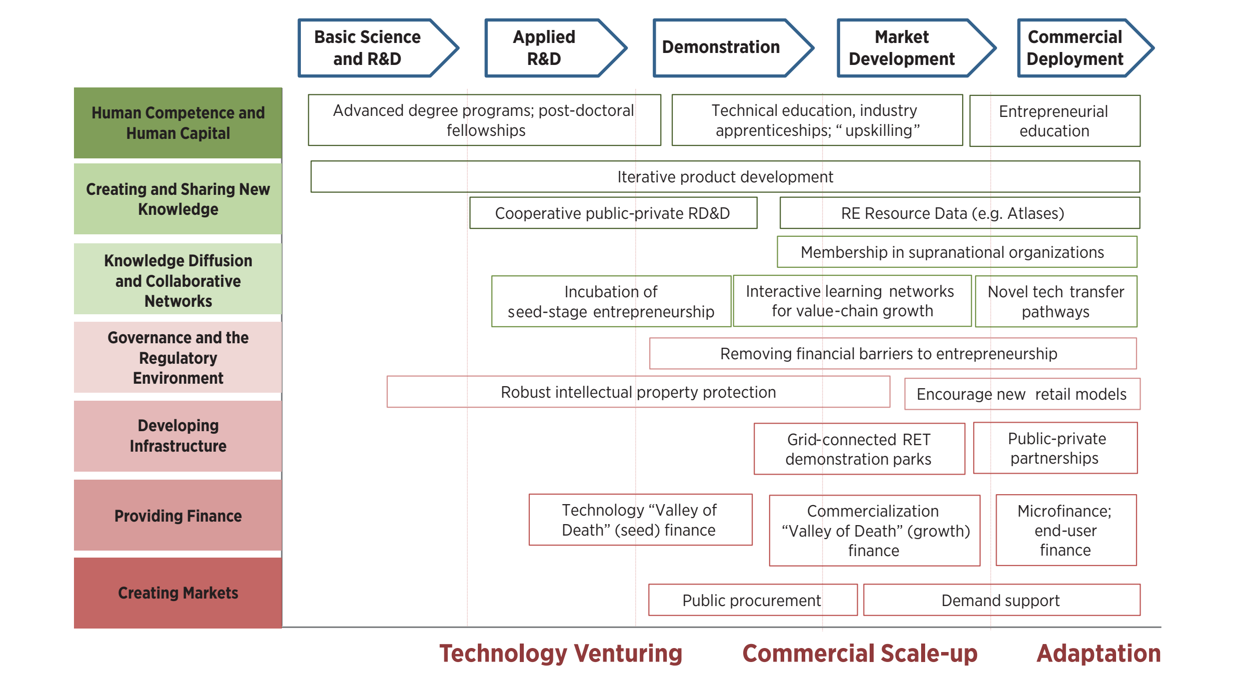
Most research funds are expected to be geared towards technologies from the generation, storage and consume functionalities due to their wide applicability in many sectors. Meanwhile, more specific CMM and conversion technologies are most likely to see less investment; nevertheless renewable mini-grid research funds are becoming increasingly available (Ellacott, 2015).

Table 33: Policy options to drive innovations

Economic	Educational	Regulatory	Market
Creating and sharing knowledge through funds and subsidies for supporting fundamental research and demonstration projects	Building competence through incentives for training and scholarships, industry support	New flexible/open standards that encourage development, removal of standards that do not fulfil realistic needs any more, sets targets, taxation, labelling, consumer information, and local institutional autonomy, protecting intellectual property to encourage patents	Flexible markets through use of instruments such as feed-in tariffs, net metering, renewable portfolio standards, government procurement and media campaigns
Developing infrastructure through public-private partnerships and public investments	Diffusing knowledge through international co-operation		
Providing financing such as loan grants and public venture funds			

Source: IRENA, 2015f, adapted by authors

Figure 23: Technology readiness level



Source: IRENA, 2015g

Developing infrastructure through public-private partnerships and public investments

Mini-grid technology sits at the interface between utilities and customers, and often is subject to governmental regulations but also must cater to the needs of market forces. Collaboration with the private sector is a rational response to this reality. New technology development through public-private partnerships are increasingly common for new product development and provide a way to commercialise research while complying with broader socio-political needs. For example, Panasonic Eco Solutions Canada has partnered with General Electric Digital Energy and University of Ontario Institute of Technology to develop the Microgrid Research and Innovation Park with public funding from the Ministry of Energy of Ontario (Ontario Ministry of Energy, 2014).

Providing financing such as loan grants and public venture funds

The need for support to deploy the innovations achieved in the laboratory and to test the results under real-life conditions is particularly relevant in renewable mini-grids because, in this case, the consumer and its behaviour is an integral part of the active functionalities. This cannot be tested in the lab, and validation and refinement are needed to ensure that it complies with its expected performance in real-life operating conditions. Many utilities, despite interest in the technology, are hesitant to use renewable mini-grids more widely in their networks due to lack of familiarity and uncertainty with their impact on their main grids. Pilot projects can overcome these hurdles and assist consumers in considering renewable mini-grids as a core tool in safely supplying their energy services, both grid-tied or autonomously. Renewable mini-grids provide a least-cost technological alternative to the traditional utility approaches of increased centralised generation and adding poles and wires. Or, in the case of energy access, they offer a sensible alternative to extending the grid from remote expensive generating plants.

For example the New York State Energy Research and Development Agency has launched the New York Prize competition that provides USD 40 million in funds for communities that want to develop their own mini-grid (NYSERDA, 2015a). The initiative invites proposals with emphasis towards storm-impacted communities in New York State, and low- and moderate-income communities, using evaluation criteria based on the benefits and impacts expected from the proposed projects (NYSERDA, 2015b).

Such efforts are expected to move forward innovations of more resilient renewable mini-grids. The California Energy Commission has a specific branch for carrying out research and energy innovation – including work on efficient, low-emission heat and electricity for on-site energy security – and is now deploying a utility mini-grid pilot project.

With regard to off-grid renewable mini-grids, there have been numerous grant projects for pilots: for example, the EU-ACP Energy Facility has financed several pilot demonstration projects in Burundi, Cape Verde and Guinea Bissau, among others. These projects have provided initial stepping stones to renewable energy-based mini-grids, including support to innovations in increasing solar fraction, metering and others. In Mexico, the Corporación Federal de Electricidad, with financing from the World Bank, has deployed 100% solar mini-grids in over 30 communities.

Educational policies

Building competence through incentives for training and scholarships, industry support

As mini-grids are increasingly deployed, a new generation of energy practitioners and engineers will be required. These energy engineers will need a new skillset beyond the traditional planning and design for centralised electrical grids. They will need to understand new generation technologies, new storage technologies and advanced controls.

There are currently no mini-grid-specific university courses, but, for example, the MIGEDIR network (MIGEDIR, 2015) has been developing curricula focused on rural mini-grids. In addition, several energy master's courses at universities do include lectures on mini-grids, and many master's and PhD students focus their dissertations on the different types of mini-grids. Policies need to encourage programmes that focus on mini-grid-specific issues and technologies. There is a need for mini-grid degrees for undergraduates, secondary degrees in mini-grids for graduate students, and continuing education for professionals. To further increase impact, policies can offer incentives for training and scholarships to encourage participation.

Diffusing knowledge through international co-operation

Diffusion of knowledge through international co-operation can engage key players in different regions to share progress. For example, the Intelligent Microgrid Lab collaboration between Aalborg University in Denmark and Tsinghua University in China seeks to spread mini-grid knowledge globally.

Policies to identify successes, as well as to catalogue lessons learned, are critical for future project development. Mini-grids are a distributed technology. Increasing access to information for sound decision making and planning will increase the ability of these smaller grids to proliferate. There are several international, regional and local institutions seeking to share information. These include IRENA, the World Bank's ESMAP group, the IEA-RETD, the EASE and EERE, ARE and JRC. HOMER Energy has created an industry partner programme that helps local organisations that would like mini-grids to connect up with international technical experts and funders to ease the creation of mini-grids.

There also is a need to better inform and incentivise end-users and utilities on, for example, using interconnected mini-grids to increase resilience. In addition, it is important to increase awareness among governments, multilateral organisations, and others of the ability of autonomous renewable mini-grids to provide quality services, achieve lower costs, and be more environmentally friendly than traditional grid-extension and stand-alone systems. These organisations can help with increasing social awareness of the benefits of renewable mini-grids.

Regulatory policies

There are increasingly more technical regulations (codes) and engineering standards (*e.g.*, plug-and-play or communication protocols) to standardise mini-grids. However, there is a need for broader international consensus geographically and across industries, as well as for more flexible and general standards that do not hinder innovations.

On one hand, numerous existing platforms for creating the necessary standards exist. Policy makers can provide financial support and/or align with standards created by traditional standards organisations such as IEC or IEEE to create sensible regulations. They also may provide support to new entrants focused on coalition building around the smart grid, such as the SmartGrid alliance or the SGIP. Such standards development should focus mainly on safety issues, *e.g.*, of interconnection of a renewable mini-grid to the main grid.

On the other hand, excessive standards pose the risk of encapsulating technologies and limiting innovations and not being able to adapt or cope with constant innovations in the industry. For example, standardising equipment/operations inside the compounds of a renewable mini-grid should be more flexible and allow architects to design according to local needs/demand, with constraints dictated mainly by appliances.

The standards that are created need to be adapted and included in regulatory frameworks to enable more competition. Appropriate implementation of these standards will help to prevent bad outcomes, for example manufacturer lock-in. Policies that enable continued competition throughout the lifetime, during repowering and retrofit will help to prevent this.

Internationally, few regulations exist that robustly cover the role for mini-grids. Mini-grids often do not fit into existing regulatory frameworks, and are complicated by split responsibilities. The state of New York is attempting to address these issues with its Reforming the Energy Vision initiative, which encourages utilities to allow customers to explore distributed options such as mini-grids (NY DPS, 2016). Appropriate regulations require a balanced approach that is flexible yet useful. A robust regulatory environment must balance regional planning while allowing for local participation with mini-grids.

For example, the United Republic of Tanzania has made big progress in defining specific regulation for mini-grid deployment and operation (Tenenbaum *et al.*, 2014). For grid-connected renewable mini-grids, many utility operators are faced with the uncertainty of how to incorporate and manage these renewable mini-grids. The values that renewable mini-grids offer do not fit into traditional interconnections for generation, which creates a need for revised approaches to interconnection and operation standards, as well as requirements on anti-islanding and fault low-voltage ride-through (Tao *et al.*, 2011).

Market policies

A number of near-commercial technologies would benefit from support in commercialisation – in particular, support to overcome the so-called valley of death that traps good research ideas before they can become commercially viable. A list of the technologies that need commercialisation support to transfer from demonstration to market deployment is provided in Section 6.

One successful approach is to offer financing mechanisms that drive renewable mini-grid deployment. An example is the renewable energy purchase tariff that is structured to enable rural energy subsidies to fund renewable mini-grid projects (Fulton *et al.*, 2010; Moner-Girona, 2009; Solano-Peralta *et al.*, 2009). This tariff structure is being considered in China, Colombia, the United Republic of Tanzania and Uganda (Arango-Manrique *et al.*, 2015; He *et al.*, 2015; Moner-Girona *et al.*, 2016). For these, financing can come from the avoided cost of energy production in rural areas, which is much higher due to the typical reliance on expensive diesel, or from international initiatives such as the GET FiT programme (Fulton *et al.*, 2010).

It is common practice in many countries to provide a tax rebate (or to forgo taxation entirely) for alternative energy generation. Common examples include the Investment Tax Credit for renewable energy in the United States, or providing a tax exemption for renewable energy generation products, which is common in many countries including Costa Rica, Haiti and Mexico. However, many of these tax incentives do not include support equipment required for renewable mini-grids. Extending these exemptions to equipment that is necessary for the five renewable mini-grid functionalities can support the deployment of renewable mini-grids and growth of the industry.

7.2 The role of private investors

Mini-grids that use renewable energy technologies are a cost-effective technology today, particularly in remote markets that currently depend on fossil fuels for reliable power. The private sector can focus on deployment of mini-grids with a long-term vision for renewable mini-grids. Renewable mini-grids will become cost-effective as storage costs continue to decline.

Advancing technologies within advanced controls (*i.e.*, CMM functionality) is a near-term goal and can enhance the roll-out of today's mini-grids.

Undertake fundamental research

There is a need for private sector investment in new technologies, even if they are not near commercialisation. Private sector involvement can help to move early innovations from the laboratory to commercial solutions.

Companies such as Sony, Toshiba, Panasonic and Samsung are investing heavily in new technological developments and designating specific funds for research. These investments include supporting internal research laboratories and facilities, and providing funds through contests or grants for other institutions.

Pilot projects

Several private players in the market are pushing investments in new technologies and research facilities. For examples, the Japanese firm Sumitomo Power System R&D Research Centre was created in 2010 and developed a micro smart grid demonstration project using four different renewable energy sources (Sumitomo Electric Industries, Ltd., 2015). A successful venture capitalist investment has been done by Aquion Energy, a company that has managed to secure private financing for developing an AHI battery. Investor-owned utilities already have been considering the use of mini-grids in their territories and should continue including renewable mini-grids in their options planning.

Deploy mini-grids

It is important to continue to deploy mini-grids even if they do not derive a majority of their energy from renewable sources today. Renewable mini-grids will increase in cost-effectiveness as storage costs decline, but there is a need for the controls and integration with intelligent end-uses today. Much of the necessary work is in bringing existing technologies together in a sensible package (Zimmermann, 2015). Investment in cost-effective mini-grid projects today and concomitant improvements in CMM and consumption technologies will form a foundation for renewable mini-grids in the next decade.

Transfer technology into the renewable mini-grid market

Much of the intellectual property identified and required for renewable mini-grids already exists in other markets. For example, car companies are investing heavily in storage technologies for transportation. There is a role for technology holders, such as car companies, to transfer their knowledge and technologies into the renewable mini-grid sector.

Participate in industry groups: develop standards and build relationships

A range of standards are being developed by industry consortia. The private sector can generate a critical mass among industry partners, reach out to utilities and work with the public sector to develop new technology standards. Collaborations between energy firms and information technology firms will leverage the strengths of each to drive the smart grid revolution that can benefit renewable mini-grids. Notable industry groups include the EMergy Alliance, SunSpec, SGIP, GridSmart, SG-CG, KSGA, ISGF and JSCA.

7.3 The role of the non-profit sector and academia

The non-profit foundation sector, such as the Rockefeller Foundation or the Bill & Melinda Gates Foundation, is co-ordinating large pools of money to drive innovation. Multilaterals can fund pilots based on proven technologies deployed in new areas. Furthermore there are a series of cross-cutting, multi-level, multilateral efforts of institutions engaging together to advance renewable mini-grids. The Clean Energy Mini-grids High-Impact Opportunity (CEMG HIO) from the Sustainable Energy for All (SE4All) initiative is a key high-level global promoter of off-grid renewable mini-grids, with over 140 registered members (Wiemann and Lecoque, 2015).

Universities and academic institutions can undertake the fundamental research necessary for renewable mini-grids. Academia can support setting research agendas that prioritise the technologies that close the gap for renewable mini-grids. For example, research institutes need to co-operate and elaborate more demanding mini-grid experiments to submit technologies to harsh real-life conditions (Tao *et al.*, 2011). Researchers play an important role in making data publicly available and in supporting start-ups out of their laboratories.

8 CONCLUSIONS

Innovation in renewable mini-grids will span many functionalities and technologies. Planning and design of renewable mini-grids will be more flexible and will be built upon ever-improving data for the underlying energy resources available in each area. Enhancements in CMM technologies are expected to include simplified interconnection of equipment, access to more flexible and robust metering technologies, and more intelligent use of generation and storage. The renewable mini-grids of the future will be built on the back of lower-cost storage chemistries that are more resilient and safer than today's. There also will be new long-term storage technologies to spread the energy available from variable renewables to periods of high demand.

In addition, there will be affordable storage options to handle high power demands. Power conversion technologies will easily interconnect with other equipment and will come bundled with capabilities to easily integrate and manage the flow of electricity. Interconnection with the main grid will be straightforward and, after the lessons learned from pilots today and in the near future, will be built upon proven approaches for integrating with the utility. Generation technologies have seen impressive cost breakthroughs (particularly solar PV), and these trends are expected to continue. Generation technologies will achieve higher efficiency (*i.e.*, better resource capture), be more robust and have lower maintenance needs.

Developments in lithium-ion batteries are among the most promising technologies for lowering the barriers to wide-scale use of renewable mini-grids. Advancements in CMM will yield smarter, more modular and scalable mini-girds, further driving deployment of the technology. The CMM will be bundled into the converters. Advancements in resource modelling, load prediction and customised planning tools will enable decision makers to make smarter planning decisions. Low-cost generation (in particular solar PV), coupled with highly efficient, flexible appliances and energy uses, will complete the mini-grid of the future.

CMM technologies are the brain of renewable mini-grids, and smarter algorithms will maximise the capabilities of technologies in other functionalities. Both research and pilot projects are critical to continuing to move forward CMM technologies, and will require support from policy makers and developers.

In addition to the core storage technologies, a research focus should be on non-LIB storage as well. Longer-term options include organic flow batteries that are more environmentally friendly, requiring no rare earths or expensive materials. Novel storage technologies, including advanced lead-acid, flywheels and even less-commercial technologies may yet prove disruptive (or complementary) to LIBs. The ability to store renewable energy for long periods in liquid (or possibly gaseous) form will further enable high penetrations of renewable energy throughout the year.

Power conversion technology costs will decrease, due in large part to commercial scale-up and improved manufacturing. In particular, the dual-mode converters that are critical to renewable mini-grids will benefit from increased usage in the market, further driving renewable mini-grids. New designs, including GaN, SiC and eventually graphite will play a growing role. Bundling of features (even crossing over into the CMM functionality) will further make distributed renewable mini-grids more user-friendly, and more robust across a wide range of environments. The technologies also will gain wider acceptance for interconnecting with utilities, further driving roll-out even in interconnected areas.

Energy-consuming devices will continue to increase in efficiency, further reducing the cost of energy services in renewable mini-grids. Much of this will come from end-uses in the larger main grid, although the flexibility of new smarter appliances will be even more critical in renewable mini-grids. Generation technologies will continue to benefit from economies of scale through wider use in the main grid. Renewable energy technologies are expected to become cheaper and even more environmentally friendly.

None of the discussed innovations are possible without the adequate support of policy makers, the private sector and researchers in particular. There is much need for funding of fundamental research that is able to generate new concept ideas. Fundamental research provides the stepping stones for breakthroughs for the next couple of decades. Funding from the public and private sector is critical to support these research activities, both jointly and independently. Additionally, policy makers need to promote regulations and access to information. Finally, policy makers play a critical role in providing market policies that can facilitate the uptake of innovations in their final stages of development and need for support prior to commercialisation. Private sector investors are expected to continue to play a major role in funding research activities. Also, private sector investors are key for moving forward concept ideas into commercial products and for eventually deploying new renewable mini-grid projects. What is more, the private sector needs to be largely involved in the development of technology standards through industry groups that collaborate with the public sector and universities.

The renewable mini-grid sector is still in its infancy. It faces challenges from lack of acceptance from utilities, and perceived competition from stand-alone systems (*e.g.*, SHS) and grid extension. However, renewable mini-grids provide a smart alternative. Initially these developments will occur in remote areas and isolated communities, or to power heavy industry. From the interconnected side, the growth will likely be on industries and campuses with high reliability needs (*e.g.*, campuses, data centres and high-end manufacturing). The focus in these areas will be on resiliency, but renewable mini-grids will provide the backbone for increased renewables as storage and generation technologies drop in cost.

Although the world is moving towards them, mini-grids that are based mainly on renewable energy are likely to be more prevalent in the more-distant future, as technology and policy evolve to understand and accept them. Technological innovations are continuing to occur in all six of the core functionalities. In the next two decades, these will drive an increase of renewable energy penetration in mini-grids and increase their deployment by making them an increasingly attractive alternative to traditional centralised grid planning and SHS.

REFERENCES

ABB, 2013. Renewable Microgrid Controller MGC600. *http://new.abb.com/docs/default-source/ewea-doc/microgrid-controller-600_en_lr(dic2013).pdf?sfvrsn=2.*

ACEEE, 2013. Better Appliances: An Analysis of Performance, Features, and Price as Efficiency Has Improved. American Council for an Energy-Efficient Economy, Washington, D.C. *http://aceee.org/research-report/a132.*

Aggarwal, V., Mohanty, P., 2015. Smart Systems and Smart Grids for Effective Governance of Electricity Supply in India, in: Kumar, T.M.V. (Ed.), E-Governance for Smart Cities, Advances in 21st Century Human Settlements. Springer Science+Business Media Singapore, pp. 159–175.

Ahlborg, H., Hammar, L., 2014. Drivers and barriers to rural electrification in Tanzania and Mozambique – Grid-extension, off-grid, and renewable energy technologies. World Renewable Energy Congress, 8–13 May 2011, Linköping, Sweden, Renew. Energy 61, 117–124.

Akhil, A.A., Huff, G., Currier, A.B., Kaun, B.C., Rastler, D.M., Chen, S.B., Cotter, A.L., Bradshaw, D.T., Gauntlett, W.D., 2013. DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. Sandia National Laboratories, Albuquerque, New Mexico, US. *http://www.sandia.gov/ess/publications/SAND2013-5131.pdf.*

ALABC, 2015. ALBAC 2013-2015 R & D Program. *http://www.alabc.org/r-d-program (accessed 21 August 2015).*

Angelou, N., Elizondo Azuela, G., Banerjee, S.G., Bhatia, M., Bushueva, I., Inon, J.G., Jaques Goldenberg, I., Portale, E., Sarkar, A., 2013. Global Tracking Framework, Sustainable Energy for All. The World Bank, Washington, D.C. *http://documents.worldbank.org/curated/en/2013/05/17765643/global-tracking-framework-vol-3-3-main-report.*

Appelrath, H.-J., Kagermann, H., Mayer, C. (Eds.), 2012. Future Energy Grid. Migration to the Internet of Energy. acatech Study, Munich, Germany. *http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Englisch/EIT-ICT-Labs_acatech-Study_Future_Energy_Grid_final.pdf.*

Appert, S., al-Mukdad, W., 2013. Advanced Inverter Technologies Report. Public Utilities Commission, State of California, Sacramento, California, US. *http://www.ourenergypolicy.org/wp-content/uploads/2013/09/CPUCAdvancedInverterReport2013FINAL.pdf.*

Arango-Manrique, A., Carvajal-Quintero, S.X., Younes-Velosa, C., 2015. How to promote distributed resource supply in a Colombian microgrid with economic mechanism?: System dynamics approach. DYNA 82, 11–18.

ARE, 2014. The Potential of Small Hydro for Rural Electrification. Focus: Latin America. Position Paper. Alliance for Rural Electrification, Brussels. *http://www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/Position_papers/ARE_Small_Hydropower_Position_Paper_2014.pdf.*

ARE, 2013. Using Batteries to Ensure Clean, Reliable and Affordable Universal Electricity Access (Position Paper – Energy Storage Campaign). Alliance for Rural Electrification, Brussels.

ARE, 2012. The potential of small and medium wind energy in developing countries. A guide for energy sector decision-makers (Position Paper). Alliance for Rural Electrification, Brussels.

Ashden Awards, 2015. SteamaCo, Kenya: Remote-controlled microgrids for rural areas. *http://www.ashden.org/winners/SteamaCo15 (accessed 2 September 2015).*

Asselbergs, K., Dijk, J., 2013. Economic life of an asset. ACORDIO BV. *http://www.napnetwerk.nl/download/?id=17687004&.*

Azri, M., Rahim, N., Elias, M., Fathi, M., 2014. Transformerless DC/AC converter for grid-connected PV power generation system. King Fahd University of Petroleum and Minerals. Arab. J. Sci. Eng. 39, 7945–7956.

Backhaus, S.N., Swift, G.W., Chatzivasileiadis, S., Tschudi, W., Glover, S., Starke, M., Wang, J., Yue, M., Hammerstrom, D., 2015. DC Microgrids Scoping Study. Estimate of Technical and Economic Benefits. Los Alamos National Laboratory , Los Alamos, New Mexico, US.

Bandhauer, T.M., Garimella, S., Fuller, T.F., 2011. A critical review of thermal issues in lithium-ion batteries. J. Electrochem. Soc. 158, R1–R25.

Bani-Ahmed, A., Weber, L., Nasiri, A., Hosseini, H., 2014. Microgrid communications: State of the art and future trends. Presented at the 2014 International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, Wisconsin, US, pp. 780–785.

Bardouille, P., Muench, D., 2014. How a New Breed of Distributed Energy Services Companies Can Reach 500mm Energy-poor Customers Within a Decade.

Bari, A., Jiang, J., Saad, W., Jaekel, A., 2014. Challenges in the smart grid applications: an overview. Int. J. Distrib. Sens. Netw. 2014, 11.

Basso, T.S., DeBlasio, R., 2004. IEEE 1547 series of standards: interconnection issues. IEEE Transactions on Power Electronics 19 (5), 1159–1162.

Battery Council International, 2012. The facts about lead: the energy solution. Chicago, Illinois, US.

Blaabjerg, F., Ionel, D.M., 2015. Renewable energy devices and systems – state-of-the-art technology, research and development, challenges and future trends. Electr. Power Compon. Syst. 43, 1319–1328.

Blum, N., Bening, C., Schmidt, T., 2015. An analysis of remote electric mini-grids in Laos using the Technological Innovation Systems approach. Technol. Forecast. Soc. Change 95, 218–233.

Blumstein, C., Taylor, M., 2013. Rethinking the Energy-Efficiency Gap: Producers, Intermediaries, and Innovation. Energy Institute at Hass, Berkeley, California, US.

Bose, S., Soni, V., Genwa, K.R., 2015. Recent advances and future prospects for dye sensitized solar cells: a review. International Journal of Scientific and Research Publications 5(4).

Bossel, U., 2006. Does a hydrogen economy make sense? Proc. IEEE 94, 1826–1837.

Bourgeois, T., Gerow, T., Litz, F., Martin, N., 2013. Community Microgrids: Smarter, Cleaner, Greener. Pace Energy and Climate Center, New York, US.

Braff, W.A., 2014. Membraneless Hydrogen Bromine Laminar Flow Battery for Large-Scale Energy Storage. Massachusetts Institute of Technology, Cambridge, Massachusetts, US.

Braff, W.A., Bazant, M.Z., Buie, C.R., 2013. Membrane-less hydrogen bromine flow battery. Nat Commun 4.

Brandt, J., 2015. CA Energy Commission funds research for renewables-based microgrid. Smart Grid News. 23 March. *http://www.smartgridnews.com/story/ca-energy-commission-funds-research-renewables-based-microgrid/2015-03-23.*

Briganti, M., Vallvé, X., Alves, L., Pujol, D., Cabral, J., Lopes, C., 2012. Implementation of a PV rural micro grid in the island of Santo Antão (Cape Verde) with an individual energy allowance scheme for demand control. Presented at the 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, Germany.

Bronski, P., Lehrman, M., Mandel, J., Morris, J., Palazzi, T., Ramírez, S., Touati, H., 2015. The Economics of Demand Flexibility: How "flexiwatts" create a quantifiable value for customers and the grid. Rocky Mountain Institute, Colorado, US.

Brucoli, M., O'Halloran, K., 2014. Microgrids: reliable power while integrating renewable generation. Eng. J. 17 July. *http://www.engineersjournal.ie/microgrids-cork-renewable-distributed-generation/.*

Buevich, M., Schnitzer, D., Escalada, T., Jacquiau-Chamski, A., Rowe, A., 2014. Fine-Grained Remote Monitoring, Control and Pre-Paid Electrical Service in Rural Microgrids. Presented at the International Symposium on Information Processing in Sensor Networks (IPSN), Berlin, Germany, pp. 1–11.

Calogero, G., Bartolotta, A., Marco, G.D., Carlo, A.D., Bonaccorso, F., 2015. Vegetable-based dye-sensitized solar cells. Chem. Soc. Rev. 44, 3244–3294.

Campeau, Z., Anderson, M., Hasselbrink, E., Kavulak, D., Shen, Y.-C., Lacerda, R., Terao, A., Caldwell, S., Defreitas, Z., Leonard, L., Mikofski, M., DeGraaff, D., Budiman, A., 2013. SunPower Module Degradation Rate. SunPower Corporation, San Jose, California, US.

Carey, B., Miller, A., 2012. The Future of Microgrids. PricewaterhouseCoopers, San Jose, California, US.

Carl, J., 2013. Distributed Power in the United States: Prospects and Policies. Hoover Press, Stanford, California, US.

CDM Executive Board, 2011. Indicative simplified baseline and monitoring methodologies for selected small-scale CDM project activity categories. Clean Development Mechanism. United Nations Framework Convention on Climate Change, Bonn, Germany.

CE Delft, 2012. Maatschappelijke kosten en baten van Intelligente Netten. Delft, The Netherlands.

Chae, S.H., Lee, Y.H., 2014. Carbon nanotubes and graphene towards soft electronics. Nano Converg. 1.

Chakrabarti, M.H., Mjalli, F.S., AlNashef, I.M., Hashim, M.A., Hussain, M.A., Bahadori, L., Low, C.T.J., 2014. Prospects of applying ionic liquids and deep eutectic solvents for renewable energy storage by means of redox flow batteries. Renew. Sustain. Energy Rev. 30, 254–270.

Cheek, J., Huyge, B., de Pomereu, J., 2011. Princess Elisabeth Antarctica: an International Polar Year outreach and media success story. Polar Res. 30.

Chen, B., Gu, B., Zhang, L., Zahid, Z.U., Lai, J.-S.J., Liao, Z., Hao, R. 2015. A high-efficiency MOSFET transformerless inverter for nonisolated microinverter applications. IEEE Transactions on Power Electronics 30 (7), 3610–22.

Chung, I.-Y., Yoo, C.-H., Oh, S.-J., 2013. Distributed intelligent microgrid control using multi-agent systems. Engineering 5 (1), 1–6.

Circutor, 2015. Micro-grid management system. Dispenser Universal System. Barcelona, Spain.

City of Boulder Colorado, n.d. A local electric utility (municipalization). Energy Future City Boulder Colorado. *https://bouldercolorado.gov/energy-future/local-electric-utility* (accessed 20 May 2015).

Clausen, P.D., Reynal, Wood, D.H., 2013. 13 – Design, manufacture and testing of small wind turbine blades, in: Brøndsted, P., Nijssen, R.P.L. (Eds.), Advances in Wind Turbine Blade Design and Materials, Woodhead Publishing Series in Energy. Woodhead Publishing, Cambridge, UK, pp. 413–431.

Colson, C.M., Nehrir, M.H., 2009. A review of challenges to real-time power management of microgrids. Presented at the IEEE Power & Energy Society General Meeting, 2009, Calgary, Canada, pp. 1–8.

Costinett, D.J., 2013. Analysis and Design of High Efficiency, High Conversion Ratio, DC-DC Power Converters. Citeseer.

C-Tech Innovation Ltd, 2014. An overview of POWAIR – A zinc air flow battery for low cost electrical energy storage. *http://ukenergystorage.co/2014/assets/downloads/presentations/j-collins.pdf.*

Daniel, C., 2015. Lithium ion batteries and their manufacturing challenges. The Bridge 45, 21–24.

Daniel, C., 2008. Materials and processing for lithium-ion batteries. Mater. Coat. 60, 43–48.

Danish Technical University, 2015. Danish Centre for Composite Structure Materials for Wind Turbines. *http://www.dccsm.dtu.dk/Home* (accessed 6 August 2015).

Das, R., 2015. Graphene: in need of business development. IDTechEx. 9 March. *http://www.idtechex.com/research/articles/graphene-in-need-of-business-development-00007529.asp.*

Debajit, P., 2012. Renewable energy mini-grids – Indian experiences. The Energy and Resources Institute, New Delhi. Presentation at ECOWAS Initiative on the contribution of the civil society and private sector to up-scaling rural energy access in the ECOWAS region, Accra, Ghana, 29 October.

Deboy, G., Rupp, R., Mallwitz, R., Ludwig, H., 2011. New SiC JFET boost performance of solar inverters. Power Electron. Eur. 29–33.

Deng, W., Pei, W., Shen, Z., Zhao, Z., Qu, H., 2015. Adaptive micro-grid operation based on IEC 61850. Energies 8, 4455–4475.

DERlab, 2015. European Distributed Energy Resources Laboratories E. V. *http://www.der-lab.net/services/testing-services/index.html.*

Deshmukh, R., 2014. Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design. eScholarship.

Dimeas, A., Drenkard, S., Hatziargyriou, N., Karnouskos, S., Kok, K., Ringelstein, J., Weidlich, A., 2014. Smart houses in the smart grid: developing an interactive network. Electrification Mag. IEEE 2, 81–93.

Dimpl, E., 2010. Small-scale Electricity Generation from Biomass: Biomass Gasification, Poverty-Oriented Basic Energy Service. GTZ-HERA, Eshborn, Germany.

DNV KEMA, 2014. Microgrids – Benefits, Models, Barriers and Suggested Policy Initiatives for the Commonwealth of Massachusetts. Massachusetts Clean Energy Center, Boston, Massachusetts, US.

Dörfler, F., Simpson-Porco, JW., Bullo, F., 2014. Plug-and-play control and optimization in microgrids. Presented at 2014 IEEE 53rd Annual Conference on Decision and Control, Los Angeles, California, US, pp. 211–216.

DTU, 2013. DTU International Energy Report 2013: Energy Storage Options for Future Sustainable Energy

Systems. Technical University of Denmark, Roskilde, Denmark.

Duduta, M., Ho, B., Wood, V.C., Limthongkul, P., Brunini, V.E., Carter, W.C., Chiang, Y.-M., 2011. Semi-solid lithium rechargeable flow battery. Adv. Energy Mater. 1, 511–516.

DWEA, 2015. DWEA Distributed Wind Vision 2015–2030. Distributed Wind Energy Association, Vermont, US.

EASE/EERA, 2013. Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap towards 2030. European Association for Storage of Energy/ European Energy Research Alliance. *http://ease-storage.eu/wp-content/uploads/2015/10/EASE-EERA-recommendations-Roadmap-LR.pdf.*

Easy Smart Grid GmbH, 2015. Local electricity exchange in mini-grids: Flexibility to integrate more renewable energy. Karlsruhe, Germany.

EATON, 2006. White Paper: Next-generation Power Quality Meters. Dublin, Ireland.

Electrovaya, 2012. Electrovaya Launches Next Generation Lithium Ion Superpolymer(R) Cell & Battery Technology: MN-HP Series. Toronto, Canada.

Ellacott, J., 2015. Utilities are putting their money where their microgrid is. Techavio.

Eloy-García, J., Guerrero, J.M., Vasquez, J.C., 2013. Grid simulator for power quality assessment of micro-grids. IET Power Electron. 6, 700–709.

EMerge Alliance, 2015. EMerge Alliance. *http://www.emergealliance.org/* (accessed 21 September 2015).

Enersys, 2014. Advanced lead-acid batteries recognized as energy efficient backup solutions for data centers.

EPO, 2015a. Global Patent Index. European Patent Office. https://data.epo.org/expert-services/start.html (accessed 2 October 2015).

EPO, 2015b. Espacenet. European Patent Office. *http://www.epo.org/searching/free.html* (accessed 2 June 2015).

ESHA, 2012. Small Hydropower Roadmap. European Small Hydropower Association. Brussels, Belgium.

Espinosa, C., 2004. Renewables: Devising a Sustainable Energy Future. 100% renewable islands. Presented at the Fourth European Conference for Sustainable Cities & Towns, Aalborg, Denmark.

Esquivel, A., 2014. Cree PV Inverter Tops 1kW/kg with All-SiC Design. Cree, Durham, North Carolina, US.

Estrada García, J.A., Liñán García, R., Picasso Blanquel, C., Silva Farías, J.L., 2013. Microrredes inteligentes en refinerías, caso México. Bol. IIE Tend. Tecnológica.

Eto, J., Lasseter, R., Schenkman, B., Stevens, J., Volkommer, H., Klapp, D., Linton, E., Hurtado, H., Roy, J., Lewis, N., 2009. CERTS microgrid laboratory test bed. Lawrence Berkeley National Laboratory, Berkeley, California, US.

EUROBAT, 2013a. Battery Energy Storage for Smart Grid Applications. EUROBAT, Brussels, Belgium.

EUROBAT, 2013b. Battery Energy Storage for Rural Electrification Systems. EUROBAT, Brussels, Belgium.

EWEA, 2013. The European Wind Initiative: Wind Power Research and Development to 2020. European Wind Energy Association, Brussels, Belgium.

EWETP, 2014. Strategic Research Agenda / Market Deployment Strategy (SRA / MDS). European Wind Energy Technology Platform.

Executive Office of Energy and Environmental Affairs, Commonwealth of Massachusetts, 2014. Community Clean Energy Resiliency Initiative. *http://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/resiliency/resiliency-initiative.html* (accessed 20 May 2015).

Fehrenbacher, K., 2013. 13 battery startups to watch in 2013. Gigaom. 14 January. https://gigaom.com/2013/01/14/13-battery-startups-to-watch-in-2013/.

Feng, Y., 2015. PolyU develops novel efficient and low-cost semitransparent perovskite solar cells with graphene electrodes. Press release. Hong Kong Polytechnic University, 7 September. *http://www.polyu.edu.hk/web/en/media/media_releases/index_id_6139.html.*

FMI, 2014. Lead Acid Battery Market: Application Analysis and Regional Outlook till 2020. Future Market Insights. *http://www.futuremarketinsights.com/reports/details/global-lead-acid-battery-market* (accessed 8 July 2015).

Fox-Davies Capital, 2013. The Lithium Market. London, UK. *doc.xueqiu.com/1497add8471193fc2e583642.pdf.*

Frankfurt School, 2015. Renewable Energy in Hybrid Mini-Grids and Isolated Grids: Economic Benefits and Business Cases. Frankfurt School – UNEP Collaborating

Centre for Climate and Sustainable Energy Finance, Frankfurt School of Finance & Management GmbH, Frankfurt, Germany. *http://fs-unep-centre.org/sites/default/files/publications/hybridgrids-economicbenefits.pdf.*

Fraunhofer ISE, 2015a. Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. (Study on behalf of Agora Energiewende). Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.

Fraunhofer ISE, 2015b. Fraunhofer ISE develops highly compact inverter for uninterruptible power supplies. Press release. Fraunhofer ISE, 3 September. https://*www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2015/fraunhofer-ise-develops-highly-efficient-compact-inverter-for-uninterruptible-power-supplies.*

Fraunhofer ISE, 2014. Photovoltaics Report. Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany. *http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf.*

Frost & Sullivan, 2014. Innovation Across Key Industries to Quadruple Revenues for Lithium-Ion Batteries. Press release, 4 September. *http://ww2.frost.com/news/press-releases/innovation-across-key-industries-quadruple-revenues-lithium-ion-batteries/.*

Fu, Y., Huang, L., Zhao, J., 2015. Micro-grid smooth switchover method based on controller state following. J. Power Energy Eng. 3, 128–135.

Fuchs, G., Lunz, B., Leuthold, M., Sauer, D.U., 2012. Technology Overview on Electricity Storage. Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Aachen, Germany.

Fuel Cell Today, 2013. Water Electrolysis & Renewable Energy Systems. Royston, UK.

Fulton, M., Kahn, B., Mellquist, N., Soong, E., Baker, J., Cotter, L., Kreibiehl, S., Rickerson, W., Meister, H.-P., 2010. GET FiT Program: Global Energy Transfer Feed-in Tariffs for Developing Countries. Deutsche Bank Group, Frankfurt, Germany.

Gaines, L., 2014. The future of automotive lithium-ion battery recycling: Charting a sustainable course. Sustain. Mater. Technol. 1–2, 2–7.

Gallagher, K.G., Goebel, S., Greszler, T., Mathias, M., Oelerich, W., Eroglu, D., Srinivasan, V., 2014. Quantifying the promise of lithium–air batteries for electric vehicles. Energy Environ. Sci. 7, 1555–1563.

Garbesi, K., Vossos, V., Shen, H., 2011. Catalog of DC Appliances and Power Systems (No. LBNL-5364E). Lawrence Berkeley National Laboratory, Berkeley, Caifornia, US.

Gershenson, D., Tilleard, M., Cusack, J., Cooper, D., Monk, A., Kammen, D., 2015. Increasing Private Capital Investment into Energy Access: The Case for Mini-grid Pooling Facilities. University of California at Berkeley, CrossBoundary, Stanford University and United Nations Environment Programme.

GIZ, 2015. Tools for Mini-grid Practitioners. Deutsche Gesellschaft für Internationale Zusammenarbeit, Eschborn, Germany.

Goetzler, W., Sutherland, T., Foley, K., 2014. Research and Development Roadmap for Next-Generation Appliances.

Gong, J., Darling, S.B., You, F., 2015. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. Energy Environ. Sci. 8, 1953–1968.

Graillot, A., 2013. Improving solar-home systems integral efficiency: financing and management model for the design, installation, capacity building, and commissioning of PV systems in rural communities of the province Azua, Barahona, Bahoruco, and San Juan of the Dominican Republic. Presented at 3rd Symposium Small PV Applications, Ulm, Germany, 17–18 June.

Graillot, A., Briganti, M., Solano-Peralta, M., Vallvé, X., 2012. 15 Years of Field Experience with the "Daily Energy Allowance" Concept as the Basis for Load Control and Guide for Social Behaviour in Rural Micro Grids. Presented at the 6th European PV-Hybrid and Mini-Grid Conference, Chambéry, France.

Greco, A., Jiang, X., Cao, D., 2015. An investigation of lithium-ion battery thermal management using paraffin/porous-graphite-matrix composite. J. Power Sources 278, 50–68.

Green, M.A., Ho-Baillie, A., Snaith, H.J., 2014. The emergence of perovskite solar cells. Nat. Photonics 8, 506–514.

Gruber, P.W., Medina, P.A., Keoleian, G.A., Kesler, S.E., Everson, M.P., Wallington, T.J., 2011. Global lithium availability. J. Ind. Ecol. 15, 760–775.

GSMA, 2015. "GSMA: The Impact of the Internet of Things." GSM Association, London, UK. *http://www.gsma.com/newsroom/wp-content/uploads/15625-Connected-Living-Report.pdf.*

Guerrero, J.M., Chandorkar, M., Lee, T.-L., Loh, P.C., 2013. Advanced control architectures for intelligent microgrids, part I: decentralized and hierarchical control. IEEE Trans. Ind. Electron. 60, 1254–1262.

Haedler, A.T., Kreger, K., Issac, A., Wittmann, B., Kivala, M., Hammer, N., Köhler, J., Schmidt, H.-W., Hildner, R., 2015. Long-range energy transport in single supramolecular nanofibres at room temperature. Nature 523, 196–199.

Hales, R.L., 2014. One of the largest grid support and solar inverter test labs. The ECOReport. 14 July. *https://theecoreport.com/one-of-the-largest-grid-support-and-solar-inverter-test-labs/.*

Harper, M., 2013. Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids. Lawrence Berkeley National Laboratory and Schatz Energy Research Center, California, US.

Hatziargyriou, N., Asano, H., Iravani, R., Marnay, C., 2007. Microgrids. Power Energy Mag. IEEE 5, 78–94.

Hayashi, Y., Matsumoto, A., 2013. DC-DC converter for DC distribution and DC microgrids. Presented at Santiago 2013 Symposium on Microgrids, Santiago, Chile.

He, Y., Pang, Y., Zhang, J., Xia, T., Zhang, T., 2015. Feed-in tariff mechanisms for large-scale wind power in China. Renew. Sustain. Energy Rev. 51, 9–17.

Hernandez, L., Baladrón, C., Aguiar, J., Carro, B., Sanchez-Esguevillas, A., Lloret, J., 2013. Short-term load forecasting for microgrids based on artificial neural networks. Energies 6 (3), 1385–1408.

HOMER Energy, 2015. HOMER Pro – Microgrid Software for Designing Optimized Hybrid Microgrids. *http://homerenergy.com/HOMER_pro.html* (accessed 19 September 2015).

HOMER Pro. 3.6 HOMER Energy, Boulder, CO US, 2016; software available at *www.homerenergy.com.*

Ho, M.-W., 2015. Supercapacitors for Flexible Energy Storage and Ultrafast Superpower. *http://www.i-sis.org.uk/Supercapacitors_for_Flexible_Energy_Storage.php* (accessed 9 September 2015).

Hoffmann, F., 2014. 60 kW Inverter with Built-In Isolation Using GaN Devices. Presented at 2014 US Department of Energy OE Energy Storage Program Peer Review, Washington, D.C., US. *http://www.sandia.gov/ess/docs/pr_conferences/2014/Thursday/Session6/05_Hoffmann_60kW_Inverter.pdf.*

Hooshmand, A., Poursaeidi, M.H., Mohammadpour, J., Malki, H.A., Grigoriads, K., 2012. Stochastic model predictive control method for microgrid management. Presented at 2012 IEEE Power & Energy Society Conference on Innovative Smart Grid Technologies, pp. 1–7.

Hoppecke, 2013. Installation, commissioning and operating instructions for vented stationary lead-acid batteries. Hoppecke, Brilon, Germany.

Huang, A.Q., Crow, M.L., Heydt, G.T., Zheng, J.P., Dale, S.J., 2011. The Future Renewable Electric Energy Delivery and Management (FREEDM) system: the energy Internet. Proc. IEEE 99, 133–148.

Huang, A.Q., She, X., Xunwei, Y., Wang, F., Wang, G., 2013. Next Generation Power Distribution System Architecture: The Future Renewable Electric Energy Delivery and Management (FREEDM) System. Presented at The Third International Conference on Smart Grids, Green Communications and IT Energy-Aware Technologies, ENERGY 2013, Lisbon, Portugal.

Hughes, G., 2012. The Performance of Wind Farms in the United Kingdom and Denmark. Renewable Energy Foundation. London, UK.

Huskinson, B., Marshak, M., Aziz, M.J., Gordon, R.G., 2014a. Small organic molecule based flow battery. WO2014052682 A2.

Huskinson, B., Marshak, M.P., Suh, C., Er, S., Gerhardt, M.R., Galvin, C.J., Chen, X., Aspuru-Guzik, A., Gordon, R.G., Aziz, M.J., 2014b. A metal-free organic–inorganic aqueous flow battery. Nature 505, 195–198.

Huskinson, B., Marshak, M., Suh, C., Er, S., Gerhardt, M.R., Galvin, C.J., Chen, X., Chen, Q., Tong, L., Aspuru-Guzik, A., Gordon, R.G., Aziz, M.J., 2014c. Organic-Based Aqueous Flow Batteries for Massive Electrical Energy Storage. Presented at 2nd International Conference on Multiscale Renewable Energy Storage, Northeastern University, Boston, Massachusetts, US, 19 August.

Hydro Tasmania, 2015. "KIREIP | King Island Renewable Energy Integration Project." *http://www.kingislandrenewableenergy.com.au/.*

IDMLL, 2015. Intelligent DC Microgrid Living Lab. http://www.et.aau.dk/research-programmes/microgrids/activities/intelligent-dc-microgrid-living-lab/ (accessed 27 August 2015).

IEA, 2014. Technology Roadmap Solar Photovoltaic Energy. OECD/IEA, Paris, France.

IEA, 2013a. Tracking Clean Energy Progress 2013. OECD/IEA, Paris, France.

IEA, 2013b. Technology Roadmap: Wind Energy – 2013 edition. OECD/IEA, Paris, France.

IEA, 2012a. Tracking Clean Energy Progress. OECD/IEA, Paris, France.

IEA, 2012b. Technology Roadmap. Hydropower. OEACD/IEA, Paris, France.

IEA-ETSAP and IRENA, 2015a. Hydropower Technology Brief. International Energy Agency Energy Technology Systems Analysis Program and International Renewable Energy Agency. http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP_Tech_Brief_E06_Hydropower.pdf.

IEA-ETSAP and IRENA, 2015b. Biomass for Heat and Power Technology Brief. International Energy Agency Energy Technology Systems Analysis Program and International Renewable Energy Agency. http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP_Tech_Brief_E05_Biomass%20for%20Heat%20and%20Power.pdf.

IEA-ETSAP and IRENA, 2013. Technology Brief E11: Solar Photovoltaics. International Energy Agency Energy Technology Systems Analysis Program and International Renewable Energy Agency. https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E11%20Solar%20PV.pdf.

IEA-PVPS, 2011. The role of energy storage for mini-grid stabilization (No. T11-02:2011). International Energy Agency Photovoltaic Power Systems Programme, St. Ursen, Switzerland.

IEA Wind, 2013. Long-term Research and Development Needs for Wind Energy for the Time 2012 to 2030. International Energy Agency, Paris, France.

IEC, 2014. Utility-interconnected photovoltaic inverters – Test procedure of islanding prevention measures. International Electrotechnical Commission, Geneva, Switzerland.

IEC, 2013. IEC TS 62257: Recommendations for small renewable energy and hybrid systems for rural electrification. International Electrotechnical Commission, Geneva, Switzerland.

IEC, 2011. Electrical Energy Storage. International Electrotechnical Commission, Geneva, Switzerland.

IEEE, 2015. IEEE SA – P2030.7 – Standard for the Specification of Microgrid Controllers. Institute of Electrical and Electronics Engineers, New York, US. http://standards.ieee.org/develop/project/2030.7.html (accessed 27 August 2015).

IEEE, 2014. Alegria, E., Brown, T., Minear, E., Lasseter, R.H., 2014. CERTS Microgrid Demonstration With Large-Scale Energy Storage and Renewable Generation. IEEE Transactions on Smart Grid 5 (2), 937–943.

IEEE, 2003. IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. IEEE Std 1547-2003, 1–28. http://ieeexplore.ieee.org/xpl/abstractMetrics.jsp?tp=&arnumber=6670071&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6670071.

IEI, 2014. Innovations Across the Grid. Partnerships Transforming the Power Sector. Edison Foundation Institute for Electric Innovation, Washington, D.C.

IIT, 2015. Microgrid at Illinois Institute of Technology. http://iitmicrogrid.net/ (accessed 27 August 2015).

Inam, W., Afridi, K.K., Perreault, D.J., 2014. High efficiency resonant DC/DC converter utilizing a resistance compression network. IEEE Trans. Power Electron. 29, 4126–4135.

Industrial Internet Consortium, 2015. Industrial Internet Consortium announces smart grid testbed. Press release, 26 March. http://www.iiconsortium.org/press-room/03-26-15.htm.

INENSUS, 2011. The business model of micro power economy. http://www.inensus.de/download/MicroPowerEconomy.pdf (accessed 11 June 2015).

Infineon Technologies, 2014. German researchers cut energy loss in half: renewable energy sources, telecommunications and lighting systems profit from new semiconductor materials. Press release, 23 June. http://www.infineon.com/cms/en/about-infineon/press/press-releases/2014/INFXX201406-048.html.

IRENA, 2015a. Off-grid Renewable Energy Systems: Status and Methodological Issues. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2015b. Renewable Power Generation Costs in 2014. IRENA, Abu Dhabi, UAE.

IRENA, 2015c. Battery Storage for Renewables: Market Status and Technology Outlook. IRENA, Abu Dhabi, UAE.

IRENA, 2015d. Global Atlas for Renewable Energy. *http://irena.masdar.ac.ae/* (accessed 21 September 2015).

IRENA, 2015e. Renewables and Electricity storage. A Technology Roadmap for REmap 2030. IRENA, Abu Dhabi, UAE.

IRENA, 2015f. Renewable Energy Technology Innovation Policy. A Process Development Guide. IRENA, Abu Dhabi, UAE.

IRENA, 2015g. IRENA INSPIRE – Information platform on renewable energy patents and standards. *http://inspire.irena.org/Pages/default.aspx* (accessed 2 October 2015).

IRENA, 2013. Renewable Energy Innovation Policy: Success Criteria and Strategies. IRENA, Abu Dhabi, UAE.

IRENA, 2012a. Wind Power (Volume 1: Power Sector, Issue 5/5), Renewable Energy Technologies: Cost Analysis Series. IRENA, Abu Dhabi, UAE.

IRENA, 2012b. Biomass for Power Generation (Volume 1: Power Sector, Issue 1/5), Renewable Energy Technologies: Cost Analysis Series. IRENA, Abu Dhabi, UAE.

IRENA, 2012c. Hydropower (Volume 1: Power Sector, Issue 3/5), Renewable Energy Technologies: Cost Analysis Series. IRENA, Abu Dhabi, UAE.

IRENA, 2012d. Electricity Storage and Renewables for Island Power: A Guide for Decision Makers. IRENA, Abu Dhabi, UAE.

IRENA, 2012e. Electricity Storage: Technology Brief. IRENA, Abu Dhabi, UAE.

Irvine, S.J.C., Candelise, C., 2014. Chapter 1. Introduction and Techno-economic Background, in: Irvine, S.J.C. (Ed.), RSC Energy and Environment Series. Royal Society of Chemistry, Cambridge, UK, pp. 1–26.

Islam, S.M.F., 2014. Financing, Policy and Regulatory Issues of Mini-grids.

ITC, 2016. Interview on Renewable Energy Innovation Outlook: Mini-grids.

Jaffe, S., 2014. The Lithium Ion Battery Market.

Jaskula, B.W., Mahdavi, M., Wallace, G.J., 2013. 2012 Minerals Yearbook – Lithium (Advance Release). US Geological Survey, Reston, Virginia, US.

Jeong, Y.J., Jang, J., Nam, S., Kim, K., Kim, L.H., Park, S., An, T.K., Park, C.E., 2014. High-performance organic complementary inverters using monolayer graphene electrodes. ACS Appl. Mater. Interfaces 6, 6816–6824.

Jordan, D.C., Kurtz, S.R., 2012. Photovoltaic degradation rates – an analytical review. Prog. Photovolt. Res. Appl.

JRC, 2013. RE2nAF. European Commission Join Research Centre Institute for Energy and Transport. *http://sunbird.jrc.it/re2naf.html (accessed 21 September 2015).*

Justo, J.J., Mwasilu, F., Lee, J., Jung, J.-W., 2013. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew. Sustain. Energy Rev. 24, 387–405.

Kaldellis, J.K., 2010. Stand-Alone and Hybrid Wind Energy Systems: Technology, Energy Storage and Applications. Woodhead Publishing, Cambridge, UK.

Karabiber, A., Keles, C., Kaygusuz, A., Alagoz, B.B., 2013. An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids. Renew. Energy 52, 251–259.

Kathiravan, P., Govindaraju, C., 2015. Implementation of multiport DC-DC converter of renewable energy for high power management application. Int. J. Concurr. Appl. Res. Eng. Manag. 1, 109–113.

Kayastha, N., Niyato, D., Hossain, E., Han, Z., 2014. Smart grid sensor data collection, communication, and networking: a tutorial. Wirel. Commun. Mob. Comput. 14, 1055–1087.

Khalifa, T., Naik, K., Nayak, A., 2010. A Survey of Communication Protocols for Automatic Meter Reading Applications (IEEE Communications Surveys & Tutorials).

KIC InnoEnergy, 2015. XGaTe. *http://www.kic-innoenergy.com/innovationproject/our-innovation-projects/xgate/* (accessed 19 September 2015).

KIC InnoEnergy, 2014. Future Renewable Energy Costs: Onshore Wind. KIC InnoEnergy, Eindhoven, The Netherlands.

Kim, B.J., Lee, S.-K., Kang, M.S., Ahn, J.-H., Cho, J.H., 2012. Coplanar-gate transparent graphene transistors and inverters on plastic. ACS Nano 6, 8646–8651.

Kjærside Storm, B., 2013. 12 – Surface protection and coatings for wind turbine rotor blades, in: Brøndsted, P., Nijssen, R.P.L. (Eds.), Advances in Wind Turbine Blade Design and Materials, Woodhead Publishing, Cambridge, UK, pp. 387–412.

Klemun, M., 2014. 5 market trends that will drive microgrids into the mainstream. Greentech Media. 9 April. *http://www.greentechmedia.com/articles/read/5-Market-Trends-That-Will-Drive-Microgrids-Into-the-Mainstream.*

Komor, P., Molnar, T., 2015. Background Paper on Distributed Renewable Energy Generation and Integration. United Nations Framework Convention on Climate Change, Bonn, Germany.

Kost, C., Mayer, J., Thomsen, J., Hartmann, N., Senkpiel, C., Philipps, S., Nold, S., Lude, S., Saad, N., Schlegl, T., 2013. Levelized Cost of Electricity. Renewable Energy Technologies. Fraunhofer Institute ISE, Freiburg, Germany.

Koutroulis, E., Blaabjerg, F., 2011. Methods for the optimal design of grid-connected PV inverters. Int. J. Renew. Energy Res. 1, 55–64.

KPMG, 2015. Energy – Quo Vadis? 2035Plus: Scenarios for Tomorrow's Energy Sector. KPMG. *http://www.kpmg.com/DE/de/Documents/energy-en-sec-2015-kpmg.pdf.*

Kullingsjö, L.-H., 2011. Drivers and barriers to renewable energy systems in Tanzania – perceptions of systems' workability among key stakeholders. Chalmers University of Technology, Gothenburg, Sweden.

Kumar, A., Schei, T., Ahenkora, A., Caceres Rodriguez, R., Devernay, J.-M., Freitas, M., Hall, D., Killingtveit, Å., Liu, Z., 2011. Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, UK and New York, NY, US.

Kumar Sahu, B., 2015. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. Renew. Sustain. Energy Rev. 43, 621–634.

Laaksonen, H.J., 2010. Protection principles for future microgrids. IEEE Trans. Power Electron. 25, 2910–2918.

Lantz, E., Wiser, R., Hand, M., 2014. WP2 IEA Wind Task 26: The Past and Future Cost of Wind Energy. International Energy Agency Wind, Paris, France.

Lasseter, R.H., 2007. Microgrids and distributed generation. J. Energy Eng. 133, 144–149.

LeVine, S., 2015. The story of the invention that could revolutionize batteries — and maybe American manufacturing as well. Quartz.

LG, 2015. Smart appliances: discover LG's Smart ThinQ appliances. *http://www.lg.com/us/discover/smartthinq/thinq* (accessed 21 September 2015).

Liang, T.-J., Lee, J.-H., 2015. Novel high-conversion-ratio high-efficiency isolated bidirectional DC-DC converter. IEEE Trans. Ind. Electron. 62, 4492–4503.

Li, B.Y., Xu, K., Li, Y.M., Li, X.Y., 2013. Research on the application of new active inverter technology in battery maintenance. Appl. Mech. Mater. 448-453, 2077–2084.

Li, B., Nie, Z., Vijayakumar, M., Li, G., Liu, J., Sprenkle, V., Wang, W., 2015. Ambipolar zinc-polyiodide electrolyte for a high-energy density aqueous redox flow battery. Nature Communications 6 (February).

Lidow, A., Strydom, J., 2012. Benchmark DC-DC Conversion Efficiency with eGaN FET-Based Buck Converters. Efficient Power Conversion Corporation, El Segundo, California, US.

Lin, H., Liu, C., Guerrero, J.M., Vasquez, J.C., Dragicevic, T., 2014. Modular power architectures for microgrid clusters. Presented at 2014 International Conference on Green Energy, pp. 199–206.

London Metal Exchange, 2015. Lead. *http://www.lme.com/metals/non-ferrous/lead/* (accessed 30 September 2015).

Lovins, A.B., 1990. The negawatt revolution. Across Board (New York) 27, 18–23.

Low Carbon Future, 2013. Superconducting magnetic energy storage.

Lu, J., Amine, K., 2013. Recent research progress on non-aqueous lithium-air batteries from Argonne National Laboratory. Energies 6, 6016–6044.

Luna, A.C., Diaz, N.L., Andrade, F., Graells, M., Guerrero, J.M., Vasquez, J.C., 2015. Economic power dispatch of distributed generators in a grid-connected microgrid. Presented at the 2015 9th International Conference on

Power Electronics and ECCE Asia (ICPE-ECCE Asia), pp. 1161–1168.

Lundstrom, B., Shirazi, M., Coddington, M., Kroposki, B., 2013. An advanced platform for development and evaluation of grid interconnection systems using hardware-in-the-loop: Part III – Grid Interconnection System Evaluator. Presented at the 2013 IEEE Green Technologies Conference, pp. 392–399.

Ma, Z., Yuan, X., Li, L., Ma, Z.-F., Wilkinson, D.P., Zhang, L., Zhang, J., 2015. A review of cathode materials and structures for rechargeable lithium–air batteries. Energy Environ. Sci. 8, 2144–2198.

Maabong, K., Muiva, C.M., Monowe, P., Sathiaraj, S.T., Hopkins, M., Nguyen, L., Malungwa, K., Thobega, M., 2015. Natural pigments as photosensitizers for dye-sensitized solar cells with TiO2 thin films. Int. J. Renew. Energy Res. 5, 54–60.

Madakasira, P., 2013. GaN and SiC-based power electronics set to deliver big value in distributed solar installations. 18 May. *http://blog.luxresearchinc.com/blog/2013/05/gan-and-sic-based-power-electronics-set-to-deliver-big-value-in-distributed-solar-installations/.*

Madsen, B., Brøndsted, P., Andersen, T.L., 2013. 11 – Biobased composites: materials, properties and potential applications as wind turbine blade materials, in: Brøndsted, P., Nijssen, R.P.L. (Eds.), Advances in Wind Turbine Blade Design and Materials. Woodhead Publishing, Cambridge, UK, pp. 363–386.

Mankowsky, R., Subedi, A., Först, M., Mariager, S.O., Chollet, M., Lemke, H.T., Robinson, J.S., Glownia, J.M., Minitti, M.P., Frano, A., Fechner, M., Spaldin, N.A., Loew, T., Keimer, B., Georges, A., Cavalleri, A., 2014. Nonlinear lattice dynamics as a basis for enhanced superconductivity in YBa2Cu3O6.5. Nature 516, 71–73.

Mao, M., Jin, P., Hatziargyriou, N.D., Chang, L., 2014. Multiagent-based hybrid energy management system for microgrids. IEEE Trans. Sustain. Energy 5, 938–946.

Marketwired, 2015. Princeton Power unveils silicon-carbide power converter demonstration. Press release, 1 June. *http://www.marketwired.com/press-release/princeton-power-unveils-silicon-carbide-power-converter-demonstration-2028878.htm.*

marketsandmarkets.com, 2014a. Microgrid Market by Type (Hybrid, Off-Grid, Grid Connected), Component (Storage, Inverter), Technology (Fuel Cell, CHP), Consumer Pattern (Urban, Rural), Application (Campus, Commercial, Defense), and Geography – Global Forecast to 2022. Markets and Markets, Pune, India

marketsandmarkets.com, 2014b. Advanced Metering Infrastructure (AMI) market worth $20.03 billion by 2019. Markets and Markets, Pune, India.

Marnay, C., Kroposki, B., Mao, M., Xu, H., Chong, A., Chung, S., Hara, R., Ise, T., Iravani, R., Katiraei, F., Albu, M., Hatziargyriou, N., Funabashi, T., Reilly, J., Driesen, J., Jimenez, G., Vallve, X., 2015. The Tianjin 2014 Symposium on Microgrids: A meeting of the minds for international microgrid experts. IEEE Electrification Mag. 3, 79–85.

Marnay, C., Lanzisera, S., Stadler, M., Lai, J., 2012a. Building Scale DC Microgrids. Presented at the IEEE EnergyTech2012 Conference, Cleveland, Ohio, US.

Marnay, C., Zhou, N., Qu, M., Romankiewicz, J., 2012b. International Microgrid Assessment: Governance, INcentives, and Experience (IMAGINE). Lawrence Berkley National Laboratory, Berkeley, California, US. *http://eetd.lbl.gov/sites/all/files/publications/lbl-5914e-imagine-microgridsjune-2012.pdf.*

Marotti, A., 2016. ComEd gets $4 million to build microgrid in Bronzeville. Chicago Tribune, 26 January.

Matteson, S., Williams, E., 2015. Residual learning rates in lead-acid batteries: Effects on emerging technologies. Energy Policy 85, 71–79.

Mazloomi, K., Sulaiman, N.B., Moayedi, H., 2012. Electrical efficiency of electrolytic hydrogen production. Int. J. Electrochem. Sci. 7, 3314 – 3326.

Mazumder, S., Chang, L., 2014. Grid Interconnection Standards for Distributed Resources and Microgrids. Presented at IEEE Applied Power Electronics Conference and Exposition ISS.

McKeon, B.B., Furukawa, J., Fenstermacher, S., 2014. Advanced lead-acid batteries and the development of grid-scale energy storage systems. Proc. IEEE 102, 951–963.

McLarty, D., Civit Sabate, C., Brouwer, J., Jabbari, F., 2015. Micro-grid energy dispatch optimization and predictive control algorithms; a UC Irvine case study. Int. J. Electr. Power Energy Syst. 65, 179–190.

Meagher, K., 2015. Interview on Renewable Energy Innovation Outlook: Mini-grids.

Meinhardt, M., Rothert, M., Engler, A., 2003. New V/f-Statics controlled Battery Inverter: Sunny Island – the key component for AC Coupled Hybrid Systems and

Mini Grids. Presented at the 2nd European PV-Hybrid and Mini-Grid Conference.

Meng, L., Savaghebi, M., Andrade, F., Vasquez, J.C., Guerrero, J.M., Graells, M., 2015. Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University. Presented at the IEEE Applied Power Electronics Conference and Exposition, pp. 2585–2592.

Meral, M.E., Dinçer, F., 2011. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renew. Sustain. Energy Rev. 15, 2176–2184.

Metz, A., Fischer, M., Xing, G., Yong, L., Julsrud, S., 2014. International Technology Roadmap for Photovoltaic (ITRPV): 2013 Results. Frankfurt, Germany.

MIGEDIR, 2015. MIGEDIR – MIcrorredes con GEneración DIstribuida de Renovables. *http://www.microrredesinteligentes.com/migedir.php* (accessed 30 September 2015).

Mirani, A.A., Ahmad, M., Kalwar, S.A., Ahmad, T., 2013. A rice husk gasifier for paddy drying. Sci Tech Dev 32, 120–125.

MIT, 2015. The Future of Solar Energy. An Interdisciplinary MIT Study. Massachusetts Institute of Technology, Cambridge, Massachusetts, US.

Mitra, I., Degner, T., Braun, M., 2008. Distributed generation and microgrids for small island electrification in developing countries: a review. SESI J. 18, 6–20.

Mohan, A., Rajan, A., 2015. A novel transformer less boost/buck DC-AC converter with current control. Int. J. Adv. Res. Electr. Electron. Instrum. Eng. 4.

Moner-Girona, M., 2009. A new tailored scheme for the support of renewable energies in developing countries. Energy Policy 37, 2037–2041.

Moner-Girona, M., Ghanadan, R., Solano-Peralta, M., Kougias, I., Bódis, K., Huld, T., Szabó, S., 2016. Adaptation of feed-in tariff for remote mini-grids: Tanzania as an illustrative case. Renew. Sustain. Energy Rev. 53, 306–318.

Mueller, S.C., Sandner, P.G., Welpe, I.M., 2015. Monitoring innovation in electrochemical energy storage technologies: a patent-based approach. Appl. Energy 137, 537–544.

Mueller-Stoffels, M., 2015. Alaska Center for Energy and Power (ACEP) Power Systems Integration (PSI). *http://acep.uaf.edu/programs/power-systems-integration.aspx* (accessed 21 September 2015).

Mueller-Stoffels, M., Light, D., Holdmann, G., Sheets, B., 2013. Gridform inverter tests and assessment. Alaska Center for Energy and Power (ACEP), Fairbanks, Alaska, US.

Murrill, M., Sonnenberg, B.J., 2010. Evaluating the Opportunity for DC Power in the Data Center (White Paper). Emerson Network Power, Columbus, Ohio, US.

Ndiaye, A., Charki, A., Kobi, A., Kébé, C.M.F., Ndiaye, P.A., Sambou, V., 2013. Degradations of silicon photovoltaic modules: a literature review. Sol. Energy 96, 140–151.

Neves, D., Silva, C.A., 2015. Optimal electricity dispatch on isolated mini-grids using a demand response strategy for thermal storage backup with genetic algorithms. Energy 82, 436–445.

new energy husum, 2014. Small Wind World Report. World Wind Energy Association, Bonn, Germany.

Nexight Group, 2010. Advanced Materials and Devices for Stationary Electrical Energy Storage Applications. US Department of Energy, Washington, D.C., US.

Nique, M., Opala, K., 2014. The synergies between mobile, energy and water access: Africa. GSM Association, London, UK.

Nitta, N., Wu, F., Lee, J.T., Yushin, G., 2015. Li-ion battery materials: present and future. Mater. Today 18, 252–264.

Nordman, B., Christensen, K., 2015. The need for communications to enable DC power to be successful. Presented at 2015 IEEE First International Conference on DC Microgrids, Atlanta, Georgia, US, pp. 108–112.

Noritake, M., Yuasa, K., Takeda, T., Hoshi, H., Hirose, K., 2014. Demonstrative research on DC microgrids for office buildings. Presented at IEEE 36th International Telecommunications Energy Conference (INTELEC), Vancouver, British Columbia, Canada, pp. 1–5.

Norplan, 2013. Norplan Study: Cost Competitiveness of Rural Electrification Solutions. Norplan and Norad, Oslo, Norway.

NREL, 2015. Best Research-Cell Efficiencies. US National Renewable Energy Laboratory. Golden, Colorado, US.

NREL, 2014. Advanced Inverter Functions to Support High Levels of Distributed Solar. US National Renewable Energy Laboratory. Golden, Colorado, US.

NREL, Mather, B., Schauder, C., 2014. Advanced Inverter Technology for High Penetration Levels of PV Generation in Distribution Systems. US National Renewable Energy Laboratory. Golden, Colorado, US.

NREL, 2012. NREL enhances the performance of a lithium-ion battery cathode. Innovation 303 (October). *http://www.nrel.gov/docs/fy13osti/55947.pdf.*

Nutkani, I.U., Loh, P.C., Blaabjerg, F., 2012. Power flow control of interlinked hybrid microgrids. Presented at 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC), Novi Sad, Serbia, pp. DS3b.17–1–DS3b.17–6.

NY DPS, 2016. Reforming the Energy Visions (REV). New York State Department of Public Service. *http://www3.dps.ny.gov/W/PSCWeb.nsf/All/CC4F2EFA3A23551585257DEA007DCFE2?OpenDocument* (accessed 25 March 2016).

Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nat. Clim. Change 5, 329–332.

NYSERDA, 2015a. NY Prize Competition Structure. New York State Energy Research and Development Authority. *http://www.nyserda.ny.gov/All-Programs/Programs/NY-Prize/Competition-Structure (accessed 14 September 2015).*

NYSERDA, 2015b. NY Prize Community Grid Competition RFP 3044. New York State Energy Research and Development Authority, Albany, New York, US.

NYSERDA, 2014. Toward a Clean Energy Future – A Strategic Outlook. New York State Energy Research and Development Authority, Albany, New York, US.

Oh, S.H., Lee, C.-W., Chun, D.H., Jeon, J.-D., Shim, J., Shin, K.H., Yang, J.H., 2014. A metal-free and all-organic redox flow battery with polythiophene as the electroactive species. J Mater Chem A 2, 19994–19998.

Office of the Federal Register and National Archives and Records Administration. 2007. United States Statutes at Large, V. 121, 2007, 110th Congress, First Session, Pts. 1-2. Government Printing Office, Washington, D.C.

Olivares, D.E., Mehrizi-Sani, A., Etemadi, A.H., Canizares, C.A., Iravani, R., Kazerani, M., Hajimiragha, A.H., Gomis-Bellmunt, O., Saeedifard, M., Palma-Behnke, R., Jimenez-Estevez, G.A., Hatziargyriou, N.D., 2014. Trends in microgrid control. IEEE Trans. Smart Grid 5, 1905–1919.

Ontario Ministry of Energy, 2014. Panasonic Eco Solutions Canada. *http://www.energy.gov.on.ca/en/smart-grid-fund/smart-grid-fund-projects/panasonic-eco-solutions-canada/.*

OPS, 2015. Exploring the issues of sustainability and renewable energy. Optimal Power Solutions Blog.

Ossenbrink, H., Huld, T., Waldau, A.J., Taylor, N., 2013. Photovoltaic Electricity Cost Maps. European Commission Joint Research Centre. Brussels, Belgium.

Outback Power, 2013. OutBack power unveils GridZero energy balancing. Press release, 27 February. *http://www.outbackpower.com/about/press-releases/148-outback/news/news-2014/376-outback-power-unveils-gridzero-energy-balancing.*

Oxford PV, 2015. Next generation solar power.

Ozpineci, B., Xu, Y., King, T., Rizy, T., 2011. Power Conversion Systems for Microgrids. Oak Ridge National Laboratory, Oak Ride, Tennessee, US.

Padilla, E., Agbossou, K., Cardenas, A., 2014. Towards smart integration of distributed energy resources using distributed network protocol over ethernet. IEEE Trans. Smart Grid 5, 1686–1695.

Palizban, O., Kauhaniemi, K., Guerrero, J.M., 2014. Microgrids in active network management — Part I: Hierarchical control, energy storage, virtual power plants, and market participation. Renew. Sustain. Energy Rev. 36, 428–439.

Papageorgiou, N., 2015. Graphene multiplies the power of light. Éc. Polytech. Fedérale Lausanne.

Parikh, P.P., Kanabar, M.G., Sidhu, T.S., 2010. Opportunities and challenges of wireless communication technologies for smart grid applications. Presented at the 2010 IEEE Power and Energy Society General Meeting, Minneapolis, Minnesota, US, pp. 1–7.

Parisio, A., Rikos, E., Tzamalis, G., Glielmo, L., 2014. Use of model predictive control for experimental microgrid optimization. Appl. Energy 115, 37–46.

Park, H.W., Lee, D.U., Park, M.G., Ahmed, R., Seo, M.H., Nazar, L.F., Chen, Z., 2015. Perovskite–nitrogen-doped carbon nanotube composite as bifunctional catalysts for rechargeable lithium–air batteries. ChemSusChem 8, 1058–1065.

Pathak, A.K., Khan, M., Gschneidner, K.A., McCallum, R.W., Zhou, L., Sun, K., Dennis, K.W., Zhou, C., Pinkerton, F.E., Kramer, M.J., Pecharsky, V.K., 2015. Cerium: an unlikely replacement of dysprosium in high performance Nd–Fe–B permanent magnets. Adv. Mater. 27, 2663–2667.

Pauzet, O., 2011. The future of smart metering: the case for public cellular communications. Sierra Wireless, Richmond, Canada.

Peters, C., 2013. SBIR Phase I: Low-Cost, Copper-Based Metallization Pastes for Solar Cell Applications. Plant PV, Oakland, California, US.

Phadke, A.A., Jacobson, A., Park, W.Y., Lee, G.R., Alstone, P., Khare, A., 2015. Powering a Home with Just 25 Watts of Solar PV: Super-Efficient Appliances Can Enable Expanded Off-Grid Energy Service Using Small Solar Power Systems. Lawrence Berkeley National Laboratory, Berkeley, California, United States.

Pham, C., Biris, V.-C., Teodorescu, R., Kerekes, T., Máthé, L., 2013. SiC-based high efficiency bidirectional battery converter for smart PV residential systems. Proc. PCIM Eur., 129–36.

Pika Energy, 2015. Our microgrid technology. *http://www.pika-energy.com/company/our-technology/.*

Pittet, A., 2012. An overview of technical aspects of mini-grids: Village Electrification through Sustainable use of Renewable Energy (VE-SuRE). Swiss Agency for Development and Cooperation, Bern, Switzerland.

PNNL, 2012. Lithium Air Electrodes. US Pacific Northwest National Laboratory, Richland, Washington, US.

POWAIR, 2015. Overview. POWAIR Zinc-Air Flow Batteries. *http://www.powair.eu/index.php?option=com_content&view=article&id=18&Itemid=19* (accessed 27 August 2015).

Power Analytics, 2015. Microgrid Basics: Power Flow Optimization with the Power Analytics Paladin® Microgrid Power Management System™ (MPMS). Power Analytics Corporation, Raleigh, North Carolina, US.

Powerhive, 2015. A highly scalable, sustainable energy access solution. Berkeley, California, US.

PPC, 2012. Xiamen University partners with leading technology and energy providers to build China's first direct-current microgrid. Press release. People Power Company, 19 March. *http://www.marketwired.com/press-release/xiamen-university-partners-with-leading-technology-energy-providers-build-chinas-1633316.htm.*

Purdue Polytechnic, 2015. Research Projects – Purdue Polytechnic Institute. *https://polytechnic.purdue.edu/facilities/grid-efficiency-lab-gel/research-projects* (accessed 16 September 2015).

PV Cycle, 2013. Annual Report 2013.

pvXchange, 2015. Price index. *http://pvxchange.com/priceindex/Default.aspx?langTag=en-GB* (accessed 27 April 2015).

Rajaraman, V., Jhunjhunwala, A., Kaur, P., Rajesh, U., 2015. Economic analysis of deployment of DC power and appliances along with solar in urban multi-storied buildings. 2015 IEEE First International Conference on DC Microgrids, Atlanta, Georgia, US, pp. 32–37.

REbus Alliance, 2015. REbus DC Microgrid. *http://rebuspower.com/* (accessed 30 September 2015).

REE, 2016. Demanda y producción en tiempo real. Red Eléctrica de España. *http://ree.es/es/actividades/demanda-y-produccion-en-tiempo-real* (accessed 31 March 2016).

RMI, HOMER Energy, CohnReznick Think Energy, Bronski, P., Creyts, J., Guccione, W., L.., Madrazo, M., Mandel, J., Rader, B., Lilienthal, P., Glassmire, J., Abromowitz, J., Crowdis, M., Richardson, J., Schmitt, E., Tocco, H., 2014. The economics of grid defection: When and where distributed solar generation plus storage competes with traditional utility service. Rocky Mountain Institute, Colorado, US.

RMI and Carbon War Room. 2015. Renewable Microgrids: Profiles from Islands and Remote Communities Across the Globe. Rocky Mountain Institute, Boulder, Colorado. *http://www.rmi.org/Content/Files/RMI-Islands-RenewableMicrogrids-FINAL-20151103.pdf.*

Roebuck, K., 2012. Microgrids: High-impact Strategies – What You Need to Know: Definitions, Adoptions, Impact, Benefits, Maturity, Vendors. Emereo Publishing, Aspley, Queensland, Australia.

Rolland, S., Glania, G., 2011. Hybrid mini-grids for rural electrification: lessons learned. Alliance for Rural Electrification and US Agency for International Development, Brussels, Belgium.

Romankiewicz, J., 2014. International Microgrid Assessment: Governance, INcentives, and Experience (IMAGINE). Eur. Counc. Energy-Effic. Econ. 2013 Summer Study Energy Effic. Hyeres Fr. 3–8 June 2013.

RWTH Aachen University, 2015. Institute for Power Generation and Storage Systems. *https://www.pgs.*

eonerc.rwth-aachen.de/go/id/dwqe/lidx/1 (accessed 19 September 2015).

SAFT, 2014. Lithium-ion battery systems. Saft SA. Bagnolet, France.

SAIC Canada, Wim van Helden Renewable Heat B.V., 2013. Compact Thermal Energy Storage Technology Assessment Report. Science Applications International Corporation Canada, Ottawa, Ontario, Canada.

Sandia National Laboratories, 2014. The Advanced Microgrid Integration and Interoperability. Albuquerque, New Mexico, US.

Sapru, V., 2014. Global Demand for Lithium-ion Batteries 2020 Vision. Frost & Sullivan, San Antonio, Texas, US.

Saravanan, P., PonGomathi, C., 2014. A boost converter for high voltage applications using three state switching cell. Int. J. Innov. Res. Adv. Eng. 1 (9), 115–121.

Schall, D., Otto, M., Neumaier, D., Kurz, H., 2013. Integrated ring oscillators based on high-performance graphene inverters. Sci. Rep. 3, 2592.

Schlichting, W., Goodman, J., 2014. Ease of installation drives North American PV mounting systems market. Sol. Ind. Mag.

Schnitzer, D., 2015. Interview on Renewable Energy Innovation Outlook: Mini-grids.

Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., von Hirschhausen, C., 2013. Current and Prospective Costs of Electricity Generation until 2050. DIW Berlin, Berlin, Germany.

Schwarzer, U., Buschhorn, S., Vogel, K., 2014. System Benefits for Solar Inverters using SiC Semiconductor Modules. Presented at the PCIM Europe 2014, Nuremberg, Germany.

SE4All, 2015. Clean Energy Mini-grids Actors. Sustainable Energy for All.

Seal, B., EPRI project's 100+ participants, Cleveland, F., Hefner, A., IEC TC57 WG17 members, 2012. Distributed Energy Management (DER): Advanced Power System Management Functions and Information Exchanges for Inverter-based DER Devices, Modelled in IEC 61850-90-7 (Version 27).

Sekisui Chemical Co. Ltd., 2013. NEC develops advanced lithium ion battery with high-energy density. Press release, 1 October.

Service, R.F., 2015. Tailpipe to tank. Science 349, 1158–1160.

Setiawan, M.A., Shahnia, F., Ghosh, A., Rajakaruna, S., 2014. Developing the ZigBee based data payload coding for data communication in microgrids. Presented at the Power Engineering Conference (AUPEC), 2014 Australasian Universities, pp. 1–6.

SEVEA, 2013. Husk Power Systems Case Study. Sevea Co., Ltd., Phnom Penh, Cambodia.

Shah, V., Booream-Phelps, J., 2015. Crossing the Chasm. Solar Grid Parity in a Low Oil Price Era.

Shea, M.J., Arnold, M.S., 2013. 1% solar cells derived from ultrathin carbon nanotube photoabsorbing films. AIP Appl. Phys. Lett. 102.

Shen, J.-M., Jou, H.-L., Wu, J.-C., 2012. Novel transformerless grid-connected power converter with negative grounding for photovoltaic generation system. IEEE Trans. Power Electron. 27, 1818–1829.

Sherman, G., 2015. Connecticut green bank drives energy resiliency Investment. The challenges and opportunities of financing microgrids. State Local Energy Report. *http://stateenergyreport.com/2015/02/12/ct-greenbanks/* (accessed 20 May 2015).

Shiomi, M., Funato, T., Nakamura, K., Takahashi, K., Tsubota, M., 1997. Effects of carbon in negative plates on cycle-life performance of valve-regulated lead/acid batteries. J. Power Sources 64, 147–152.

SVTC, 2009. Toward a Just and Sustainable Solar Energy Industry. Silicon Valley Toxics Coalition. San Jose, California, US.

SMA, 2014. Project M5BAT: The world's first modular large-scale battery storage system to be built in Aachen. Press release. Niestetal, Germany.

Smart Inverter Working Group, 2014. Recommendations for Updating the Technical Requirements for Inverters in Distributed Energy Resources: Smart Inverter Working Group Rule 21 Recommendations for the CPUC. California Public Utilities Commission, San Francisco, California, US.

SOCOMEC, 2015. SUNSYS PCS2. Socomec Group, Benfeld, France.

SOFI, 2016. Solar Fuels Institute. *http://www.solar-fuels.org/ (accessed 24 March 2016).*

Solano-Peralta, M., 2015. Estado actual de la energía solar fotovoltaica en Latinoamérica y el Caribe. Organización Latinoamerica de Energía (OLADE), Quito, Ecuador.

Solano-Peralta, M., Moner-Girona, M., van Sark, W.G.J.H.M., Vallvè, X., 2009. "Tropicalisation" of feed-in tariffs: a custom-made support scheme for hybrid PV/diesel systems in isolated regions. Renew. Sustain. Energy Rev. 13, 2279–2294.

Soshinskaya, M., Crijns-Graus, W.H.J., Guerrero, J.M., Vasquez, J.C., 2014. Microgrids: Experiences, barriers and success factors. Renew. Sustain. Energy Rev. 40, 659–672.

Speirs, J., Contestabile, M., Houari, Y., Gross, R., 2014. The future of lithium availability for electric vehicle batteries. Renew. Sustain. Energy Rev. 35, 183–193.

Sridhar, P., Arulkumar, 2014. An efficient single-input multiple output power supply using DC-DC boost converter. Presented at the International Conference on Engineering Technology and Science 2014, Tamil Nadu, India.

Staffell, I., Green, R., 2014. How does wind farm performance decline with age? Renew. Energy 66, 775–786.

Sugumaran, N., Everill, P., Swogger, S.W., Dubey, D.P., 2015. Lead acid battery performance and cycle life increased through addition of discrete carbon nanotubes to both electrodes. J. Power Sources, 9th International Conference on Lead-Acid Batteries – LABAT 2014 279, 281–293.

Sumitomo Electric Industries, Ltd., 2015. Power System R&D Center. *http://global-sei.com/technology/rd/power/ (accessed 15 September 2015).*

Sustainable Power Systems, 2015. Innovation in Microgrid Automation. *http://www.sustainablepowersystems.com/* (accessed 21 September 2015).

Tao, L., Schwaegerl, C., Narayanan, S., Zhang, J.H., 2011. From laboratory microgrid to real markets – challenges and opportunities. Presented at the 2011 IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), pp. 264–271.

Taouil, K., Jellad, T., Chtourou, Z., 2014. Community-coupled microgrids for the implementation of a smart grid in Tunisia. Int. J. Energy Technol. Policy 10, 183–199.

Tenenbaum, B., Greacen, C., Siyambalapitiya, T., Knuckles, J., 2014. From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa. The World Bank, Washington, D.C.

Thien, T., Axelsen, H., Merten, M., Zurmühlen, S., Münderlein, J., Leuthold, M., Uwe Sauer, D., 2015. Planning of Grid-Scale Battery Energy Storage Systems: Lessons Learned from a 5 MW Hybrid Battery Storage Project in Germany. Presented at Battcon 2015, Orlando, Florida, US.

Thirumurthy, N., Harrington, L., Martin, D., Thomas, L., Takpa, J., Gergan, R., 2012. Opportunities and challenges for solar minigrid development in rural India. NREL/TP-7A40-55562. US National Renewable Energy Laboratory, Golden, Colorado, US.

Tool, C.J.J., Burgers, A.R., Manshanden, P., Weeber, A.W., Van Straaten, B.H.M., 2001. Influence of wafer thickness on the performance of multicrystalline Si solar cells: an experimental study. Energy Research Centre of the Netherlands ECN, Petten, The Netherlands.

Trabish, H., 2015. Hawaiian Electric's plan to end solar net metering, explained. Utility Dive. 26 January. *http://www.utilitydive.com/news/hawaiian-electrics-plan-to-end-solar-net-metering-explained/356432/.*

Transphorm, 2015. Transphorm's key partner customer Yaskawa Electric launches PV inverter for mass production. *http://www.transphormusa.com/2015-02-05* (accessed 20 August 2015).

Traversi, F., Russo, V., Sordan, R., 2009. Integrated complementary graphene inverter. AIP Appl. Phys. Lett. 94.

Underwriters Laboratories, 2014. Aging effects on lithium-ion batteries. Sustain. Energy J.

UNDP, 2013. Photovoltaic Power Plants in Lebanon. United Nations Development Programme, Lebanon.

US DOE, 2015a. US Department of Energy Global Energy Storage Database. *http://public.tableau.com/views/DOEGlobalEnergyStorageDatabase/InstallationsOverTime?:embed=y&:showVizHome=no&:host_url=https%3A%2F%2Fpublic.tableausoftware.com%2F&:tabs=yes&:toolbar=yes&:animate_transition=yes&:display_static_image=yes&:display_spinner=yes&:display_overlay=yes&:display_count=yes&:-showVizHome=no&:loadOrderID=0*
(accessed 11 September 2015).

US DOE, 2015b. US Department of Energy Wind and Water Power Program Funding in the United States: Testing, Manufacturing, and Component Development Projects for Utility-scale and Distributed Wind Energy. US Department of Energy, Washington, DC.

US DOE, 2014. Energy Department announces funding to improve the resiliency of the electric grid. US Department of Energy. Press release, 7 February. *http://energy.gov/articles/energy-department-announces-funding-improve-resiliency-electric-grid.*

US DOE, 2013. Grid Energy Storage. US Department of Energy, Washington, D.C.

US DOE, 2012a. Summary Report: US Department of Energy 2012 Microgrid Workshop. Chicago, Illinois, US.

US DOE, 2012b. Carbon-Enhanced Lead-Acid Batteries. US Department of Energy, Washington, D.C.

US DOE, 2011. Power Electronics Research and Development Program Plan. US Department of Energy, Washington, D.C.

US EPA, 2013. Energy Star Market and Industry Scoping Report Solar Inverters. US Environmental Protection Agency, Washington, D.C.

USGS, 2015. Mineral Commodity Summaries 2015 – Lithium. US Geological Survey, Reston, Virginia, US.

Vakalis, S., Baratieri, M., 2014. Technological advancements in small scale biomass gasification: case study of South Tyrol. Presented at the 2nd International Conference on Sustainable Solid Waste Management, Athens, Greece.

Vallvé, X., 2012. Technical note PV2012-4 on inverter type and transfer relay for net metered RE generating plants. CEDRO.

van Helden, W., Rommel, M., 2015. Compact Thermal Energy Storage: Material Development for System Integration. International Energy Agency Solar Heating and Cooling Programme Task 42.

Vigneron, J., Razazian, K., 2012. G3-PLC Powerline Communication Standard for Today's Smart Grid. G3-PLC Alliance.

Villareal, C., Erickson, D., Zafar, M., 2014. Microgrids: A Regulatory Perspective. CPUC Policy Plan. Div. Canadian Patent Utility Coalition.

Virtuani, A., Pavanello, D., Friesen, G., 2012. Overview of Temperature Coefficients of Different Thin Film Photovoltaic Technologies. Presented at 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, 6-10 September, pp. 4248–4252.

Viswanathan, V., Crawford, A., Thaller, L., Stephenson, D., Kim, S., Wang, W., Coffey, G., Balducci, P., Gary Yang, Z., Li, L., others, 2012. Estimation of capital and levelized cost for redox flow batteries. USDOE-OE ESS Peer Review. Washington, D.C.

Viswanathan, V., Kintner-Meyer, M., Balducci, P., Jin, C., 2013. National Assessment of Energy Storage for Grid Balancing and Arbitrage Phase II Volume 2: Cost and Performance. US Department of Energy, Washington, D.C.

Voith, 2015. Voith hydropower turbines. Heidenheim an der Brenz, Germany.

Wang, F., Kim, S.-W., Seo, D.-H., Kang, K., Wang, L., Su, D., Vajo, J.J., Wang, J., Graetz, J., 2015. Ternary metal fluorides as high-energy cathodes with low cycling hysteresis. Nat. Commun. 6, 6668.

Wang, L.Y., Wang, C., Yin, G., Wang, Y., 2014. Weighted and constrained consensus for distributed power dispatch of scalable microgrids. Asian J. Control.

Wang, X., 2014. Managing End-of-Life Lithium-ion Batteries: An Environmental and Economic Assessment. Rochester Institute of Technology, Rochester, New York, US.

Waugaman, B., 2014. Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capabilities Technology Demostration (JCTD). US Department of Defense, Arlington, Virginia, US.

Wei, T.-S., Fan, F.Y., Helal, A., Smith, K.C., McKinley, G.H., Chiang, Y.-M., Lewis, J.A., 2015. Colloidal suspensions: biphasic electrode suspensions for Li-Ion semi-solid flow cells with high energy density, fast charge transport, and low-dissipation flow. Adv. Energy Mater. 5.

Wen, C.X., Liu, Z.Y., Li, Z.X., 2015. Droop control of parallel dual-mode inverters used in micro grid. Presented at 2015 International Conference on Power Electronics and Energy Engineering (PEEE 2015), Hong Kong, China.

Wesoff, E., 2015. Microgrid Evolution: Energizing Co. gets $250M for grid project finance. Greentech Media. 11 May. *http://www.greentechmedia.com/articles/read/*

Microgrid-Evolution-Energizing-Co-Gets-250-Million-for-Grid-Project-Finan.

Westrick, K., 2014. Combining HOMER with GIS Methodologies in Support of Off-Grid Microgrid Policy Development and Financing in Colombia.

Whaite, S., Grainger, B., Kwasinski, A., 2015. Power quality in DC power distribution systems and microgrids. Energies 8, 4378–4399.

Whirlpool, 2015. Smart Appliances Featuring Smart Home Technology Whirlpool. *http://www.whirlpool.com/smart-appliances/* (accessed 21 September 2015).

Whittaker, S., 2013. Challenges to Financing Micro-grids (and other small projects).

Wiemann, M., Lecoque, D., 2015. SE4ALL High Impact Opportunity Clean Energy Mini-grids: Mapping of clean energy mini-grids support providers and programmes.

Wilhelm, C., Kranzer, D., Burger, B., 2010. Development of a highly compact and efficient solar inverter with silicon carbide transistors. Presented at 2010 6th International Conference on Integrated Power Electronics Systems (CIPS), Nuremburg, Germany, pp. 1–6.

Wilkins, G., 2010. Technology Transfer for Renewable Energy. Taylor & Francis Group, Abingdon, UK.

Willems, S., Aerts, W., De Jonge, S., Haeseldonckx, D., van Willigenburg, P., Woudstra, J., Stokman, H., 2013. Lirias: Sustainable Impact and Standardization of a DC Micro Grid. Presented at the Ecodesign International Symposium, KU Leuven, Jeju Island, Republic of Korea.

Wiser, R., Bolinger, M., 2014. 2013 Wind Technologies Market Report. US Department of Energy, Washington, D.C., US.

Wong, D.H.C., Thelen, J.L., Fu, Y., Devaux, D., Pandya, A.A., Battaglia, V.S., Balsara, N.P., DeSimone, J.M., 2014. Nonflammable perfluoropolyether-based electrolytes for lithium batteries. Proc. Natl. Acad. Sci. 111, 3327–3331.

Wood, D.L., Li, J., Daniel, C., 2015. Prospects for reducing the processing cost of lithium ion batteries. J. Power Sources 275, 234–242.

Wood, E., 2015a. But what if the microgrid fails too? Microgrid Knowledge. microknowledge.com.

Wood, E., 2015b. Rumor is true. Oncor unveils first-of-a-kind microgrid. Microgrid Knowledge. microgridknowledge.com.

World Bank Group, 2006. Technical and Economic Assessment of Off-Grid, Mini-Grid, and Grid Electrification Technologies. The World Bank, Washington, D.C.

Xu, J., Dou, S., Liu, H., Dai, L., 2013. Cathode materials for next generation lithium ion batteries. Nano Energy 2, 439–442.

Xu, J.-J., Wang, Z.-L., Xu, D., Meng, F.-Z., Zhang, X.-B., 2014. 3D ordered macroporous $LaFeO_3$ as efficient electrocatalyst for Li–O_2 batteries with enhanced rate capability and cyclic performance. Energy Environ. Sci. 7, 2213.

Yan, Y., Qian, Y., Sharif, H., Tipper, D., 2013. A survey on smart grid communication infrastructures: motivations, requirements and challenges. IEEE Commun. Surv. Tutor. 15, 5–20.

Yang, H., Kannappan, S., Pandian, A.S., Jang, J.-H., Lee, Y.S., Lu, W., 2015. Nanoporous graphene materials by low-temperature vacuum-assisted thermal process for electrochemical energy storage. J. Power Sources 284, 146–153.

Yang, H., Withers, F., Gebremedhn, E., Lewis, E., Britnell, L., Felten, A., Palermo, V., Haigh, S., Beljonne, D., Casiraghi, C., 2014. Dielectric nanosheets made by liquid-phase exfoliation in water and their use in graphene-based electronics. 2D Mater. 1, 011012.

Ye, M., Wen, X., Wang, M., Iocozzia, J., Zhang, N., Lin, C., Lin, Z., 2015. Recent advances in dye-sensitized solar cells: from photoanodes, sensitizers and electrolytes to counter electrodes. Mater. Today 18, 155–162.

Yoo, B.-K., Yang, S.-H., Yang, H.-S., Kim, W.-Y., Jeong, Y.-S., Han, B.-M., Jang, K.-S., 2011. Communication architecture of the IEC 61850-based micro grid system. J. Electr. Eng. Technol. 6, 605–612.

York, D., Molina, M., Neubauer, M., Nowak, S., Nadel, S., Chittum, A., Elliot, N., Farley, K., Foster, B., Sachs, H., Witte, P., 2013. Frontiers of Energy Efficiency: Next Generation Programs Reach for High Energy Savings (No. U131). American Council for an Energy-Efficient Economy, Washington, D.C., US.

You, P., Liu, Z., Tai, Q., Liu, S., Yan, F., 2015. Efficient semitransparent Perovskite solar cells with graphene electrodes. Adv. Mater. 27, 3632–3638.

Zhang, F., 2015. Economic and Market Analysis of DC Microgrid with Photovoltaic – A Case Study from Xiamen University DC Microgrid. Presented at the Symposium on Microgrids, Aalborg, Denmark. *http://microgrid-symposiums.org/wp-content/uploads/2015/09/10-Zhang-Economic-Market-Analysis-20150818.pdf.*

Zhang, F., Yang, Y., Ji, C., Wei, W., Chen, Y., Meng, C., Jin, Z., Zhang, G., 2015. Power management strategy research for DC microgrid with hybrid storage system. Presented at the 2015 IEEE First International Conference on DC Microgrids, Atlanta, Georgia, US, pp. 62–68.

Zhang, Q., 2013. The current status on the recycling of lead-acid batteries in China. Int J Electrochem Sci 8, 6457–6466.

Zhang, Y., Stokes, N., Jia, B., Fan, S., Gu, M., 2014. Towards ultra-thin plasmonic silicon wafer solar cells with minimized efficiency loss. Sci. Rep. 4.

Zhao, X., Liu, S., 2013. Design of a monitoring system of micro-grid. Smart Grid Renew. Energy 04, 198–201.

Zhengyu Lin, Jin Du, Jiande Wu, Xiangning He, 2015. Novel communication method between power converters for DC micro-grid applications. Presented at the 2015 IEEE First International Conference on DC Microgrids, Atlanta, Georgia, US, pp. 92–96.

Zhu, X., Han, X., Qin, W., Wang, P., 2015. Past, today and future development of micro-grids in China. Renew. Sustain. Energy Rev. 42, 1453–1463.

Zhu, Z., Hong, M., Guo, D., Shi, J., Tao, Z., Chen, J., 2014. All-solid-state lithium organic battery with composite polymer electrolyte and pillar[5]quinone cathode. J. Amer. Chem. Soc. 136 (47), 16461–64.

Zimmermann, J., 2015. Interview on Renewable Energy Innovation Outlook: Mini-grids.

Zubieta, L.E., 2015. Power management and optimization concept for DC microgrids. Presented at the 2015 IEEE First International Conference on DC Microgrids, Atlanta, Georgia, US, pp. 81–85.

ANNEX 1:

Detailed drivers for renewable mini-grids

This Annex describes innovation drivers across both phases of technology innovation, through political, economic, social, environmental and technological considerations.

Political and institutional drivers impact market and innovation in both the public and private sectors. These drivers help to establish policy goals, mandates, public initiatives, support mechanisms and regulations. Examples include providing access to energy, increasing the use of renewables, pushing R&D and piloting cutting-edge projects. For example, in many Caribbean islands, government policies to lower the cost of energy are driving the commercial scale-up of renewable energy for the grids of small islands. This illustrates that key drivers include establishing mandates and goals to encourage applied technological innovation. Other political drivers include defined funding sources for renewable mini-grid technologies, and co-ordinated research initiatives in these technologies. Drivers do not always have to be political and can manifest in unusual ways. For example, in Haiti, unevenly enforced and unclear regulations are encouraging non-governmental institutions, such as NRECA and EarthSpark, to use mini-grids to provide energy access. However, these projects are early-stage pilots and are best defined as technology venturing.

Economic drivers involve economic and financial tools to increase the funding available for and quality of renewable mini-grids. These tools include encouraging market-based competition, supplying loans, creating funds and providing grants to encourage technological development. Specific grant funding for research can help to advanced earlier-stage innovation and primary research. A critical economic driver is to provide an alternative to traditional energy supplies and to diversify the energy mix. This is particularly important in areas with limited and expensive options. For off-grid areas, renewable mini-grids provide an economic alternative to diesel generators. For on-grid areas they provide an alternative to utility monopolies and provide resilience.

Social drivers are those that benefit individuals and communities through improved energy options and greater community choice, as well as those that provide basic human rights. Social drivers can include a community's preferences for renewable technologies, as well as human rights and development-focused initiatives to create more sustainable, more reliant electricity. Social factors drive markets and innovation by highlighting the humanitarian goal of improving energy access in underserved areas. Communities, businesses and organisations that strive for more-sustainable energy alternatives are also driving deployment and innovation.

Environmental considerations are important for deployment and innovation, because renewable mini-grids provide one of the least environmentally damaging options for producing reliable power. They enable the use of renewables at high penetration rates, which in turn provide a pathway for the transformation of an electrical sector to derive a majority of energy from renewable sources. They also reduce reliance on fossil fuel as an energy source, providing an alternative to the biggest environmental challenge for stationary electricity. Renewable mini-grids have been used in green marketing programmes and as a way to provide power while addressing environmental concerns generally and, in particular, in environmentally sensitive areas.

Technological drivers include those that lower costs, that improve electrical services, and that address the need to facilitate the integration of renewables as well as the need to bolster the main grid infrastructure. The technological drivers for improved electrical services are the increasing demand for reliable, low-cost power in remote areas, the need to back up the grid from disruptions, and the resilience to recover from disruptive events such as storms and hurricanes. Renewable mini-grids also are increasingly being used to integrate renewables into grids.

In subsequent sections, this report will describe the key technological innovations needed to ensure that the technology drivers can push the technology forward and increase deployment across all renewable mini-grid markets.

Political drivers

Table 34: Political and institutional drivers for renewable mini-grid deployment and innovation

Political and institutional:	Deploy	Innovate	Example	AB	AF	IC	ILI
Basic energy access mandate by government or other	x		In remote, rural areas worldwide solar-based mini-grids are being used increasingly to meet local, national and regional access goals.	x	x		
Electrification today before potential future grid extension is feasible: helps to make a community "grid-ready"	x		The Les Anglais mini-grid in Haiti is designed to connect with the Electricité d'Haïti utility grid if grid extension initiatives reach the community.	x	x		
Government-sponsored programmes, political priorities (funding to spur commercial investment in technology)	x	x	The US DOE SunShot programme established a USD 1/W installed cost goal for utility-scale PV for 2020, which drove manufacturers and installers to push for lower costs. The low cost of solar has benefited renewable mini-grids.	x	x	x	x
Grid security and independence policy goals; demand for local control of generation	x	x	Massachusetts' Community Clean Energy Resiliency Initiative explored the potential for clean energy mini-grids to provide grid resiliency.			x	x
Government regulations that mandate renewable energy penetration at the community level (*e.g.*, renewable portfolio standards) Environmental regulations and requirements	x	x	Boulder, Colorado seeks to create a municipal utility to increase and be able to mandate an increased use of renewable energy.			x	
Public funding, research funds and grants for mini-grids (funding for all phases of fundamental technological research)	x	x	The "Microgrid Research, Development, and System Design" Funding Opportunity Announcement from the US DOE will encourage renewable mini-grid innovation for resiliency. California Energy Commission funds are being used to provide innovation on DC mini-grids.	x	x	x	x

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; Blum et al., 2015; Bourgeois et al., 2013; Brandt, 2015; City of Boulder Colorado, n.d.; Deshmukh, 2014; Executive Office of Energy and Environmental Affairs, 2014; Gershenson et al., 2015; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; IEA, 2012a; Rolland and Glania, 2011; Romankiewicz, 2014; Tenenbaum et al., 2014; US DOE, 2014, 2013b)

Economic drivers

Table 35: Economic drivers for renewable mini-grid deployment and innovation

Economic:	Deploy	Innovate	Example	AB	AF	IC	ILI
Ability to be designed to improve financial sustainability through reduced operational costs, by spending more initially on renewables and storage	x			x	x	x	x
Ability to be used to improve green marketing and to comply with corporate social responsibility goals	x						x
Improve access to capital and loans for deploying renewables technologies	x			x	x	x	x
Low-cost financing and low-interest loans to overcome high upfront costs	x			x	x	x	x
Venture capitalist investment in a technology	x	x	Multiple investments by venture capitalists in new improved battery technology start-ups. Stonepeak Partners USD 250 million finance facility for mini-grids.	x	x	x	x
National or international grants and subsidies for technological innovation and research	x	x	Connecticut Green Bank Drives Energy Resiliency Investment. Mini-grids for a critical facilities fund in New York State. Investment tax credits for renewable energy in the United States for solar, which are applicable to renewable mini-grids, provide funding to deploy near-commercial renewable mini-grid technologies.	x	x	x	
Demand for lower-cost energy supplies than are locally available	x	x		x	x	x	x
Rising grid-energy costs and expensive grid support	x	x				x	x

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; Bourgeois et al., 2013; CE Delft, 2012; Deshmukh, 2014; Fehrenbacher, 2013; Gershenson et al., 2015; Karabiber et al., 2013; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; NYSERDA, 2014; Rolland and Glania, 2011; Romankiewicz, 2014; Sherman, 2015; Tenenbaum et al., 2014; Wesoff, 2015

Social drivers

Table 36: Social drivers for renewable mini-grid deployment and innovation

Social:	Deploy	Innovate	Example	AB	AF	IC	ILI
Development goals, including electricity for productive uses, income-generating activities, social development, improved living conditions, improved health care, and education	X			X	X		
Rising demand from communities and industrial complexes that want reliable, resilient sustainable service	X					X	X
Philanthropic initiatives from charities, NGOs, religious and social organisations to improve energy access in underserved communities	X			X	X		
Consumer and community preferences for renewable energy over other technologies	X					X	X
Improved alignment of technology to meet evolving social demands	X	X	Innovation in metering equipment to provide demand-side management and feedback to users can improve tariff collection rates.	X	X		

Source: Aggarwal and Mohanty, 2015; Gershenson et al., 2015; Graillot et al., 2012; Komor and Molnar, 2015; Kullingsjö, 2011; Rolland and Glania, 2011; Romankiewicz, 2014

Environmental drivers

Table 37: Environmental drivers for renewable mini-grid deployment and innovation

Environmental:	Deploy	Innovate	Example	AB	AF	IC	ILI
Carbon credits and emission trading schemes	X			X	X	X	X
Green marketing and corporate social responsibility	X					X	X
Reduced reliance on fossil fuels	X	X	"Zero fossil fuels for Galapagos" Initiative to deploy mini-grids in the Galapagos Islands.	X	X	X	X
Environmental concerns	X	X	Aquion Energy has created a battery so environmentally friendly that it is advertised as "the battery you can eat", although it is not recommended for actual consumption.	X	X	X	X
Improved integration of distributed renewable energy	X	X	Hawaii and California are exploring the use of mini-grids to mitigate the impacts of variable PV generation on their distribution grids.	X	X	X	X

Source: Karabiber et al., 2013; Rolland and Glania, 2011; Romankiewicz, 2014

Technological drivers

Table 38: Technological drivers for renewable mini-grid deployment and innovation

Technological:	Deploy	Innovate	Example	AB	AF	IC	ILI
Improve service quality and reliability of electricity supply of main grid	X	X	Smart Power Infrastructure Demonstration for Energy Reliability and Security, USA (SPIDERS).			X	X
Provide or improve service in off-grid areas	X	X	GSM remote monitoring is used in rural areas of Africa to track service and energy usage. The information gathered is used to determine maintenance service and to facilitate a pay-as-you-go programme.	X	X		
Improved integration of distributed generation technologies	X	X	The island of Oahu, Hawaii has deployed significant amounts of solar PV on its distribution grid. However, Oahu is now beginning to retrofit the grid with renewable mini-grids to prevent technical problems on the feeders.			X	X
Improved resilience through diversity of supply	X	X	Distributed generation can provide reliable electricity during hazardous events. If residents of the north-eastern United States during 2012's Hurricane Sandy had renewable mini-grids, they would have been able to use their rooftop PV to power local homes and businesses. However, few residents had renewable mini-grid technologies, and they were unable to use their PV assets.			X	X
Utilities' need for grid optimisation for congestion relief and ancillary services	X	X	Australia has one of the largest renewable energy potentials in the world. Utilities servicing remote regions of the country currently supply about 5 GW of energy to remote locations in the outback with liquid fuel and gas power plants. As a result of new technologies such as improved energy storage, the falling cost of renewable energy technology, the rise in fuel costs and the proven reliability of renewable mini-grids, these remote servicing utilities are focusing on renewable-based grid expansions.			X	X
Technological breakthroughs from research and development, to improve performance and lower costs		X	The CERTS created a Microgrid Laboratory Test Bed in 2009 to ease the integration of small energy resources into a microgrid. The sharp decline in PV prices made solar the preferred technology for renewable mini-grids in the past five years.	X	X	X	X

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; IEEE, 2014; Deshmukh, 2014; Eto et al., 2009; Gershenson et al., 2015; IEA-ETSAP and IRENA, 2015a; IRENA, 2012e; Karabiber et al., 2013; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; Nique and Opala, 2014; Rolland and Glania, 2011; Romankiewicz, 2014; Waugaman, 2014; Wilkins, 2010; Zhu et al., 2015)

ANNEX 2:

Barriers to renewable mini-grid innovation

Barriers to innovation in this Annex are grouped by barrier type (political and institutional, economic, social, environmental and technological). In contrast to drivers, barriers are more likely to be split across whether the core goal is improved electrification in autonomous regions (AB, AF type) or improved reliability in interconnected mini-grids (IC, ILI type).

Many of the political barriers are related to the inertia from the historical use of traditional energy generation technologies: subsidies for diesel fuel or the assumption of grid extension in remote areas; in areas already connected to the grid there is an expectation of most power coming from a centralised grid. There is a need to rethink traditional regulation focused in protecting consumers from utilities, towards a framework where renewable mini-grids allow energy consumers to participate in the energy market. In addition, there is limited regulation to adopt quality standards specifically for renewable mini-grids. The development of the IEC 62257-1 (IEC, 2013) standard has been useful for autonomous renewable mini-grids, but its access, adoption by countries and further use is required. Interconnected mini-grids should comply with enacted quality standards and country grid codes, but there is still need to further develop specific codes and standards for their interconnection and operability.

Economic barriers limit technology venturing by limiting the funding available for transitioning to commercial scale-up. In commercial scale-up, these barriers manifest to limit cost-effectiveness and increase investment risk. These barriers may discourage researchers from pursuing research and investors from deploying renewable mini-grids. Research funds are frequently cut, in particular those geared towards new concept ideas. Financing continues to be a barrier, with costs expected to decrease as the use of renewable mini-grids expands, plus further recognition of non-economic added-value of renewable mini-grids.

Social barriers in most cases relate to the perception of renewable mini-grids as being unsuitable for providing access to modern, quality and reliable energy services. Social barriers can clearly limit the deployment of renewable mini-grids, but on the other hand can be the reason for promoting further innovations to address technological concerns. In addition, the diffusion of know-how, experiences, case studies and pilot projects can provide policy makers and communities with better embracing of the technologies.

Even if renewable mini-grids seek to address environmental concerns and increase the use of renewable energy technologies, there are still some barriers and considerations. In particular, as with any other technology, the life cycle and impacts (even if limited) should be assessed and diminished as much as possible.

Finally, technological barriers are clear aspects of innovation challenges that must be addressed. Technological barriers are clear opportunities for improvements and innovations that are discussed in Section 5. The needs for improved controls and further incorporation of variable renewables in generation are crucial aspects to be dealt with.

Identifying a range of barriers for market deployment provides transparency on the obstacles that may be present during the planning, implementation and/or operational phases. These barriers also are known to hinder innovation, but at the same time represent opportunities for innovations themselves to address such hurdles. It is necessary for policy makers, investors, communities and developers to address the aforementioned barriers to mitigate and potentially eliminate these market obstacles. Despite the challenges created by these barriers, the overall benefits of renewable mini-grid installations have proven to far outweigh these hurdles.

Political barriers

Table 39: Political and institutional barriers to renewable mini-grid deployment and innovation

<table>
<tr><th></th><th>AB</th><th>AF</th><th>IC</th><th>ILI</th></tr>
<tr><td rowspan="10">Political</td><td colspan="4">Uncertain government policy, laws and regulations specific to renewable mini-grids</td></tr>
<tr><td colspan="4">Lack of effective institutional arrangements</td></tr>
<tr><td colspan="4">Regulations based on traditional systems applied to mini-grids</td></tr>
<tr><td colspan="2">Limited political leverage/clout in remote areas</td><td colspan="2"></td></tr>
<tr><td colspan="4">Lobbying from non-renewable energy sectors (e.g., natural gas)</td></tr>
<tr><td colspan="2">Political requirements that all communities receive equivalent technological development</td><td colspan="2"></td></tr>
<tr><td colspan="2">Government adherence to funds from top-down international organisations (e.g., widespread use of uniform stand-alone solar home systems)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Subsidies for diesel and petroleum fuels</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td colspan="2">Utility resistance to mini-grids</td></tr>
<tr><td colspan="4">Limited availability and access to technology and quality standards for renewable mini-grid applications</td></tr>
</table>

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; Blum et al., 2015; Bourgeois et al., 2013; Brandt, 2015; City of Boulder Colorado, n.d.; Deshmukh, 2014; Executive Office of Energy and Environmental Affairs, 2014; IEA-ETSAP and IRENA, 2015a; IRENA, 2012e; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; Rolland and Glania, 2011; Romankiewicz, 2014; Tenenbaum et al., 2014; US DOE, 2014, 2013b); key expert interviews

Economic barriers

Table 40: Economic barriers to renewable mini-grid deployment and innovation

<table>
<tr><th></th><th>AB</th><th>AF</th><th>IC</th><th>ILI</th></tr>
<tr><td rowspan="10">Economic</td><td colspan="4">Investment risk from economic and political instability, including corruption, oligarchic democracies, and/or disruptive regime changes</td></tr>
<tr><td colspan="4">Limited access to financing and funding R&D for growth technologies</td></tr>
<tr><td colspan="2">Low ability to pay in rural remote regions coupled with inherently higher energy costs</td><td colspan="2"></td></tr>
<tr><td colspan="4">Lack of subsidies and financial incentives to foster the technology to mature commercial status</td></tr>
<tr><td colspan="4">High start-up and high capital costs compared to other options</td></tr>
<tr><td colspan="2">Limited or no private sector involvement</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td colspan="2">Low utility-grid tariffs and tariffs that subsidise environmental costs (i.e., ignored externality costs)</td></tr>
<tr><td colspan="4">Multilateral bank and government technology selection that focuses mainly/exclusively on lowest-cost solutions (e.g., use of grid extension even if in some cases environmental impacts can be larger, or use of SHS which will provide limited basic access)</td></tr>
<tr><td colspan="2">Parody of: Investments can be “low” in comparison to major infrastructure projects of priority interest to multilateral banks or governments; or prefer other lower-cost solutions</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td colspan="2">Government budget is mainly geared/focused towards technology innovation in military activities/applications (OECD countries R&D in energy represents 1/6 of budget for R&D in defence)</td></tr>
</table>

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; Bourgeois et al., 2013; CE Delft, 2012; Deshmukh, 2014; Fehrenbacher, 2013; Gershenson et al., 2015; Karabiber et al., 2013; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; NYSERDA, 2014; IEA, 2013a; Rolland and Glania, 2011; Romankiewicz, 2014; Sherman, 2015; Tenenbaum et al., 2014; Wesoff, 2015)

Social barriers

<table>
<caption>Table 41: Key social barriers to renewable mini-grid market deployment</caption>
<tr><th></th><th>AB</th><th>AF</th><th>IC</th><th>ILI</th></tr>
<tr><td rowspan="14">Social</td><td colspan="4">Lack of international, national and local legitimacy (e.g., residents may be distrustful of new technologies or projects that do not appear to them to meet their needs)</td></tr>
<tr><td colspan="2">Limited local demand for electricity (e.g., users that have only very basic energy needs such as lighting and mobile phone charging)</td><td colspan="2" rowspan="2"></td></tr>
<tr><td colspan="2">Unsuitable aid/grant criteria for locality</td></tr>
<tr><td colspan="4">Conflicts with local authority structures (e.g., local industry, churches, communities, etc.).</td></tr>
<tr><td colspan="2">Resistance to cultural change (i.e., loss of indigenous cultures)</td><td colspan="2" rowspan="4"></td></tr>
<tr><td colspan="2">Lack of involvement from local communities</td></tr>
<tr><td colspan="2">Insufficiently concentrated population/end-uses</td></tr>
<tr><td colspan="2">Perception that renewable mini-grids are inferior to the main grid</td></tr>
<tr><td colspan="2">Concerns with long-term sustainability of renewable mini-grid projects. Perception that projects are not viable in the long term; very few examples are present and operating.</td><td colspan="2"></td></tr>
<tr><td colspan="2">Limited access/availability of technical expertise</td><td colspan="2"></td></tr>
<tr><td colspan="2">Top-down replication of projects in different regional, country or local settings without consideration of local needs</td><td colspan="2"></td></tr>
<tr><td colspan="2">Unwillingness to visit/work in remote areas, and/or condescending approach</td><td colspan="2"></td></tr>
<tr><td colspan="4">Opposition to local generation: Not In My Backyard (NIMBY)</td></tr>
<tr><td colspan="4">Lack of technical know-how in multilateral and financing institutions or ”copy-paste syndrome”</td></tr>
</table>

Source: Aggarwal and Mohanty, 2015; Gershenson et al., 2015; Graillot et al., 2012; Komor and Molnar, 2015; Kullingsjö, 2011; Rolland and Glania, 2011; Romankiewicz, 2014

Environmental barriers

<table>
<caption>Table 42: Environmental barriers to renewable mini-grid deployment and innovation</caption>
<tr><th></th><th>AB</th><th>AF</th><th>IC</th><th>ILI</th></tr>
<tr><td rowspan="5">Environmental</td><td colspan="2">Lack of programmes for electronic waste</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td colspan="2">Local air quality restrictions for combustion-driven generators (back-up and biomass)</td></tr>
<tr><td colspan="4">Even if environmentally friendly technologies are been promoted, full product life cycle should continue to be addressed – limits of resources</td></tr>
<tr><td colspan="2">Can power environmentally detrimental activities such as mining, oil drilling and other high-impact activities</td><td colspan="2"></td></tr>
<tr><td colspan="4">Lack of recognition of environmental benefits of renewable mini-grids</td></tr>
</table>

Source: Karabiber et al., 2013; Rolland and Glania, 2011; Romankiewicz, 2014

Technological barriers

Table 43: Technological barriers to renewable mini-grid deployment and innovation

<table>
<tr><th></th><th>AB</th><th>AF</th><th>IC</th><th>ILI</th></tr>
<tr><td rowspan="7">Technological</td><td colspan="2"></td><td colspan="2">Interconnection, interoperability</td></tr>
<tr><td colspan="4">Resource planning</td></tr>
<tr><td colspan="2"></td><td colspan="2">System operations</td></tr>
<tr><td>Technology not specific to low-cost (bottom-of-pyramid) design</td><td colspan="3"></td></tr>
<tr><td colspan="4">Lack of modularity</td></tr>
<tr><td colspan="4">Low capacity factors of variable renewable energy technologies</td></tr>
<tr><td colspan="2">Uncertainty in the face of possible future central grid extension</td><td colspan="2"></td></tr>
</table>

Source: Aggarwal and Mohanty, 2015; Ahlborg and Hammar, 2014; IEEE, 2014; Blum et al., 2015; Deshmukh, 2014; Gershenson et al., 2015; IEA-ETSAP and IRENA, 2015a; IRENA, 2012e; Karabiber et al., 2013; Komor and Molnar, 2015; Kullingsjö, 2011; Kumar Sahu, 2015; Nique and Opala, 2014; NREL et al., 2014; Rolland and Glania, 2011; Romankiewicz, 2014, 2014; Waugaman, 2014; Wilkins, 2010; Zhu et al., 2015)

ANNEX 3:

Worldwide deployment and stakeholders

Examples of renewable mini-grid deployment by region are depicted in Table 44:

Table 44: Examples of renewable mini-grid projects worldwide

Region	Examples
US and Canada	PV-solar in California (*e.g.*, Borrego Springs micro-grid); wind-hydro in Kodiak, Alaska; solar in Olney, Maryland; PV-wind-diesel at Oncor's System Operating Services Facility in Texas; solar-natural gas at Niobrara Energy Park, Colorado (still in development); Illinois Institute of Technology Microgrid; University of California San Diego (renewable energy increasing, but based primarily on combined heat and power)
Mexico, Central America and the Caribbean	Small hydro in Nicaragua and Guatemala; PV mini-grids in Mexico; microgrids in oil refineries; Necker Island and Bonaire; biogas in Tuffet, Haiti
South America	Large PV-diesel in Cobija and El Espino, Bolivia; large PV-diesel in Santa Cruz, Ecuador; solar-diesel in Padrecocha, Peru
Europe	Wind-solar-biomass in Wildpoldsried, Germany; wind-solar in Canary Islands; wind-PV in Kythnos Island in Greece; wind-diesel-hydro in El Hierro, Spain
North Africa	PV in Morocco; solar in Tunisia
Sub-Saharan Africa	PV in Cape Verde and Volta Region in Ghana; PV-diesel in Guinea Bissau and Chad; PV-diesel-biomass in Kenya and Tanzania
North and Central Asia	Wind in Murmansk Oblast
South and East Asia	Small hydro in Nepal; PV in Malaysia, Indonesia and India; PV-wind-diesel in China (*e.g.*, on the islands of Nanji, Dawanshan and Dong'ao); biomass gasifiers in India
Middle East	PV-diesel in West Bank, Palestine; PV in Egypt
Oceania	Solar-diesel in Daly River; wind-solar-biodiesel on King Island
Antarctica	Antarctic Research Station Princess Elisabeth

Source: Briganti et al., 2012; Cheek et al., 2011; Deshmukh, 2014; Espinosa, 2004; Estrada García et al., 2013; Hatziargyriou et al., 2007; Rolland and Glania, 2011; Taouil et al., 2014; Tenenbaum et al., 2014; Thirumurthy et al., 2012)

Stakeholder relations

Stakeholders include private developers, public companies, consultancy and engineering companies, multilaterals, NGOs, governments, researchers and developers, manufacturers, think tanks, universities and investors. Each plays different roles during the innovation life cycle, as summarised in Table 45:

Table 45: Roles of key stakeholders in mini-grids

	Private developer	Public company	Consultancy/ Engineering	Multi-lateral	NGO	Govern-ment	R&D centres	Manu-facturer	Think tank	Uni-versity	In-vestor
Basic R&D						XX	XXX		X	XXX	
Applied R&D			X	X		X	XX	XXX	X	XXX	X
Demonstration	X	X	X	XX	X	X	X	XX	X	XX	X
Market development	X	X	X	XXX	XX	XX		X	X		XX
Market deployment	XXX	XXX	X	X	X	X		X	X		XXX

KEY: xxx = critical driving role; xx = key participant; x = important stakeholder

Governments, research institutions and universities are the key players for initial technology innovation. Once technological innovations have been proven in laboratories, then manufacturers, university incubators, multilateral organisations, and governments will play an important role in demonstrating the feasibility of them by testing laboratory concepts in real-life conditions. Investors and the public and private sectors will further invest in the final stages of product development and towards its commercialisation to finally deploy the technology. NGOs and think tanks are crucial for bridging technological capabilities due to innovation and the social needs for implementation in communities.

ANNEX 4:

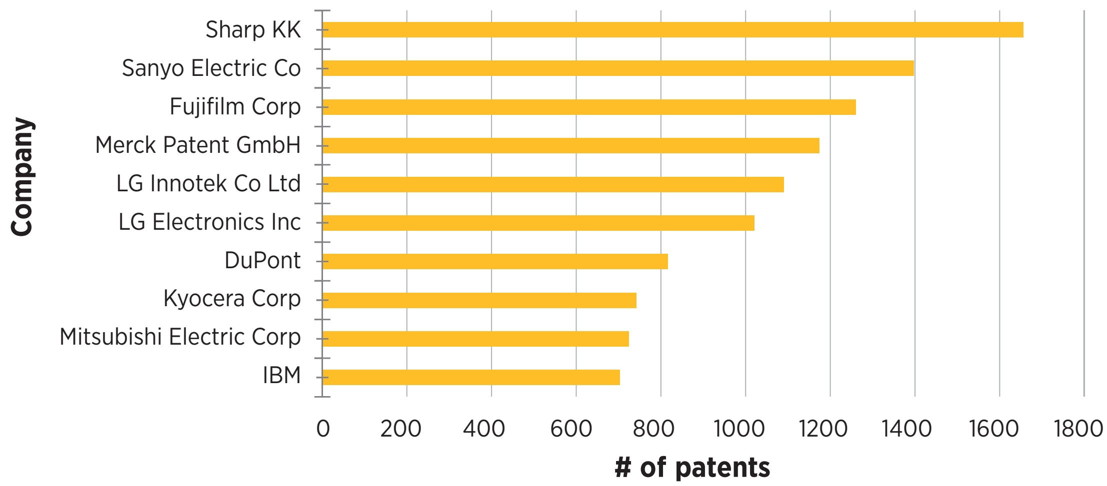
Detailed patent review

This Annex provides a series of patent reviews. The European Patent Office (EPO) search engine, Espacenet, and the Global Patent Index provide searchable databases of patents from more than 90 countries. Nearly 300 Cooperative Patent Classification (CPC) codes were researched that reflect specific groups, subgroups, classes or subclasses of research that will impact renewable mini-grids. The CPC codes were selected from IRENA's INSPIRE patent tool (IRENA, 2015g). These data on patent applications filed, which cover the period from 2010 to 2014, provide insights on which renewable mini-grid technologies are being funded, as well as general interest levels. The results of these searches show trends towards commercialisation for most of the core technologies. The general trend is positive, and interest in their potential to transform the energy sector has continued to grow.

Plan and Design

The plan-and-design patent review focused on tools for modelling and simulation. The patent offices that have filed the most patent applications from 2010 to 2014 for modelling and simulation technologies were those of China, with over 540 patent applications filed, followed by the United States, the World Intellectual Property Organisation (WIPO) for international patents, Japan, EPO, Canada, the Republic of Korea, Germany, Australia and Chinese Taipei (EPO, 2015a; EPO, 2015b). The leading patent-generating companies within the last five years are listed in Figure 24:

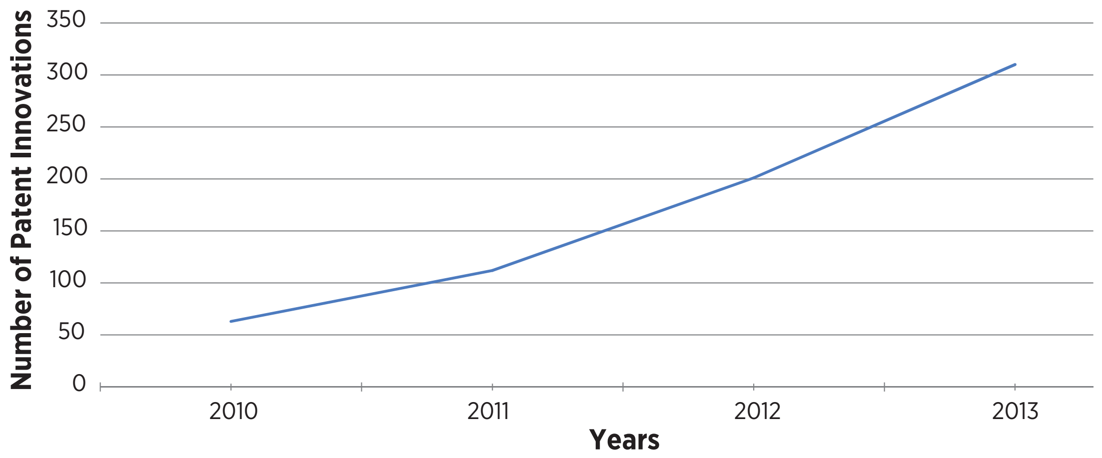
Figure 24: Top 10 companies for CMM modelling and simulation patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

There has been a consistent rise in patents for modelling and simulation technologies in the past five years, as shown in Figure 25:

Figure 25: Number of patents for modelling and simulation technologies filed from 2010 to 2014

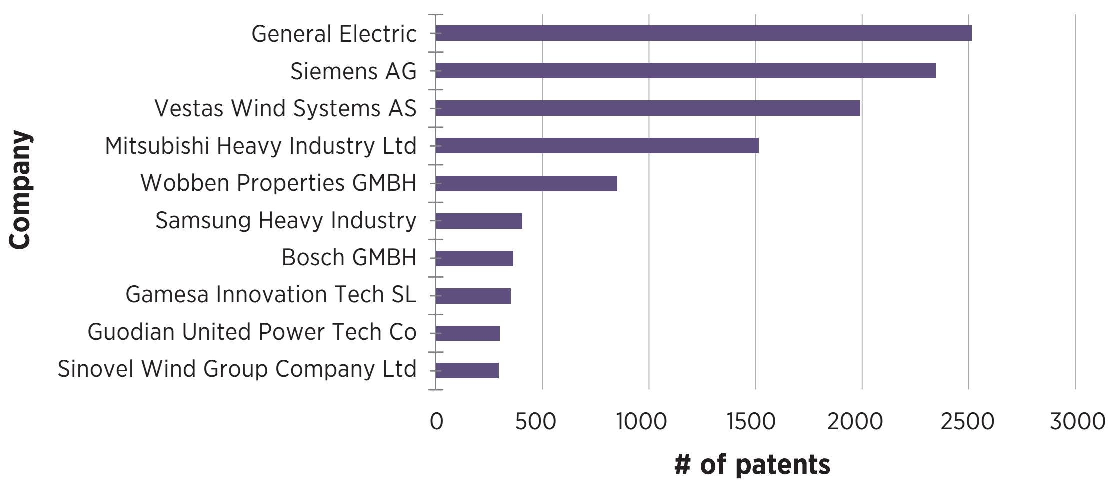


Source: Author elaboration; EPO, 2015a; EPO, 2015b

CMM

The country where the most patents were filed from 2010 to 2014 was China, with almost 12 000 patents filed. The United States trailed with just over 11 000, followed by Japan, Germany, the Republic of Korea, Chinese Taipei, France and the United Kingdom. Significant numbers of patents also were registered internationally through WIPO, and for all of Europe through EPO. Corporations holding the most number of patents for the 2010 to 2014 period are listed in Figure 26:

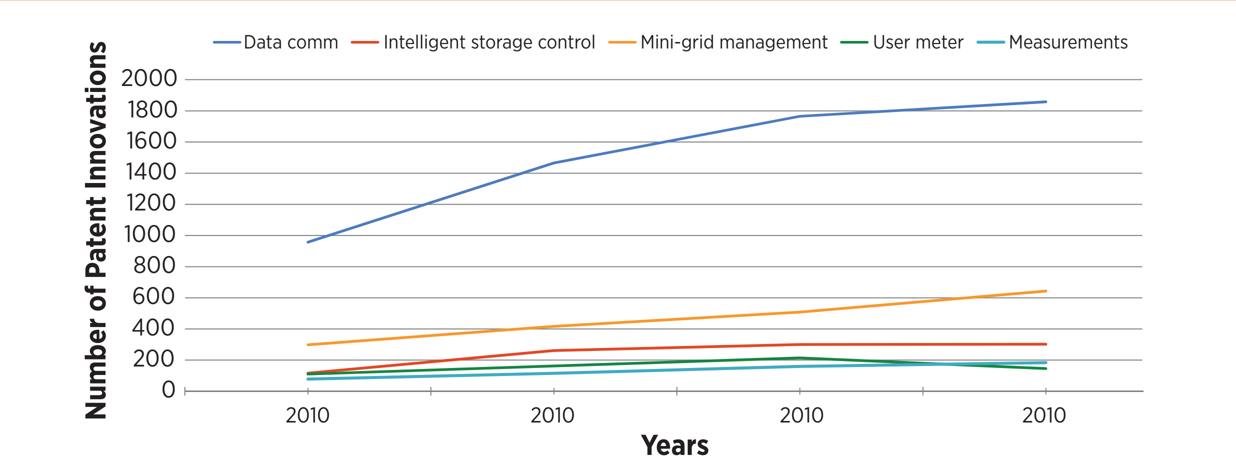
Figure 26: Top 10 companies for all CMM technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Patent applications for data-communication technologies have followed the general trend of increases except for in 2014, during which there was a significant deviation in the trend. This was most likely because of patents pending approval. Mini-grid management technologies and measurement technologies saw a consistent increase. There was not a major increase in innovations in intelligent-storage-control equipment technologies, and for user-meter technologies there was a drop (see Figure 27). Below is a more detailed review of patent trends in CMM technologies.

Figure 27: Number of patents for CMM technologies filed from 2010 to 2013

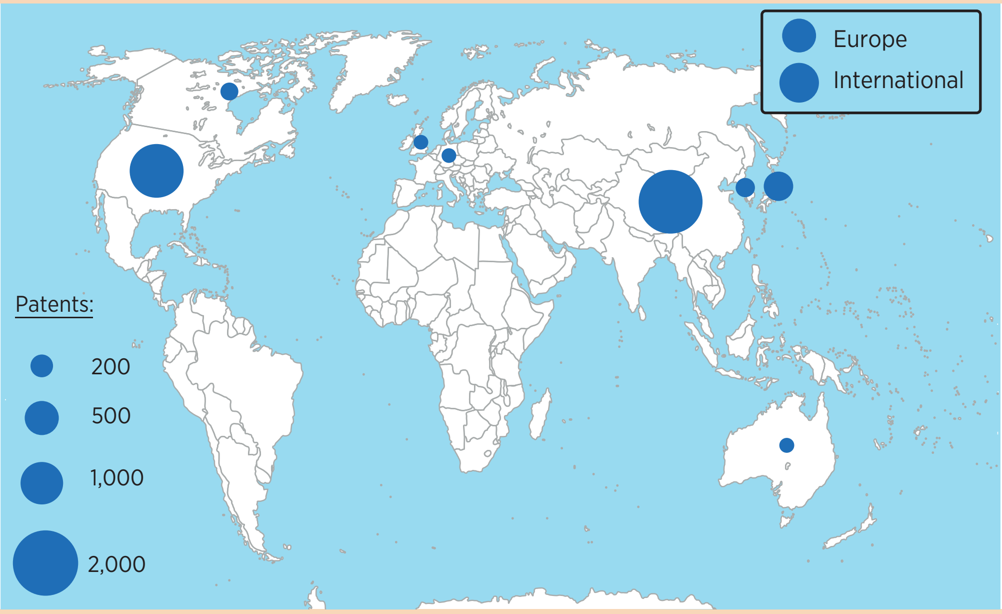


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Data communication

The patent offices that filed the most patents from 2010 to 2014 for data communication technologies were those of China, with over 2 200 patent applications filed, followed by the United Sates, WIPO, EPO, Japan, the Republic of Korea, Canada, the United Kingdom, Australia and Germany (EPO, 2015a; EPO, 2015b). See Figure 28:

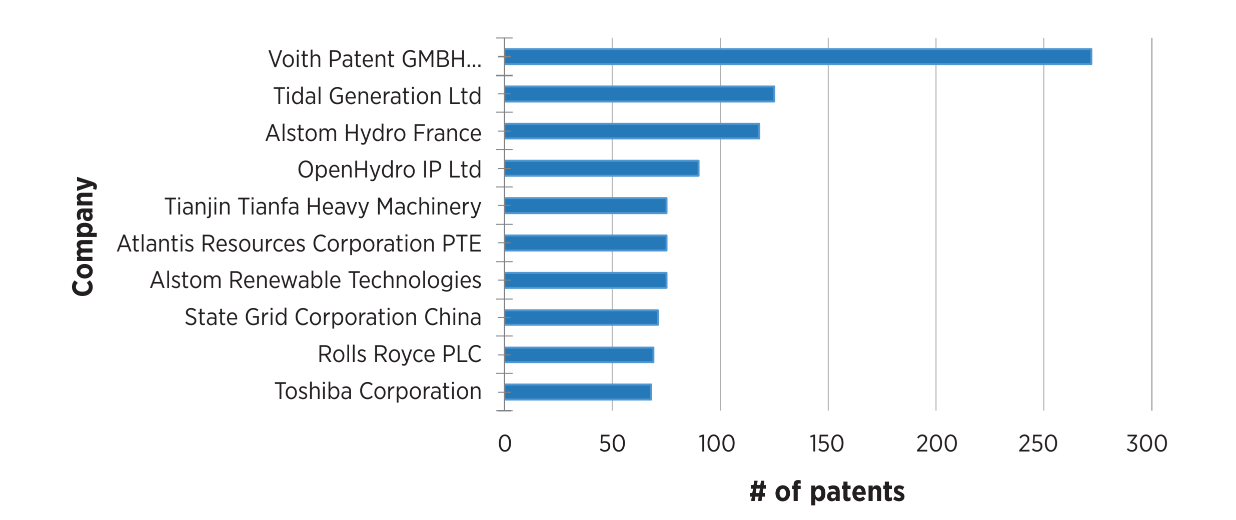
Figure 28: Top 10 countries for CMM data communication patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporate leaders in holding patents in that period included State Grid Corporation of China and General Electric, each with approximately 340 patent applications filed. They are followed by Itron Inc., Panasonic Corp., Siemens AG, Sony Corporation, LG Electronics Inc., Shanghai Municipal Electric Power, Jaibin Chin and Elster Solutions LLC. See Figure 29:

Figure 29: Top 10 companies for CMM data communication patents filed from 2010 to 2014

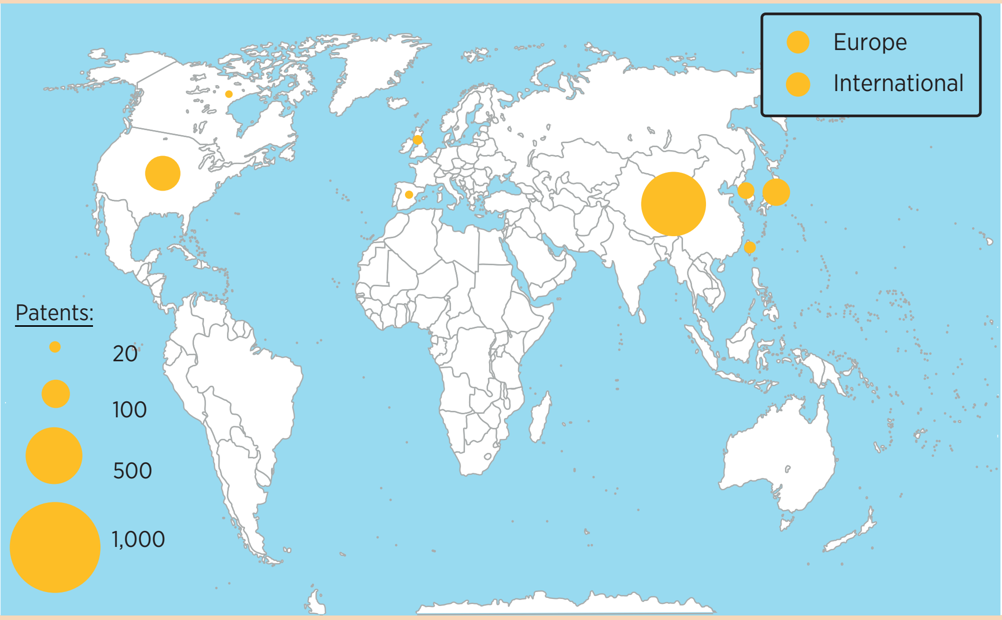


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Intelligent storage control

The patent office that filed the most applications from 2010 to 2014 was China's, with approximately 730 applications filed, followed by those of the United States, Japan, WIPO, EPO, the Republic of Korea, the United Kingdom, Chinese Taipei, Canada and Spain (EPO, 2015a; EPO, 2015b). See Figure 30:

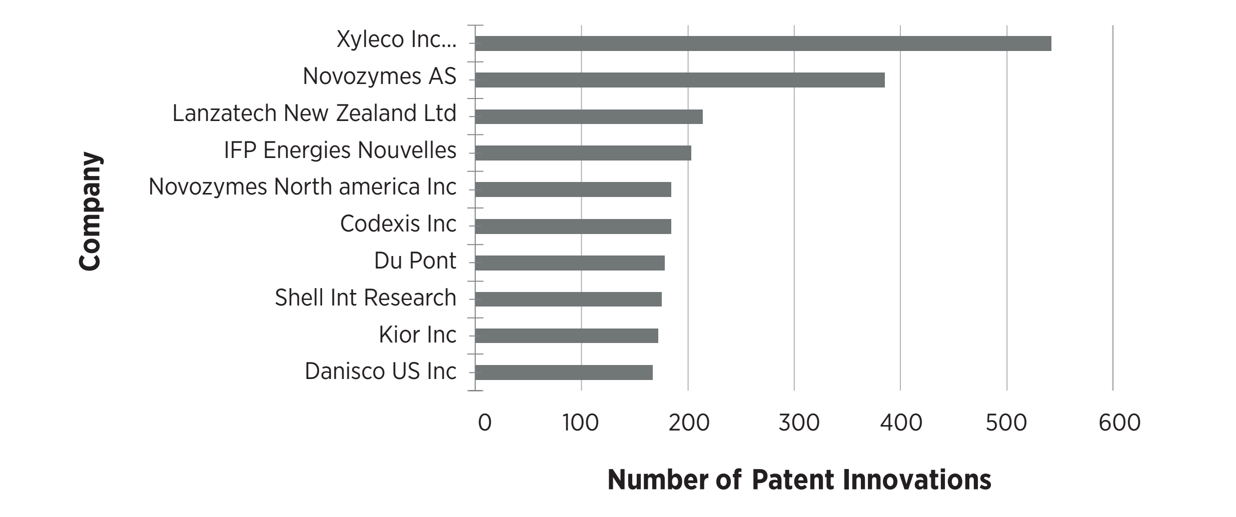
Figure 30: Top 10 countries for CMM intelligent storage control patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

The corporations that held the most number of patents in the period included Samsung SDI Company Limited with approximately 42 patent applications filed, followed by Eaton Corporation, Hon Hai Precision Industry Company Ltd., Kyocera Corp., Sanyo Electric Co., State Grid Corporation of China, BAE Systems Control Inc., Huawei Tech Co., General Electric and Shimizu Construction Company Ltd. See Figure 31:

Figure 31: Top 10 companies for CMM intelligent storage control patents filed from 2010 to 2014

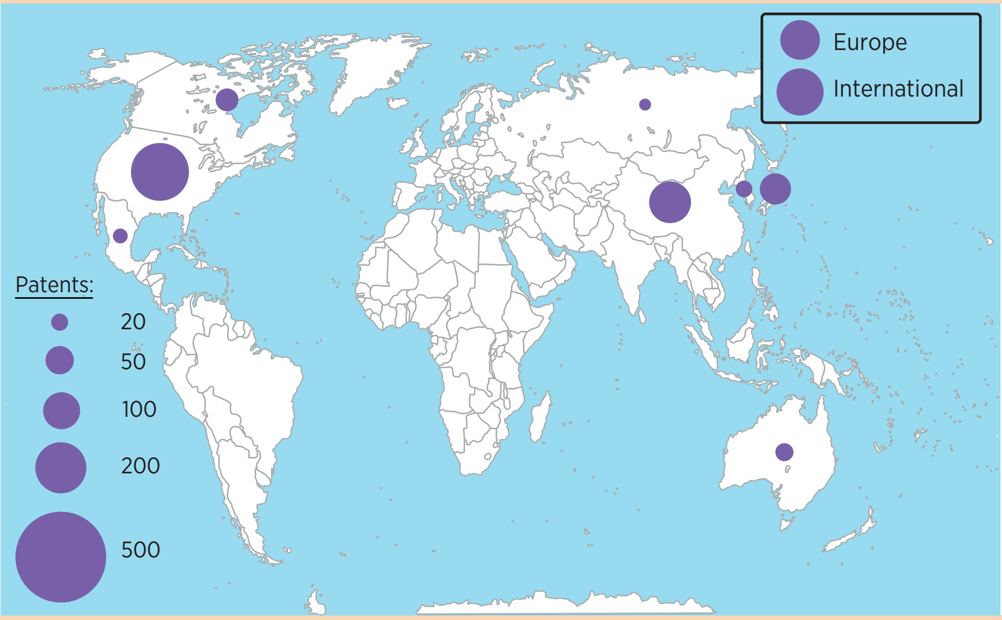


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Measurements

The patent offices that filed the most patent applications from 2010 to 2014 were those of the United States, with approximately 250 patent applications filed, WIPO, which received almost 150 patents, China, EPO, Japan, Canada, Australia, the Republic of Korea, Mexico and the Russian Federation (EPO, 2015a; EPO, 2015b). See Figure 32:

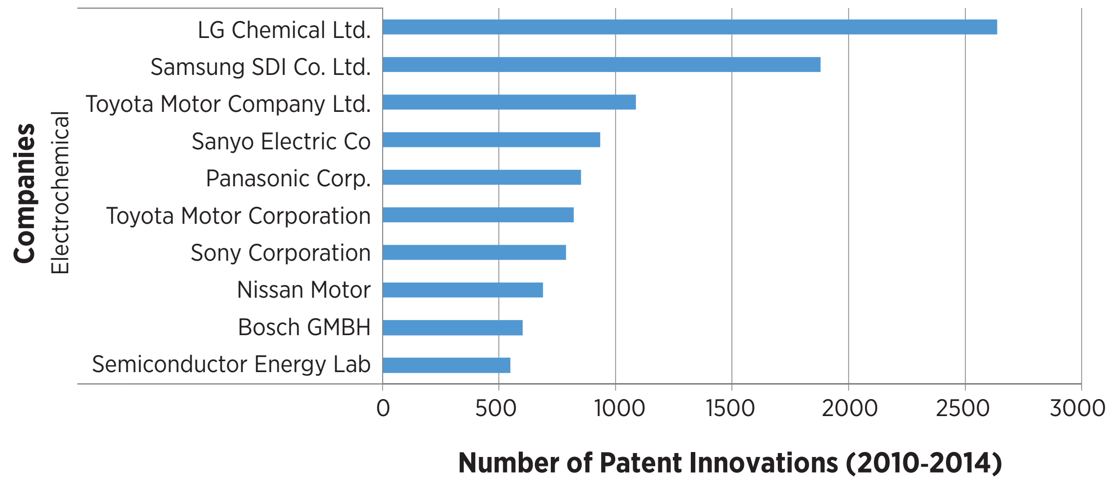
Figure 32: Top 10 countries for CMM measurement patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporations with the most number of patents in the period included but were not limited to General Electric, with approximately 75 patents filed, followed by Accenture Global Services Ltd., Schweitzer Engineering Lab Inc., State Grid Corporation of China, Spirae Inc., Toshiba, Sensus USA Inc., Corinex Communications Corporation, Schneider Electric Industry and Siemens AG. See Figure 33:

Figure 33: Top 10 companies for CMM measurements patents filed from 2010 to 2014

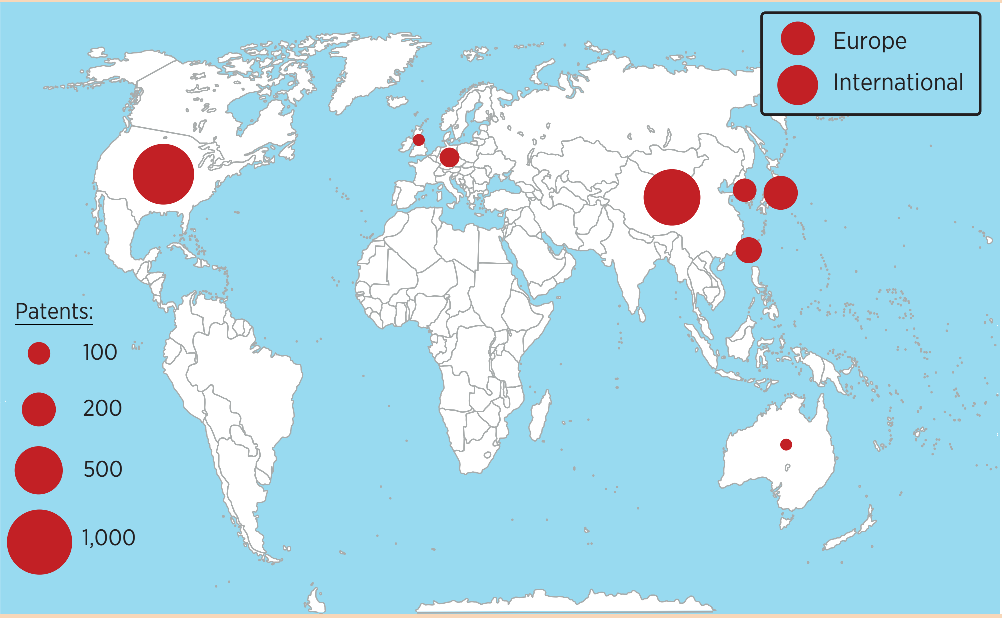


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Mini-grid management

The patent offices that filed the most patents from 2010 to 2014 for mini-grid management technologies were those of the United States, where more than 820 patent applications were filed, followed by those of China, WIPO, Japan, EPO, Chinese Taipei, the Republic of Korea, Germany, the United Kingdom and Australia (EPO, 2015a; EPO, 2015b). See Figure 34:

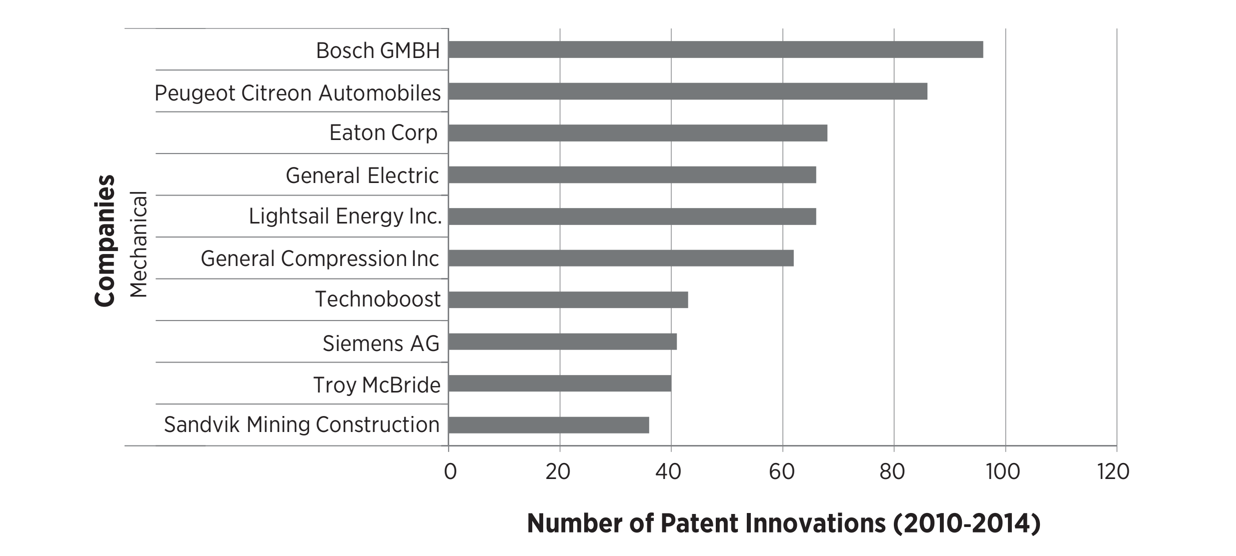
Figure 34: Top 10 countries for CMM mini-grid management patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders in the period included but were not limited to Mitsubishi Electric Corporation, with 85 patent applications filed, followed by Fuji Electric Company Ltd., Murata Manufacturing Co., Samsung Electro-Mechanics, Bosch, Huawei Tech Co., Fujitsu Limited, System General Corporation, Siemens AG and the Panasonic Corporation. See Figure 35:

Figure 35: Top 10 companies for CMM mini-grid management patents filed from 2010 to 2014

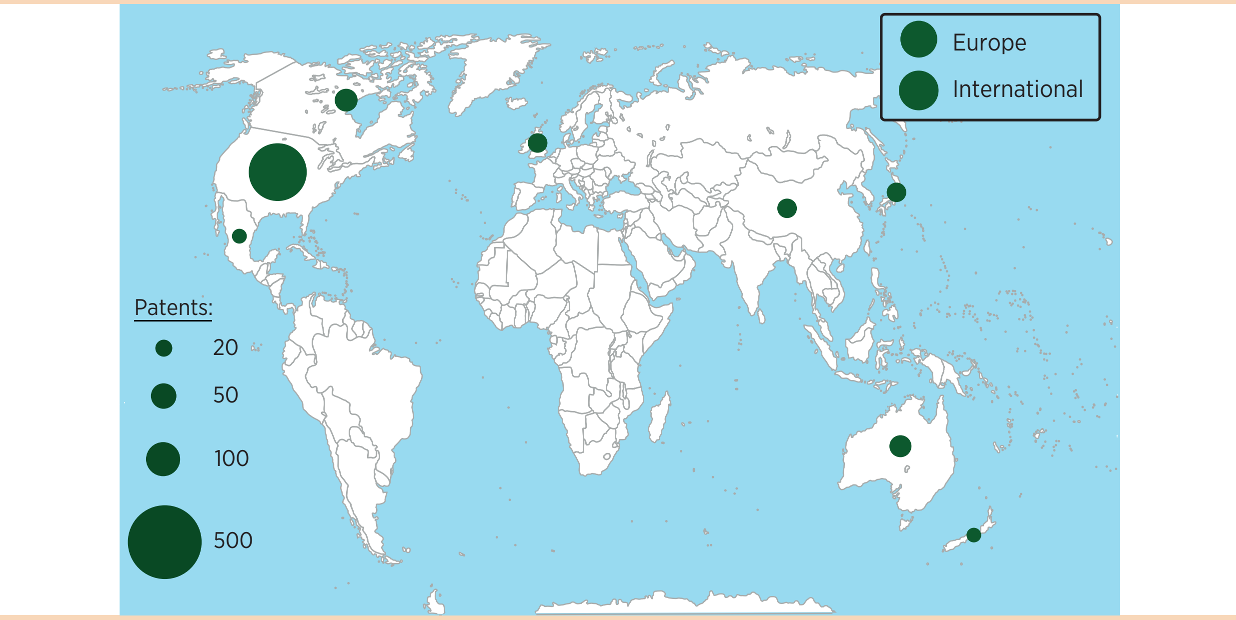


Source: Author elaboration; EPO, 2015a; EPO, 2015b

User meters

The patent offices that filed the most patents from 2010 to 2014 were those of the United States, with approximately 300 patent applications filed, WIPO, which received more than 130 international patents, EPO, Canada, Australia, Japan, China, the United Kingdom, New Zealand and Mexico (EPO, 2015a; EPO, 2015b). See Figure 36:

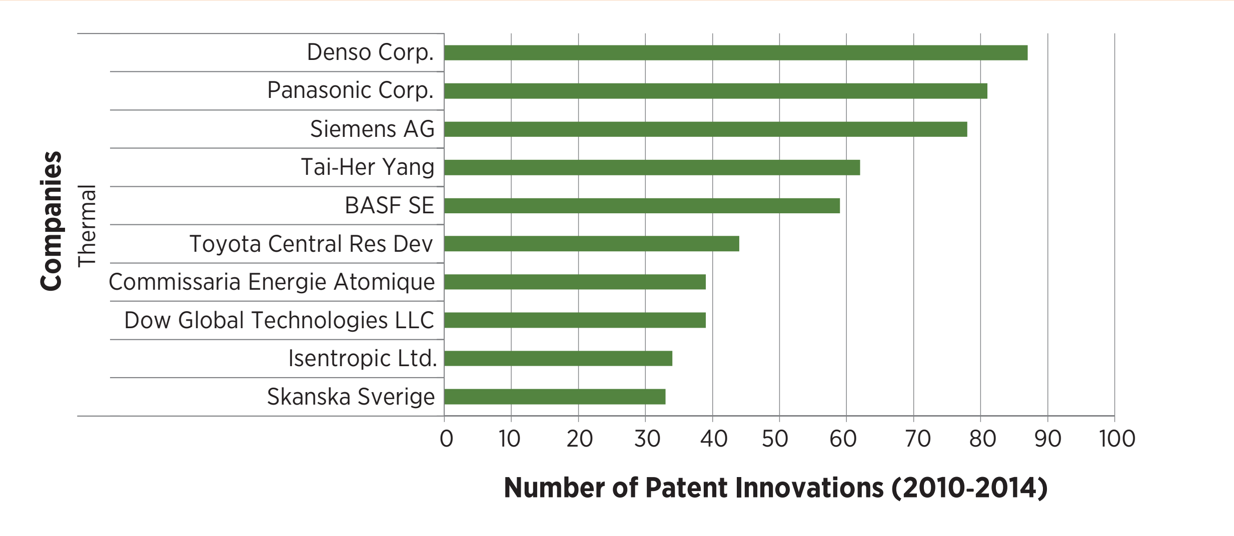
Figure 36: Top 10 countries for CMM user meter patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders in the period included but were not limited to General Electric, with approximately 116 patent applications filed, Itron Inc., Elster Solutions LLC, Silver Spring Networks Inc., LG Electronics Inc., Panasonic Corp., Nagravision, Toshiba Research Europe Ltd., Hoonbong Lee and Yanghwan Kim. See Figure 37:

Figure 37: Top 10 companies for CMM user meter patents filed from 2010 to 2014

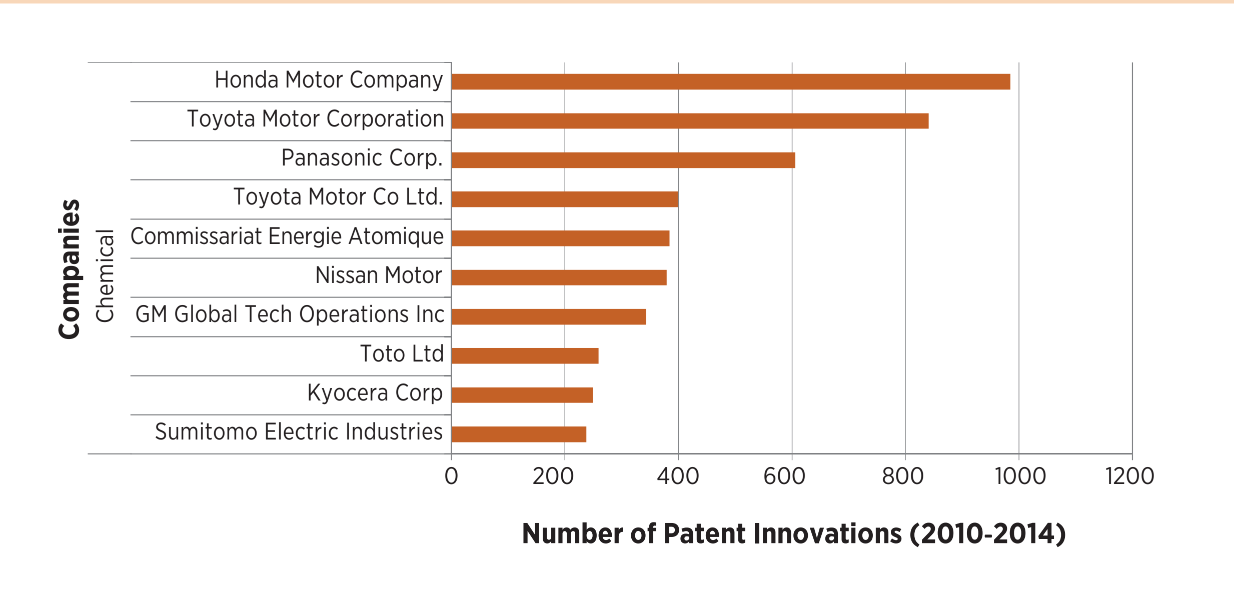


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Store

The patent office that filed the most patents from 2010 to 2014 for storage was that of China, with more than 30 000 patents filed in the period. It was followed by those of Japan, the United States, WIPO, the Republic of Korea, EPO, Germany, Chinese Taipei, France and Canada. Figure 38 shows corporations that held the most patents in the period.

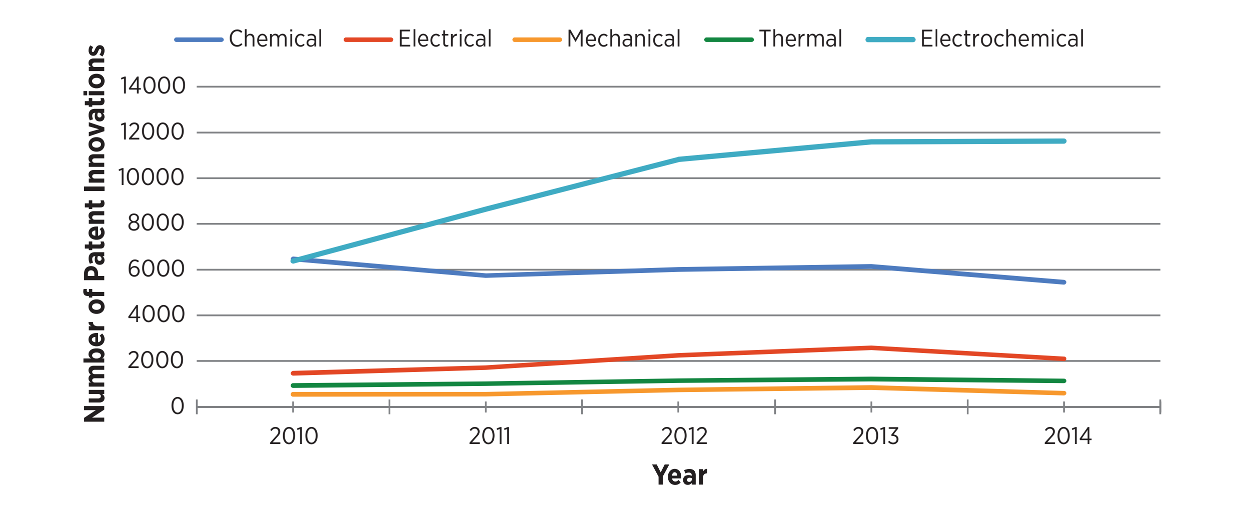
Figure 38: Top 10 companies for all storage technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Digging into the details reveals a declining trend for chemical storage applications, while those for electrochemical storage increased. Until 2013, there also appeared to be increased interest in thermal and electrical storage technologies, and to a lesser extent a similar trend was observed for mechanical storage. However, the share of patents in these categories is small in comparison with electrochemical storage. See Figure 39:

Figure 39: Number of patents for storage technologies filed from 2010 to 2014

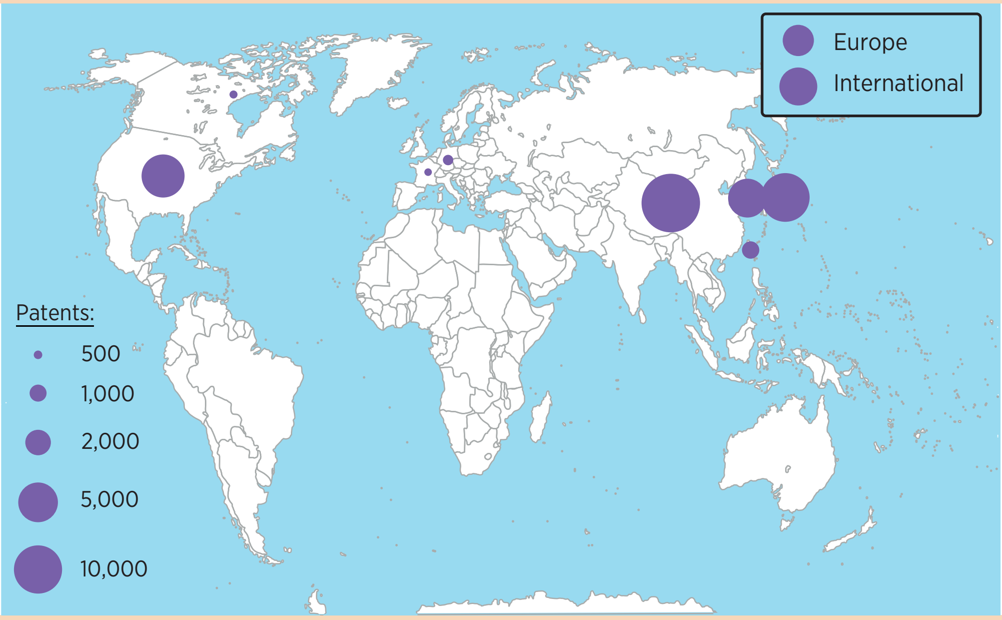


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Electrochemical

The patent office that filed the most patent applications from 2010 to 2014 was China's, with over 14 800 patent applications filed, followed by those of Japan, the United States, the Republic of Korea, WIPO, EPO, Chinese Taipei, Germany, Canada and France (EPO, 2015a; EPO, 2015b). See Figure 40:

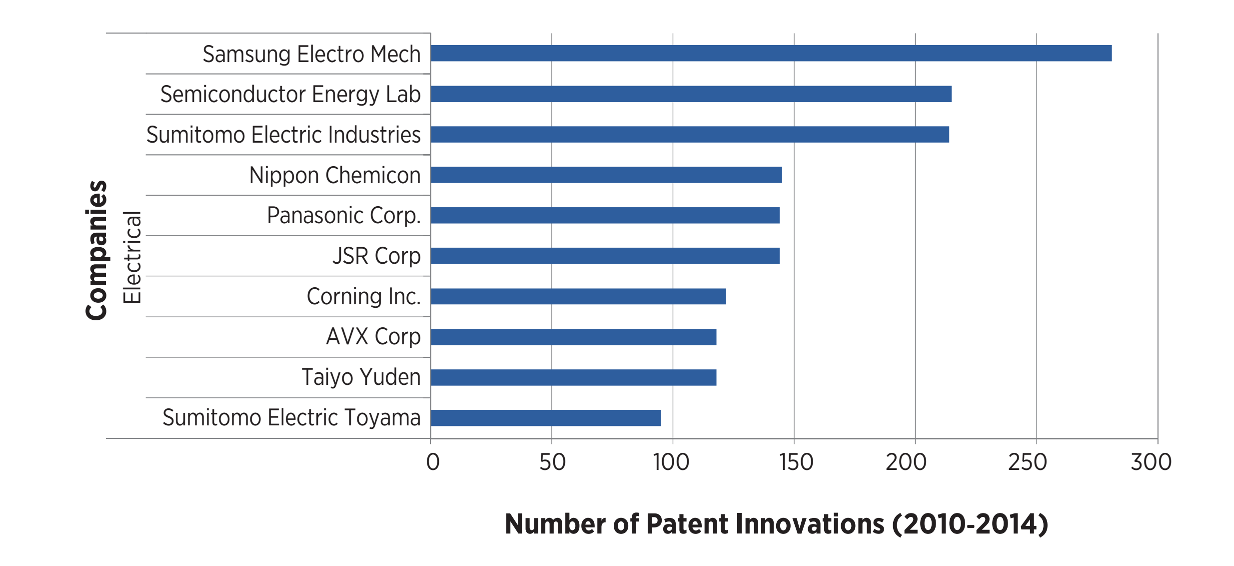
Figure 40: Top 10 countries for electrochemical storage patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major commercial patent holders in the period include LG Chemical Ltd. with approximately 2 638 patent applications filed, followed by Samsung SDI Co. Ltd., Sanyo Electric Co., Panasonic Corporation, Toyota Motor Corporation, Sony Corporation, Nissan Motor, Bosch and Semiconductor Energy Lab. See Figure 41:

Figure 41: Top 10 companies for electrochemical storage patents filed from 2010 to 2014

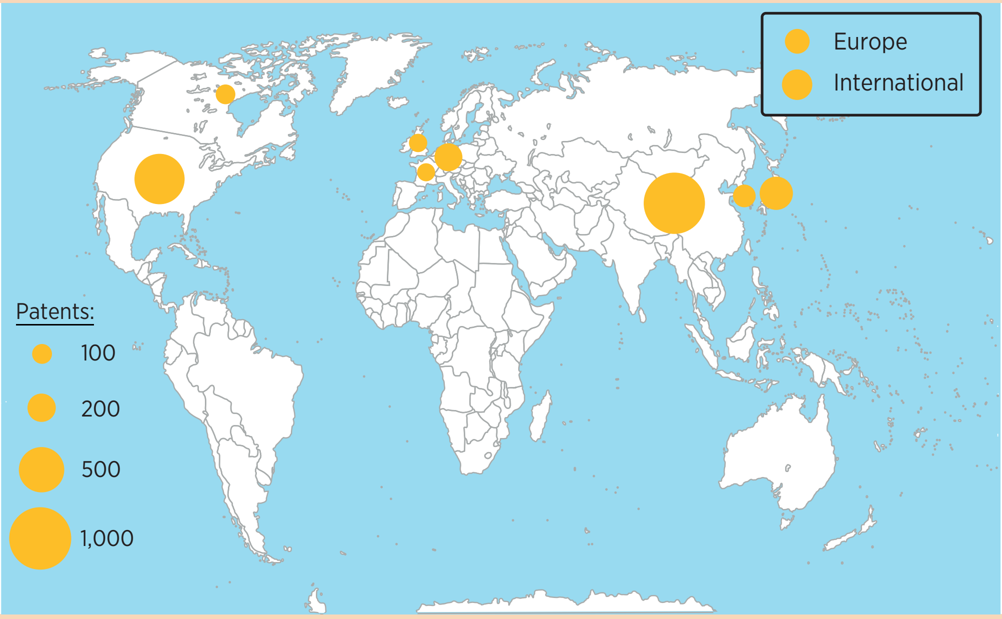


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Mechanical

The patent office that filed the most patent applications from 2010 to 2014 for mechanical storage technologies was China's, with 985 patents filed, followed by those of the United States, WIPO, EPO, Japan, Germany, France, United Kingdom and Canada (EPO, 2015a; EPO, 2015b). See Figure 42:

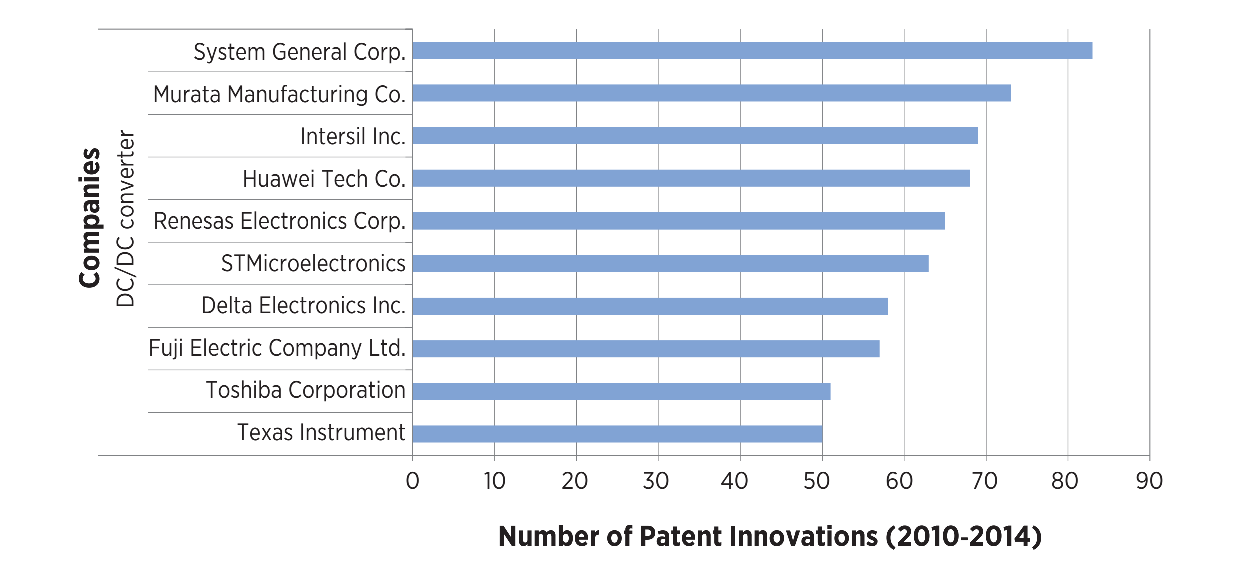
Figure 42: Top 10 countries for mechanical storage patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders from 2010 to 2014 included Bosch, with 96 patents filed, followed by Peugeot Citroen Automobiles, Eaton Corporation, Lightsail Energy Inc., General Electric, General Compression Inc., Technoboost, Siemens AG, Troy McBride and Sandvik Mining Construction. See Figure 43:

Figure 43: Top 10 companies for mechanical storage patents filed from 2010 to 2014

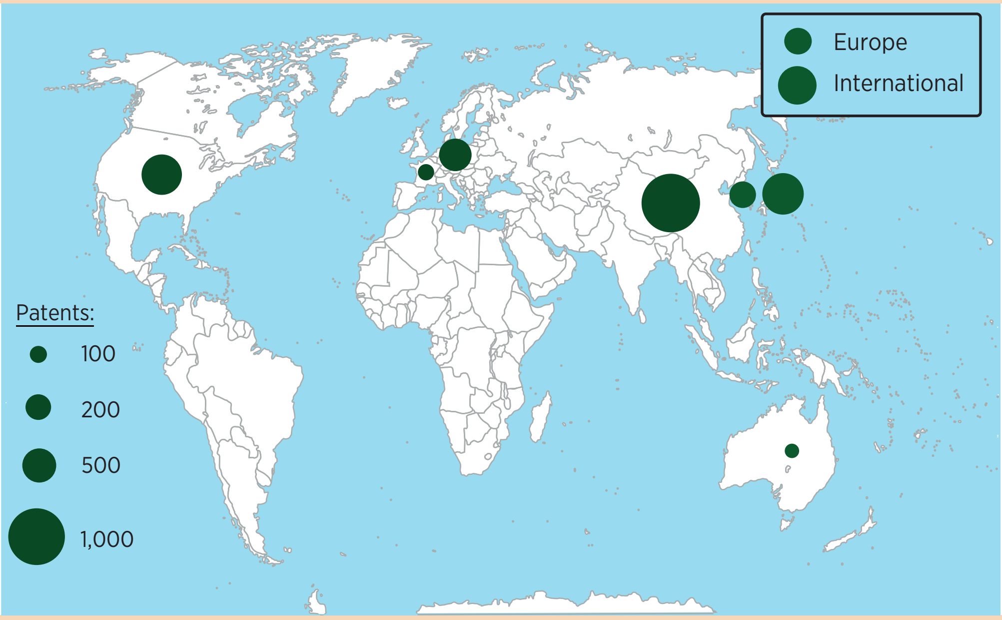


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Thermal

The patent offices that filed the most patents from 2010 to 2014 for thermal storage technologies included China's, with over 1 200 patents filed, followed by those of WIPO, the United States, Japan, EPO, Germany, the Republic of Korea, France and Australia (EPO, 2015a; EPO, 2015b). See Figure 44:

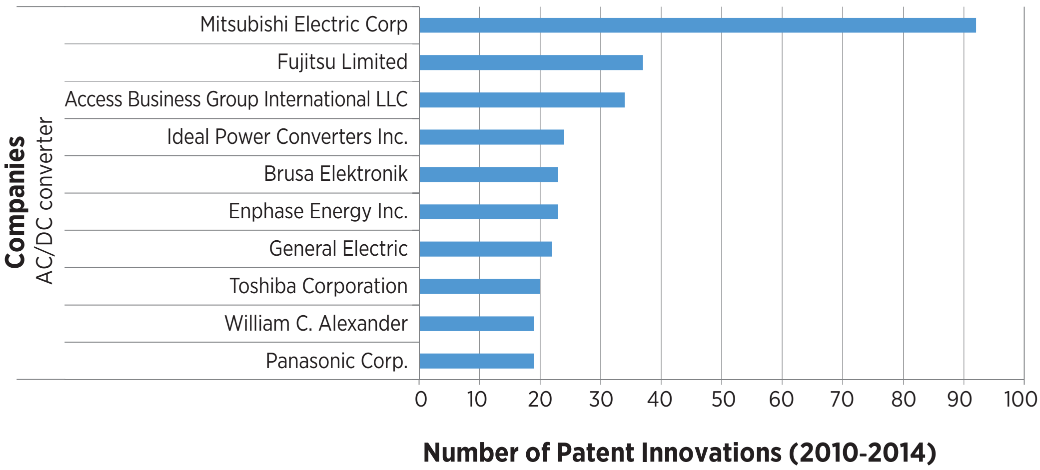
Figure 44: Top 10 countries for thermal storage patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporations with the most patents in the period include Denso Corporation, with 87 patents filed, followed by Panasonic Corporation, Siemens AG, Tai-Her Yang, BASF, Toyota Central Research & Development, Commissariat Energie Atomique, Isentropic Ltd. and Skanska Sverige. See Figure 45:

Figure 45: Top 10 companies for thermal storage patents filed from 2010 to 2014

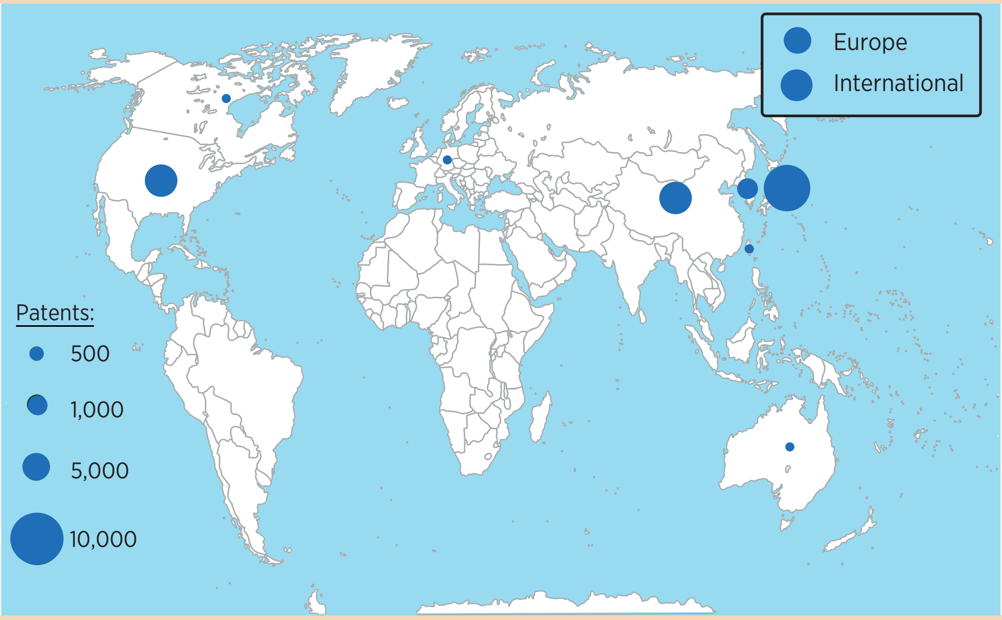


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Chemical

The patent office that filed the most patents from 2010 to 2014 was Japan's, with almost 8 000 patent applications filed, followed by those of the United States, China, WIPO, the Republic of Korea, EPO, Germany, Canada, Chinese Taipei and Australia (EPO, 2015a; EPO, 2015b). See Figure 46:

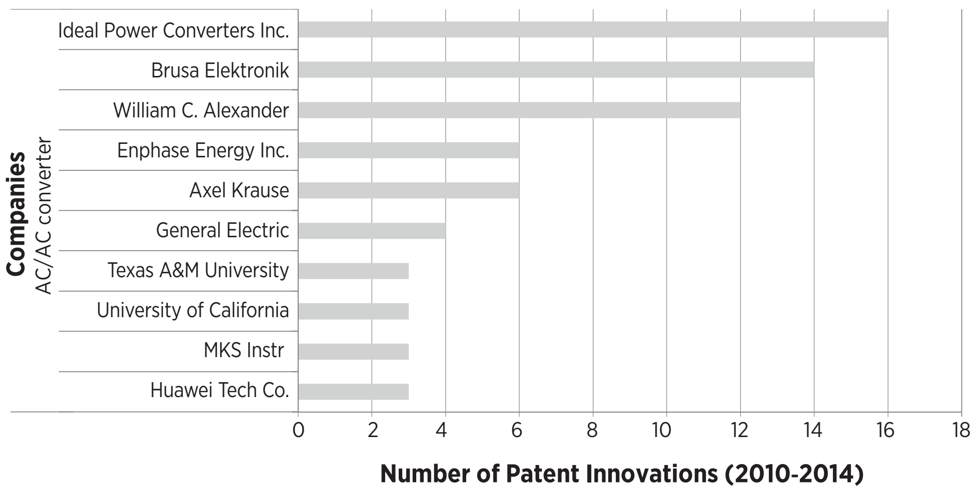
Figure 46: Top 10 countries for chemical storage patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders included Honda Motor Company, with approximately 985 patent applications filed, followed by Toyota Motor Corporation, Panasonic Corporation, Toyota Motor Company Ltd., Commissariat Energie Atomique, Nissan Motor, GM Global Tech Operations Inc., Toto Ltd., Kyocera Corp. and Sumitomo Electric Industries. See Figure 47:

Figure 47: Top 10 companies for chemical storage patents filed from 2010 to 2014

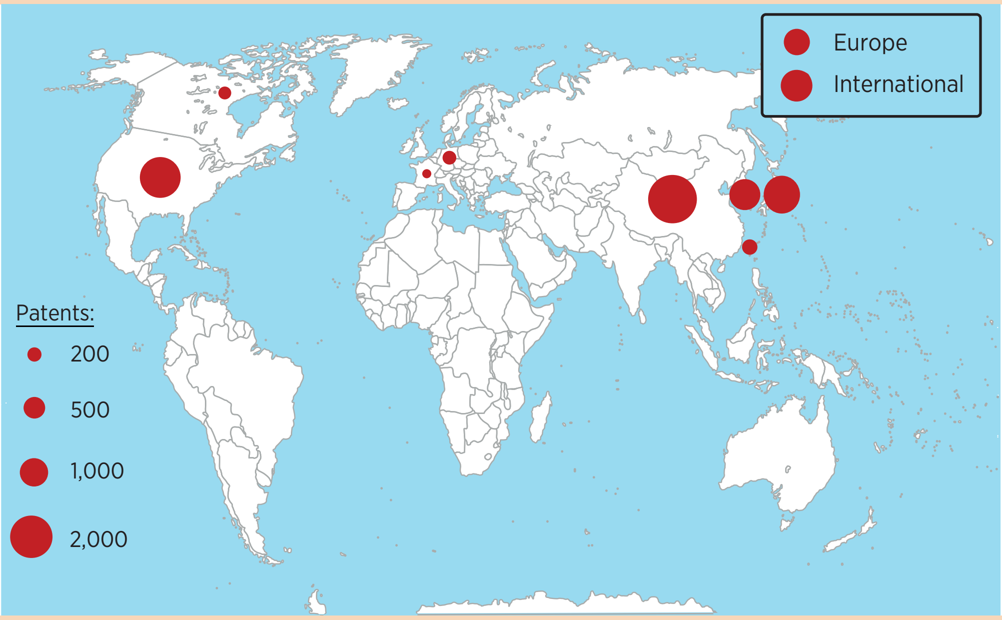


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Electrical

The patent offices that filed the most applications from 2010 to 2014 were China's, with almost 2 500 patent applications filed, followed closely by those of the United States, with approximately 2 050 patents filed, Japan, WIPO, the Republic of Korea, EPO, Chinese Taipei, Germany, Canada and France (EPO, 2015a; EPO, 2015b). See Figure 48:

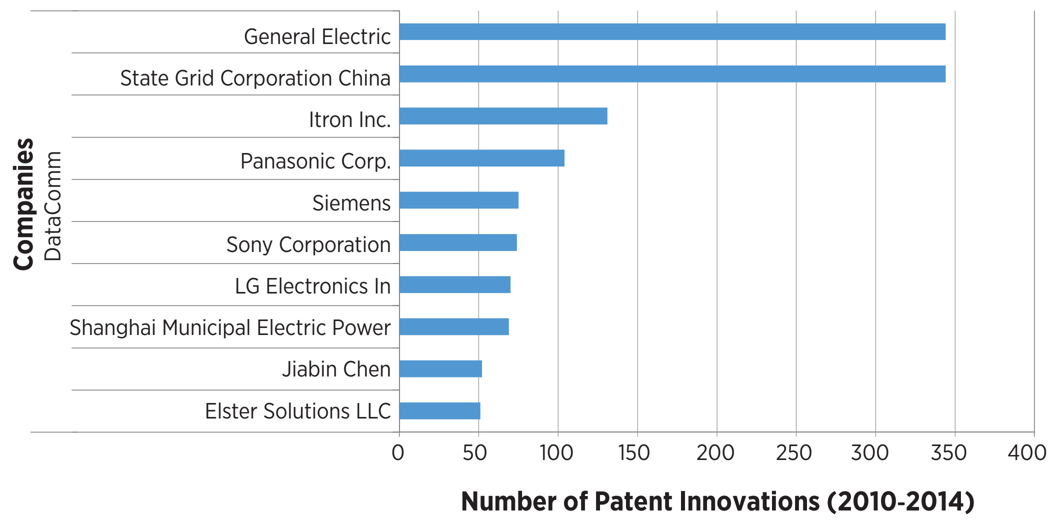
Figure 48: Top 10 countries for electrical storage patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders included but were not limited to Samsung Electro Mechanics, with approximately 280 patents filed, followed by Semiconductor Energy Laboratory Co., Sumitomo Electric Industries, Nippon Chemicon, Panasonic Corp., JSR Corp., Corning Inc., Taiyo Yuden, AVX Corp. and Sumitomo Electric Toyama. See Figure 49:

Figure 49: Top 10 companies for electrical storage patents filed from 2010 to 2014

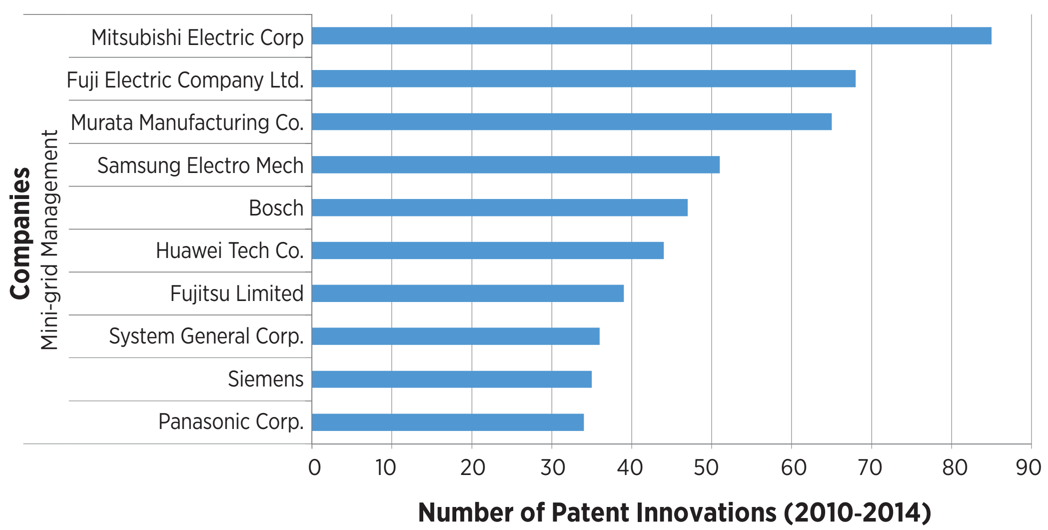


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Convert

The countries that filed the most patents from 2010 to 2014 were the United States, followed by China, Japan, Chinese Taipei, the Republic of Korea, Germany, Canada and Australia (EPO, 2015a; EPO, 2015b). Major corporate patent holders in the period are listed in Figure 50:

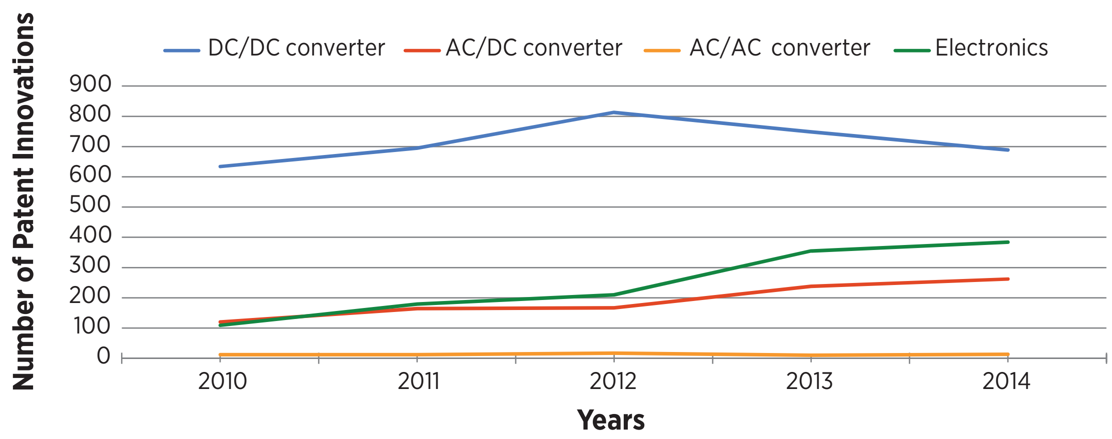
Figure 50: Top 10 companies for conversion technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

The 2010 to 2014 period featured an increase in patents for conversion between AC and DC and for innovations applicable to all power conversion electronics.

Figure 51: Number of patents for power conversion technologies filed from 2010 to 2014

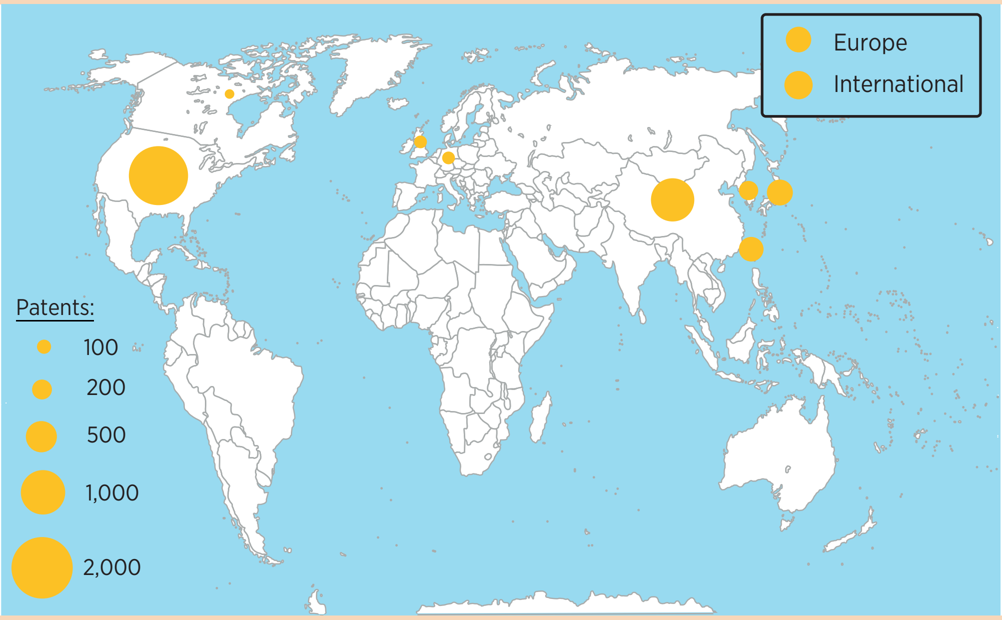


Source: Author elaboration; EPO, 2015a; EPO, 2015b

DC-DC conversion

The patent offices that filed the most applications from 2010 to 2014 were China's, with almost 800 patent applications filed, followed by those of WIPO, Japan, EPO, Chinese Taipei, the Republic of Korea, Germany, Canada and the United Kingdom (EPO, 2015a; EPO, 2015b). See Figure 52:

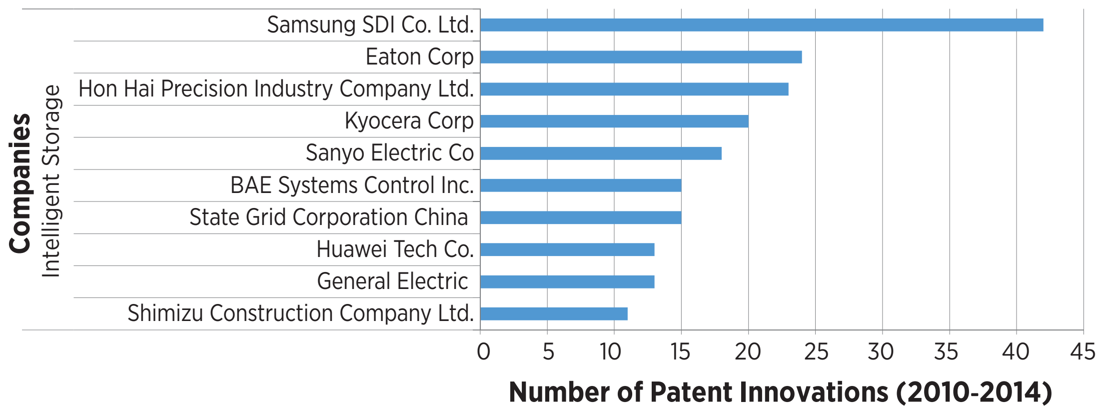
Figure 52: Top 10 countries for DC-to-DC conversion patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent filers in the period included System General Incorporated with approximately 83 patent applications filed, followed by Murata Manufacturing Inc., Intersil Inc., Huawei Tech Company, Renesas Electronics Corp., STMicroelectronics, Delta Electronics Inc., Fuji Electric Company Ltd., Toshiba Corporation and Texas Instruments. See Figure 53:

Figure 53: Top 10 companies for DC-to-DC for conversion patents filed from 2010 to 2014

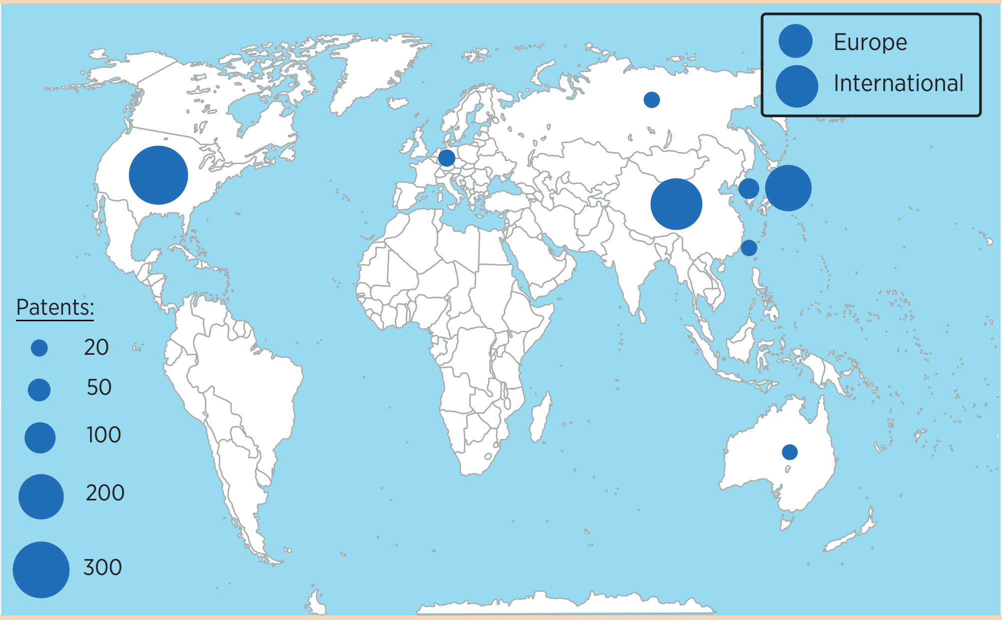


Source: Author elaboration; EPO, 2015a; EPO, 2015b

AC-DC conversion

The patent offices that filed the most applications from 2010 to 2014 were those of the United States, with over 330 patent applications filed, followed by China, Japan, WIPO, EPO, the Republic of Korea, Germany, Chinese Taipei, Australia and the Russian Federation (EPO, 2015a; EPO, 2015b). See Figure 54:

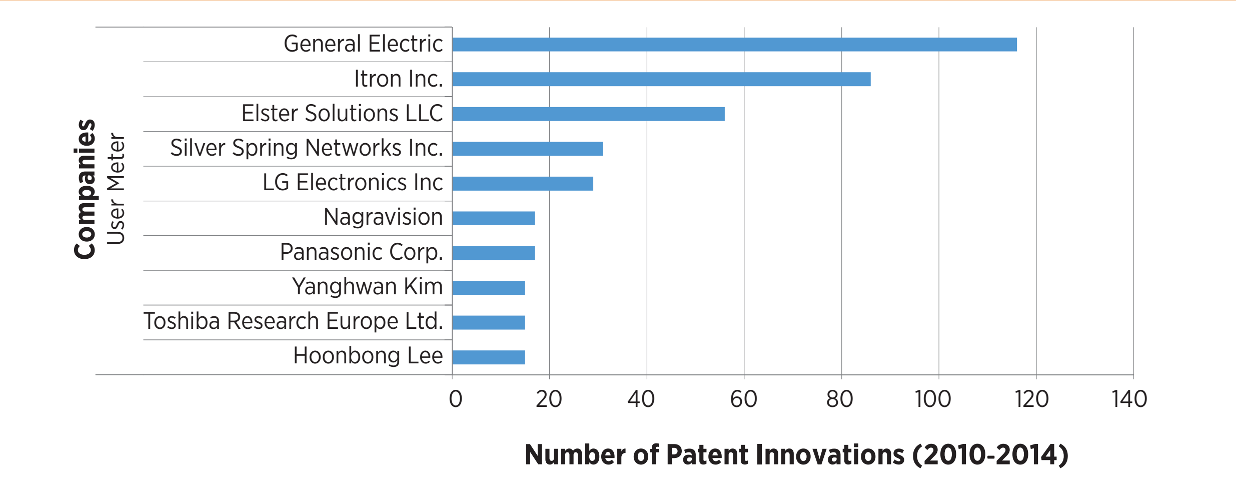
Figure 54: Top 10 countries for AC-to-DC conversion patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent filers included Mitsubishi Electric Corporation with 92 patent applications filed approximately, followed by Fujitsu Limited, Access Business Group International LLC, Ideal Power Converters Inc., Enphase Energy Inc., Brusa Elektronik, General Electric, Toshiba Corporation, Panasonic Corporation and William C. Alexander. See Figure 55:

Figure 55: Top 10 companies for AC-to-DC conversion patents filed from 2010 to 2014

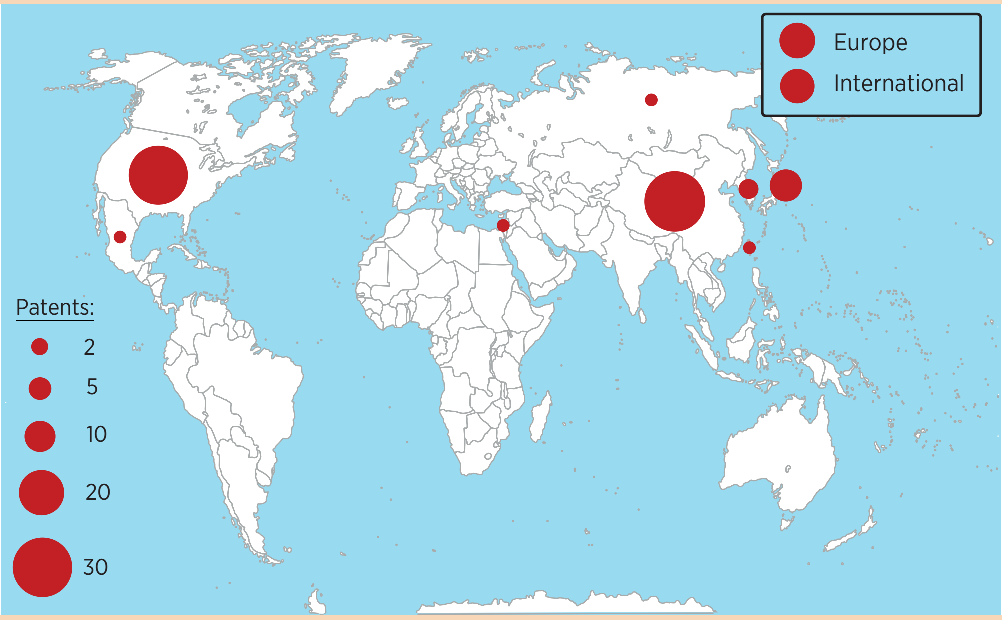


Source: Author elaboration; EPO, 2015a; EPO, 2015b

AC-AC conversion

The patent offices that filed the most patents from 2010 to 2014 were China's, with 31 patent applications filed, followed closely by those of the United States with approximately 30, then EPO, WIPO, Japan, the Republic of Korea, Chinese Taipei, the Russian Federation, Mexico and Israel (EPO, 2015a; EPO, 2015b). See Figure 56:

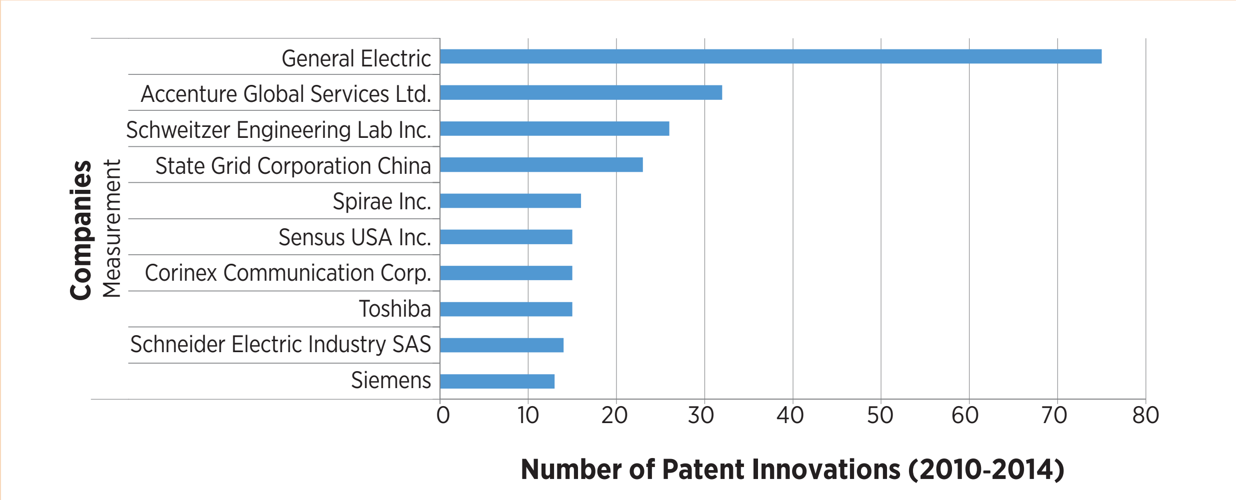
Figure 56: Top 10 countries for AC-to-AC conversion patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporations that held the most number of patents in the past five years included but were not limited to Ideal Power Converters, with approximately 16 patents filed, followed by Brusa Elektronic, William C. Alexander, Axel Krause, Enphase Energy Inc., General Electric, University of California, Texas A&M University, MKS Instruments and Huawei Tech Company. See Figure 57:

Figure 57: Top 10 companies for AC-to-AC conversion patents filed from 2010 to 2014

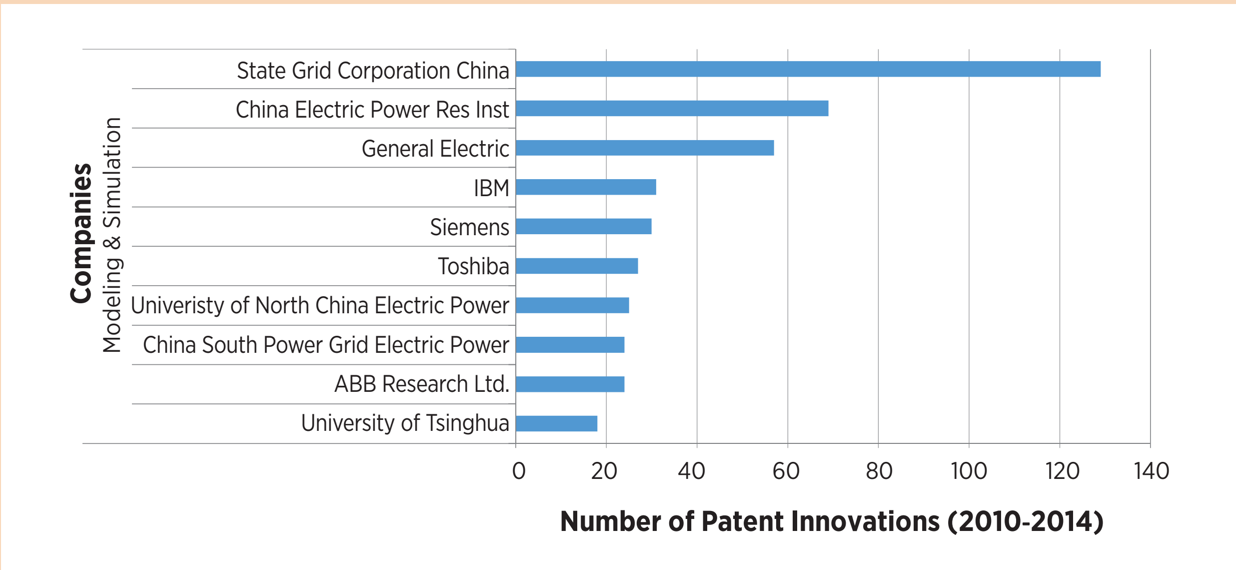


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Consume

The patent offices that filed the most patents from 2010 to 2014 were those of the United States, with 2 096 patents filed, followed by China, WIPO, Japan, EPO, the Republic of Korea, Chinese Taipei, Germany, the United Kingdom and Canada (EPO, 2015a; EPO, 2015b). Major corporate patent holders in the period are listed in Figure 58:

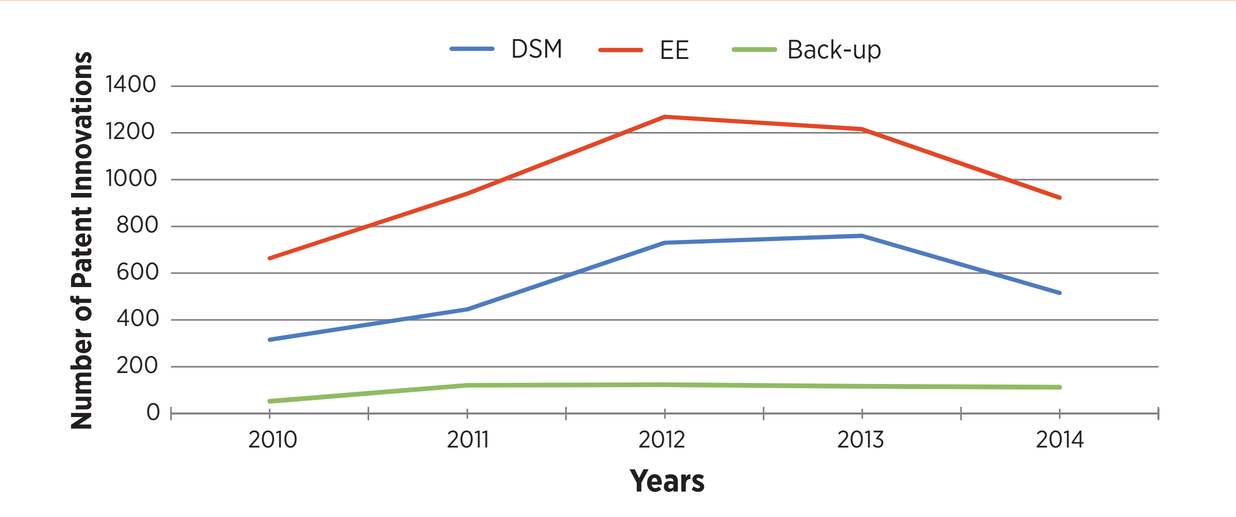
Figure 58: Top 10 companies for all consumption technologies patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

From 2010 to 2013 there was a slight increase in energy efficiency and DSM patents filed, followed by a drop in 2014 because of a backlog of pending ones. Figures related to filed patents for back-up technology patents filed have been more stable. See Figure 59:

Figure 59: Number of patents for consumption technologies from 2010 to 2014

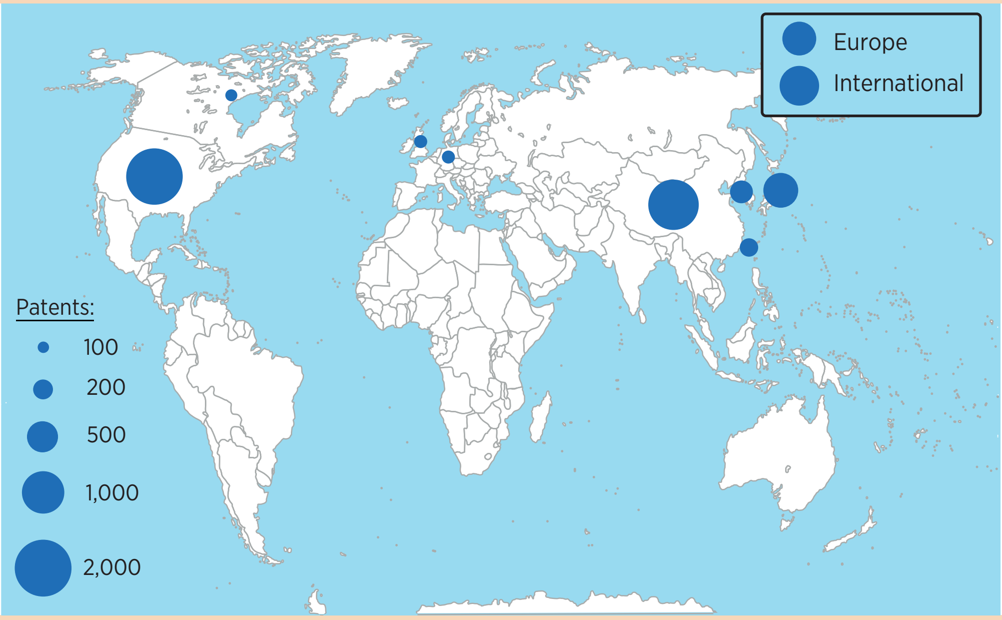


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Demand-side management

The patent offices that filed the most patents from 2010 to 2014 were those of the United States, with more than 1 970 patents filed, followed by China, WIPO, EPO, Japan, the Republic of Korea, Chinese Taipei, the United Kingdom, Germany and Canada (EPO, 2015a; EPO, 2015b). See Figure 60:

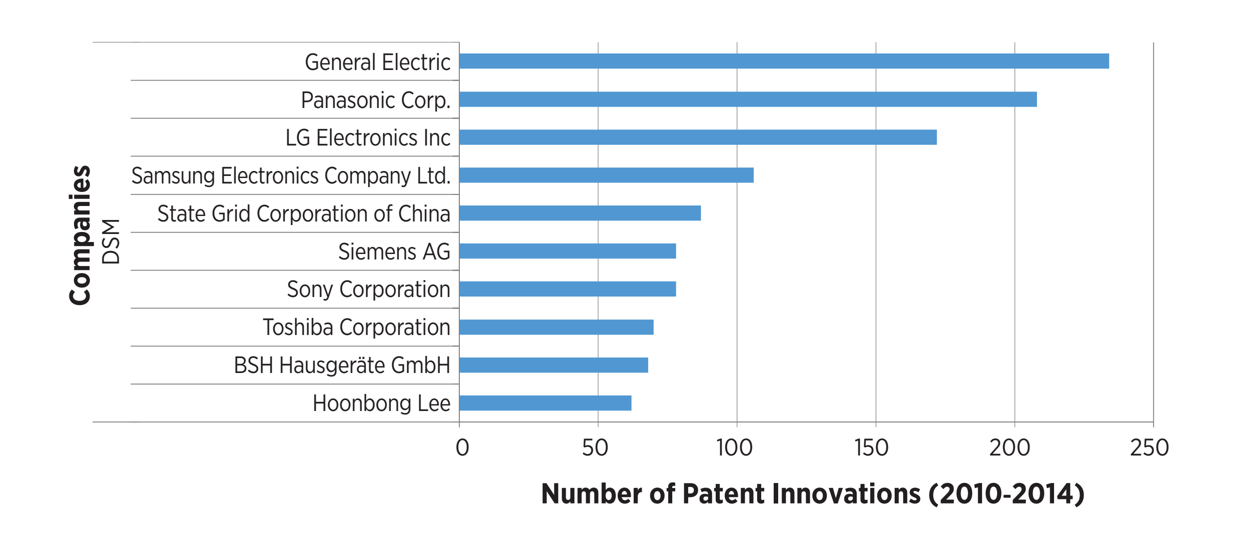
Figure 60: Top 10 countries for DSM patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders in the period included but were not limited to General Electric, with 234 patent applications filed approximately, followed by Panasonic Corporation, LG Electronics Inc., Samsung Electronics Company Ltd., the State Grid Corporation of China., Sony Corporation, Siemens AG, Toshiba Corporation, BSH Hausgeräte GmbH and Hoonbong Lee. See Figure 61:

Figure 61: Top 10 companies for DSM patents filed from 2010 to 2014

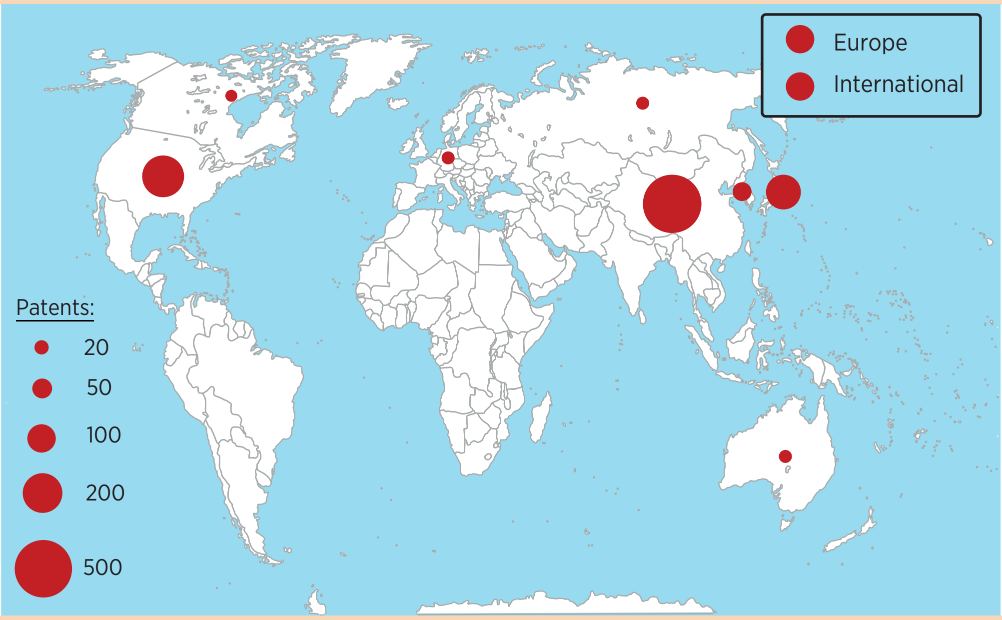


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Energy efficiency

The patent offices that filed the most patents from 2010 to 2014 were China's, with approximately 468 applications filed, followed by those of the United States, Japan, WIPO, EPO, the Republic of Korea, Canada, the Russian Federation, Germany and Australia (EPO, 2015a; EPO, 2015b). See Figure 62:

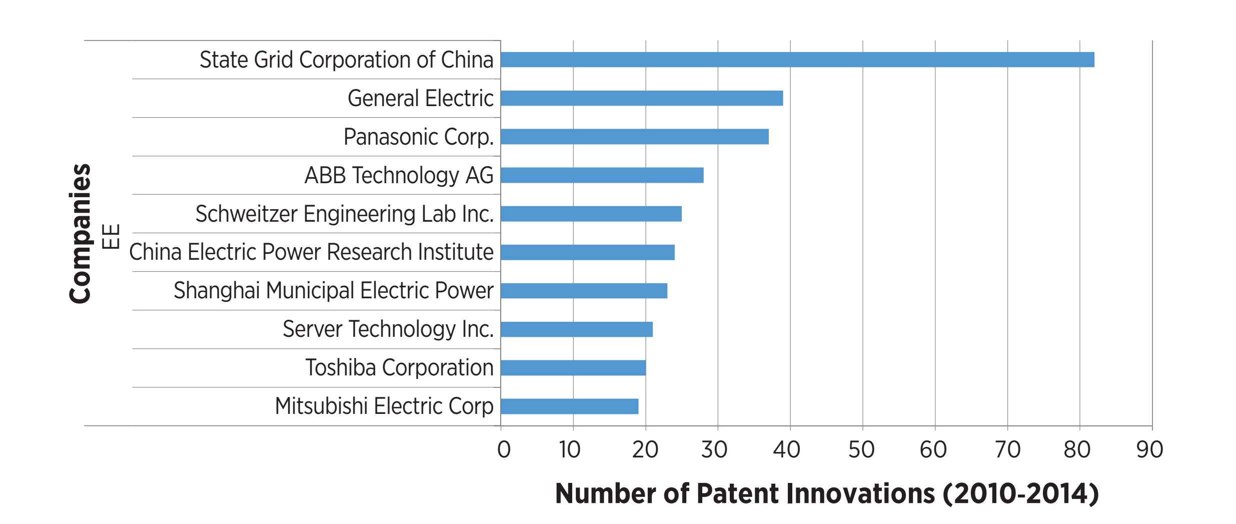
Figure 62: Top 10 countries for energy efficiency patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders in the period included State Grid Corporation of China, with approximately 82 patent applications filed, followed by General Electric, Panasonic Corporation, ABB Technology AG, Schweitzer Engineering Lab Inc., China Electric Power Research Institute, Shanghai Municipal Electric Power, Server Technology Inc., Toshiba Corporation and Mitsubishi Electric Corporation. See Figure 63:

Figure 63: Top 10 companies for energy efficiency patents filed from 2010 to 2014

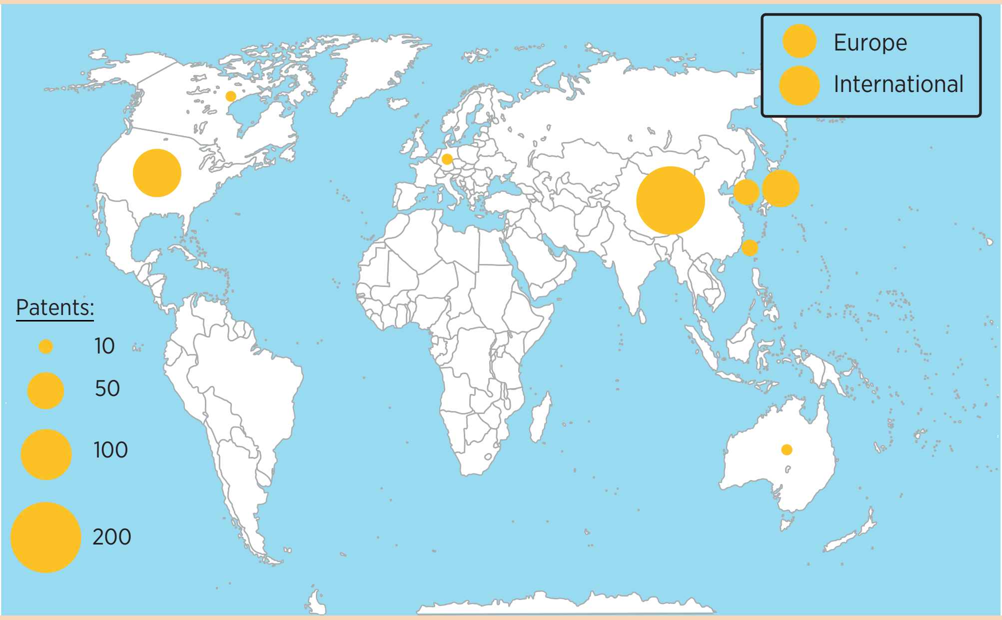


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Back-up

The patent offices that filed the most patents from 2010 to 2014 were China's, with over 180 patent applications filed, followed by those of the United States, with approximately 100 patent applications filed, WIPO, Japan, EPO, the Republic of Korea, Chinese Taipei, Canada, Australia and Germany (EPO, 2015a; EPO, 2015b). See Figure 64:

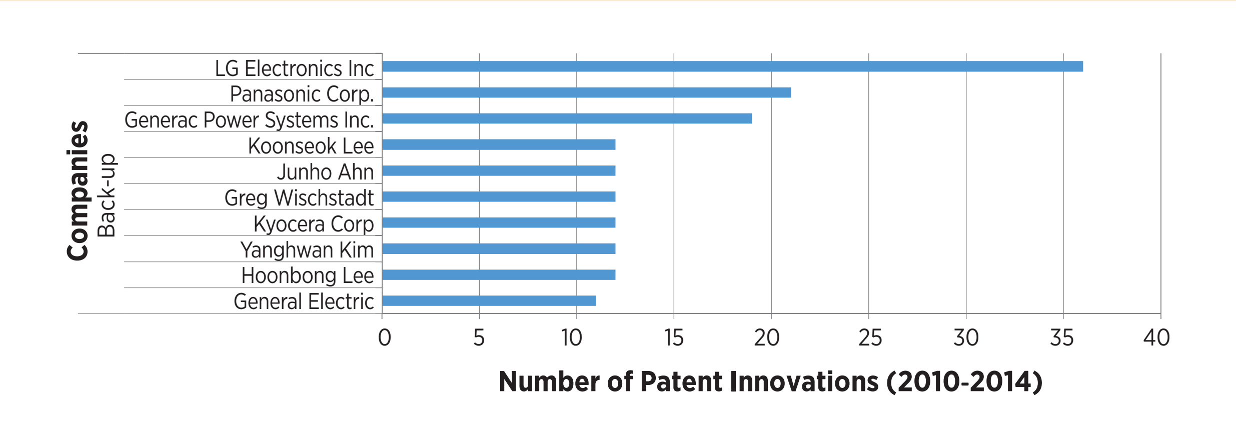
Figure 64: Top 10 countries for back-up patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporations holding the most patents included but were not limited to LG Electronics Inc. with approximately 36 patents filed, followed by Panasonic Corporation, Generac Power Systems Inc., Greg Wischstadt, Koonseok Lee, Hoonbong Lee, Kyocera Corporation, Yanghwan Kim, Junho Ahn and General Electric. See Figure 65:

Figure 65: Top 10 companies for back-up patents filed from 2010 to 2014

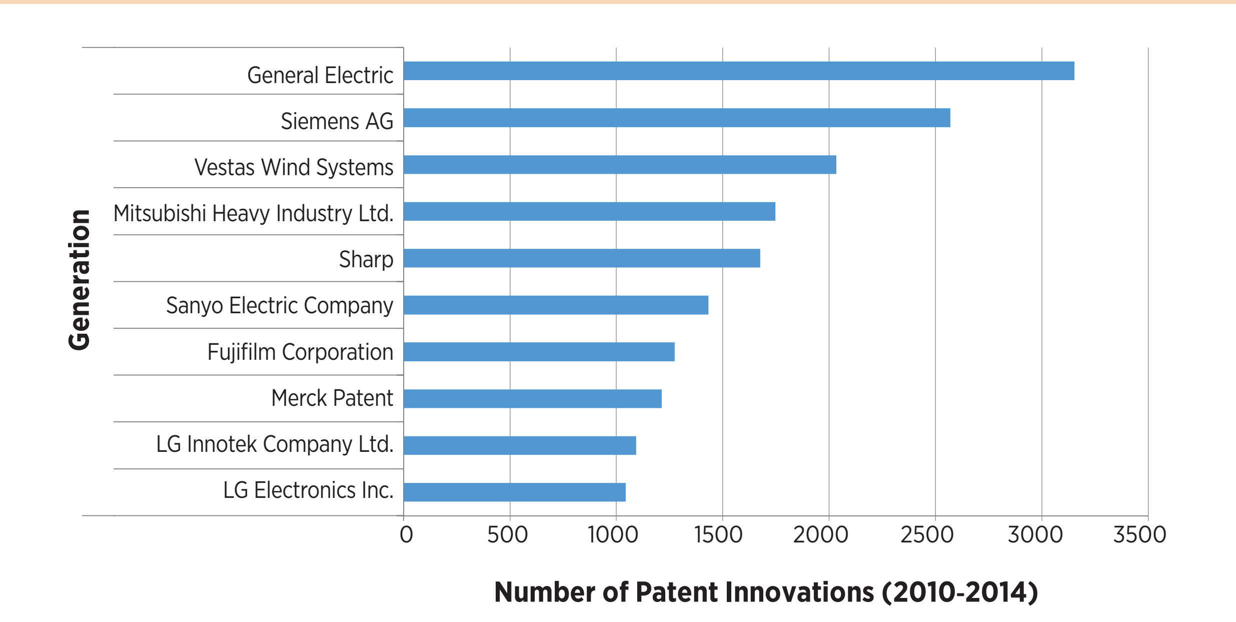


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Generate

The patent office that filed the most applications from 2010 to 2014 for generation was China's, with over 50 000 patents filed, followed by the United States with over 30 000, WIPO, Japan, the Republic of Korea, EPO, Chinese Taipei, Germany, Canada and Australia (EPO, 2015a; EPO, 2015b). Major corporate patent holders are listed in Figure 66:

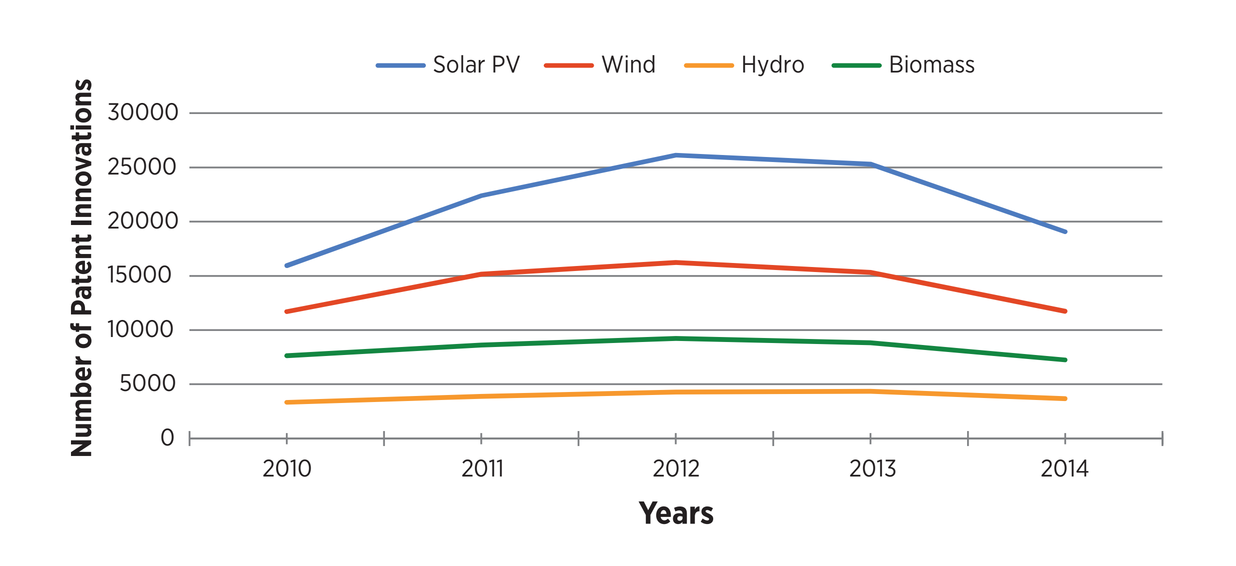
Figure 66: Top 10 companies for all generation technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 201a; EPO, 2015b5

Filed patents on PV and wind turbines peaked in 2012 and have decreased since. The sharp decrease observed in 2014 might be due to patents that were not yet reported to the EPO database.

Figure 67: Number of patents for generation technologies filed from 2010 to 2014

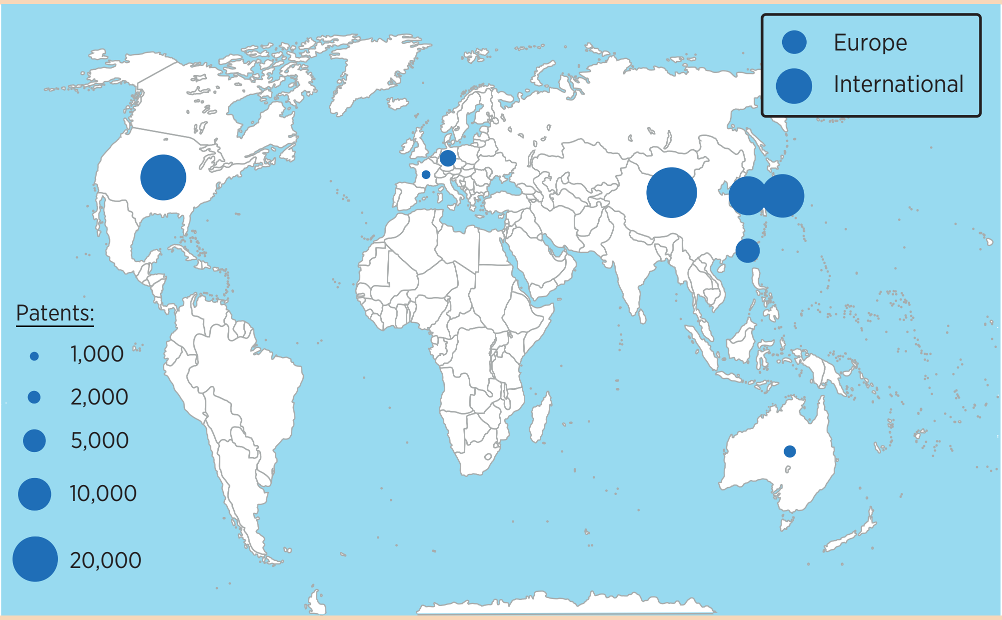


Source: Author elaboration; EPO, 2015a; EPO, 2015b

PV

The patent offices that filed the most applications from 2010 to 2014 were China's, with almost 22 274 patents filed, followed by those of the United States, Japan, the Republic of Korea, Chinese Taipei, Germany and Australia (EPO, 2015a; EPO, 2015b). See Figure 68:

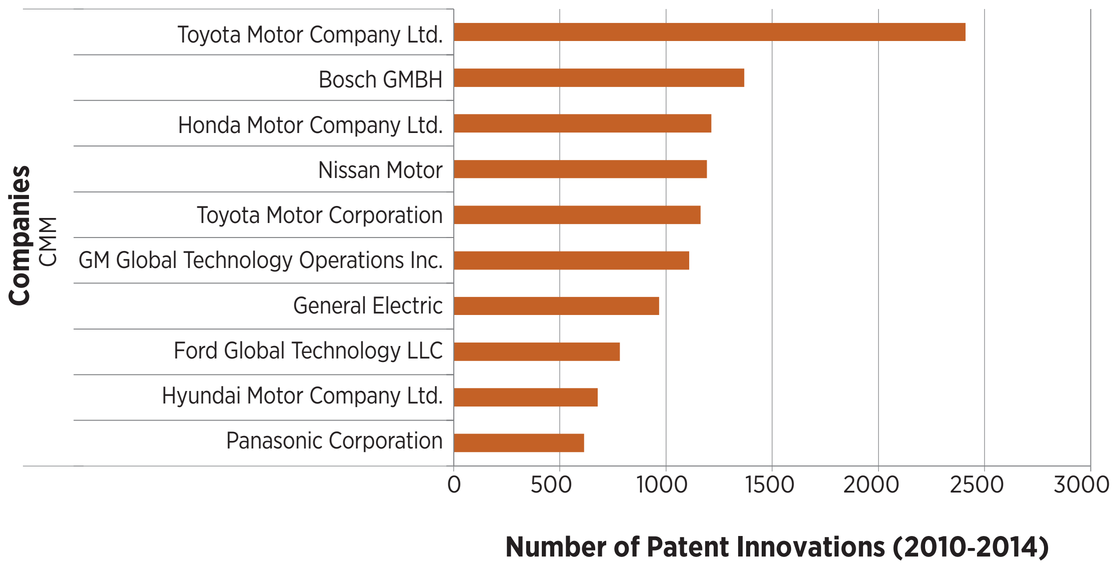
Figure 68: Top 10 countries for solar PV patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders included Sharp, with approximately 1 660 patents filed, followed by Sanyo, Fujifilm Corporation, Merck, LG Innotek and LG Electronics, DuPont, Kyocera and Mitsubishi Electric. See Figure 69:

Figure 69: Top 10 companies for solar PV patents filed from 2010 to 2014

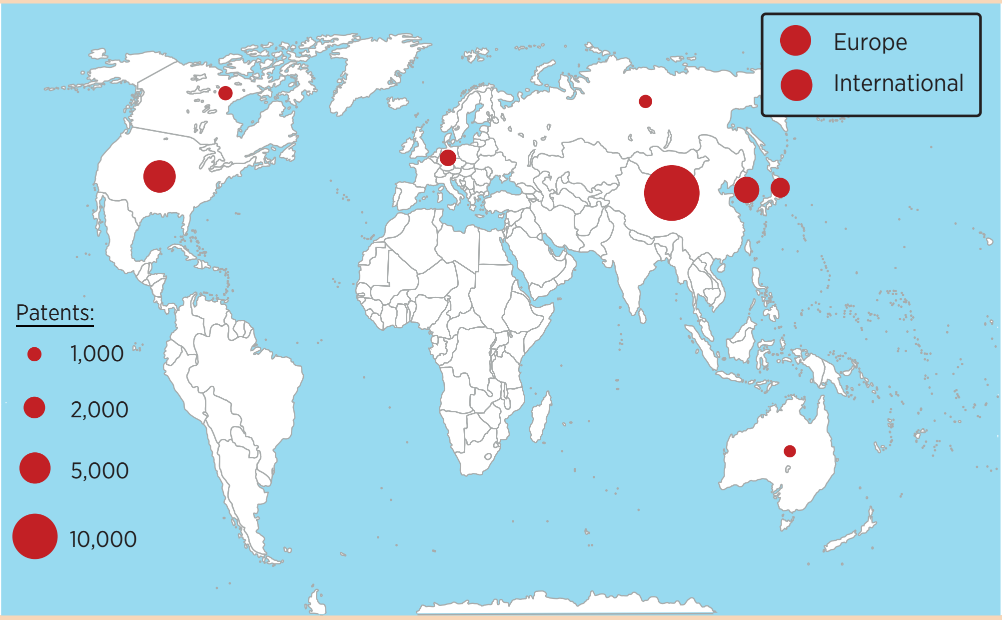


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Wind

The patent offices that filed the most applications from 2010 to 2014 were China's, with almost 16 000 patents filed, followed by those of the United States, WIPO, EPO, the Republic of Korea, Japan, Germany, Canada, the Russian Federation and Australia (EPO, 2015a; EPO, 2015b). See Figure 70:

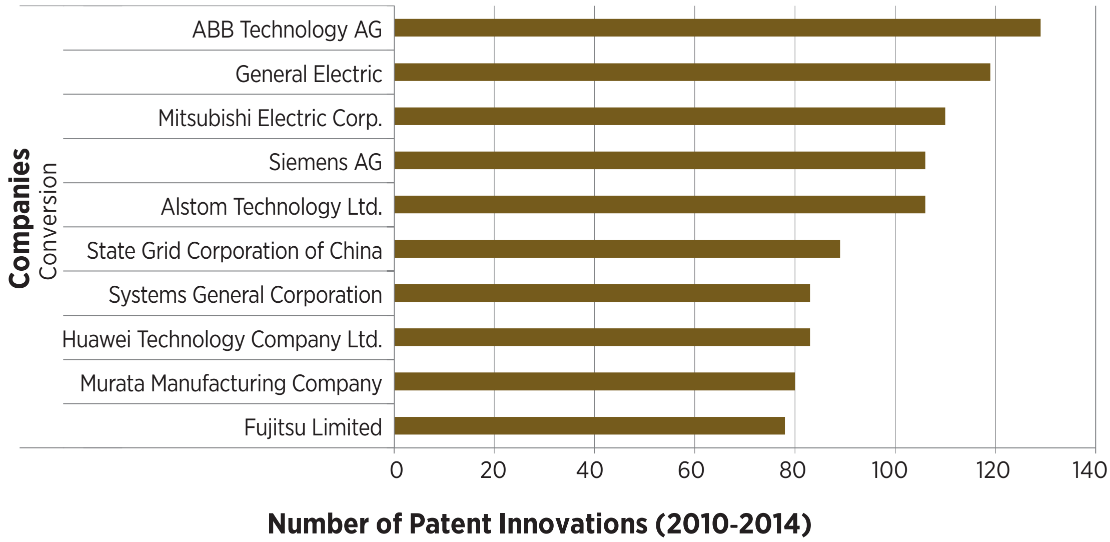
Figure 70: Top 10 countries for wind turbine patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Corporations holding the most patents included General Electric, with approximately 2 513 patents filed, followed by Siemens AG, Vestas Wind Systems AS, Mitsubishi Heavy Industry Ltd., Wobben Properties, Samsung Heavy Industry, Bosch, Gamesa Innovation Tech, Guodian United Power Tech and Sinovel Wind Group Company Ltd. See Figure 71:

Figure 71: Top 10 companies for wind turbine patents filed from 2010 to 2014

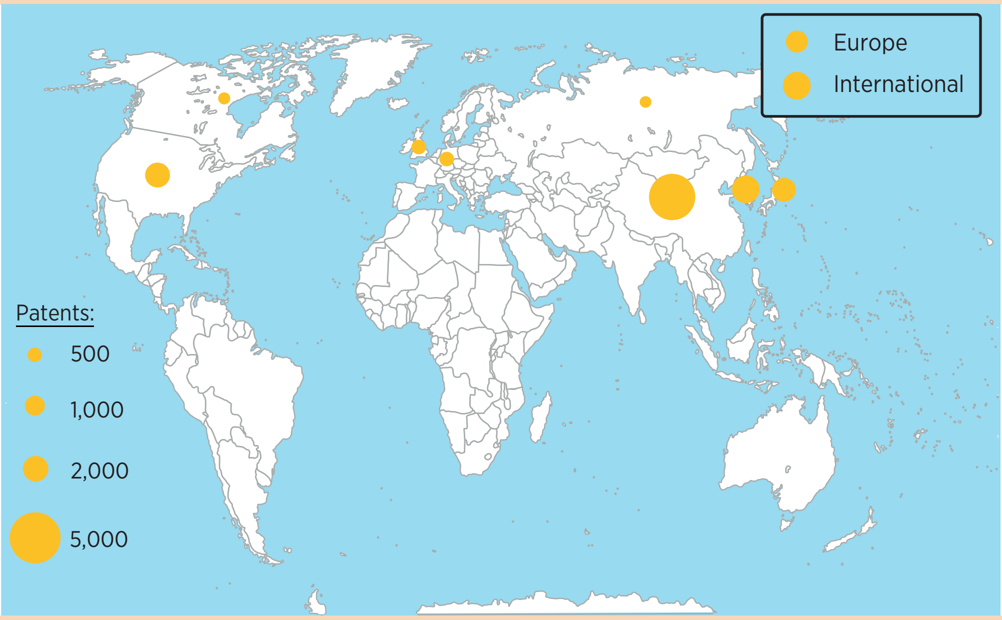


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Hydro

The patent offices that filed the most patents from 2010 to 2014 for hydroelectric technologies were China's, with more than 4 400 patents filed, followed by those of WIPO, the Republic of Korea, the United States, Japan, EPO, Germany, the United Kingdom, Canada and the Russian Federation (EPO, 2015a; EPO, 2015b). See Figure 72:

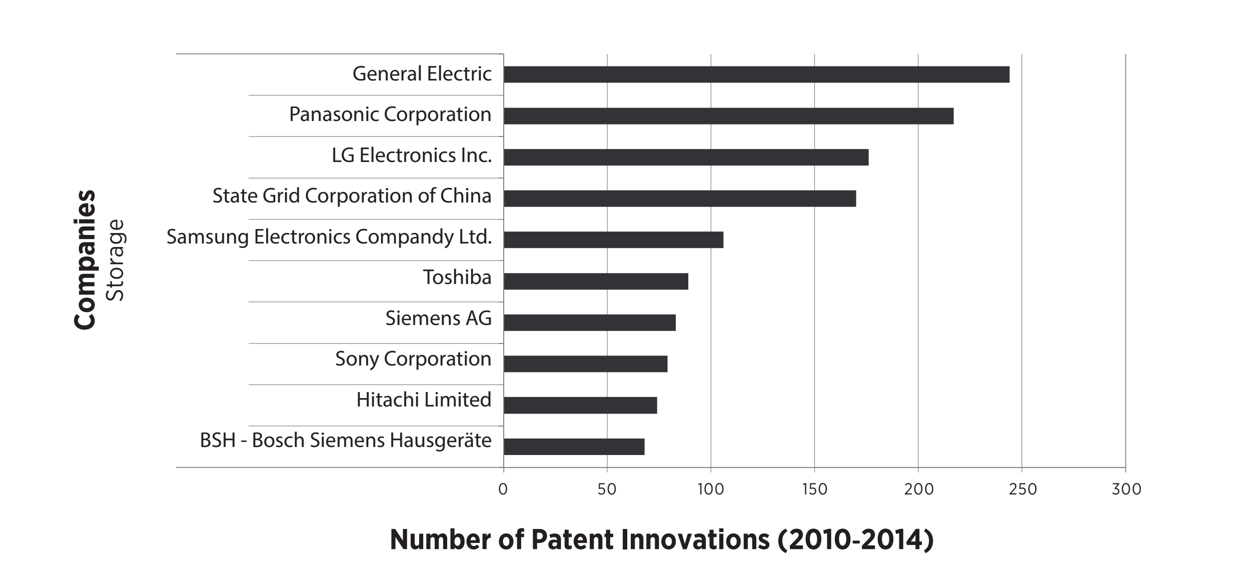
Figure 72: Top 10 countries for hydro turbine patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders included Voith Patent, with approximately 272 patents filed, followed by Tidal Generation Ltd., Alstom Hydro France, OpenHydro IP Ltd., Tianjin Tianfa Heavy Machinery, Atlantis Resources Corp., Alstom Renewable Technologies, State Grid Corporation of China, Rolls Royce and Toshiba Corp. See Figure 73:

Figure 73: Top 10 companies for hydro turbine patents filed from 2010 to 2014

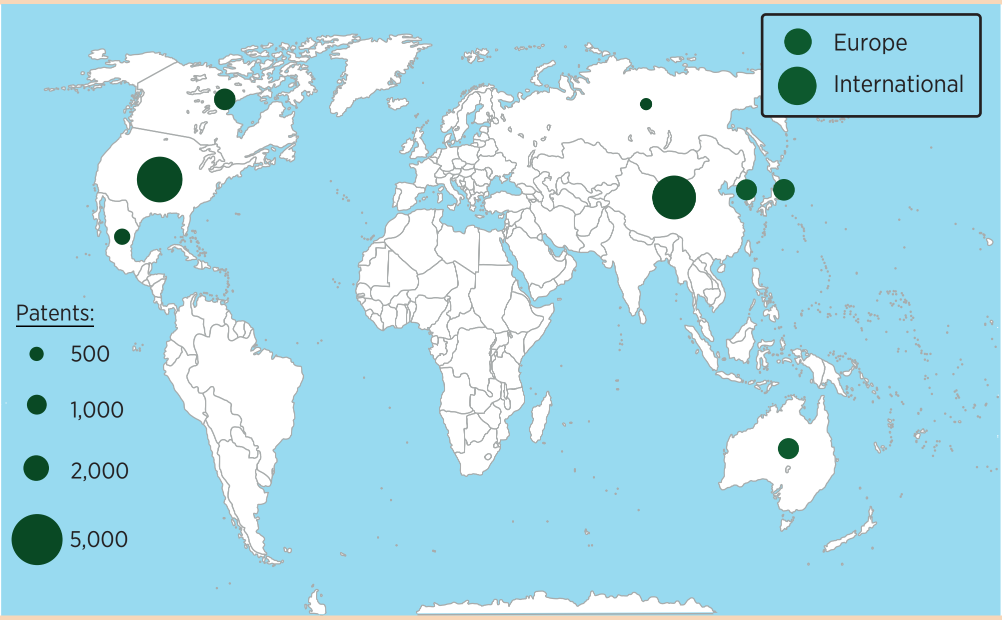


Source: Author elaboration; EPO, 2015a; EPO, 2015b

Biomass

The patent offices that filed the most applications from 2010 to 2014 were that of the United States, with 4 000 patent applications filed, followed closely by those of China, with 3 900 patents filed, WIPO, EPO, Canada, Japan, Australia, the Republic of Korea, Mexico and the Russian Federation (EPO, 2015a; EPO, 2015b). See Figure 74:

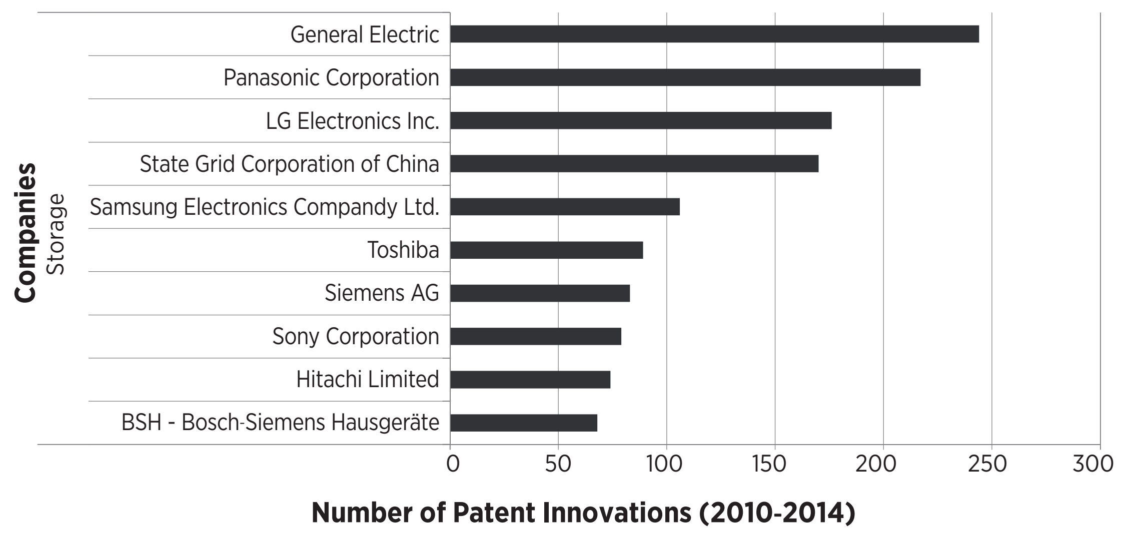
Figure 74: Top 10 countries for biomass technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

Major corporate patent holders included but were not limited to Xyleco Inc., with 542 patents filed, followed by Novozymes, Lanzatech New Zealand Ltd., IFP Energies Nouvelles, Codexis Inc., DuPont, Shell Int Research, Kior Inc., and Danisco US Inc. See Figure 75:

Figure 75: Top 10 companies for wind turbine patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015a; EPO, 2015b

ANNEX 5:

Indicators

Plan and design, CMM and consume

The indicators for the plan and design, CMM and consume functionalities are qualitative and are derived from the findings of the innovations research, including literature review and key expert interviews.

Store

Most of the literature provides projections of indicators through 2030. The slope between the years 2025 and 2030 was extrapolated to project out to 2035. Most values for lead-acid and flow batteries were based on Fuchs et al. (2012). Advanced lead-acid battery values were available up to 2020 (IRENA, 2015a). A linear extrapolation was performed to 2025 and 2035. Values for lithium-ion batteries were taken from IRENA (2015a), Jaffe (2014) and RMI *et al*. (2014). Also, in all cases, values provided by the EASE/EERE study were considered and verified. Flow battery and LIB values were derived from Viswanathan *et al*. (2013). Values for flywheels were the least common in reports, and were derived primarily from the EASE/EERE report value for 2030. Many references provide a range of values which were used to sanity-check the values, *i.e.*, providing both the lower and highest value, unless such was significantly higher or lower in comparison to other literature. In isolated cases with no values found, the authors used professional judgement.

Generate

Values for PV technologies were abundant, and were based mainly on Metz *et al*. (2014), which provides values for 2024. For 2035, costs from the IEA Solar PV Roadmap were used (IEA, 2014). The lifetime projections were based on professional judgement.

For wind turbines costs were based on DWEA (2015), which includes cost projections to 2030. Values for 2025 were interpolated and for 2035 were linearly extrapolated. Lifetime values are based on literature that describes improvements to materials, which was converted to quantitative estimates using professional judgement.

Given the technological maturity, costs for small hydropower are expected to have limited cost reductions, with technological innovations focused mainly on lower-cost and more efficient civil engineering (IRENA, 2012c). The Tracking Clean Energy Progress report from the IEA (IEA, 2012a) estimates that small hydropower costs will remain the same through 2020. These factors led to our conclusion that there would be limited changes in the indicators.

Values for gasification technologies were derived from IRENA's report on biomass costs (IRENA, 2012b) which expects a 22% cost reduction for gasifiers by 2020. The value was extrapolated linearly into the future for 2025 and 2035.

Convert

For conversion technologies, very limited data were found in the literature about expected cost reductions or expected efficiency improvements. Grid-forming inverters included the most data. They are expected to follow PV cost reductions through 2025 and 2050 (Fraunhofer ISE, 2015a). A similar cost trend was assumed for grid-forming and dual-mode inverters. Efficiency improvements were estimated in all cases using professional judgement and through consideration of comments from interviewed inverter manufacturers. The lifetime indicators were similarly derived.

ANNEX 6:

Generation state of the art and outlook

State of the art in generation

Renewable power generation is central to renewable mini-grids. The most common renewable energy generation technologies applicable for most renewable mini-grids are PV, wind, hydro and some biomass applications. PV and wind are prevalent in all renewable mini-grid types, while hydro and biomass technologies are more common in off-grid applications. Most generation technologies have achieved their technological maturity and are favoured with low-costs due to their increased use in grid projects. New generation technology innovation will need major breakthroughs from the current state of the art, which will most likely focus on using fewer and more abundant materials, lowering costs and improving operating conditions.

Solar PV

Solar PV is one of the most widely used renewable energy technologies, due to declines in the cost of the technology, coupled with its modular/scalable deployment and relative ease of installation and operation. Solar PV is particularly important because the resource is easy to predict using readily available tools and it can be deployed in most areas globally, even Arctic areas and in both grid-connected and autonomous environments. Table 46 summarises the main indicators for PV.

Costs

PV modules today cost 75% less than in 2009 (IRENA, 2015b). PV technology's ease of installation, a reduction in materials used, improved manufacturing and less-expensive racking systems are expected to bring costs down further into the future (IEA, 2014). In addition, manufacturers already guarantee 80-90% of nameplate performance for 20 years, and up to 70% for 30 years (Campeau *et al.*, 2013).

Operation and maintenance (O&M) costs for PV installations are usually cited as USD 0.01–0.03/kWh or around 1.5% of CAPEX costs (IEA, 2014; Ossenbrink *et al.*, 2013) depending on the maturity of the market. O&M costs refer to periodical cleaning, inspection and replacement of modules. It also depends on market maturity (Fraunhofer ISE, 2014). Even if O&M costs represent a minimal cost of the LCOE (*see* Glossary of Terms), improved remote monitoring as preventive maintenance plus a critical mass in O&M services for PV can bring them down further.

Technology

Commercially mature silicon-based PV modules have reached a 20% solar efficiency, getting close to the limit (IEA, 2014). Meanwhile, third-generation modules have potential for up to 50% efficiencies and have already reached 46% efficiencies in the laboratory (Jordan and Kurtz, 2012; NREL, 2015). Temperature also impacts the

Table 46: Summary of state of the art for PV technologies

	Small-scale (rooftop)	Large-scale (utility-scale)
KI 1: Installed cost (USD/W)	2.00–3.50	1.0–2.5
	0.50–0.90 (module only)	
KI 2: LCOE (USD/kWh)	0.15–0.25	0.10–0.20
KI 3: Lifetime (years)	25–30	
Renewable mini-grid type	All	
Solar efficiency	12–21%	
Temperature co-efficient (%/°C)	(-0.13)–(-0.48)	
Degrading factor (%/year)	0.5–1	

Source: IRENA, 2015b; Jordan and Kurtz, 2012; MIT, 2015; Ndiaye et al., 2013; IEA, 2014; Ossenbrink et al., 2013; pvXchange, 2015; Virtuani et al., 2012 efficiency. Efficiency losses due to temperature can easily add up to 5-10% of total output depending on the environmental conditions.

PV market share is dominated by second-generation silicon-based modules, mainly polycrystalline modules (>90%), and to a lesser extent CdTe thin-film (Fraunhofer ISE, 2014). Third-generation technologies such as multi-junction, dye-sensitised and organic cells are still away from full commercialisation (IEA, 2014). Third-generation technologies represent higher efficiency possibilities, and in the case of organic cells a reduced environmental impact.

Social and Environmental

Although PV is considered a low-impact renewable energy technology, the manufacturing of PV modules requires the use of highly toxic materials, *e.g.*, silicon tetrachloride, silane gas, sulphur hexafluoride, nitrogen trifluoride and cadmium (SVTC, 2009). The energy payback time for a PV system can be as much as two years, depending on the technology and location of the installation (Fraunhofer ISE, 2014). The full life-cycle of modules is being addressed by initiatives such as PV Cycle to ensure recyclability of modules and end-of-life disposal by manufacturers (PV Cycle, 2013). Besides, studies point out the necessity of standardisation of silicon and slurry recycling procedures in order to reduce production costs (Metz *et al.*, 2014), or the focus on the use of alternative, more abundant organic materials.

Wind turbines

Wind technologies have several classification schemes that are based on whether the unit has a horizontal or vertical axis, the geographic location of turbine, *i.e.*, onshore or offshore, and its size, *i.e.*, small wind turbines (SWT, between 100 and 1 000 kW) or large wind turbines (LWT, between 1.0 and 2.5 MW) (DWEA, 2015). There are also very small wind turbines (VSWT, less than 100 kW), but their capital costs are much higher (USD 6 000 – 8 500/kW), and in the United States their market share decreased significantly in 2013 (Wiser and Bolinger, 2014). Wind turbines also can be classified according to the number of blades, gearbox design, rotor placement and rotational speed, among others (IRENA, 2012a). Table 47 summarises the key and specific indicators for SWT and LWT.

Cost

Wind turbine costs declined significantly until 2004, when prices started to increase due to rising steel and cement prices and a shift to offshore projects (IRENA, 2012a). Prices are considered to have stabilised in 2010-2011. A literature review from the IEA identified that most studies report a further 20-30% cost reduction expected by 2030 (Lantz *et al.*, 2014). O&M costs average around USD 50-80/kW/year depending on the turbine size and location. O&M costs can represent up to 20-25% of overall LCOE, where improved installation and maintenance techniques are expected to drive this cost down.

Technology

Cut-in wind speeds (*see* Glossary of Terms) of wind turbines range between 2 and 5 m/s in general. However, it has been possible to generate power by harnessing wind with speed lower than this. For example, Honeywell's gearless turbine WT6500 has a cut-in speed as small as 0.2 m/s. In addition, capacity factors (*see* Glossary of

Table 47: Summary of state of the art for wind turbines

Indicators	Small wind (horizontal-axis)	Large wind (horizontal-axis)
KI 1: Installed cost (USD/kW)	4 000–4 500	1 500–3 500
KI 2: LCOE (USD/kWh)	0.12–0.28	0.06–0.14
KI 3: Lifetime (years)	> 20–25	
Renewable mini-grid type	AB, AF, IC	IC, ILI
Cut-in speed (m/s)	2–4	3–5
Output decline (%/year)	≤ 1.5 %	1.5–1.9

Source: ARE, 2012; DWEA, 2015; Hughes, 2012; IRENA, 2012a; Kost et al., 2013; Staffell and Green, 2014

Terms) in wind turbines have increased from 22% in 1998 to over 30-40% in 2015.

Current wind turbine lifetime exceeds 20 years, with turbines installed in the 1990s still in operation. With regard to output a decline of 1.5-1.9%/year was estimated for onshore LWT (Staffell and Green, 2014). The performance of large wind farms declines more rapidly than small ones (Hughes, 2012). In addition, main declines are observed in the latter years, with older wind farms deteriorating more rapidly (Staffell and Green, 2014). Some companies are offering a guaranteed yearly output above 90% (Enercon) in return for an annual fee.

According to (IRENA, 2012a), the key factors in improving performance and cost efficiency of SWT will be more efficient installation and maintenance techniques, as well as advances in SWT technology and manufacturing.

Social and Environmental

Some of the main environmental concerns for wind turbines stem from their potential impact on bird and bat populations, which can be minimised. With regard to land use, this can be addressed by siting projects, *e.g.*, in brownfields. There is occasional opposition from communities that are concerned with visual and sound impacts of wind projects.

Hydro turbines: run-of-river

Hydro turbines provided the first renewable power source for autonomous mini-grids. There are two factors that differentiate hydro turbines: size and technology. These factors can have an impact on several aspects related to cost, efficiency and head. The most common turbine types are Kaplan and Pelton turbines, while Francis, cross-flow and hydrodynamic screws are less common. The most common size classifications are: pico hydro (< 5 kW), micro-hydro (<100 kW), mini-hydro (<1 MW) and small-hydro (< 10 MW) (ARE, 2014). This report only evaluates run-of-river (*see* Glossary of Terms) hydro technologies and excludes large hydropower (>10 MW). Table 48 summarises the main indicators for hydro technologies.

Cost

Hydropower plants have high upfront costs that include civil works for necessary infrastructure and electro-mechanical equipment. Electromechanical equipment can represent more than half of the initial capital expenditures (CAPEX) in the case of small-scale hydropower plants, but this depends on the location and accessibility of the project (IRENA, 2015b).

In most regions the LCOE of small hydro technologies reflects the most mature installation sites for the renewable energy technology generation sources. The LCOE breakdown for small-scale hydro plants show that the main variation in cost is due to equipment and the electrical connection/construction (IRENA, 2015b). O&M costs for small hydropower are usually higher than for solar PV technologies: smaller-scale hydro turbines have O&M costs of USD 45-250 kW/year, while larger systems are around USD 40-50 kWh/year. Capacity factor in hydro turbines depends highly on the resource availability and can vary from 30% to 60%.

Technology

For all systems of up to 10 MWe, turbine efficiency can reach up to 92% and maximum plant availability is 98%.

Table 48: Summary of state of the art for hydropower

Indicators	Pico, micro and mini-hydro	Small hydro
KI 1: Installed cost (USD/kW)	3 400–10 000	1 000–4 000
KI 2: LCOE (USD/kWh)	> 0.27	0.02–0.19
KI 3: Lifetime (years)	30 (economic)	> 30
Renewable mini-grid type	AB, AF, IC	IC
Turbine efficiency	Up to 92%	Up to 92%
Minimum head (m)	1–3	3–10
Flow (m^3/s)	1–5	1–5

Source: ARE, 2014; Asselbergs and Dijk, 2013; ESHA, 2012; IEA-ETSAP and IRENA, 2015a; Roebuck, 2012; Voith, 2015

The selection of turbine type depends on the head range and flow rate, as well as on non-technical aspects such as maintenance requirements and transportation (Roebuck, 2012). Technology-wise, hydro turbines are considered a well-matured technology, where the main barriers consist of siting selection. Future improvements are most likely to be concentrated towards using hydro turbines in new and different sites and harnessing a wider range of head, flow speeds and seasonal variations.

The technical lifetime of small hydro plants can reach 100 years (IEA-ETSAP and IRENA, 2015a). Nonetheless, even if physically the hydro turbines can last as long as 100 years, the economic lifetime is defined as "the time after which money is saved by abandoning the asset", usually just above 30 years after which major refurbishment is required. As with other technologies, an improved lifetime though more robust materials would yield better LCOE and minimise environmental impacts. Some installations use variable speed turbines to maximise the energy production, which can often offset the slightly higher initial cost.

Social and Environmental

Regarding environmental considerations of hydro installations, there is an impact on river biodiversity. However, smaller hydro plants tend to have a lower impact on fish populations.

Biomass technologies

There are two major types of biomass technologies: mass-burn and gasification. Mass-burn technologies are used primarily for larger-scale grids and therefore are not addressed in this report (IEA-ETSAP and IRENA, 2015b). Biomass gasification is used mainly at small scale in India and some parts of Africa (SEVEA, 2013). These biogas pilots are mostly in autonomous mini-grids. Table 49 summarises the indicators for biogasification technologies (*see* Glossary of Terms).

Table 49: Summary of state of the art for biogasification technologies

Indicators	Small-scale gasifiers
KI 1: Installed cost (USD/kW)	2 000–5 000
KI 2: LCOE (USD/kWh)	0.07–0.24
KI 3: Lifetime (years)	5–12
Renewable mini-grid type	AB
Efficiency (%)	10–25

Source: Dimpl, 2010; IEA-ETSAP and IRENA, 2015b; IRENA, 2012b; Mirani et al., 2013; SEVEA, 2013; Vakalis and Baratieri, 2014

Cost

Installation costs are generally low for biomass technologies, but they are expected to have higher operation costs. The installed plant capital costs drawn from a survey of international sources include a range from USD 2 000/kW to USD 5 000/kW (IEA-ETSAP and IRENA, 2015b; IRENA, 2012b). Almost 40-50% of the LCOE can be due to costs related to the feedstock (IRENA, 2012b).

Internal combustion engines suffer more wear and tear with biogas than with traditional fuels, increasing both maintenance costs and shortening the lifetime. O&M costs are usually 5-6.5%/year of the capital cost for smaller-scale applications, excluding feedstock costs. The hourly operation cost of biogasification is relatively high due to the challenges of operating and maintaining not only the gasifier, but also managing the increased challenges due to impurities in the fuel once fed into a generator. Due to the lack of data (and variation within known data), the O&M costs presented here should be considered as estimates.

Technology

Small-scale gasifier applications are usually less efficient, due to additional gasification process which has efficiencies of 50-70%. Gasification is still limited to very small-scale applications up to 100 kW, with hefty maintenance work usually required in particular for cheaper ones (Dimpl, 2010). In addition, even if improvements have been achieved in the last four to five years, reliable off-the-shelf technologies are limited (Dimpl, 2010). There are still issues concerning feedstock that can be used in gasifiers, which is limited mainly to dry chopped wood, charcoal and rice husk. Companies like Husk Power in India and AllPowerLabs in California have made significant progress with small-scale gasifiers, with several projects deployed in India, Haiti and Liberia, among others. The capacity factor is commonly 50-85%, which depends mainly on biomass availability, type of feedstock and maintenance works.

Gasification is fraught with problems related to soot and tar in the production process. Gasification process also requires a consistent, low-moisture feedstock. Another complication is that there are few equipment providers with significant numbers of installations at this scale. In a similar vein, there is limited public data about expected operational costs of these plants (Dimpl, 2010). In summary, gasification, in general, has significant O&M costs, particularly when used in combination with an electrical generator due to fouling issues.

Social and Environmental

Biomass technologies have land-use issues, in particular related to competition for land with food crops. However, some fuel choices, such as residual or crop waste, have the advantage that feedstock will not compete with food crops, with benefits for waste stream reduction. Still, availability and inconsistent feedstock quality can complicate feedstock selection. Additionally, challenges/concerns remain with regard to the purity of the produced gases content of tar and soot, which can be carcinogenic and pose severe environmental and health threats (Dimpl, 2010).

Prospects for generation innovation

Generation technologies are expected to improve over the coming two decades, both in terms of cost and performance. In particular, solar PV is expected to play a major role due to the technology's flexibility, modularity and ease of implementation (Blaabjerg and Ionel, 2015). It is expected that renewable mini-grids will increasingly use hybridisation of multiple sources (*e.g.*, solar/wind or solar/hydro).

Priority Gap 1 – Lower capital costs for generation

Renewable energy generation costs for PV in particular have seen an impressive reduction in the last five years.

Need: New, lower-cost designs for PV

Ground-breaking designs and new materials may be able to yield further cost reductions for PV in the coming decades. PV module costs have dropped to USD 0.50/Wp and are expected to reach USD 0.30/Wp in the coming decade (Metz *et al.*, 2014) and further down to USD 0.15-0.40/Wp by 2050 (Fraunhofer ISE, 2015a).

- **R&D 1: Use new, thinner/stronger materials for PV**

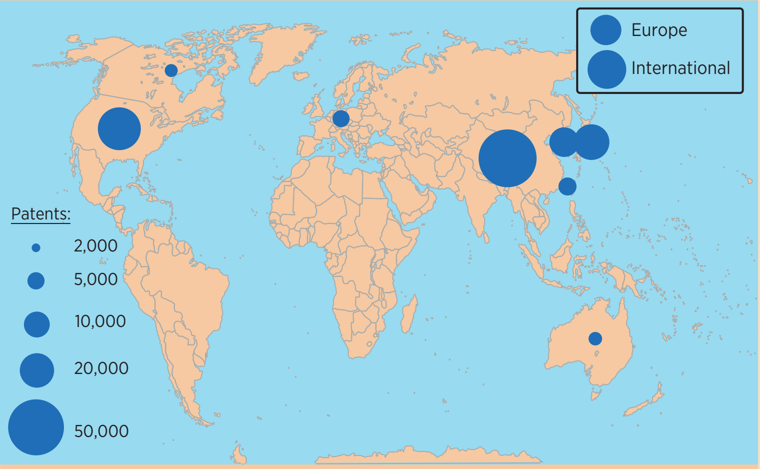
  In the next decade, crystalline silicon will continue to be the dominant material used in PV modules (Metz *et al.*, 2014; MIT, 2015), with monocrystalline cells surpassing the use of polycrystalline cells due to improvements in manufacturing and their higher potential efficiencies. Technologies such as thin films and multi-junction show promise in the next decade and will have a larger share of the market (IEA, 2014). By 2020 new market possibilities are expected for such emerging technologies, and in the next two decades nanotechnology and nanomaterials, *e.g.*, transparent electrodes based on nanoparticle metal oxides, are expected to play the largest role in emerging technologies, which will allow for improved energy management in the cells and hence their efficiencies (IEA, 2014). Overall, the LCOE of PV is expected to drop 45% by 2025 and 60% by 2035, as compared to 2013 costs (IEA, 2014). PV costs today are heavily linked to the costs of the raw materials and the manufacturing costs.

  Promising options include dye-sensitised solar cells (DSSC), organic cells, quantum wire, quantum dots, Perovskite cells, thermoelectric devices and the use of graphene (IEA, 2014). DSSC and organic cells have been the most patented and researched in the decade between 2005 and 2015. DSSC are expected to yield lower costs as efficiency is increased (Bose *et al.*, 2015). State-of-the-art DSSCs already achieve 11% efficiency in the lab and are attractive due to the use of low-cost materials such as ruthenium, fluorine-doped tin oxide (most researched and lower cost) and other metal oxides, which are also lightweight, flexible, have low toxicity and are easy to manufacture (Calogero *et al.*, 2015; Ye *et al.*, 2015).

  Still vegetable-based and other organic dyes have a greater cost reduction potential, and even less toxicity, but they are at their infancy, in particular to the achievable efficiency (Calogero *et al.*, 2015). For example, scientists from the University of Botswana and Yale University are researching the use of natural extracts such as

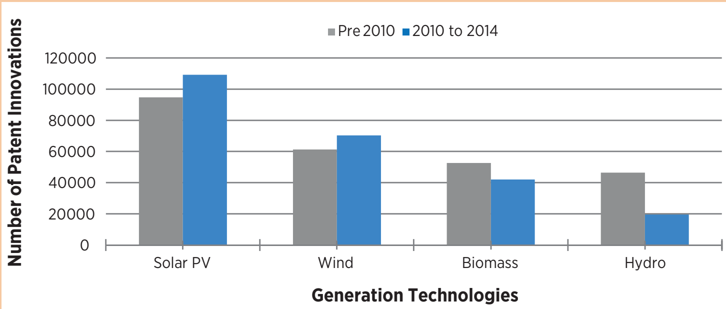
Consumption Technologies: Patent Review

Figure 76: Top 10 countries for all generation technology patents filed from 2010 to 2014



Source: Author elaboration; EPO, 2015

Figure 77: Number of patents for generation technologies for all years prior to 2010 and for 2010-2014



Source: Author elaboration; EPO, 2015

Top institutions patenting generation technologies, 2010-2014

- General Electric
- Siemens AG
- Vestas Wind Systems
- Mitsubishi Heavy Industry Ltd.
- Sharp
- Sanyo Electric Company
- Fujifilm Corporation
- Merck Patent
- LG Innotek Company Ltd.
- LG Electronics Inc.

In the past five years there has been a noticeable decrease in patent applications for this technology, with a reduction in patent applications of approximately 70% compared to all previous years.

Further patent details are provided in Annex 4.

Trending topics on patents:

- PV: materials (in the last five years, particularly on organic cells, dye-sensitised solar and monocrystalline silicon cells), module characteristics, PV concentrators and power management functions. In the last five years focus was also on generic improvements (modules, tracking, lifetime, performance, etc.).
- Wind: gearbox improvements, followed by blades or rotors, control equipment, horizontal-axis turbines and generator.
- Biomass: biofuels, particularly created from waste (i.e., biofuel production by fermentation of organic wastes)
- Hydro: tidal stream and damless hydropower

morula, lemon and bougainvillea to make DSSC as an alternative to ruthenium. Lemon dye cells achieve a very low efficiency of 0.036% but are a promising innovation over the next couple of decades to reduce costs and to produce a more environmentally friendly solar cell (Maabong *et al.*, 2015).

Organic solar cells also are a promising third-generation technology. These third-generation solar cells have the potential to cost as low as USD 0.10/Wp (Irvine and Candelise, 2014). Nevertheless, many research institutions are now transferring their attention to Perovskite solar cells as a more promising and efficient technology. Apart from the efficiency potential their production is simpler, lower-cost and requires less energy than silicon-based modules (Green *et al.*, 2014). Oxford PV, a spinout from Oxford University, is researching and seeking commercialisation of Perovskite PV cells with expected costs of USD 0.35/Wp in the near term (Oxford PV, 2015). At Hong Kong Polytechnic University researchers are working on a Perovskite solar cell that uses a graphene electrode achieving a 12% efficiency and a potential cost as low as USD 0.065/Wp (Feng, 2015; You *et al.*, 2015).

Another innovative breakthrough that will potentially radically influence the PV sector is the use of graphene in module construction. Although it is too soon to extract conclusions, scientists at École Polytechnique Fédérale de Lausanne in Switzerland have demonstrated the "photon-electron multiplication effect" of graphene, that is, the ability of the material to excite several electrons when absorbing a single photon. An effect of using graphene at solar modules would increase PV efficiency, since they could exploit all light spectrum with reduced losses (Papageorgiou, 2015). Other research has been taking place exploiting the properties of carbon nanotubes for increasing solar panel efficiency (Shea and Arnold, 2013).

- **R&D 2: Reduce the size of silicon wafers**

Silicon wafers account for approximately 57% of the current solar cell price (Metz *et al.*, 2014). There are a range of innovations such as casting wafers with a conventional thickness from molten silicon to reduce their thickness, replacing ingots, saws and slurry. Reductions in wafer thickness from 300μm to 200μm a decade ago yielded a 20% reduction in silicon needed (Tool *et al.*, 2001). The current average 180μm thickness is expected to decrease further within the next decade, but as the theoretical limit of silicon wafer thickness is reached, alternative innovations will be required in subsequent decades. Research ongoing at Swinburne University together with Stanford University has proven in the laboratory the use of ultra-thin wafers that are a tenth of current thickness using light-trapping strategy. They potentially achieve 15% efficiency, but it is still over a decade before such technology will be readily available (Metz *et al.*, 2014; Zhang *et al.*, 2014). Efficiency improvement innovations also will have an impact in reducing space requirements, leading to less railing, cabling and other materials.

- **R&D 3: Reduce the amount and cost of conductive metals**

Replacing expensive silver with less-expensive copper is promising as a lower-cost alternative (Metz *et al.*, 2014; MIT, 2015; IEA, 2014), since copper is 70 times cheaper than silver. The use of silver is expected to drop from 0.14 grams/cell to 0.030 grams/cell by 2025 (Metz *et al.*, 2014). Silver use represents approximately USD 0.02-0.08/Wp (Metz *et al.*, 2014; Peters, 2013), hence USD 0.015-0.06/Wp can be achieved with its gradual replacement in the next decade (Ibid.).

R&D 4: Increase ease of installation of PV

With regard to the ease of use of PV, in particular the mounting rack will be improved for ease of installation, *e.g.*, with rigid frames being replaced by other mounting structures (Metz *et al.*, 2014). Already plenty of new products are coming onto the market that offer simpler racking systems that require less materials and are faster and easier to install, such as rail-less mounting systems and ballasted ground systems. Module manufacturers are integrating racking systems into their products, and rack manufacturers are incorporating the installation service into their portfolios, with many claims of efficient, faster and easier mounting times but with little evidence or quantification of such benefits (Schlichting and Goodman, 2014). In the United States it is expected that mounting systems for

PV will drop by up to 9% in the next few years (Schlichting and Goodman, 2014). ITRPV expects that mounting costs will be reduced by 12% in the coming decade (Metz *et al.*, 2014).

Need: New, lower-cost designs for wind

Wind turbines already have seen price drops in the past decade. This trend is expected to continue. For example, DWEA (2015) estimates that SWT could drop down from USD 4 500/kW to USD 2 800/kW.

- **R&D 1: Explore innovative wind turbine designs**
  Horizontal-axis wind turbines (HAWT) are expected to continue being the main wind-based generation technology in the market. A literature review from the IEA identified that most studies report a further 20-30% cost reduction expected by 2030 (IRENA, 2012a; Lantz *et al.*, 2014). Other studies showed that the CAPEX of wind turbines will remain at the same levels as 2015. The 2030 target for small wind turbines is to drop the installed costs by around 50% (DWEA, 2015). The LCOE of the coming decades is expected to fall, first showing a rapid decline up to 2023 and then dropping by less than 1% per year. The reduction of the O&M costs could reach 20-23% until 2050 (IEA, 2013b). Other more conservative estimates foresee for 2025 that the LCOE for onshore wind can be reduced by only 5.5% caused by a reduction in O&M costs and a parallel increase in wind energy production due to technological advances (KIC InnoEnergy, 2014). Higher production volumes, onsite production facilities and increased manufacturing automation also are expected to bring costs down (Lantz *et al.*, 2014).

- **R&D 2: Improve existing wind turbine designs**
  Most of the opportunities to bring costs down are expected to be through better design and performance of wind turbines, including advanced drivetrain designs, enhanced frequency and voltage control, use of lightweight advanced materials, adaptive temperature control and anti-icing coatings, amongst others (IEA Wind, 2013). HAWT can be improved slightly through the optimisation of the rotor size, blade aerodynamics, blade pitch control, resource modelling, mid-speed drive trains and hub assembly, among other innovations that are expected to bring wind turbine LCOE down by up to 6% by 2025 (KIC InnoEnergy, 2014).
  There is a large body of research for alternatives to HAWT, but new patents have flagged relative to patents prior to 2010. While hundreds of new breakthroughs and conceptual designs have been announced and publicised, in particular for small turbines, in the last decade none of these "revolutionary" designs have succeeded (DWEA, 2015). According to DWEA (2015) the true promise for lower costs in small wind turbines will be attained through more advanced technology for HAWT, *e.g.*, more effective rotors and blade structure designs, more efficient generators, optimised power electronics, improved tower design and the use of taller towers. Vertical-axis wind turbines (VAWT), in particular for very small mini-grids, may play a larger role in the next decade (new energy husum, 2014).

- **R&D 3: Explore the use of new materials for wind turbines**
  Research also has focused on replacing materials used for wind turbines and developing cheaper and more abundant options, *e.g.*, using carbon fibre blade manufacturing and possibilities of blade elements or segmented blades, and use of recyclable components (IEA Wind, 2013). Research is ongoing for the use of cerium, a widely available and inexpensive rare earth that could replace magnets made of expensive dysprosium currently used in wind turbines (Pathak *et al.*, 2015). Still, small and medium-scale wind turbines are receiving less R&D interest and support, with a strong focus on larger-scale offshore turbines in Europe (EWEA, 2013; EWETP, 2014) and the United States, *e.g.*, out of DOE's USD 109 million Fiscal Year 2015 wind research budget only USD 3 million was destined for R&D activities for small and medium-sized turbines (DWEA, 2015).

- **R&D 4: Research techniques to increase production from small wind turbines**
  Small wind turbines are expected to streamline installations through cementless foundations, other anchoring techniques, labour-saving equipment designs, and system designs to eliminate the need for cranes in installations

(DWEA, 2015). According to Schröder et al. (2013), the installation costs of systems smaller than 250 kW account for 30% of the total installed costs. Other companies reconsider the two-blade, downwind design as a way to reduce production costs by producing the same amount of energy as the three-blade ones.

Priority Gap 2 – Reduce maintenance needs

Maintenance costs are particularly significant for wind, biomass and hydro technologies. A wind turbine's mechanical parts are prone to failure due to wear and tear. In addition, improvements such as advanced drivetrain designs, enhanced frequency and voltage control, fault ride-through capacity, use of lightweight materials, use of larger rotors and taller towers can improve performance and reliability of wind turbines and generate cost reductions (Lantz *et al.*, 2014).

Need: More robust designs and fewer moving parts for small wind turbines

Research is ongoing to improve preventive maintenance, the use of stronger more robust materials, and better designs that can allow for lower O&M needs and increase the lifetime of wind turbines.

- **R&D 1: Develop more robust designs with fewer moving parts for small wind turbines**
  The small wind turbine industry is focusing on reducing the O&M requirements through value-engineering, smart structures and advanced monitoring (DWEA, 2015). It is expected that in the next decade wind turbines will start incorporating sensors on blades to monitor fatigue and damages, and signal for needed repairs. Other improvements geared towards O&M activities themselves that will yield some cost reductions in the next decade are improved weather forecasting, better inventory management, optimised inspection activities, turbine condition-based maintenance, wide control strategies, condition monitoring and holistic asset management (KIC InnoEnergy, 2014). Research is focusing on tools that improve preventive maintenance strategies through the analysis of past performance and standard approaches to reporting and reducing corrective maintenance needs (IEA Wind, 2013). Besides there are new designs coming out such as rotors downwind of the tower, turbines with two blades or even turbines with no blades (IEA, 2013b; Schröder *et al.*, 2013).

- **R&D2: Research more robust materials for use in wind turbine blades**
  Layer protection and coating are commonly from polyester, epoxy, polyurethane or acrylic, which suffer erosion on turbines in harsh climate conditions; hence the need for improved testing and materials (Kjærside Storm, 2013). Research on stronger and lighter materials for wind turbine blades is being done at the Danish Centre for Composite Structures and Materials for Wind Turbines (Danish Technical University, 2015). The use of timber for very small turbines and fibre-reinforced composite for larger ones are expected to improve the fatigue behaviour of small and medium-scale turbines, which generally suffer from more wear and tear due to the higher rotational speeds (Clausen *et al.*, 2013). Likewise, the use of biobased composites is a promising option than can improve lifetime performance and the environmental life cycle of wind turbines (Madsen *et al.*, 2013). "Smart" blade materials are being researched in order to automatically adjust pitch for different wind speeds automatically. This will strengthen materials and provide them with higher resistance to wear and tear.

Need: Reduced maintenance needs for biogas generation

Improved gasification that limits the build-up of soot, tar and other contaminants in the biogas will significantly reduce the maintenance requirements for these systems and improve the performance of the engines.

- **R&D 1: Explore improvements to the gasification process to reduce maintenance needs for biogas generation**
  The critical innovation need for biomass technology is reducing maintenance requirements, particularly for feedstock quality issues. Biogasification technologies suffer from critical problems with soot and tar in the production process. Work is ongoing to improve performance of the gasification process that can allow gasifiers to handle more types and less

homogeneous feedstocks. Research is ongoing in India by Husk Power System and in the United States by All Power Labs. The XGaTE project led by AVA-CO_2 is optimising larger-scale gasifiers to be able to handle all kinds of fuels including wet biomass and biowaste (KIC InnoEnergy, 2015). Without this innovation, biogeneration is unlikely to be cost-competitive with other generation options.

Priority Gap 3 – Improve efficiency and increase energy capture

Silicon-based solar technologies are already close to their theoretical efficiency limit, but still have room for improving their efficiency. More promising are other emerging third-generation technologies which have a bigger potential of achieving efficiencies as high as 60% (Irvine and Candelise, 2014).

For small wind turbines, DWEA (2015) projects that the capacity factor of small wind turbines will increase 50% by 2030, and large turbines will increase 70%. For example, increasing tower heights and turbine sizes can shift capital costs up; however, those improvements will cause the capacity factor to increase, lowering the overall energy costs (KIC InnoEnergy, 2014; Schröder *et al.*, 2013).

Need: Improved cell efficiency for PV modules, particularly at warm temperatures and over lifetime

- **R&D 1: Improve silicon-based solar PV modules**
  There are limited efficiency improvements possible for silicon-based PV as these are already reaching their theoretical limits (IEA, 2014). By 2024, 15% of solar cells are expected to be light-sensitive on both sides, and a large share will contain a glass layer instead of the traditional non-transparent backsheet (double-glass modules). For example, an increase in module performance by 2% by 2025 can be done by improving the transmission of the front cover glass of the modules (Metz *et al.*, 2014) . The use of self-healing nano-layers on solar cells is expected to improve the lifespan of PV modules (IEA, 2014). An achievement that could impact vertically the efficiency of solar panels in the next decades is the use of supramolecular nanostructures for energy transport in room temperatures. For the moment the transportation length achieved is a few micrometres (Haedler *et al.*, 2015).

- **R&D 2: Continue to research third-generation solar cells**
  Breakthroughs with Perovskite cells have surpassed lab efficiencies over 20% in less than three years of research on its use in PV applications (NREL, 2015). At Northwestern University researchers estimated that Perovskite titanium oxide (TiO_2) solar cells can have energy pay-back periods as low as three months since no high-purity silicon or rare metals are used. Perovskite cells are estimate to achieve efficiencies of over 30% by 2017 (Gong *et al.*, 2015).

Need: Improve performance for wind

An increased cut-in speed will allow the use of turbines in areas with lower average speeds and with less consistent wind regimes and increase their capacity factors. Output decline in wind turbines can be as high as 16% within a decade (Staffell and Green, 2014). It is expected that the use of stronger materials will reduce this power decline output, improving performance and overall economics.

- **R&D 1: Research designs that increase production from small wind turbines**
  Higher capacity factors are expected to be achieved, up to 20% for very small turbines (1-3 kW) and up to 34% for 1-2.5 MW medium-size turbines by 2030 (DWEA, 2015). Such improvements are expected through a combination of technology improvements, *e.g.*, the use of larger rotors and taller towers to harness higher wind speeds (DWEA, 2015). The use of polyurethane-based composites is being researched for their lighter weight that is expected to increase overall turbine life. Combined with carbon nanotubes this also can increase their support and strength (US DOE, 2015b).

Need: Improved low-flow and low-head performance for hydro turbines

The trend towards investigating opportunities of low-head hydropower has led to the development of a new series of hydro turbines exploiting the kinetic energy of the rivers, instead of the potential energy like mainstream turbines.

- **R&D 1: Research hydro designs that can harness low head and low flow**
  Research is ongoing on the development of low-head turbines such as the StreamDiver from Voith and the Stream turbine from JAG Seabell Co. Other new designs need no head, such as the 5 kW turbine from Smart Hydro Power that can exploit the flow of the rivers with velocities from 1.2 m/s. Those high-technology turbines can take advantage of existing water streams such as irrigation canals and can be used hybridised with storage, auxiliary gensets or other renewable source during dry seasons. Such turbines are in their initial deployment stage. Some new technologies are more environmental friendly solutions by avoiding oil and lubricating the bearings with the use of water (Voith, 2015), while others integrate a system for garbage collection, like the Japanese generator "Power Archimedes". Furthermore, hydropower plants generating power with low-head turbines require minimum intervention in the natural landscape, since they require no dam construction or penstock. This also decreases the civil works and engineering costs.

- **Better materials and ICT for hydro turbines**
  Innovations to increase the efficiency and energy yield of hydropower are related to the material selection for turbine manufacturing and the coatings. For example, stainless steel, fibreglass and other plastic material can achieve better performance by reducing friction (IEA, 2012b). Furthermore, the use of computational fluid dynamics, algorithms and artificial intelligence can lead to higher efficiencies and cost reductions (Kumar *et al*., 2011).

Indicators

The following tables summarise the expected impact of the innovations on the expected values for 2025 and 2035 key indicators for generation.

Costs for small hydro have a limited scope for cost reductions, with technological innovations driven mainly by lower cost and more efficient civil engineering (IRENA, 2012c). Meanwhile the *Tracking Clean Energy Progress* report from the IEA (IEA, 2012a) foresees that small hydropower costs will remain the same by 2020.

Table 50: PV technology indicators

	2015		2025 (Metz *et al*., 2014)		2035 (IEA, 2014)	
	Small-scale	Large-scale	Small-scale	Large-scale	Small-scale	Large-scale
KI 1: Installed cost (USD/Wp)	2.00–3.50	1.00–2.50	1.00–1.90	0.50–1.40	0.40–0.80	0.20–0.60
	0.50–0.90 (module only)		0.33		0.3–0.5	
KI 2: LCOE (USD/kWh)	0.15–0.25	0.10–0.20	0.09–0.14	0.06–0.11	0.04–0.05	0.02–0.04
KI 3: Commercial lifetime (years)	25–30		30–40		40–50	

Source: Metz et al., 2014; IEA, 2014

Table 51: Wind turbine indicators

	2015		2025 (DWEA, 2015)		2035 (DWEA, 2015; linear extrapolation)	
Indicators	**Small wind (horizontal-axis)**	**Large wind (horizontal-axis)**	**Small wind (horizontal-axis)**	**Large wind (horizontal-axis)**	**Small wind (horizontal-axis)**	**Large wind (horizontal-axis)**
KI 1: Installed cost (USD/kW)	4 000–4 500	1 500–3 500	3 200–3 600	1 200–2 800	2 400–2 700	900–2 100
KI 2: LCOE (USD/kWh)	0.12–0.28	0.06–0.14	0.11–0.27	0.06–0.13	0.09–0.24	0.05–0.12
KI 3: Lifetime (years)	> 20–25	> 20–25	> 25 increase with preventive measures	> 25 increase with preventive measures	> 30	> 30

Source: DWEA, 2015

Table 52: Hydropower plant indicators

	2015		2025 (IRENA, 2012c)		2035 (IRENA, 2012c)	
Indicators	**Pico, micro and mini-hydro**	**Small hydro**	**Pico, micro and mini-hydro**	**Small hydro**	**Pico, micro and mini-hydro**	**Small hydro**
KI 1: Installed cost (USD/kW)	3 400–10 000	1 000–4 000	Limited changes expected	Limited changes expected	Limited changes expected	Limited changes expected
KI 2: LCOE (USD/kWh)	> 0.27	0.02–0.19	Limited changes expected	Limited changes expected	Limited changes expected	Limited changes expected
KI 3: Lifetime (years)	30 (economic)	> 30	> 30 (no major improvements expected)	> 30 (no major improvements expected)	> 30 (no major improvements expected)	> 30 (no major improvements expected)

Source: IRENA, 2012c; IEA, 2012a, 2010

Table 53: Biogasification generation indicators

Indicators	**2015**	**2025 (IRENA, 2012b)**	**2035 (linear extrapolation)**
KI 1: Installed cost (USD/kW)	2 000–5 000	3 500	3 000
KI 2: LCOE (USD/kWh)	0.07–0.24	0.05–0.19	0.03–0.15
KI 3: Lifetime (years)	5–12	10–15	> 15

Source: IRENA, 2012b

ANNEX 7:

Renewable mini-grid price prediction: Modelling input summary

This Annex contains a detailed summary of the inputs and methodology used to determine the optimal system design, renewable fraction and cost in Section 3.1. The key inputs are summarised in Table 54:

AB (Autonomous Basic service) allowed up to 2.6 weeks of unserved energy demand per year and a 16-hour daily served load. AF (Autonomous Full service) provided 24-hour power and limited this unserved load to 0.5 week — comparable to utility grid reliability. The analysis used a 6% nominal discount rate with 2% inflation rate, and average diesel fuel price of USD 1/L.

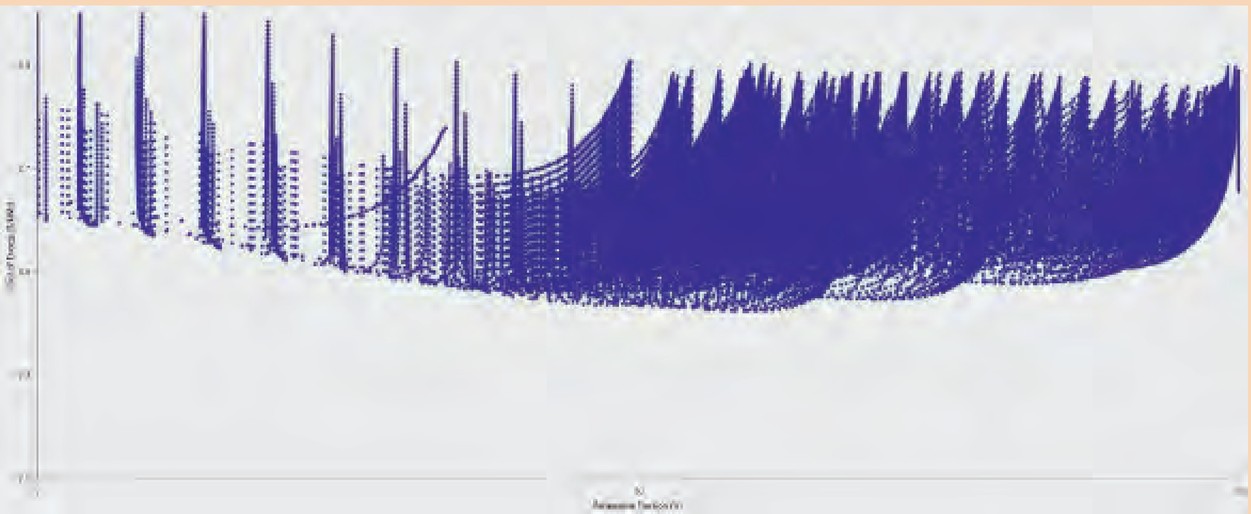
The inputs were modelled in the HOMER Pro software to calculate the levelised cost of energy for thousands of potential system designs. The various system designs

*Table 54: Summary of key cost inputs for renewable mini-grid cost and renewable fraction modelling**

Year	Installed cost of PV	Installed cost of battery	Battery technology	Dual-mode converter costs	Administrative and distribution costs
2005	USD 6.00/Wp	USD 542/kWh	LAB	USD 1 900/kW	USD 0.12/kWh
2015	USD 2.50/Wp	USD 950/kWh	LIB	USD 1 575/kW	USD 0.10/kWh
2025	USD 1.50/Wp	USD 400/kWh	LIB	USD 1 260/kW	USD 0.09/kWh
2035	USD 0.60/Wp	USD 250/kWh	LIB	USD 1 025/kW	USD 0.08/kWh

These numbers may vary according to local market factors

Figure 78: Cost of potential AB renewable mini-grid designs in 2015, comparing renewable fraction (%) on the x-axis vs. levelised cost of energy (USD/kWh) on the y-axis



Source: Author elaboration with HOMER Pro, 2016

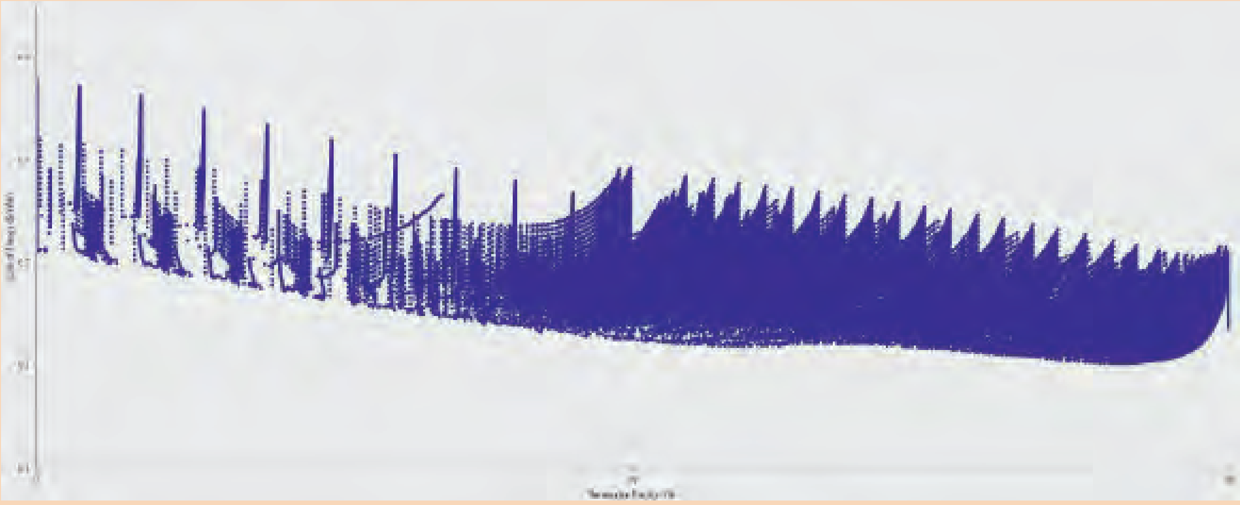
and options modelled for years 2015 to 2035 are plotted in Figure 78 through Figure 80 comparing each potential systems renewable fraction (RF) versus LCOE, where

$$RF = \frac{\text{Useful energy from renewable sources [kwh/yr]}}{\text{Total energy served [kwh/yr]}}$$

and

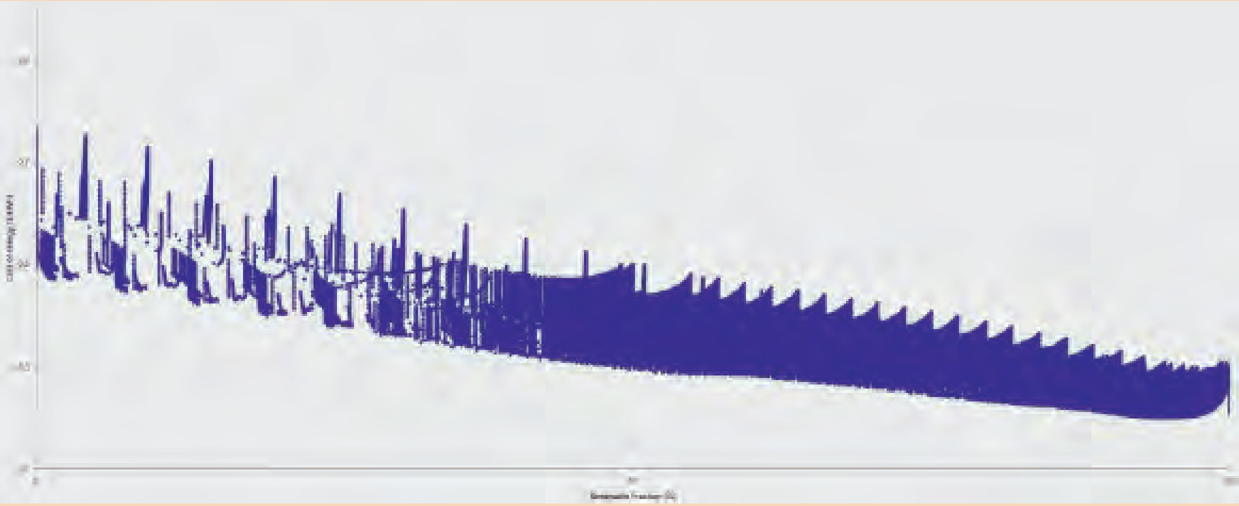
$$LCOE = \frac{\text{Average annual cost [USD/yr]}}{\text{Total energy served annually [kwh/yr]}}$$

Figure 79: Cost of potential AB renewable mini-grid designs in 2025, comparing renewable fraction [%] on the x-axis vs. levelised cost of energy [USD/kWh] on the y-axis



Source: Author elaboration with HOMER Pro, 2016

Figure 80: Cost of potential AB renewable mini-grid designs in 2035, comparing renewable fraction [%] on the x-axis vs. levelised cost of energy [USD/kWh] on the y-axis



Source: Author elaboration with HOMER Pro, 2016

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