QUALITY INFRASTRUCTURE FOR SMART MINI-GRIDS

A contribution to the Small Island Developing States Lighthouse Initiative 2.0

ISBN 978-92-9260-278-9 Citation: IRENA (2020), Quality Infrastructure for Smart Mini-grids, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

Acknowledgements

This report was prepared by IRENA in close collaboration with the Alliance for Rural Electrification (ARE) and the International Electrotechnical Commission (IEC). It forms part of the "SIDS Lighthouses Initiative 2.0" project, which is supported by the Ministry of Foreign Affairs of Denmark.

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IRENA colleagues who provided valuable review and support include: Adrian Whiteman, Carlos Ruiz, Dolf Gielen, Liliana Andreia Morais Gomes, Paul Komor, Yong Chen, Neil MacDonald, Stephanie Clarke, Ali Yasir, Roland Roesch and Michael Taylor.

ARE members participated in the case studies collection in Chapter 3; IRENA appreciates the valuable input provided by Ensol, Geres, Mlinda, Nayo Tropical, Suninbox, SparkMeter and Xant.

Chapters in this report were edited by Erin Crum.

Key insights of these report were gathered through technical interviews and consultation with experts: Luke Van Zeller (Infratec), Sam Duby (TFE Energy), Chengshan Wang, Xiaopeng Fu, Peng Li (Tianjin University), Frédéric Madry (PowerCorner Tanzania), David Butler (Hydro Tasmania), Ian Baring-Gould (National Renewable Energy Laboratory), Brandon Hayashi and David Potter (OpTerra Energy Services), Enrique Garralaga Rojas (SMA Solar Technology), Juan Ceballos, Michiel Van Lumig and Wouter Vancoetsem (Engie), Nathalie Baumier (Smart Energy) and Wu Ming (China Electric Power Research Institute).

IRENA is grateful for the support of the Ministry of Foreign Affairs of Denmark in producing this publication.

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KEY FINDINGS

This report highlights the crucial role of quality infrastructure (QI) -standards, testing, certification- for a rapid and sustained market growth for renewable mini-grids. Transforming the global energy system in line with global climate and sustainability goals calls for rapid uptake of renewables for all kinds of energy use. Renewable mini-grids can be key providers of electricity access in remote areas and islands. Furthermore, interconnecting one mini-grid with another, or else with the main grid, can bring multiple benefits. Grid-connected mini-grids can increase power resilience and reliability, while allowing the integration of higher share of renewable electricity and therefore decreasing energy costs.

Mini-grids are complex systems with different suppliers, they are developed for different applications and there is often high regulatory uncertainty regarding their installation and operation. The sustainable market growth and long-term profitability of mini-grid systems requires quality infrastructure (QI).

Key findings:

- IRENA analysis identified a global market with an installed capacity of 4.16 gigawatts (GW) of off-grid renewable energy mini-grids, predominantly power by bioenergy linked to industrial mini-grids. Hydropower mini-grids in particular have recently increased their deployment in the community and industry sectors. Solar PV mini-grid installations are commonly used for commercial, community and agriculture purposes.
- Mini-grids using 100% renewable energy are becoming a **cost-competitive** solution compared with mini-grids based on liquid fossil fuel generators. The levelised cost of electricity (LCOE) of renewable mini-grids ranges from USD 0.39 per kilowatt-hour (kWh) to USD 0.75/kWh, with prospects of decreasing to USD 0.20/kWh by 2035.
- Innovations and technological advancements continue to expand the range of uses and improve the operation of mini-grids. The core **functionalities** for a renewable mini-grid are power generation, energy storage, conversion, consumption, and Control, manage and measure (CMM). Internet of things (IoT) based platforms will form the backbone of the CMM functionality in the future, while innovations in storage technology will enhance the applications for mini-grids.
- Examples of mini-grids that stopped operating after just a few years illustrate how a lack of QI (from poor components quality to lack of inspection or training) leads to the loss of the investment, the loss of the expected electricity production, and more generally damages the national market reputation. Mini-grids market development must go hand in hand with QI development.
- **Quality infrastructure (QI)**, including comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology, is key to reduce risks associated to mini-grids development. Effective QI can improve finance conditions, reduce legal, regulatory and performance uncertainty, further reduce LCOE and enhance trade and scalability of mini-grid markets.
- Currently most of the QI is oriented to the functionality of individual components of a mini-grid, and not to the overall mini-grid system. However, mini-grids are complex systems and should not be considered as the simple sum of their parts. A comprehensive approach to the development of QI is necessary.
- The main **challenge** for mini-grid lies with system-level testing. More flexible and cost–effective testing methods can reduce this risk perception associated with mini-grids. The combination of physical components with simulations allows testing of the control functionality of a mini-grid without having to construct the complete mini-grid, while limiting testing costs and facilitating easy adjustments.
- A gradual approach to integrate QI in policy frameworks is required. Policies should consider the constant evolution of mini-grids and refer to different levels of QI at different times at market development. The experience from the solar PV market uptake shows that mini-grids also need a certain level of national and international QI for a sustainable market.

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

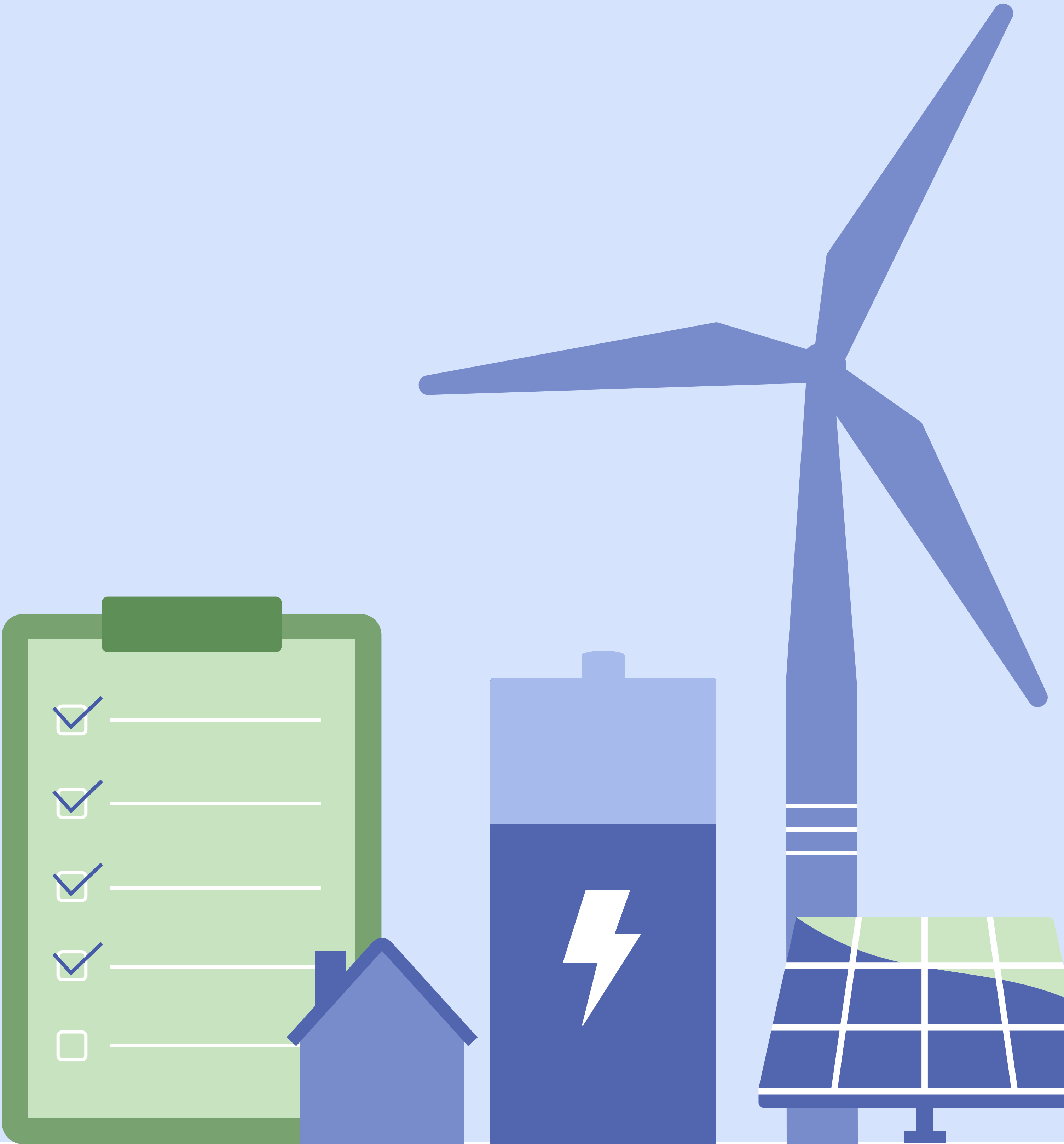
AB	autonomous basic
AC	alternating current
AF	autonomous full
AFSEC	African Electrotechnical Standardization Commission
ANSI	American National Standards Institute
BIPM	Bureau International des Poids et Mesures
BOS	Balance of Storage Systems
BSI	British Standards Institution
C&I	commercial & industrial
CCHP	combined cooling, heat and power
CEC	California Energy Council
CENELEC	European Committee for Electrotechnical Standardization
CHIL	control hardware-in-the-loop
CIGRE	Council on Large Electric Systems
CMM	control, manage and measure
CO_2	carbon dioxide
DC	direct current
DER	distributed energy resources

DERlab	Distributed Energy Resources Laboratories
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DNO	distribution network operator
DSO	distribution system operator
EES	electrical energy storage
EHS	environmental health and safety
ELV	extra-low voltage
EMS	energy management system
EPC	engineering, procurement and construction
EPIC	Electric Power and Intelligent Control
ESAM-TAC	Energy Storage and Microgrid Training and Certification
ESIF	Energy Systems Integration Facility
ESS	energy storage system
ETSI	European Telecommunications Standards Institute
EURAMET	European Association of National Metrology Institutes
EV	electric vehicle
EVSE	electric vehicle supply equipment
EWURA	Energy and Water Utilities Regulatory Authority
GBA	Green Business Area
GW	gigawatt
HECO	Hawaiian Electric Company
HIL	hardware-in-the-loop
IAF	International Accreditation Forum
IC	interconnected community system
ICLI	interconnected large industry system
IDCOL	Infrastructure Development Company Limited
IEC	International Electrotechnical Commission
IECRE System	IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications
IED	intelligent electronic devices
IEEE	Institute of Electrical and Electronics Engineers
ILAC	International Laboratory Accreditation Cooperation
INSPIRE	International Standards and Patents in Renewable Energy
IoT	internet of things
IPP	independent power producer
ISA	International Society of Automation

ISO	International Organization for Standardization
ITU	International Telecommunication Union
kV	kilovolt
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt-hour
kWp	kilowatt peak
LCOE	levelised cost of electricity
Li-ion	lithium-ion
LVDC	low-voltage DC
MCC	Microgrid Certification Center
MEC	Microgrid Education Center
MID	microgrid interconnect devices
MPPT	maximum power point tracker
MSL	Microgrid Systems Laboratory
MSME	micro, small and medium enterprises
MSP	mini-grid service package
MW	megawatt
MWp	megawatt peak
NAB	national accreditation board
NCSC	Northern Customer Service Center
NEC	National Electrical Code
NFPA	National Fire Protection Association
NMI	national metrology institute
NREL	National Renewable Energy Laboratory
NSB	national standards bodies
NTU	Nanyang Technological University Singapore
O&M	operations and maintenance
OIML	International Organization of Legal Metrology
PCC	point of common coupling
PELV	protected extra-low voltage
PEMFC	proton-exchange membrane fuel cell
PHIL	power hardware-in-the-loop
PLN	Perusahaan Listrik Negara
PV	photovoltaic

QAF	Quality Assurance Framework
QI	quality infrastructure
QMS	quality management system
REIDS	Renewable Energy Integration Demonstrator Singapore
RESEU	Renewable Energy System Schemes of the EU
SCADA	Supervisory Control and Data Acquisition
SCC	Standards Coordinating Committee
SEforALL	Sustainable Energy for All
SELV	safety extra-low voltage
SGCC	State Grid Corporation of China
SIEM	Smart Integrated Energy Microgrid
SPP	small power producer
SWaT	Secure Water Treatment
TC	technical committee
TS	technical specifications
TSO	transmission system operator
TUMT	Tianjin University microgrid test bed
USAID	US Agency for International Development
V	volt
V2G	vehicle to grid
WADI	Water Distribution
WTO	World Trade Organization

SUMMARY FOR POLICY MAKERS



Advancing electricity access and enhancing livelihoods for islands and remote communities

Renewable mini-grids, which combine loads and renewable energy resources, are seeing growing motivation for their deployment, driven by the many benefits these integrated energy infrastructures can bring to key market segments such as islands and remote communities. Renewable mini-grids can provide electricity access, increase power resilience and reliability, reduce energy costs and carbon footprints, and improve the quality of life.

With increasing deployment, it is crucial to look at these systems' performance, durability and adaptability to new developments. This sheds light on the crucial role of developing quality assurance mechanisms and so-called "quality infrastructure", explained in depth in this report, to successfully secure robust renewable mini-grids that can serve present and future human generations.

Renewable mini-grids of the future

The growth of mini-grid markets should be accompanied by a strong quality infrastructure that ensures that the implemented systems will deliver the expected services and benefits in the long term. International standards, testing and licensing facilities are key to ensuring the high quality of deployed mini-grids.

The core functionalities for a renewable mini-grid are: power generation; energy storage; conversion; consumption; and control, manage and measure (CMM).

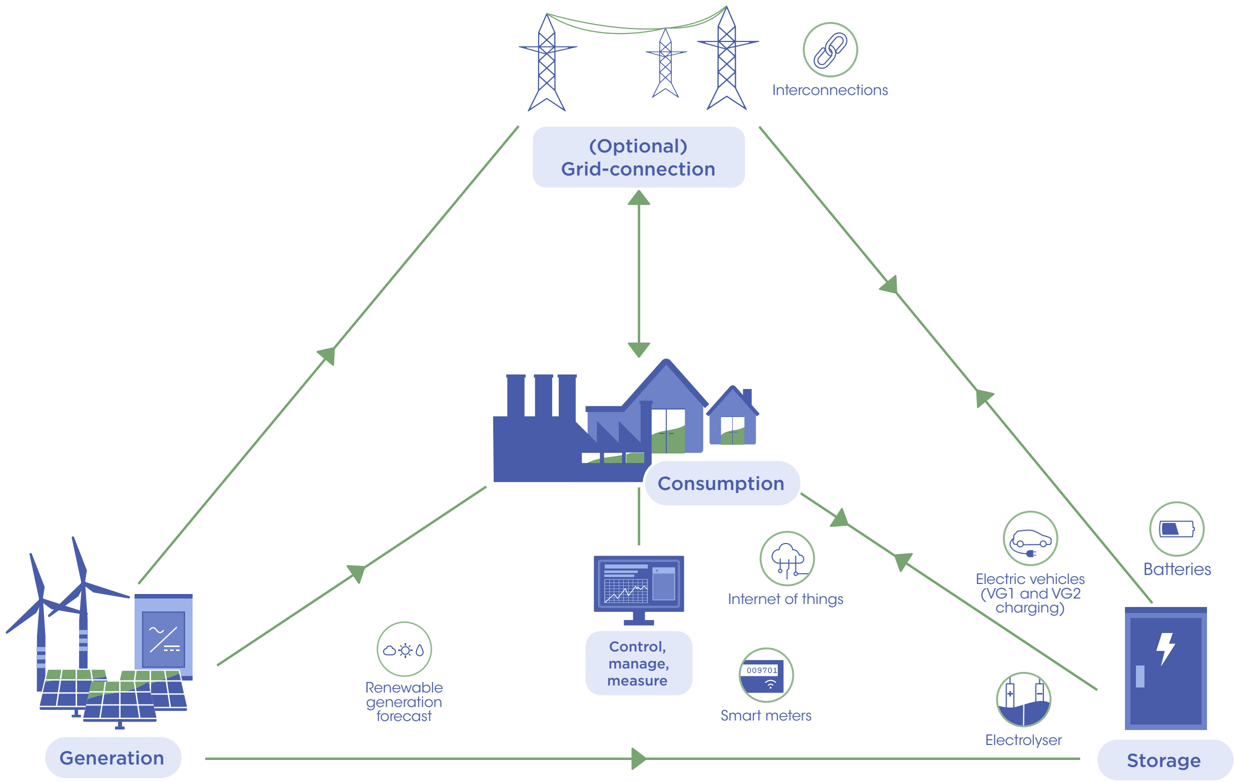
Ongoing innovations and technological advancements are adding complementing functionalities to mini-grids, improving their operation and making them more complex.

Renewable mini-grids of the future will have more advanced CMM operations, due to the development and widespread use of smart meters and internet of things (IoT) solutions, as well as improved data availability and forecast of renewable energy generation. Mini-grids have an inherent level of intelligence and data collection. IoT-based platforms will form the backbone of CMM functionality in the future.

Innovations in storage technologies will also impact the mini-grids of the future, with storage technologies ranging from batteries to electrolyser technologies, with different applications. The integration of electric vehicles (EVs) has many benefits for mini-grids as they can be seen as storage for intermittent renewable generation. However, it also poses a set of challenges that are different from those involved in the integration of EVs in a national grid infrastructure.

On the consumer side, the traditional consumers-to-prosumers transition is accompanied by a variety of technological innovations ranging from local generation, storage and controls to innovative transaction technologies. Also, as shown in Figure 1, mini-grids are great environments for peer-to-peer electricity trading, which facilitates a better use of the local generated electricity between consumers.

Figure 1 Renewable mini-grids of the future



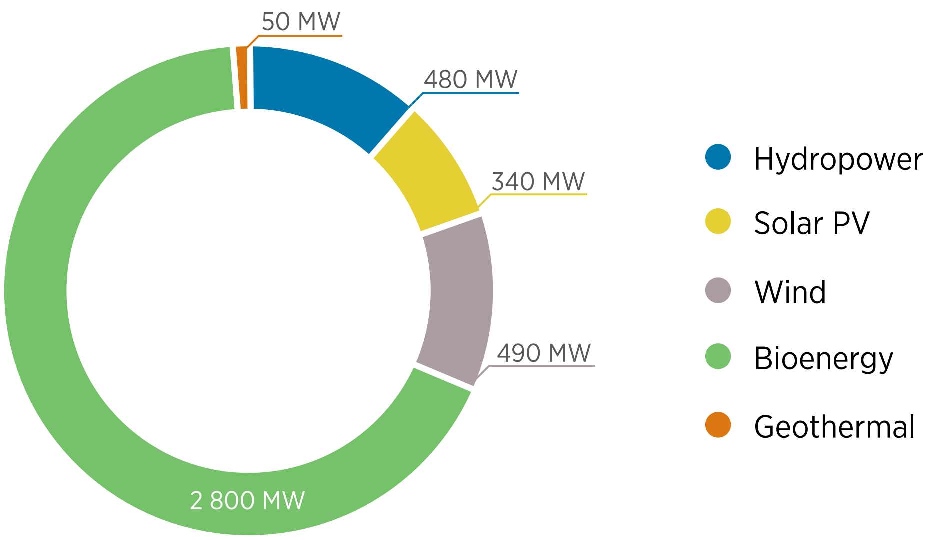
Note: V1G = smart charging; V2G = vehicle-to-grid.

Today's renewable mini-grids

Many efforts have been made to collect mini-grid data, but multiple sources still vary from one to the other. As a very fast-moving sector in recent years, it hasn't been easy to estimate the global share of mini-grids, grid-connected and off-grid, powered by renewable energy sources. Estimates are clearer for the global share of mini-grids: there are about 19 000 installed mini-grids globally, and about half use diesel and other fossil fuel-powered generators (ESMAP, 2019). There is a great market potential to replace this large quantity of emitting mini-grids with renewable energy sources.

As illustrated in Figure 2, IRENA analysis identified an installed capacity of 4.16 gigawatts (GW) of off-grid renewable energy mini-grids, serving a population of at least 8 million people. Bioenergy-based mini-grids show the highest installed capacity, due to the fact that they are often used in high-power industrial mini-grids. Wind- and hydropower-based mini-grids are deployed across different end-use sectors. Hydropower mini-grids in particular have recently increased their deployment in the residential and industry sectors. Solar photovoltaic (PV) mini-grid installations are commonly used for commercial, residential and agriculture purposes.

Figure 2 Total capacity of autonomous (off-grid) mini-grids (megawatts)



Note: MW = megawatts.
Based on: (IRENA, 2018a).

When possible, interconnecting a mini-grid with another one or with the main grid can bring a series of benefits, changing the operation mode of mini-grids. The different mini-grid types are summarised in Figure 3. Grid-connected renewable mini-grids can make the power supply more reliable and resilient as well as boost renewable sources to be a significant contributor to energy generation. However, autonomous renewable mini-grids are mainly relevant for remote areas, both for rural electrification and for facilities in remote areas.

The off-grid and interconnected mini-grids are expected to see enhanced deployment in coming years, and the grid-connected segment is expected to see the biggest growth as a result of the increasing mini-grid activity of utilities and growing grid issues in urban, commercial and industrial areas (Global data, 2018).

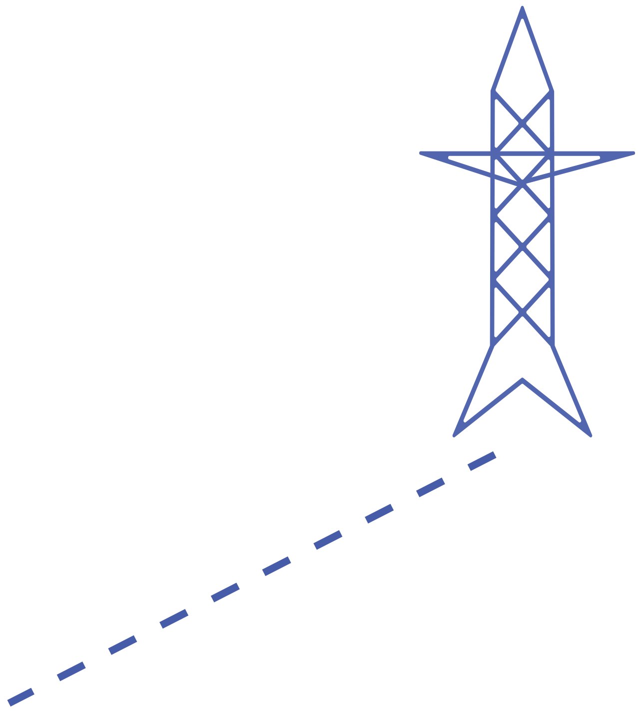
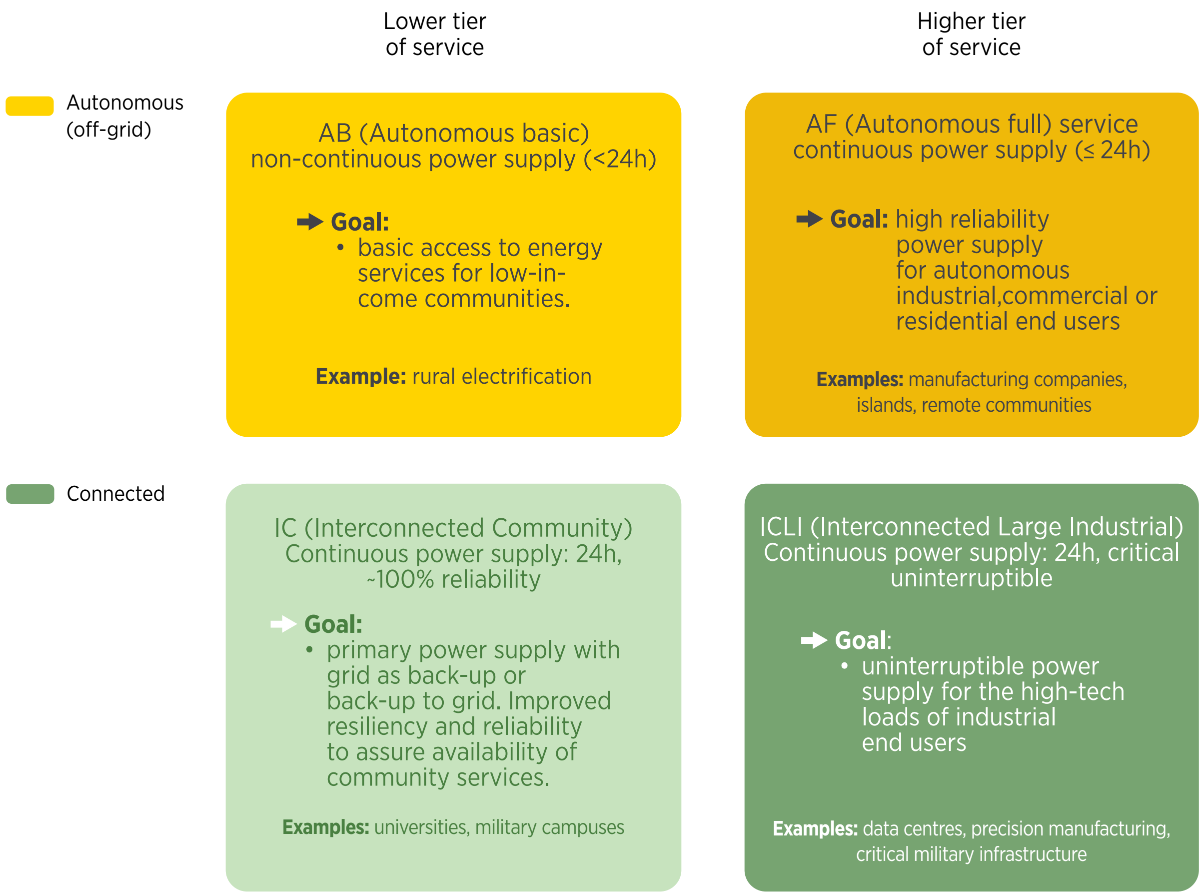


Figure 3 Mini-grid types

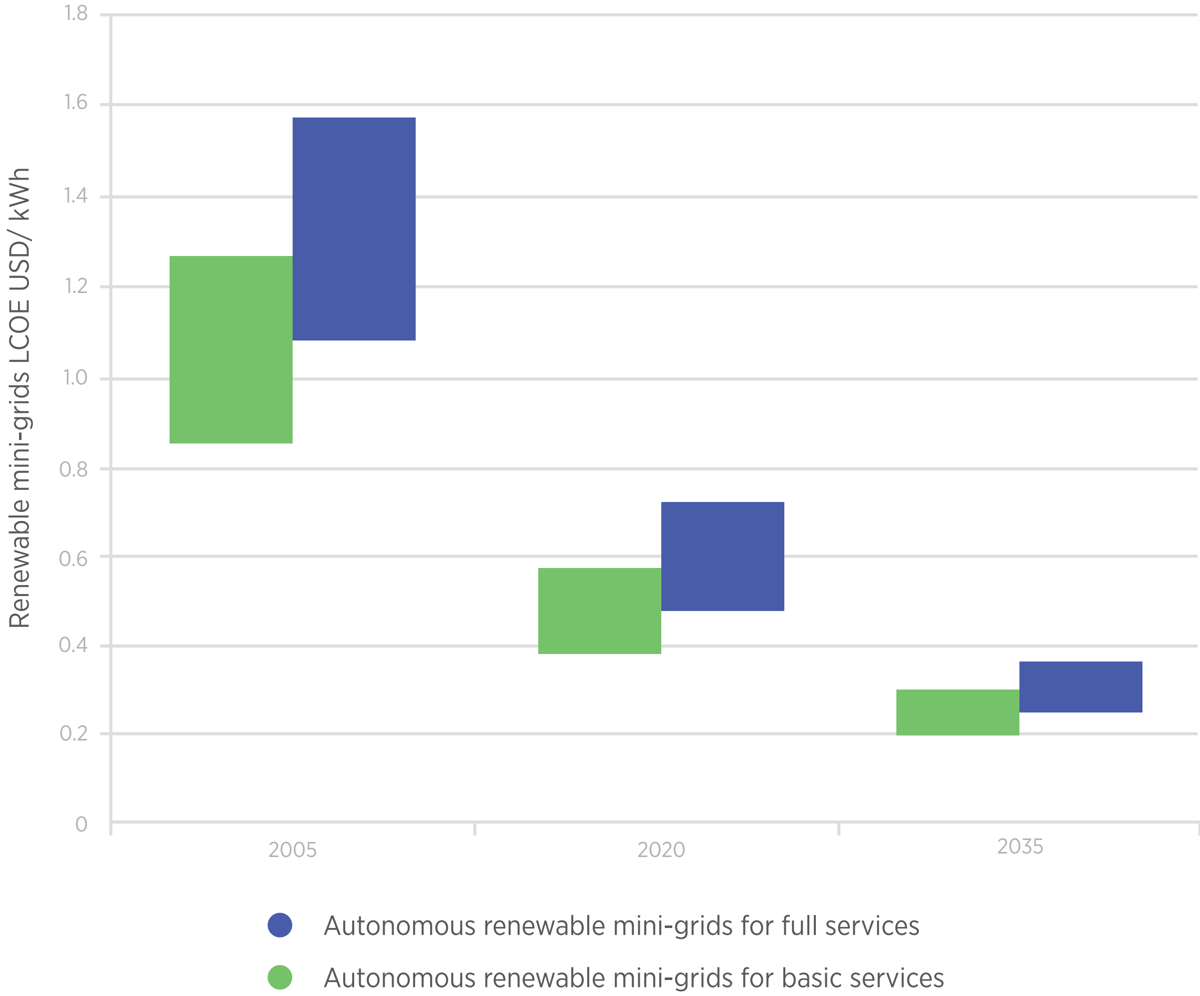


Based on: (IRENA, 2016a).

Renewable mini-grids are becoming economically viable and are an attractive cost-competitive option to conventional generators.

Although the cost of mini-grid hardware has generally declined in recent years as a result of increased competition and policy-driven incentives, the downwards evolution of soft costs, which are associated with customised engineering studies and regulatory, environmental and interconnection compliance, is sometimes restricted because of non-competitive regulatory friction (Cherian, 2017). Therefore, these costs currently represent a larger percentage of total costs compared with past years. Figure 4 summarises the findings for 100% renewable energy-based autonomous basic service and autonomous full service community mini-grids, where the levelised cost of electricity (LCOE) in 2020 for the autonomous basic ranges from USD 0.39 per kilowatt-hour (kWh) to USD 0.58/kWh and for autonomous full from USD 0.50/kWh-USD 0.75/kWh. Mini-grids using 100% renewable energy are a cost-competitive solution compared with small gasoline and diesel generators (USD 0.35/kWh-USD 0.70/kWh (Agenbroad, et al., 2018)).

Figure 4 Unsubsidised cost ranges for renewable mini-grids from 2005 to 2035 for a 100% renewable energy community system

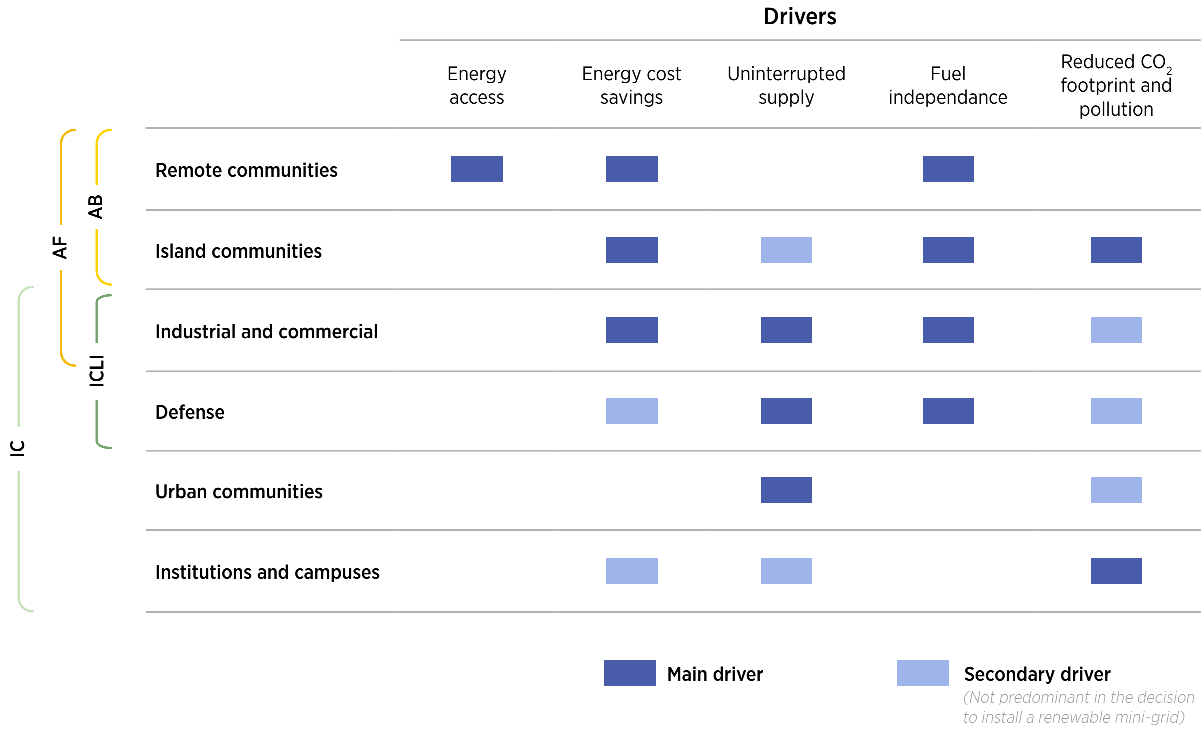


Based on: (IRENA, 2017c).

Further deployment of renewable mini-grids is driven by a mix of benefits provide: energy access, energy cost savings (including fuel savings), improved service quality and supply independence, reduced carbon dioxide (CO2) emissions and pollution, and fulfilment of renewable energy targets.

For islands and remote communities (without access to a distribution grid, *e.g.* desert or mountain communities), energy access is the primary driver. The integration of renewable energy in these mini-grids enables a decrease in the cost of energy, with additional benefits of service quality, positive environmental impact and quality of life. The drivers encountered for the different categories and applications of mini-grids are presented in Figure 5.

Figure 5 Drivers for renewable mini-grid segments



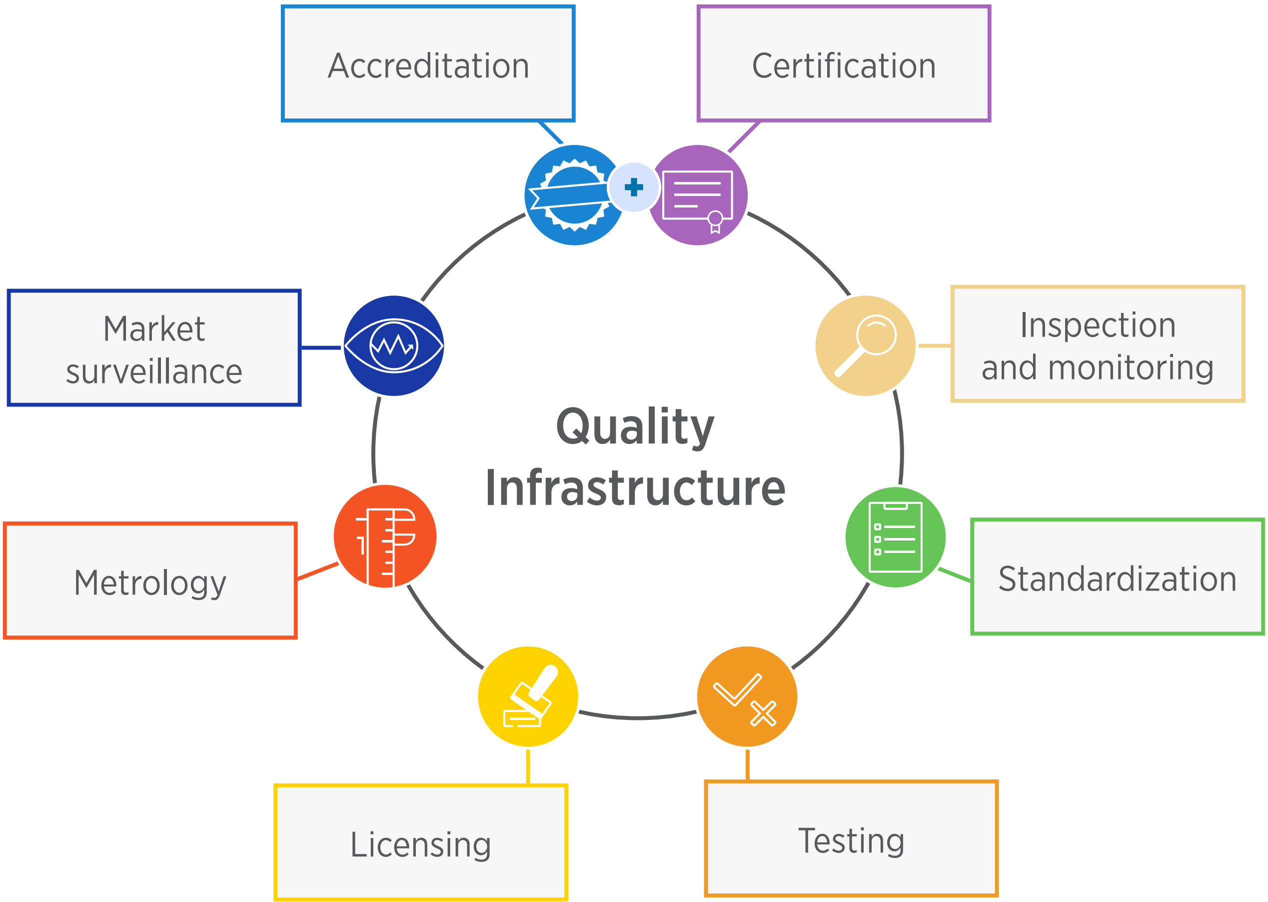
Based on: (ABB, 2018).

Quality infrastructure

The sustainable market growth and long-term profitability of mini-grid systems require quality infrastructure (QI). Mini-grids are complex systems with different suppliers, they are developed for different applications, and most of the time there is high regulatory uncertainty regarding their installation and operation. QI, including comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology, is key to reducing risks. Figure 6 illustrates the QI elements.

The key to reduce high regulatory certainty is QI, including comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology.

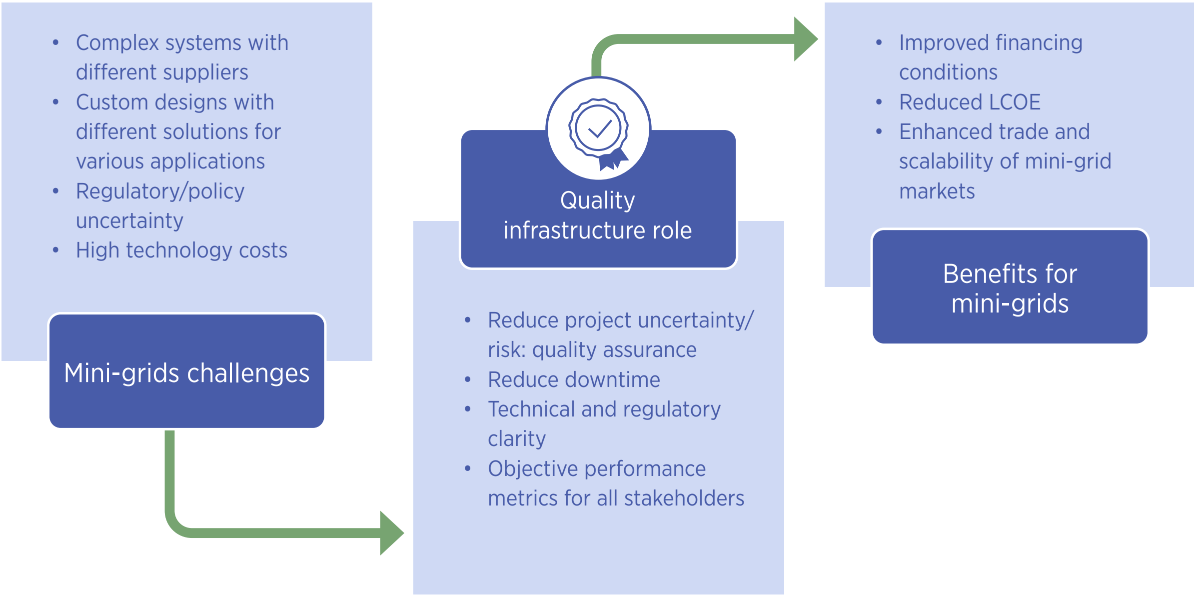
Figure 6 QI elements



A weak QI, from low-quality components to lack of inspection or training, leads to the loss of the investment and expected electricity production, and more generally damages the national market reputation. Mini-grid market development must go hand in hand with QI development.

QI's main goal is to promote quality products, processes and services; to prevent or overcome market barriers; and to make technical co-operation easier (IRENA, 2015a). This would ultimately reduce system downtime and improve mini-grid operation and maintenance. QI also entails a direct economic benefit for stakeholders (reduced LCOE) in that its presence reduces risk for investors and leads to better financing conditions for future projects, illustrated in Figure 7. The technical and regulatory clarity that QI brings along stimulates sustainable innovation and instils confidence in global mini-grid markets. This in turn facilitates trade and allows mini-grid system providers to easily expand their operations across different regions.

Figure 7 Goals and results of QI for mini-grids



This report identifies that today, most of the QI and standardisation work is oriented to the functionality of individual components of a mini-grid, and not to the overall mini-grid system. In the pathway towards smart mini-grids, further efforts are needed to elaborate standards and other QI elements at a mini-grid system level. To achieve this, current gaps in each of the mini-grids functionalities have to be filled. Figure 8 gives initial recommendations in how to alleviate these gaps and brings light to initial quality practices being adopted; however, stronger efforts are required to guarantee reliable operation of mini-grids and a smooth transition towards smart mini-grids in all regions.

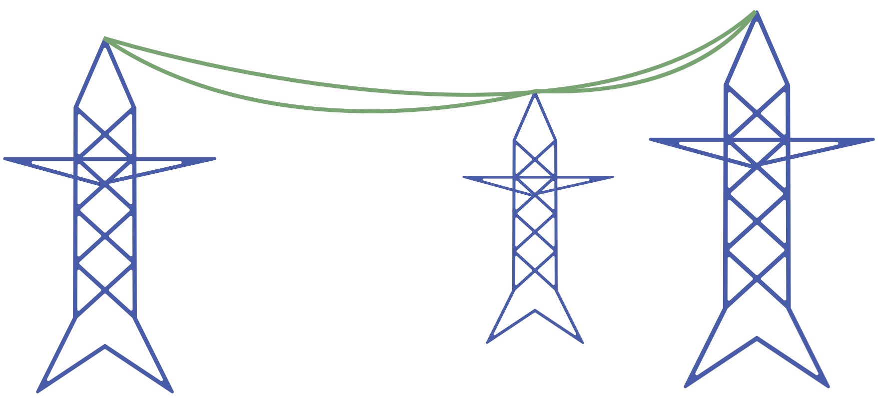


Figure 8 Standardisation gaps and recommendations for functionalities of current mini-grids and of mini-grids of the future

Functionality	Gaps	Recommendations	Examples of quality infrastructure
Planning and design	Lack of standardised project planning and forecasting	Framework to specify the level of service, predicted load/generation and configuration	IEC Technical Specification 62257 series guidelines for small renewable energy and hybrid systems for rural electrification IEEE SCC21 (Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage)
	Lack of uniform or mini-grid adapted terminology	Mini-grid terminology/configuration standard for all service tiers	
	EHS regulations and standards required, especially for lower-tier mini-grids	Standardised EHS procedure containing a land utilization assessment, essential safety standards and a decommissioning plan	
Storage	Insufficient or unclear safety standards for battery technologies	Provide codes of conduct and installation guidelines with a focus on end-user safety and hazards	IEC Standardisation Technical Committee 120 focus on grid-integrated electrical energy systems IEC SC 21A standards on individual battery aspects IEC 61427-1 standards focus on the on- and off-grid applications of secondary cells and batteries for renewable energy storage
	Standardised functional description and testing of storage solutions	Reduce uncertainty about the specifications of innovative storage solutions in mini-grids	Energy Storage Lexicon: dictionary explaining battery specifications and requirements by NRECA
	Electric vehicles and V2G charging	Standards and test producers should be harmonised and updated with advanced communication capabilities, to enable bi-directional controlled charging and meter electricity flows	ISO Standard 15118 on road vehicles — vehicle-to-grid communication interface Open Clearing House Protocol (OCHP)
CMM	Incompatibility of communication protocols	Standardised communication protocols facilitating mini-grid extensions	IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems Interoperability standards (IEEE P2030.7 and IEEE P2030.8) Different layers of interoperability by the GridWise Architecture Council EN 50549 standards series covering the requirements for generating plants to be connected in parallel with distribution networks Pre-standardisation activities regarding interconnection requirements of DER by European Distributed Energy Resources Laboratories (DERlab)
	A lack of national standards, codes and regulations concerning the possible integration of mini-grids in a larger grid	Grid extension QI has to assure a return on investment in the case of a grid extension. Several schemes are possible	
	Grid regulations not adapted to mini-grid service levels	Grid regulations and standardisation adapted to operational demand of the end users.	
	Discrepancies in regulatory responsibilities between grid operators and mini-grid suppliers		
	Short-term forecasting requires further QI development	Adapt to more irregular and dynamic load and production curves of renewable mini-grids	Meteorological models and simulations using satellite data and sky cameras
	Roll-out of smart meter devices and introduction of new functionalities	A continuous quality assurance effort is required	ETSI Smart Meters Coordination Group (SM-CG)
	QI for internet of things and cybersecurity	Development of open, comprehensive and preferably international standards will be required in the future, together with ongoing vigilance to ensure cybersecurity	EcoStruxure Microgrid Advisor cloud-based system by Schneider Electric

current mini-grids   mini-grids of the future

Note: EHS = Environment, health and safety; IEC = International Electrotechnical Commission; SC = Subcommittees; IEEE = Institute of Electrical and Electronics Engineers; NRECA = National Rural Electric Cooperative Association; EN = European Standards.

Functionality	Gaps		Recommendations	Examples of quality infrastructure
Conversion	Gaps	Unclear conversion requirements for mini-grids	Guidelines stating conversion requirements depending on the level of service	UL 1741 Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
		Clear national mini-grid interconnection standards and regulations	Interconnection standards to be developed and adapted	IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
Consumption	Gaps	Household wiring safety aspects for low-tier mini-grids in electrification efforts	Bridge regulatory gaps concerning energy transactions, self-generation and self-consumption	IEC 60364-7-712 Standard Electrical installations of buildings – Part 7-712
		Transition from consumer to prosumer requires further QI development	Bridge regulatory gaps concerning energy transactions, self-generation and self- consumption	Standards by ISO/TC 307 Blockchain and distributed ledger technologies
Interoperability	Gaps	Proprietary aspects in mini-grid components	Define proprietary standards interoperability with other standards, key for future development of mini-grids	Microgrid test bed by the Tianjin University

Mini-grids are complex systems and should not be considered as the simple sum of their parts. A comprehensive approach to the development of QI is necessary.

The various parts that make up a QI should be able to identify appropriate standards for all aspects of mini-grids, to regulate their correct application and to verify effectively the conformity of mini-grids.

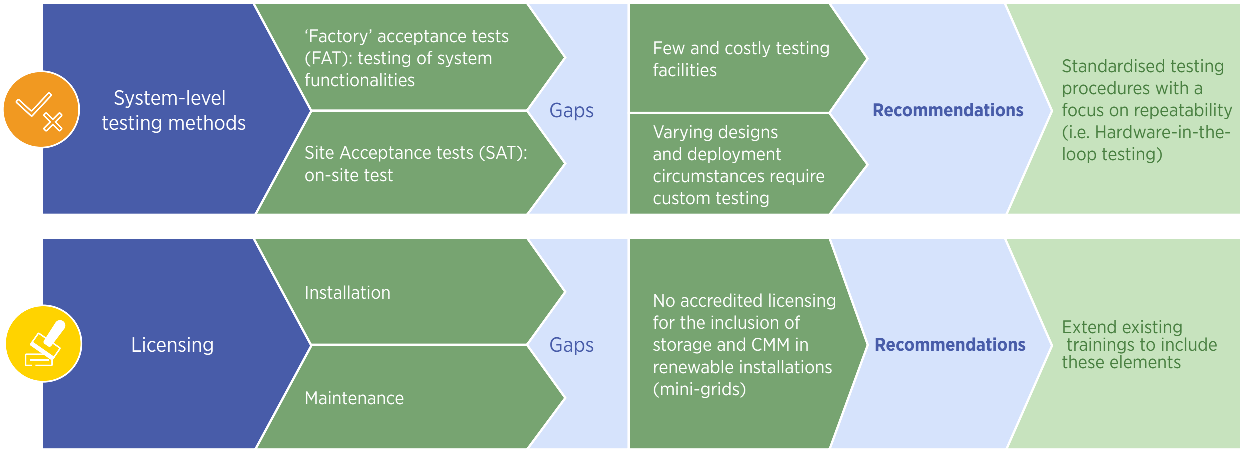
Major standardisation work is mainly oriented to each functionality, and not to the overall mini-grid system. Further efforts are needed to elaborate standards at the system level. To achieve this, current gaps in each one of the mini-grid's functionalities have to first be filled. Bundling standards referring to aspects such as safety, design and operation in a single set of documents which comprehensively describes the development and/or operation of a renewable mini-grid in its totality would considerably reduce the complexity of quality assurance for a mini-grid.

A main challenge for mini-grids lies with the system-level testing. The main goal of mini-grid testing is to make it easy and safe to repeat a mini-grid system in varying circumstances. Standardised testing procedures that allow mini-grid CMM equipment to be tested in varying conditions and in different configurations are key to doing this. Nowadays, mini-grids system-level testing is often done through physical tests during system building and commissioning, or even at the end of mini-grid deployment. This results in a higher risk perception by stakeholders.

More flexible and cost-effective testing methods will reduce this risk perception associated with mini-grids. The combination of physical components with simulations allows testing of the control functionality of a mini-grid without having to construct the complete mini-grid, while limiting testing costs and facilitating easy adjustments.

A mini-grid's quality of operation depends on the quality of its components and design, but also on its installation and maintenance. There are no accredited certification bodies for mini-grid installers (and operators) yet, as there are for PV installations and other renewable energy resources, mainly due to the absence of relevant standards. Where licensing requirements, *e.g.* for PV installers, already exist, the extension of existing licence trainings to include storage and system control could be a solution.

Figure 9 Gaps and recommendations in testing and licensing of mini-grid systems



Quality infrastructure: costs and benefits

QI implementation and execution measures require effort and upfront financing, but this results in long-lasting, high-quality mini-grids, which ultimately result in market growth, better remuneration for players throughout the value chain, more stringent protection for consumers and fewer carbon emissions.

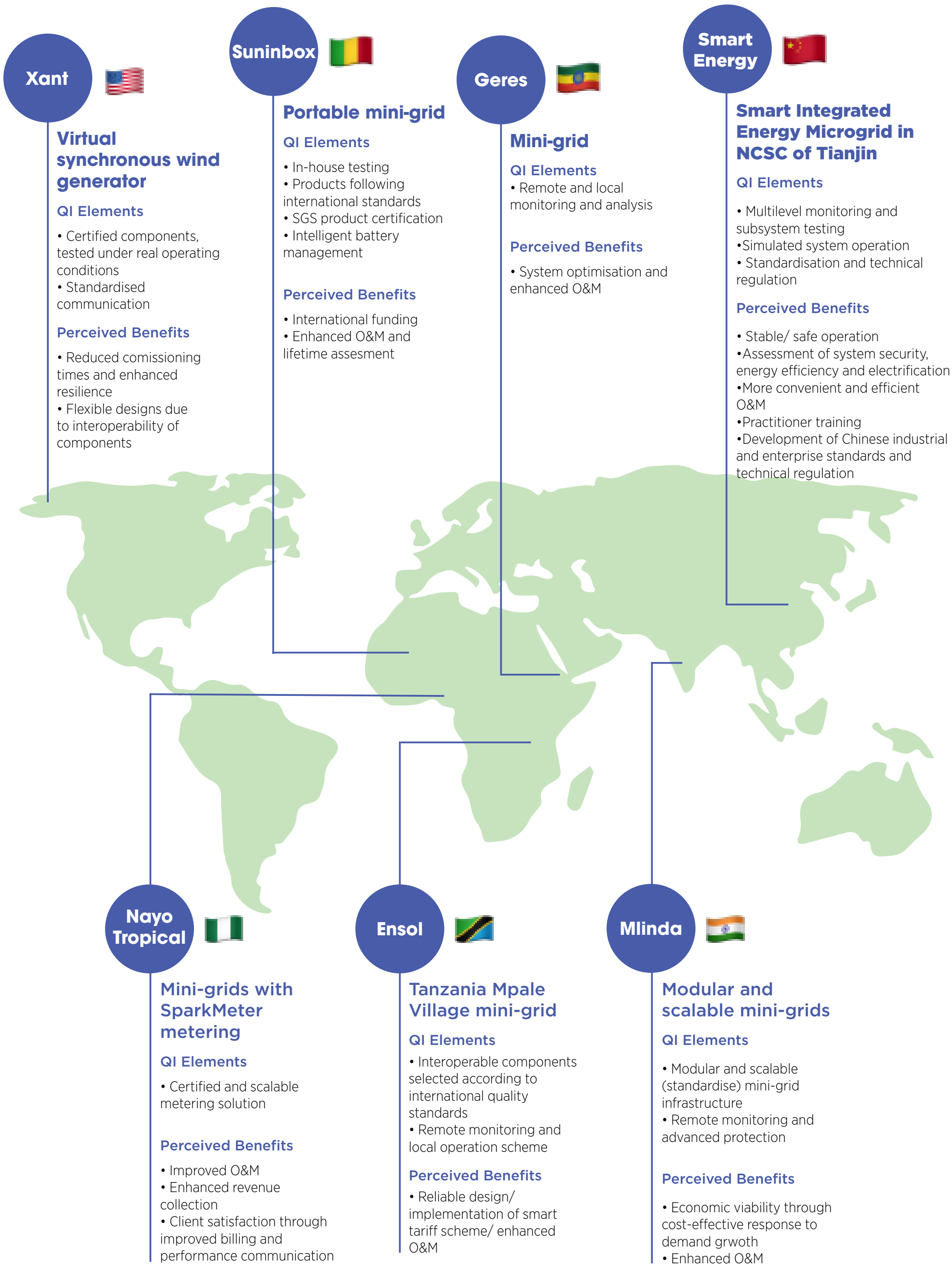
The implementation of QI ensures that installed systems will deliver the expected services at the expected quality level. This mitigates the costs associated with low-quality systems, which must be frequently repaired or replaced in order to deliver expected services in the long term, and/or are capable of delivering only lower-quality services.

At early market stage, the first and main QI benefit is the reduction of legal, regulatory and performance uncertainty. Uncertainty reduction creates a more interesting financial climate, unlocking investments needed for market growth towards maturity.

In addition to mitigating the cost of low quality, QI also aids in the practical realisation of mini-grid benefits. It is difficult to quantifiably correlate these benefits to the successful implementation of QI. Therefore, indicators are used that quantify the benefits of QI or justify the QI upfront cost. For example, reliability **(availability** of an acceptable level of service) and resiliency (reaction to a problem) can both be enhanced by mini-grids, and more specifically by a mini-grid's ability to island itself. QI can help mini-grids in efficiently providing resilience and reliability by using standardised planning, clear definition of standards and regulation on the islanding and reconnection of mini-grids, and testing to assess correct mini-grid behaviour in abnormal situations.

Figure 10 illustrates the importance of quality infrastructure in the deployment and operation of various types of mini-grids. The report analyses seven case studies that point out the great importance of elements of QI (*e.g.* standards, testing, monitoring and technical regulation) and how it has proven to increase the performance and reliability of the mini-grids, leading to benefits for developers, operators and end users.

Figure 10 Mini-grid cases with QI elements and perceived benefits



Note: NCSC = Northern Customer Service System; O&M = operation and maintance.
Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

The stakeholder roles

QI has benefits for a number of stakeholders, including those charged with its development: it limits risk, cost and market-entry barriers for developers; ensures safe, qualitative and affordable energy services to end users; ensures economic performance for investors; and enables reaching key public targets such as access for the population to qualitative, reliable energy services and reduction of carbon footprint. The roles of the various QI stakeholders are briefly described in Figure 11.

Figure 11 Stakeholders of mini-grids and their roles in QI

Note: IPPs = independent power producers; DESCOs = distributed energy services companies;

Integration into policy frameworks

Policy plays a key role in the growth of renewable energy mini-grids. The solar PV market has shown that QI together with a favourable investment climate, incentives and regulations are essential for a rapid market uptake. Likewise, mini-grids need a certain level of national and international QI for a sustainable market.

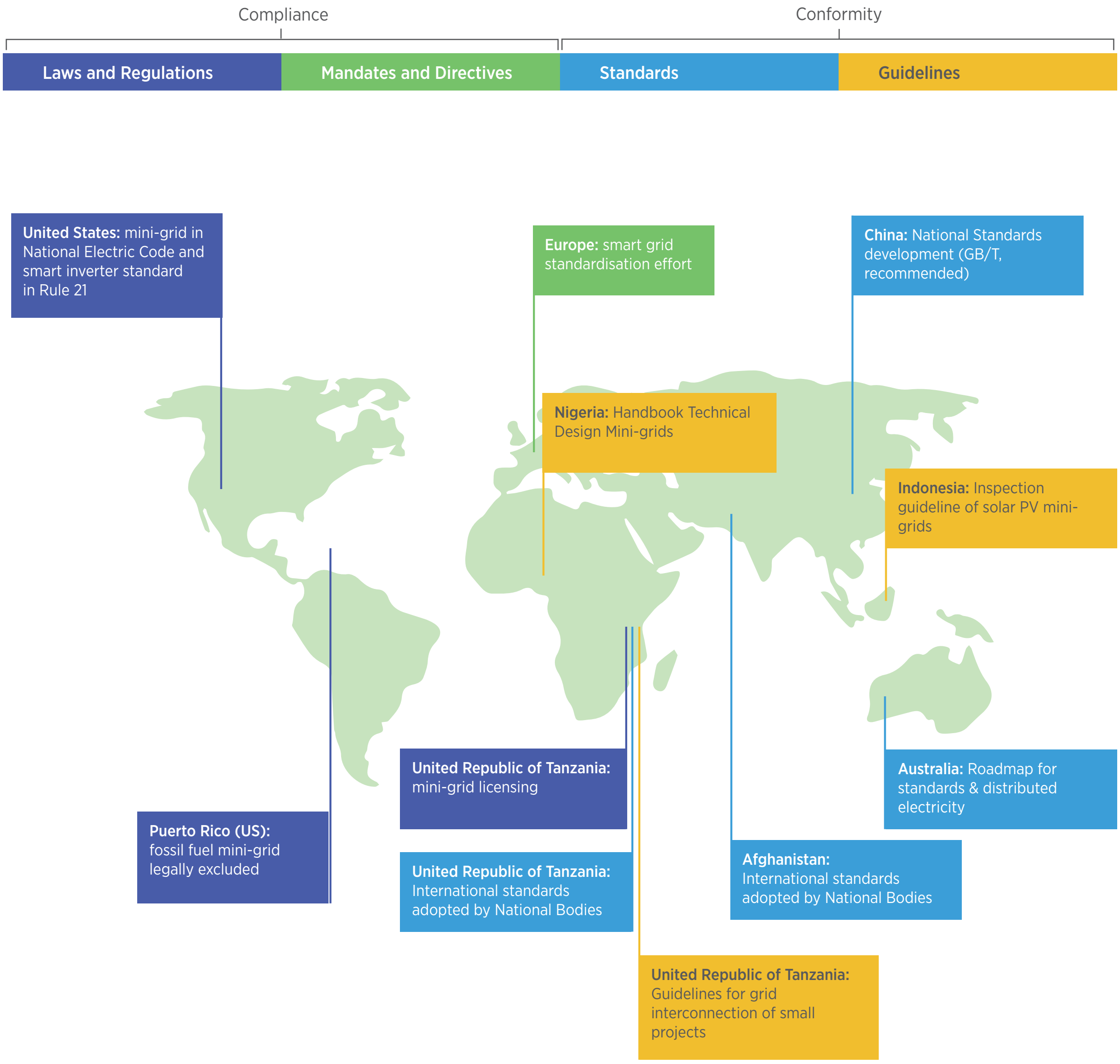
QI development benefits all stakeholders, but the complexity of mini-grids and the disruption they generate for traditional business models create bottlenecks in the process (decision-making inertia resulting in difficulties to develop comprehensive QI). In this context, policy is key to ensuring not only the affordability of mini-grids, but also that safety issues are addressed appropriately and that reliability and quality of service to the end customer are ensured. To that end, QI provides the means to assess the conformity of mini-grids with relevant standards and best practices and their compliance with appropriate regulations.

One of the biggest difficulties is to formulate clear policy goals that can catalyse mini-grid implementation, taking into account demographic changes, industrial evolution, urban development and the electrical infrastructure required.

In this context of constant evolution of mini-grids, a gradual approach to integrate QI in policy frameworks is required: policy should refer to different levels of QI at different times of market development.

Policy mechanisms can facilitate conformity (through guidelines, development of national standards or participation in international standardisation) or impose compliance (through regulations, licensing and enlisting procedures). In an incipient mini-grid market it might be easier and more effective for policy makers to issue safety and design guidelines than to integrate QI into legislative actions (laws, mandates and technical regulations), which are more suited to a more mature market. Figure 12 illustrates the different levels in which QI can be enforced or implemented, and illustrates cases from different countries that have included QI in their policies and guidelines.

Figure 12 Different aspects of policy referring to QI



Note: GB/T: China National Standards.
Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

A recurring challenge to develop a mini-grid policy or establish a legal framework that consistently refers to mini-grid QI is the fact that there are various types of mini-grids, with different requirements and characteristics.

Recommendations for policy makers to improve QI for renewable mini-grids

Policy makers should first refer to the available international and national quality infrastructure when drafting mini-grid regulations and policy. When doing this, it is crucial to consider the current level of market development and to adjust quality requirements accordingly, a list of key recommendations is represented in Table 1. The predominant focus should be end-user safety and reliability of supply.

Table 1 Recommendations to effectively develop quality infrastructure for renewable mini-grids

Policy challenge	Recommendations
Formulate clear and comprehensive policies that cover the entire range of mini-grid complexity and variety	**Include the various stakeholders** in the drafting of mini-grid policy and regulations and make use of **pioneer projects** to establish quality requirements and to support QI development for different tiers of service: Complex large-scale systems have a high market-entry barrier. As such, QI for these systems is mostly developed by private companies (proprietary QI), with the required know-how. Initially these systems will operate in a regulatory grey zone that will allow policy makers to implement the return of experience in clear public policy to lower the market barrier. In lower-tier mini-grids, the market barrier is lower due to a lower system complexity. Policy incentivised QI and regulations are essential to protect the market from substandard installations. In a first stage, policy should proactively refer to QI, established in more developed markets.
	Stimulate the **development of standardised mini-grid configuration** instead of tailored projects. This will also enable the development of a more comprehensive QI policy. For example, grant-funding opportunity and roadmap initiative by the California Energy Council stimulate standardised repeatable mini-grids (down to a finite number of configurations) (CEC, 2018).
International QI is often not adapted to regional needs	**Represent national interests in international technical standardisation committees** and possibly establish mirroring national committees to be in line with international standardisation efforts.
	Make use of the international return of experience to **draft guidelines and handbooks** that limit the administrative and technical barriers for mini-grid developers and investors.

Innovation environment and evolution of mini-grids systems is faster than standardisation	**Adopt forward-looking planning** in the policies, helping to achieve climate goals. With many innovations taking place, mini-grids as a system have to be adjusted to these developments. QI should play a more important role in a digitalised and decentralised world and foresee these trends and prepare for it.
Uncertainties about national regulations and quality requirements	Provide a **dedicated mini-grid regulation** or include mini-grids in the national electric code. Regulatory texts should provide: A **clear legal definition** of what is considered a mini-grid A **mini-grid classification**, based on size, ownership structure and/or the level of grid services provided **Procedural requirements**, depending on the classification (*e.g.* certification, registration, commissioning and reporting) A clear referral to **QI elements** where needed.
Enhance the perceived benefits of QI	**Link incentives to mini-grid quality elements** or reward mini-grid developers that develop systems following international best practices. This can be done in the licensing procedure, by providing financial incentives or in the form of funds and support for innovative mini-grids that monitor and communicate their performance.
	Control the quality of imported components to avoid substandard components that could lead to malperformance. A clear national regulatory framework for mini-grids that is based on national and international quality control systems will facilitate international trade and development.
Lack of collaboration platforms for QI development	**Enable more spaces and platforms for QI development.** This calls for joint action among standard-making bodies, governments, the private sector and academia.

QUALITY
INFRASTRUCTURE FOR
SMART
MINI-GRIDS

A contribution to the Small Island Developing States Lighthouse Initiative 2.0

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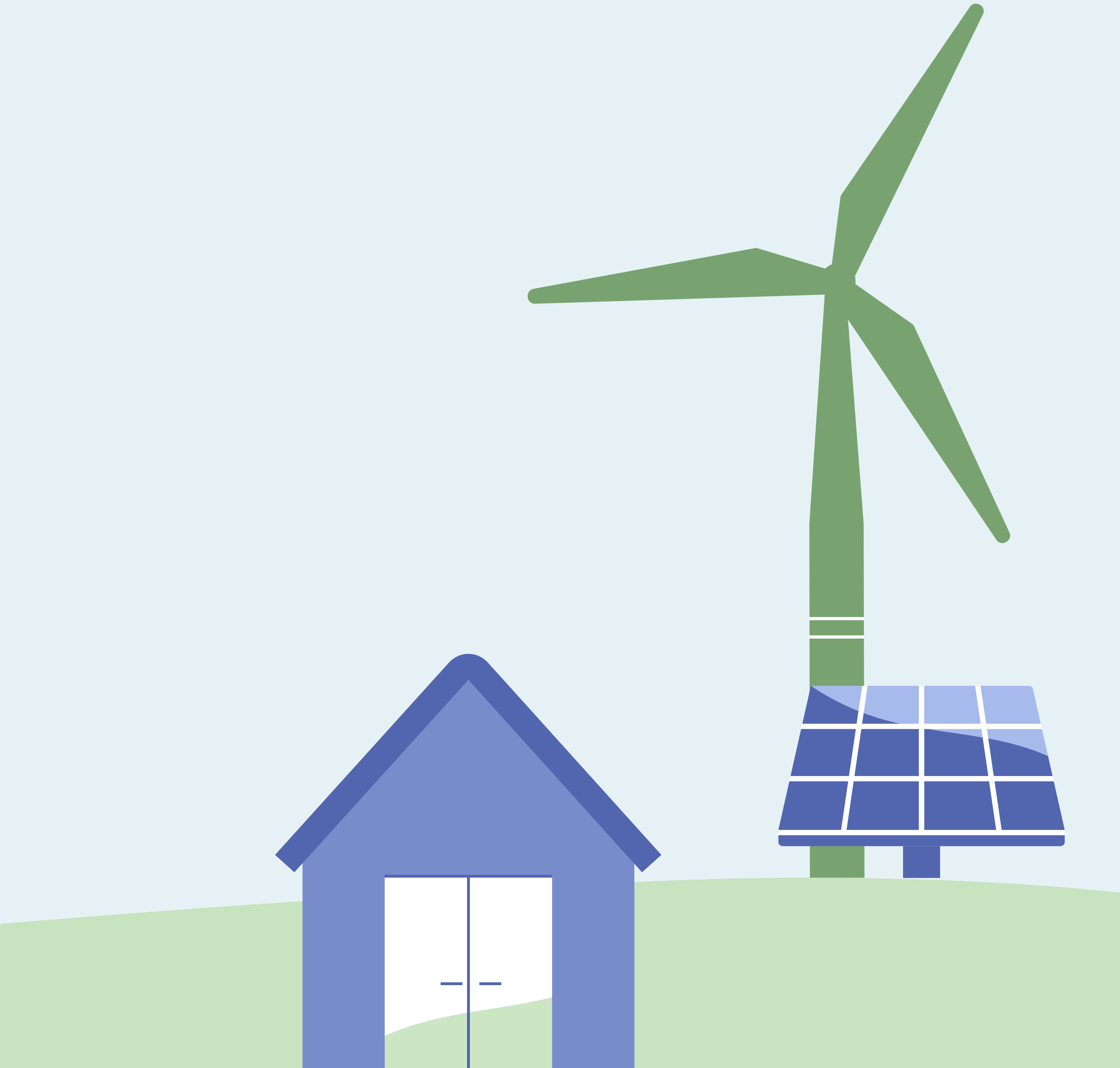


1. RENEWABLE MINI-GRIDS OVERVIEW, MARKET STATUS AND COSTS

Chapter 1 explains what mini-grids are and how these systems work. Key information follows on the global market and cost status. The chapter's last section underlines the crucial role of quality infrastructure to upscale and secure mini-grid markets.

Key information in this chapter:

» mini-grid functionalities and types

» market shares

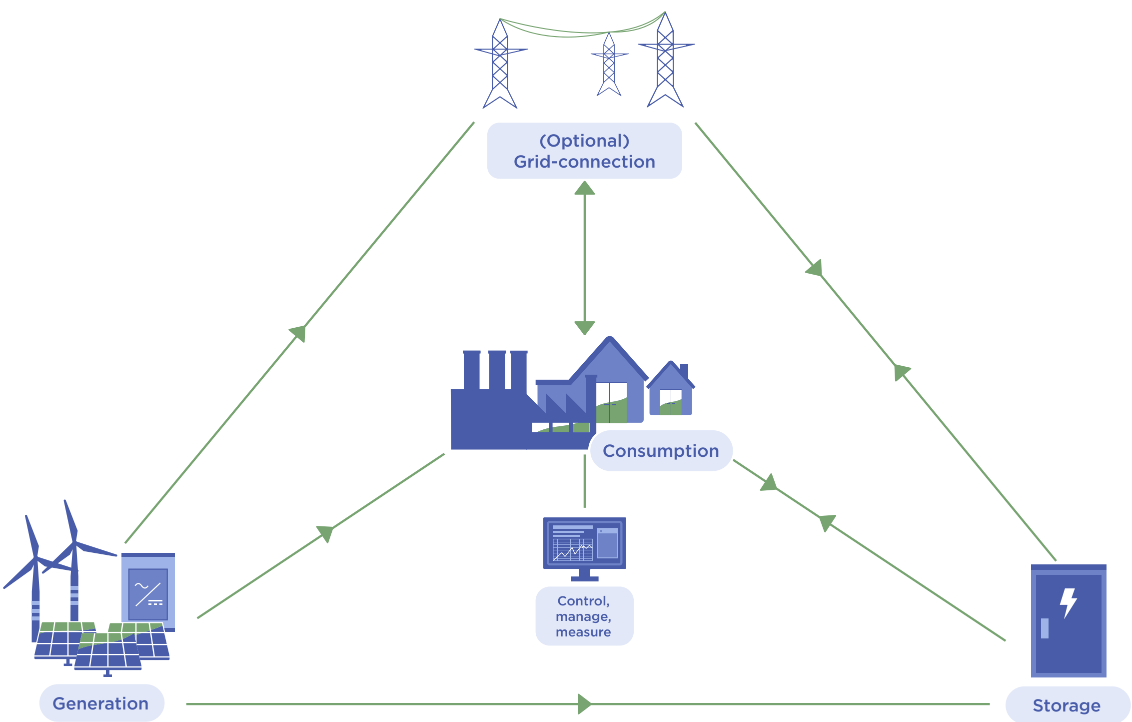
» costs and levelised cost of electricity (LCOE)

» importance of quality infrastructure to upscale mini-grid markets.

1.1 Overview and state of the art on renewable mini-grids

Renewable mini-grids combine loads and renewable energy sources. When planning and designing one of these integrated energy infrastructures, all of its core functionalities, as detailed in the *Innovation Outlook of mini-grids* (IRENA, 2016a), need to be considered: power generation; energy storage; conversion; consumption; and control, manage and measure (CMM). Grid-connected mini-grids have an additional functionality: grid connection. A visualisation of these functionalities is presented in Figure 13.

Figure 13 Mini-grid functionalities



Planning and design

The planning and design of mini-grids strongly depends on the socio-economic use cases, the objective of the installation (electrification, resiliency, efficiency, etc.), and the political and regulatory framework. The initial process requires preliminary modelling, development of a business model, resource planning and engineering of the overall project. Mini-grid development must also be incorporated in broader energy planning (*e.g.* national electrification programmes and renewable energy policies). It is necessary to find a balance between this centralised planning and the local needs and constraints of mini-grid development. Ideally this balance is readily taken into account in policies aimed to help mini-grid developers meet local needs.[1]

Power generation

Renewable mini-grids can generate power using either a single energy source or a combination of several energy resources/hybrids. The generation of electric power from these sources is achieved using equipment such as photovoltaic (PV) panels, wind turbines, hydroelectric turbines or biogas generators. In some cases diesel generators are used to serve as back-up or to complement the other generators.

Storage

Storage units are used to balance the production intermittency, increase the flexibility of operation and limit the disruptive impact of renewable generation curtailment. They can also be used to enhance the efficiency of mechanical generators by preventing them from working at part load. Energy storage is imperative to increase how much renewable energy can be used, as it enables energy usage to be disassociated from its time of production, when required.

Energy storage is a broad concept. It can range from batteries (secondary and flow batteries) and fuel cells to mechanical systems such as pumped hydro systems, compressed air energy storage and flywheel energy storage, and electrical storage systems such as superconducting magnetic energy storage. Although enabling technologies, such as flywheels, are increasingly used in mini-grids, this report will mostly focus on battery storage.

Conversion

Power conversion allows the exchange of electric energy across the mini-grid among various components with different electrical characteristics (alternating current [AC] or direct current [DC], voltage levels, etc.). Conversion equipment is categorised according to its input and output power: converters (DC-to-DC, AC-to-AC), rectifiers (AC-to-DC) and inverters (DC-to-AC). In certain cases the conversion from DC power (*e.g.* from PV panels) to AC power is not included, which results in a DC mini-grid. These mini-grids have an improved efficiency due to lower conversion losses.

Consumption

Consumption includes the technologies that make the consumption of energy more flexible and efficient. Mini-grids can provide basic services such as lighting as well as more complicated services such as meeting commercial or industrial energy demand.

1 The IRENA project navigator is an online platform providing comprehensive, easily accessible, and practical information, tools and guidance to assist in the development planning of bankable renewable energy projects (IRENA, 2018b).

Control, manage and measure

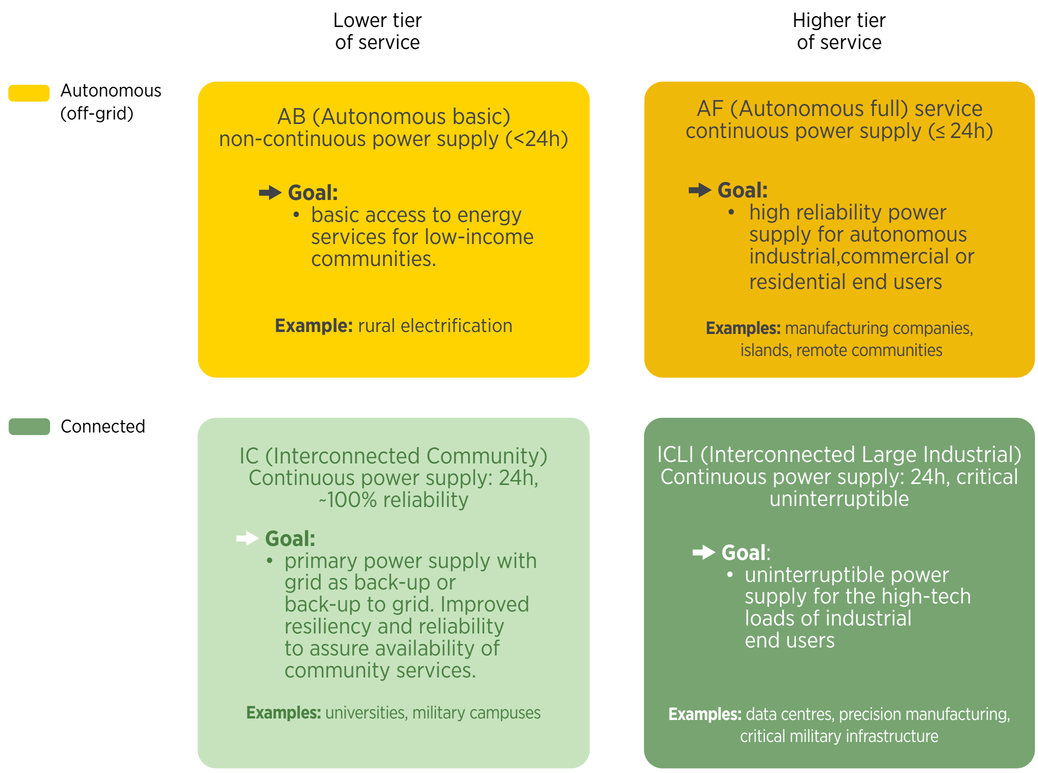
CMM elements let mini-grids work as part of a network of devices that are all interconnected and at the same time enhance the entire structure's energy performance. Controllers ensure the optimal integration of renewable energy technologies while maintaining the reliable and economic operation of the system. The hardware and software that manage mini-grids link energy generation/storage and consumption by allowing communication and managing energy flows between them. One could say the control functionality maintains the power balance within the system (*e.g.* frequency and voltage control), while the management functionality executes the energy management strategy (*e.g.* directing energy flows based on weather forecasts). Smart meters can help inform managers and investors on profitability, load profile trends, revenue projections, quantification of losses, and operations and maintenance (O&M) costs, which in turn provides investors with tools to accurately extrapolate current usage patterns to future mini-grids and hence enable intelligent decision-making. Additionally, web-based project aggregation platforms can help standardise and centralise data to facilitate efficient market transactions among project developers, investors, donors, governments and suppliers.

This functionality also entails the required protections for a safe mini-grid operation.

Grid connection

Mini-grids' categorisation is based on how they connect to the grid and what level of service they provide to end users, as described in Figure 14 (IRENA, 2016a). A renewable mini-grid can be connected to the main grid, or can be off-grid, in which case it is considered autonomous. The off-grid (remote) mini-grid segment is expected to see increased deployment in coming years; however, the grid-connected segment is expected to see the biggest growth as a result of the increasing mini-grid activity of utilities and growing grid issues in urban, commercial and industrial areas (Global data, 2018).

Figure 14 Mini-grid types



Based on: (IRENA, 2016a).

Example of AB renewable mini-grid

A remote rural village on an island in the Krishna river saw a solar mini-grid successfully installed and connected in 2014. The village of Neelakantarayanagaddi, in Karnataka, India, now has light and mobile charging for its 44 households. It consists of 1.2 kilowatts peak (kWp) PV capacity, 400 ampere-hours of capacity for 48 volt (V) batteries, and a control panel with a DC charge regulator and data monitoring capabilities. The distribution voltage used is 48 V DC. The project was promoted in order to i) provide for the immediate needs of the community with the most appropriate technology; ii) match the community ability to pay, including how much they can pay and how often; and iii) establish which services could be introduced later, incrementally building on the existing infrastructure and operational mode (Armstrong Energy Foundation Ltd, 2014).

Examples of IC renewable mini-grids

- Hangzhou Dianzi University tested a stable mini-grid system with high penetration of intermittent power, located on the university campus. The mini-grid achieved about 50% of the electricity generation from solar PV sources. It is powered by 120 kilowatts (kW) PV complemented with a 120 kW diesel generator and fuel cells. It also has a 100 kW capacitor and a 50 kW storage battery. The system aims to keep up a constant flow of electricity where it couples with the grid. The fluctuation during the operation was within 5 kW of the targeted power flow (Berkeley Lab, 2018).

- One of several projects targeting 100% renewable community mini-grids is in Yackandandah, Victoria, Australia, its first. Rooftop solar systems, battery storage, and the smart energy monitoring and management system power the mini-grid, which targets powering the community of 169 homes with 100% renewable energy by 2022 (AusNet Services, 2017).

1.2 Deployment, market status and costs

The recent growth in the total amount of power installed in mini-grids worldwide has greatly exceeded expectations, having a continuous expansion across the years , as seen in Figure 15. As availability of data is still a limitation, it is difficult to quantify the total renewable energy mini-grid capacity; however, IRENA has taken the lead to better understand the deployment of renewable energy mini-grids disconnected from the main grid; this section presents further insights about off-grid systems.

Off-grid mini-grids have seen strong market growth in areas that are hard to access or remote, such as rural Africa and Southeast Asian (rural electrification). IRENA estimates that at least 9 million people worldwide are connected to an off-grid mini-grid. The three main renewable energy sources used in these mini-grids are hydropower, solar power and biogas, with hydro and solar seeing the fastest growth (in number of people served) in recent years, as illustrated in Figure 16 (IRENA, 2018a). Although these mini-grids are classified based on their main renewable energy source (*e.g.* solar mini-grids), it is very well possible that they also use other sources.

The off-grid segment is expected to see significant growth in areas besides rural electrification, due to the upcoming installation of new projects in remote areas such as Australia, the Arctic Circle and the Russian Federation, and the replacement/hybridisation of ageing diesel generators in industry segments. Much of the new renewable capacity in mini-grid installations consists of diesel replacements/hybridisation, keeping the gensets as back-up. Few of them install 100% renewable mini-grids.

Figure 15 Global number of people served by hydro-, solar- and biogas-based mini-grids (in millions)

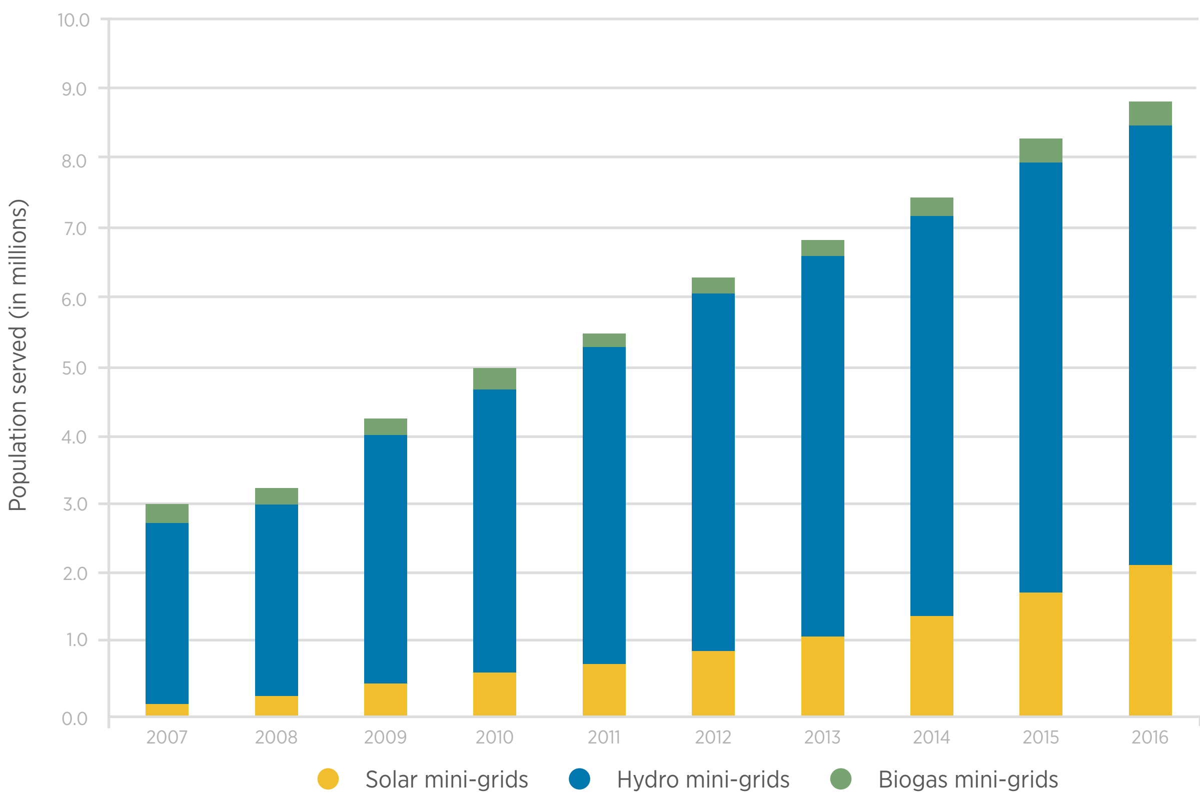
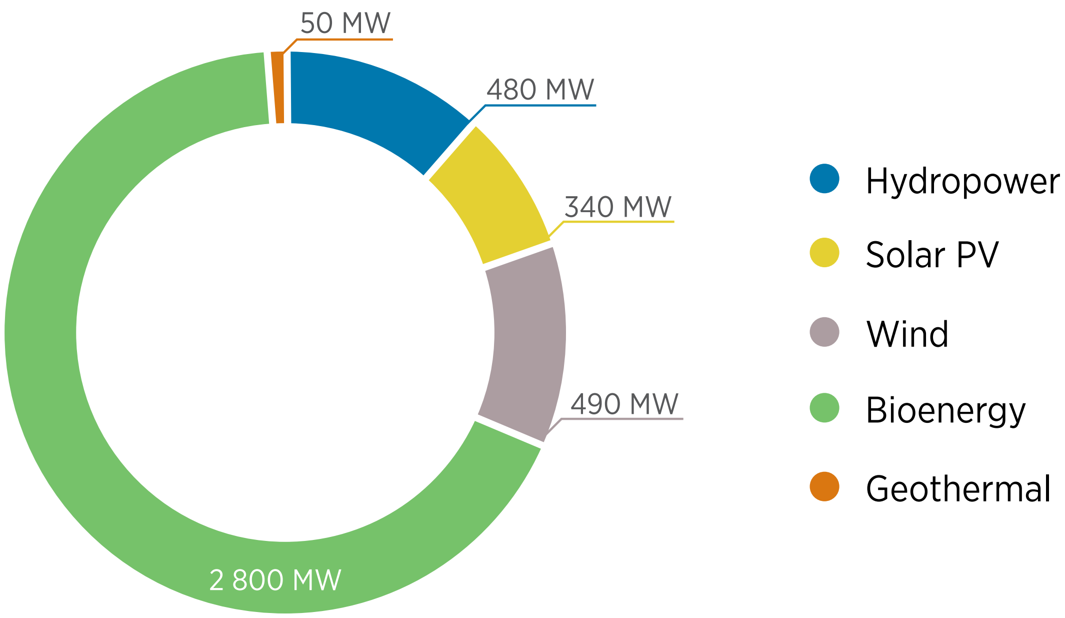


Figure 16 Total capacity of autonomous (off-grid) mini-grids (MW)



Note: MW = megawatts.
Based on: (IRENA, 2018a).

For off-grid systems, IRENA estimated 4.16 gigawatts of renewable mini-grid installed capacity by 2018. As seen in Figure 16, bioenergy-based mini-grids show the highest installed capacity, due to the fact that they are often used in high-power industrial mini-grids. Wind- and hydropower-based mini-grids are deployed across the different end-use sectors. Hydropower mini-grids in particular have recently increased their deployment in the residential and industry sectors. Solar PV mini-grid installations are commonly used for commercial, residential and agriculture purposes.

Examples of CO_2 reductions in off-grid mini-grids

» In the Marble Bar project in Western Australia, a hybrid PV diesel project allows the PV plant generates 60% of the daytime electricity demand, avoiding 1 100 tonnes of carbon dioxide (CO_2) annually (ABB, 2018).

» At the Ross Island project in Antarctica, wind turbines have been integrated into the mini-grid with grid stabilisation using a flywheel. The peak power wind penetration is up to 70%, saving 2 800 tonnes of CO_2 annually (Cleiton, 2016).

Grid-connected renewable mini-grids can make the power supply more reliable and resilient as well as boost renewable sources to be a significant contributor to energy generation. The aforementioned need for a reliable back-up system in regions with grid reliability issues and the enhanced interest from utilities in the mini-grid market explain the expected growth of the grid-connected mini-grid segments (Figure 14). The several different types of grid-connected mini-grids had a combined market share of about 55% as of 2017 with a forecast market share of over 60% in 2022 (Global data, 2018).

Mini-grid deployment drivers by market segment

Figure 17 describes the main drivers for renewable mini-grid deployment by market segment (see Figure 14 for mini-grid types).

In general, the following factors motivate the installation of mini-grids:

- energy access
- energy bill savings
- improvement of service quality and independence from utility supply (reliability and resilience improvement)
- renewable energy targets.

The key mini-grid market segments are islands and remote communities (without access to a distribution grid, *e.g.* desert or mountain communities), for which energy access is the primary driver. The integration of renewable energy in these mini-grids enables a decrease in the cost of energy, with additional benefits of service quality, positive environmental impact and quality of life.

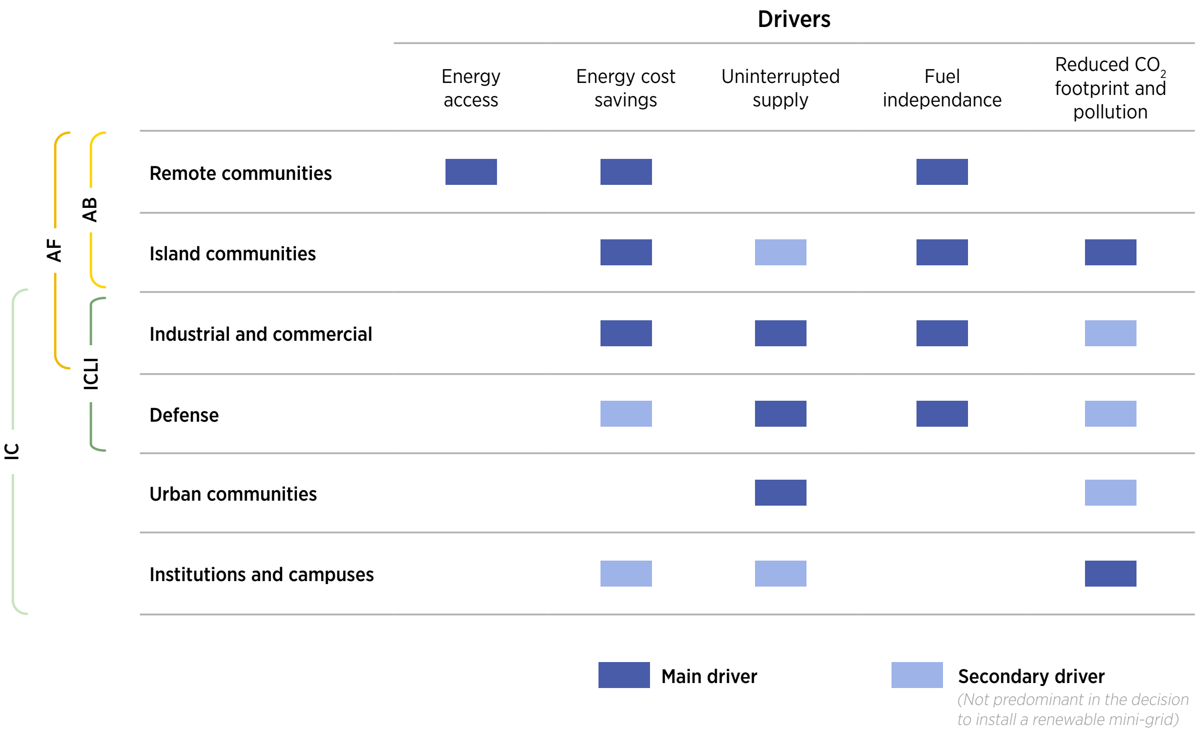
Another important market segment is commercial and industrial (C&I) facilities. More of these facilities are installing low-carbon mini-grids which run with predominantly renewable power. Mini-grids meet the needs of a wide range of C&I facilities such as:

- facilities in off-grid areas that require mini-grids in order to meet their energy needs
- productive sites with inconsistent energy supplies that require mini-grid support for reliable and affordable power
- sites in areas with reliable grids that are looking to make self-production more economical, improve resiliency and/or reduce carbon emissions.

Examples of C&I mini-grids

- DeGrussa Copper Gold Mine in Australia is one of the biggest mini-grids in the world. It integrates a 10.6 MW solar PV field and a battery storage system with the diesel generation already there to reliably produce baseload power and reduce CO_2 emissions by 12 000 tonnes per year.
- The new California campus of Apple is powered by 100% renewable energy sources and will include 17 MW of rooftop solar and be supported by a mini-grid that has 4 MW of power from Bloom Energy fuel cells. On-site generation will meet about 75% of the campus power requirements during the workday, with the rest coming from a 130 MW solar PV project built by Monterey County and First Solar (World, 2017).

Figure 17 Main drivers for renewable mini-grid segments



Based on: (ABB, 2018).

Key cost components of renewable mini-grids

Mini-grid costs are difficult to generalise, as they depend on a variety of site-specific use cases. In order to assess the profitability of a specific mini-grid, the LCOE must be compared with existing energy tariffs. Factors that have to be taken into account when estimating a mini-grid LCOE are:

- Asset selection and presence of existing assets (capital expenditures)
- Size of the system (economies of scale reduce the LCOE)
- Cost of capital and financing conditions
- Variability in seasonal energy demand as well as differences in politics, payments and prices.
- Location: remote projects usually have higher LCOEs because construction and O&M costs are higher. Interviewed professionals reported that extra logistics and implementation costs accounted for up to 10-20% of total project costs
- Regulatory requirements (*e.g.* distribution configuration requirements and reliability) (Adams, et al., 2017).

Examples of mini-grid cost breakdown

Mini-grid 1 is an island mini-grid in the Pacific. The existing conventional diesel generators are progressively being phased out and some existing conventional diesel generators retrofitted for biodiesel (1.2 million litres per year) to obtain a 90% share of renewables. The LCOE of the system was calculated to be USD 0.39 per kilowatt-hour (kWh). A sample cost breakdown of recently deployed mini-grids is given in Table 2.

Table 2 Example of cost breakdown in recently deployed mini-grid in the Pacific

AF mini-grid Pacific	Installed capacity	CAPEX (installation)	OPEX/Fuel costs	CAPEX replacement (in 2029)	OPEX replacement (in 2029)
PV	5.4 megawatts peak (MWp)	USD 1 853/kWp	USD 40/kWp	No expected replacement	No expected replacement
Wind	825 kWp	USD 3 940/kWp	USD 90/kWp	No expected replacement	No expected replacement
Battery	5 MW/10.5 MWh	USD 474/kWh	USD 10/kWh/year	USD 173/kWh	USD 5/kWh/year
Converter	/	USD 474 per kilovolt-ampere (kVA)	/	USD 347/kVA	/
Biodiesel	/	Readily installed	USD 0.8 per litre +1.36%/year	No expected replacement	No expected replacement
Controller	/	USD 232/kWp*	/	No expected replacement	No expected replacement

* Taken from another comparable mini-grid

Mini-grid 2 is a small hybrid PV-diesel mini-grid in Southeast Asia. The LCOE of the system was calculated to be USD 0.39/kWh as well.

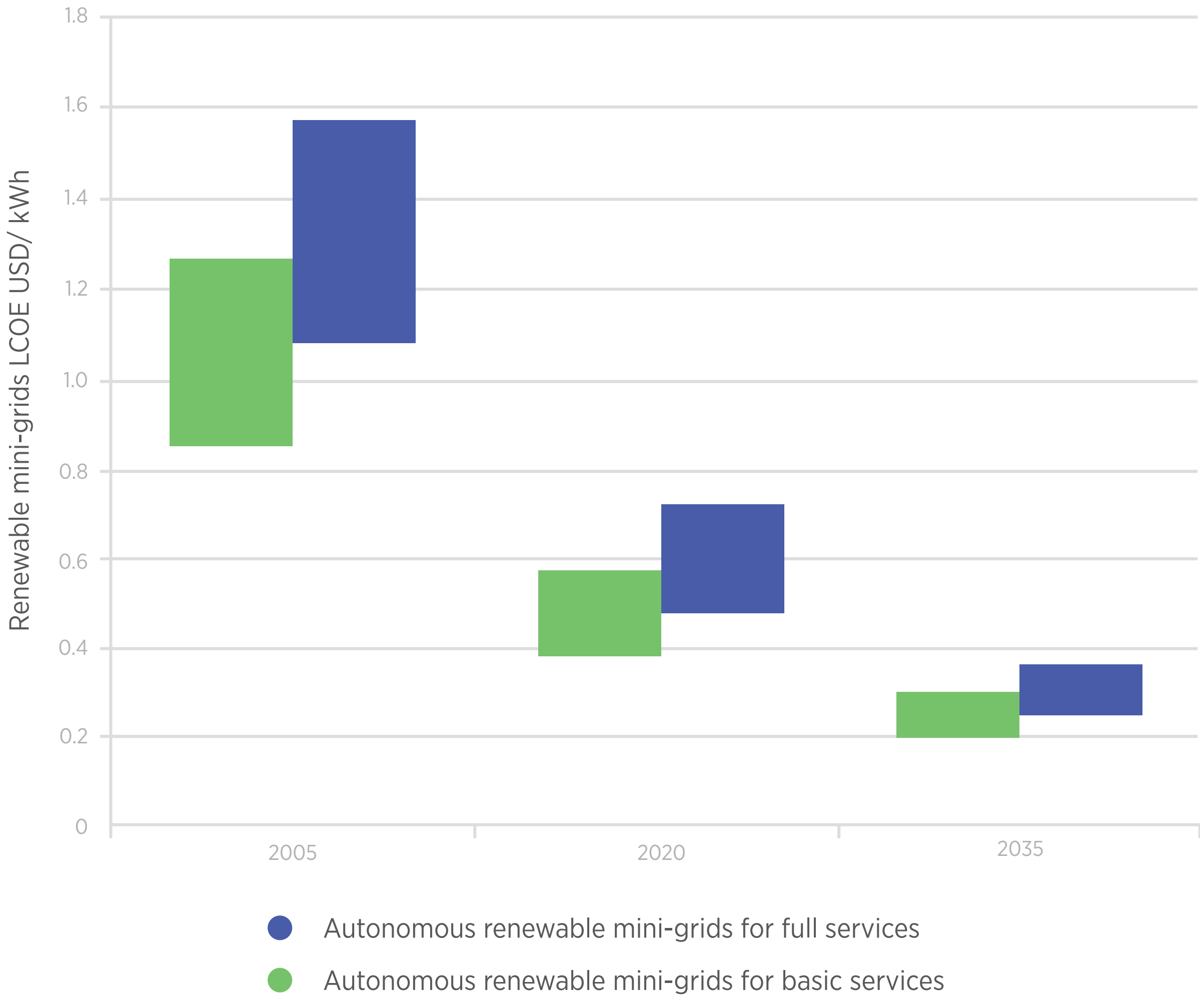
Table 3 Example of cost breakdown in recently deployed mini-grid in Southeast Asia

AF mini-grid Southeast Asia	Installed capacity	CAPEX (installation)	OPEX/Fuel costs
PV	5.4 MWp	USD 804/kWp	USD 4.86/kWp/year
Battery	Lithium Ion: 730 kWh	USD 641/kWh	USD 3.58/kWh/year
Inverter and controller	/	USD 236/kW	USD 2.36/kW/year
Diesel	160 kW	USD 307.2/kW (all taxes included)	USD 6.14/kW/year

Although the cost of mini-grid hardware has generally declined in recent years as a result of increased competition and policy-driven incentives, the downwards evolution of "soft" costs, which are associated with customised engineering studies and regulatory, environmental and interconnection compliance, is sometimes restricted because of non-competitive regulatory friction (Cherian, 2017). As a result, these costs currently represent a larger percentage of total costs compared with past years.

Figure 18 summarises the findings for 100% renewable energy-based AF and AB community mini-grids and illustrates the past and decreasing cost trends for mini-grids. The LCOE costs in 2020 for the AB range from USD 0.39/kWh to USD 0.58/kWh, and for AF from USD 0.50/kWh to USD 0.75/kWh. The 100% renewable energy mini-grids are a cost-competitive solution in comparison with small gasoline and diesel generators (USD 0.35/kWh to USD 0.70/kWh) (Agenbroad, et al., 2018).

Figure 18 Unsubsidised cost ranges for renewable mini-grids from 2005 to 2035 for a 100% renewable energy community system



Based on: (IRENA, 2017c).

1.3 Quality infrastructure to support market development

Investments made in renewable mini-grids are steadily growing, and this trend is expected to accelerate in the coming years. Large investments in renewable mini-grids are anticipated, with the goal of increased electricity access and power resilience on the one hand, and reduced power costs and carbon footprints, through larger shares of renewable power generation, on the other hand. As described in Section 1.2, renewable mini-grids are thus expected to become a significant part of energy systems worldwide.

As mentioned in the introduction, the sustainable market growth and long-term profitability of mini-grid systems requires quality infrastructure (QI). QI has the goal of reducing system downtime and improving mini-grid O&M. It thus entails a direct economic benefit for stakeholders (reduced LCOE) in that its presence reduces risk for investors and leads to better financing conditions for future projects. The technical and regulatory clarity that QI brings along stimulates sustainable innovation and instils confidence in global mini-grid markets. This in turn facilitates trade and allows mini-grid system providers to easily expand their operations across different regions.

Mini-grids are complex systems and should not be considered as the simple sum of their parts. Therefore a comprehensive approach to the development of QI is necessary. The various players that make up a QI should be able to identify appropriate standards for all aspects of mini-grids, to regulate their correct application and to verify conformity of mini-grids with appropriate standards and regulations.

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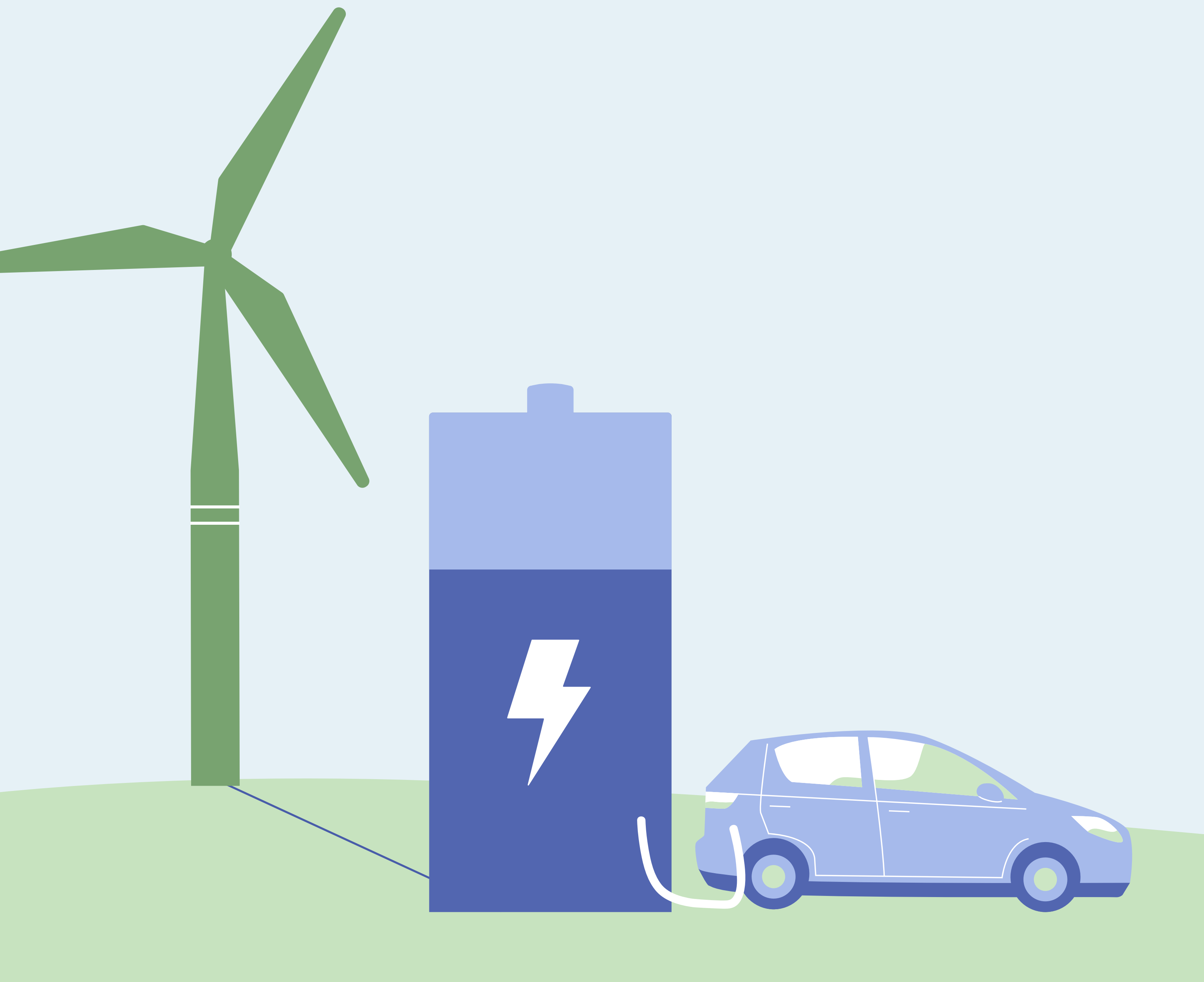


2. QUALITY INFRASTRUCTURE AND CURRENT USES FOR MINI-GRIDS

Chapter 2 evaluates the existing quality infrastructure (QI) for the main functionalities of a mini-grid. It studies current quality practices and identifies gaps and recommendations to assure reliable and sound mini-grids.

Key information in this chapter:

» quality infrastructure definition and the role of stakeholders
» applicable standards for mini-grids
» metrology and testing methods
» inspection and monitoring
» licensing
» certification and accreditation.

2.1 Introduction to quality infrastructure

What is quality infrastructure?

QI is an umbrella term combining a number of services, regulations and institutions that are required for the assurance of system or product quality. It includes (IRENA, 2017a):

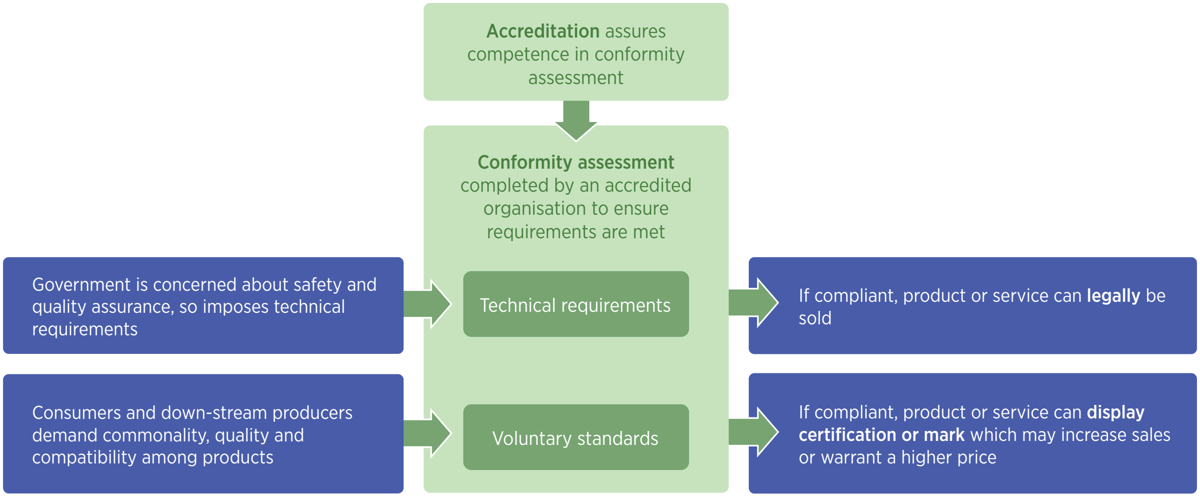
- standards
- certifications
- testing procedures
- accreditation
- inspection bodies
- metrology
- market surveillance

For further explanations concerning each of these aspects, it is relevant to refer to *Quality Infrastructure for Renewable Energy Technologies: Guidelines for Policy Makers* (IRENA, 2015a). Overall, QI includes public and private organisations; policies, laws and regulations; and the practices that are necessary for quality, safe and environmentally sound goods, services and processes.

Domestic markets need QI to operate effectively, and it must be recognised internationally so that products can be implemented in foreign markets. QI is needed to promote and sustain economic development and environmental and social well-being.

The aforementioned QI elements are often combined in a national or international conformance framework that is used to judge whether a particular product, system or service meets a standard or complies with a technical requirement. As is displayed in Figure 19, laboratories (testing), inspection bodies and certification bodies can verify conformity with technical regulations or voluntary standards that exist for the product, system or service. In turn, these institutions can be accredited to ensure competence in their conformity assessment.

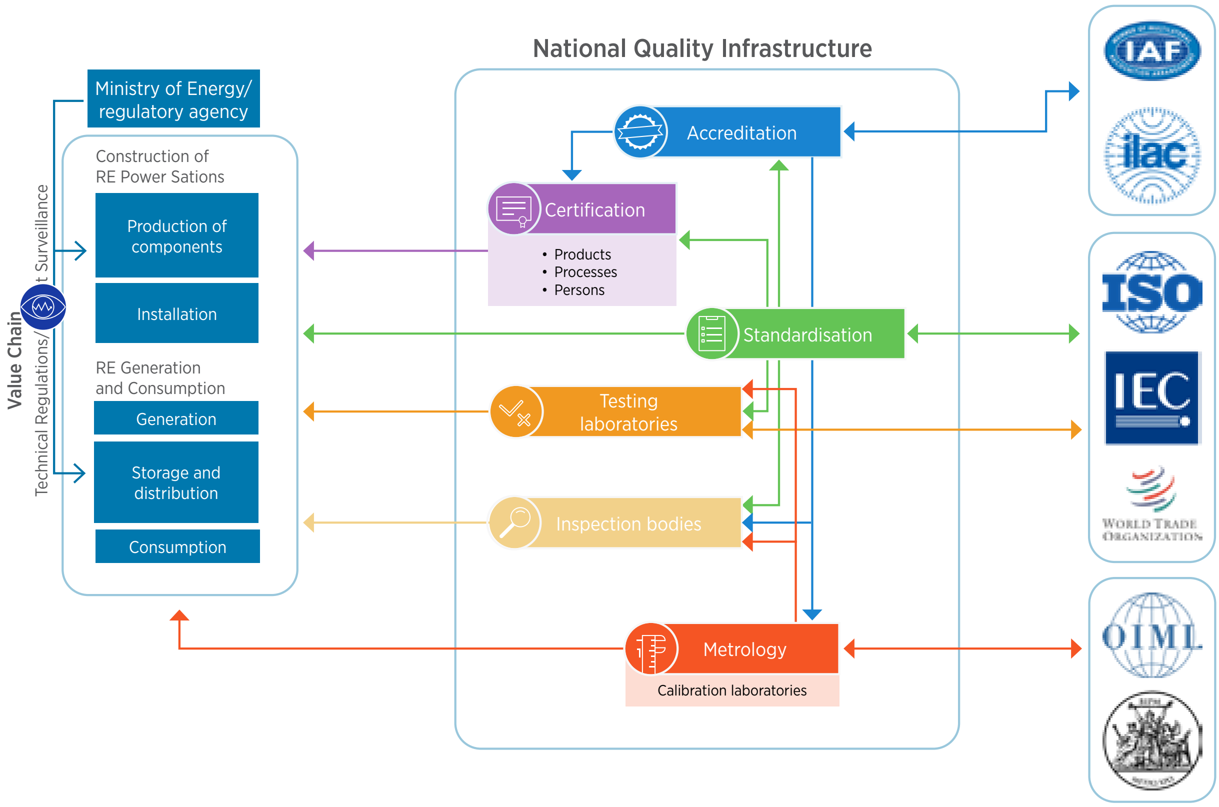
Figure 19 Conformance framework to manage the various QI elements



Source: (Ministry of Business, Innovation and Employment, 2018).

A graphical illustration of the different components in a national QI and relationships among international and national QI elements for the value chain of renewable energy generation and consumption is shown in Figure 20.

Figure 20 Illustration of international and national QI elements and their relationship



Note: IAF = International Accreditation Forum; ILAC = International Laboratory Accreditation Cooperation; ISO = International Organization for Standardization; IEC = International Electrotechnical Commission; WTO = World Trade Organization; OIML = International Organization of Legal Metrology; BIPM = Bureau International des Poids et Mesures.
Based on data from the National Metrology Institute of Germany (Physikalisch Technische Bundesanstalt). (IRENA, 2015).

What are quality infrastructure's main goals?

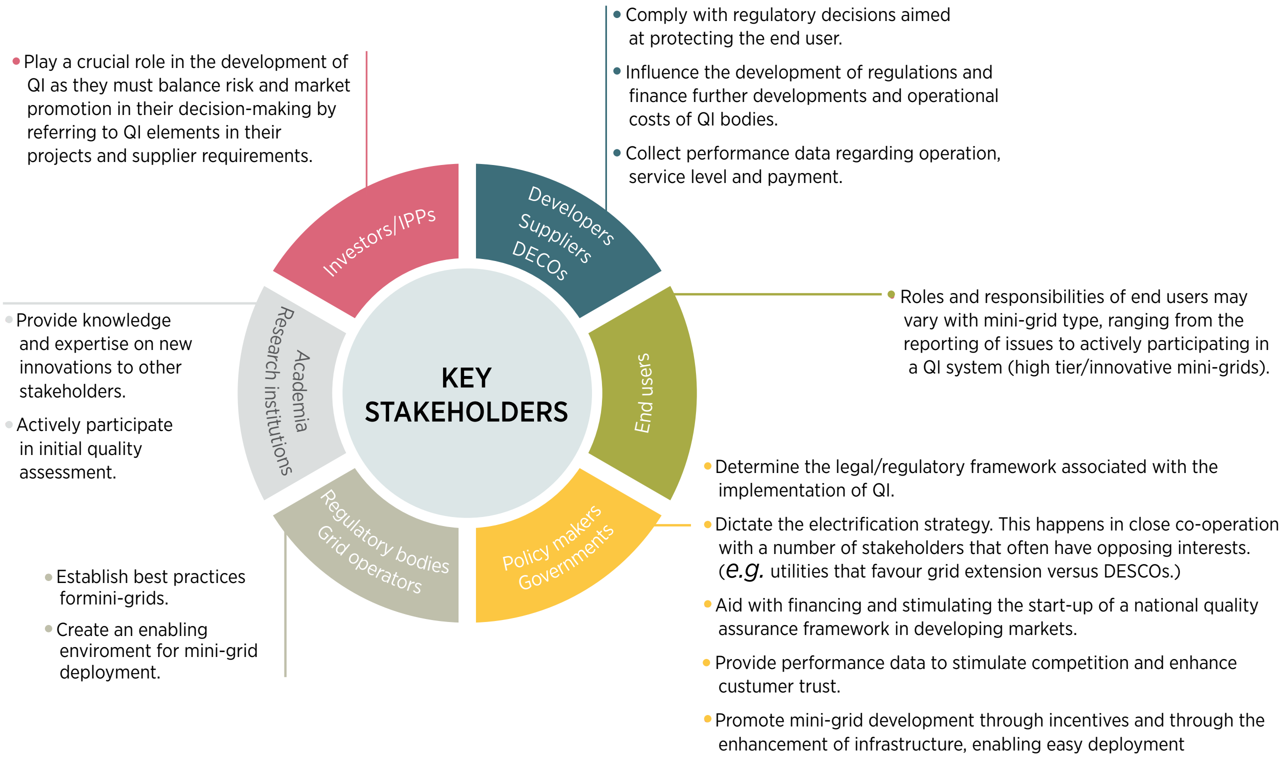
QI's main goal is to promote quality products, processes and services, to prevent or overcome market barriers, and to make technical co-operation easier (IRENA, 2015a).

For mini-grids specifically, the goal is to reduce uncertainty concerning the quality of service delivered. The presence of QI should increase a customer's willingness to pay, instil market confidence and reduce the barriers present for investments on a global scale. This should enable economies of scale and scope. With QI in place, the cost of more reliable energy will drop and the diffusion of mini-grid technologies will be enhanced. The development of a well-designed QI will thus eventually lead to an increased realisation of customer benefits (NIST, 2014a).

To whom is quality infrastructure addressed?

QI has benefits for a number of stakeholders, including those charged with its development. The roles of the various QI stakeholders are briefly described in Figure 21 (Meister Consultants Group, Inc., 2017).

Figure 21 Roles of key stakeholders in QI for mini-grids



Quality infrastructure and mini-grids

The following sections cover the existing standards, testing methods, and accreditation and certification processes for the main functionalities of a mini-grid, along with existing metrology requirements.

An exhaustive description of QI for mini-grids would be quite extensive, as mini-grids are composed of several subsystems, with different infrastructures, depending on the supplier. For each of the components and communication layers, a different set of standards and regulations may apply, and depending on the maturity of the considered technology, knowledge concerning the operational and risk exposure characteristics may vary. As such, this report focuses on system-level QI development and uses a selection of examples as demonstration. The following is thus not to be considered comprehensive for all mini-grid applications.

2.2 Standards

Mini-grid systems have to conform to certain standards so developers and suppliers can show that their system or product will serve its purpose. Most countries have regulations that rely on standards.

ISO/IEC definition of a standard

According to the ISO/IEC 17000, a standard is defined as "a document, established by consensus and approved by a recognised body, which provides for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context. Standards can address a wide range of topics, including safety issues, design issues, performance and reliability" (IRENA, 2015).

In the following section a short overview of the different mini-grid aspects currently covered by (mostly) international standards is given. This is not an exhaustive list of available standards, but more a general overview of the QI development. Note that there is no such thing as a universal mini-grid and that the relevance of standards will vary with the components, complexity and size of each project.

International, regional or national standards?

There are a number of international organisations that develop mini-grids standards and guidelines. They develop new standards in technical committees (TCs) and adapt existing national standards to be consistent within an international context.

When national or regional standards are defined, they are mostly adapted from international standards or foreign national standards, according to the maturity of the market and the complexity of the systems. United States national standards, for example, are of little relevance to the United Republic of Tanzania mini-grid market (mostly energy access), since they are focused on high-complexity systems with strict requirements for reliability and power quality. They would not only lack relevance, but might even create a development barrier if referred to in regulations. Dedicated international standards or guides such as the Quality Assurance Framework for Mini-Grids (QAF) published by the National Renewable Energy Laboratory (NREL) (Baring-Gould, 2016) are a more suitable inspiration for standardisation efforts in this case.

A list of some of the most well-known and active national, regional and international standards bodies can be found in Appendix A.

Which standards exist for mini-grids?

Standardisation of certain individual components or subsystems of a mini-grid has reached an advanced stage due to technological maturity and enhanced deployment under various circumstances. The interaction among different subsystems, networks and devices requires uniformity in design, implementation and operation. This is termed interoperability, and is crucial for the interconnection of mini-grids, the connection to a national grid and internal equipment connections. Because of this, a holistic approach to the description of existing standards will be used, based on the six core functionalities of mini-grids presented in Chapter 1.

The following sections describe the existing or developing standards for each functionality. For an extensive review of existing renewable energy standards, the link to the responsible standardisation bodies and a short description of the content of said standards, refer to the INSPIRE database (International Standards and Patents in Renewable Energy) provided by IRENA (IRENA, 2020).

IRENA INSPIRE database

The IRENA INSPIRE database (IRENA, 2020) allows the browsing of existing IEC and ISO standards based on keywords (*e.g.* mini-grid), technology group (*e.g.* solar/wind energy) and aspects covered (*e.g.* installation and certification).

An example of a mini-grid standard search result in the INSPIRE database:

IRENA INSPIRE
INTERNATIONAL STANDARDS AND PATENTS IN RENEWABLE ENERGY

IEC TS 62257-9-2 ed2.0 : Recommendations for small renewable energy and hybrid systems for rural electrification. Part 9-2: Integrated systems - Microgrids

Abstract:

IEC TS 62257-9-2:2016(E) specifies microgrids made of overhead lines because of technical and economical reasons in the context of decentralized rural electrification. The microgrids... Read More

Normative references:

IEC 61439 (all parts), Low-voltage switchgear and controlgear assemblies IEC 62257 (all parts), Recommendations for renewable energy and hybrid systems for rural electrification... Read More

Body: **IEC** | Ref.-No: **IEC TS 62257-9-2 ed2.0**

Technology: **Rural Elec** | Publication: **9/27/2016** | Aspect: **Installation** | Status: **Active** | More: **IEC Website**

Link: http://inspire.irena.org/Pages/home.aspx

A relevant set of existing and upcoming standards for most common smart grid and mini-grid systems can be found in reports such as *SEGCG/M490/G_Smart Grid Set of Standards Version 4.*1 developed by the European Committee for Standardization, the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (CG-SEG, 2017).

Due to the rapid evolution of mini-grids and their variety of applications, standardisation is bound to lag behind. Because of this, many innovative players have developed in-house quality infrastructure schemes to compensate for the lack of up-to-date international and national standards. With time, these industry standards will form the base of new standards. Although industry and utilities have always been very influential in the development of standards and regulations, a shift towards more government and policy involvement is to be expected, due to the disruptive character of mini-grids. Gaps identified by specialists with operational, regulatory and academic involvement in mini-grids are presented in the following sections, along with recommendations.

Planning and design

Available standards

Few standards currently exist on the subject of planning and design. The most comprehensive ones are offered by:

- The Institute of Electrical and Electronics Engineers (IEEE) SCC21 (Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage), which sponsored the Working Group for the General Planning and Design of the Microgrid. This working group develops IEEE project 2030.9: Recommended Practice for the Planning and Design of the Microgrid.
- The IEC Technical Specification (TS) 62257 series, which includes a number of guidelines for small renewable energy and hybrid systems for rural electrification. The articles related to the planning and design functionality are parts 2-6 of the series (project management/implementation guidelines) (IEC, 2015).
- The IEC TS 62898 series, which contains guidelines for microgrid planning, specification and operation.

Gaps

- **Project planning**: One of the main planning issues expressed by interviewed project developers is the lack of (national) standards and associated regulations concerning environmental codes, end of life, franchise rights, transportation (*e.g.* transport safety standards) and other logistic aspects. Uncertainty concerning these issues affects the cost assessment capabilities of project developers.
- **Forecasting**: There is uncertainty regarding the reporting of predicted generation, load and system scalability. The international standards given above address some of the aforementioned aspects, but they require country-specific adaptations.
- **Terminology**: Difficulties arise in accurately describing of the goals and the equipment used for mini-grid deployment in terminology that is clear for all stakeholders.
- **Environmental, health and safety**: An aspect easily overlooked in the development of a mini-grid is the environmental, health and safety (EHS) risk. Mini-grids can cause chemical pollution (*e.g.* from battery leaks or disposal of photovoltaic [PV] panels) or prove hazardous if there is a lack of local codes and regulations protecting the environment and the end users.

Recommendations

- **Project planning and forecasting**: In order to limit upfront risk and thus enhance financing opportunities, project developers should be able to state the levels of service, the predicted generation, serviced load and the configuration they provide in a standardised manner.

  Specifying the level of service can also be done using the IEC TS 62257 series, the multi-tier framework developed by the World Bank and Sustainable Energy for All (SEforAll) (ESMAP, 2015), or the QAF developed and published by the United States Department of Energy's NREL along with the Clean Energy Ministerial and Power Africa (Baring-Gould, et al., 2016). The QAF provides a more nuanced framework regarding the levels of service as well as an accountability and reporting framework.

  The levels of service provided in a QAF can be defined by:

  - power quality (voltage sags/swells, frequency variations, harmonic distortion, ripple, switching noise)
  - power availability (power draw, available energy and duration of daily service)
  - power reliability (System Average Interruption Frequency Index, System Average Interruption Duration Index).

  Uncertainty in lower-tier systems will be reduced through the implementation of the QAF, as the consistency and inter-system learning will benefit developers. Making sure reporting is accurate by spelling out reporting requirements and clarifying verification process will structure the development process.

- **Terminology:** A mini-grid configuration is mainly determined by the generation equipment (including storage) and the distribution system (single or three phase, low/medium voltage, overhead/underground, alternating current [AC]/direct current [DC]). The goal of a mini-grid terminology and configuration standard would be to clearly and comprehensively detail the design and the associated generation and load servicing capabilities for all service tiers. This standard would also include operational and maintenance requirements.

- **EHS:** Planning for environmental and social factors decreases project risk, makes smooth project implementation more likely and ensures a sustainable project that will mesh well in the local community (USAID, 2018a). The requirements for EHS assessments may vary locally, but should minimally contain a land utilisation assessment, essential safety standards and a decommissioning plan. There are a (limited) number of national component safety standards (*e.g.* GB/T 34866-2017: Vanadium flow battery – Safety requirements), but there are very few system-level codes or standards bundling all EHS aspects into a set of documents. IEC TS 62257-3:2015 provides guidelines on the protection of the environment, recycling and decommissioning of rural electrification projects.

  A strategy could be to provide project developers with a questionnaire to quantify the impact throughout the phases of a project and how these risks could be addressed.

  "The annotated questionnaire: Environmental, health and safety risks" and "The tracking checklist: Environmental, health and safety impact management" developed by the US Agency for International Development (USAID) are examples of such assessment guides.

Power generation

Available standards

As described in Chapter 1, a renewable (hybrid) mini-grid can be powered by several (distributed) generation units. A set of standards exists for each of these generation units, describing safety, operation, maintenance, etc.

A detailed description of each possible generation unit would exceed the scope of this report. A list of standards with a small description for each of these units can be found in Appendix B. The INSPIRE database from IRENA provides a more comprehensive and in-depth overview.

Standards concerning the interconnection of generators and their control will be discussed in the section on the control, manage and measure (CMM) functionality.

Gaps

» **Adaptation to service level:** Although certain generators have well-developed national QI, their application in a mini-grid often lies outside the scope of existing regulations, standards and quality mechanisms, especially for lower-tier mini-grids. For example, for central ground-mounted PV plants, there are comprehensive standards and control mechanisms concerning mounting and racking of PV units (*e.g.* UL 2703). The IEC is also building a comprehensive set of international guidelines addressing mini-grid generation (*i.e.* IEC TS 62257). However, for lower-tier mini-grids, national or regional quality control mechanisms are rarely present, leading to increased mini-grid failure rates due to structural damage.

Recommendations

Writing dedicated power generation standards for mini-grid purposes might prove expensive and ineffective. Other options are:

» Inserting mini-grid-specific considerations in existing generator standards and referring to these standards in system-level standards.

» A mini-grid-specific guideline describing supplier selection (*e.g.* required certifications, warranty conditions), installation and inspection techniques of different generator types. Some articles in the IEC TS 62257 series address these aspects for rural electrification mini-grids (*e.g.* IEC TS 62257-9-5, 1, IEC TS 62257-7-1 and IEC TS 622571-13-1 and 2).

» Training developers, technicians and operators to detect and report suspected quality issues and substandard installations.

Storage

Available standards

Many standards concerning storage have already been published, covering a number of battery and other energy storage technologies. Note that there is a difference between standards describing individual battery aspects (*e.g.* the standards from IEC SC 21A) and standards describing the system aspects of energy storage (*e.g.* IEC TC 120, which focuses on grid-integrated electrical energy storage [EES] systems).

Once again the IEC TS 62257 series contains a number of energy storage guidelines (safety, installation EHS, etc.) for rural electrification (*e.g.* in IEC TS 62257-9-5, IEC TS 62257-8-1). Furthermore, IEC 61427-1 and 2 are notable as they focus on the on- and off-grid applications of secondary cells and batteries for renewable energy storage.

Gaps

» **Safety**: Despite existing standardisation efforts (at the time of writing, TC 120 is drafting IEC 62933-5-2: EES systems Part 5-2: Safety requirements for grid-integrated EES systems – electrochemical-based systems), there is still uncertainty from developers and end users about the presence of large-scale lithium-ion battery installations in densely populated sites (*e.g.* schools, hospitals) due to insufficient or unclear safety standards for new battery technologies. This limits their deployment and causes developers to fall back on gensets in these situations.

Recommendations

» Comprehensive storage standards require knowledge of safety issues and field experience. The role of QI should be to proactively provide codes of conduct and installation guidelines focused on safety and hazard management. An example of such guidelines is the Australian Clean Energy Council *Battery Installation Guidelines for Accredited Installers* (Clean Energy Council, 2017).

» Training of end users and operators about possible hazards and safety procedures in case of a thermal runaway situation may remove some of this uncertainty.

Control, manage and measure

Available standards

CMM involves many different components and technologies that vary greatly depending on the mini-grid. Manufacturers of different components often use a proprietary approach for their design, which limits the interoperability of a number of components.

In an attempt to provide relevant standards for each aspect of the CMM functionality, a subdivision is made into five sub-functionalities:

» control

» data communication

» metering and monitoring

» interoperability and interconnection

» protection.

Control

Controls are either short-term, which make sure the grid is stable, or long-term, which make strategic management decisions for the mini-grid (IRENA, 2016a).

Controls can be divided into three hierarchical components (Reilly, 2015):

» **Primary**: based on local measurements. It includes islanding detection, output control and power sharing.

» **Secondary**: controls central mini-grid operation, whether grid-connected or islanded.

» **Tertiary:** the highest level of control. Determines long-term and "optimal" set points based on the requirements of the host grid.

These controls are often combined in an energy management system and a power management system.

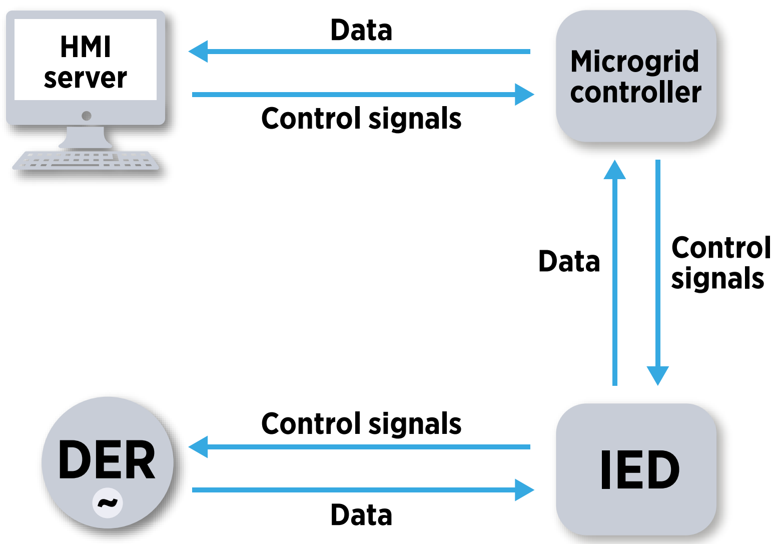
Standards relevant for mini-grid controllers are being developed, but gaps still exist. Examples of relevant standardisation efforts dealing with the aforementioned aspects are found in Appendix B.

Data communication

In the data communication process, sensors gather data that is then captured and sent to controllers. The controllers generate commands that are in turn transmitted to the actuators in the automated systems (IRENA, 2016a).

The data flow between mini-grid components is represented in Figure 22. Intelligent electronic devices (IEDs) receive power system data from distributed energy resources (DERs). This data is used in the mini-grid controller as a feedback signal. The controller subsequently sends reference values of voltage, frequency, active and reactive power, and control signals to the IEDs. These then provide control signals to the DERs and loads (Bani-Ahmed, et al., 2014).

Figure 23 Data flow between mini-grid components



Note: HMI = human machine interface.
Based On: (Bani-Ahmed, et al., 2014).

The set of standards deemed relevant for data communication purposes is determined by the communication technology, protocol, etc. Several standards can be found in Appendix B.

Metering

Next-generation energy meters do more than measure the energy consumption of end users. They possess functionalities that allow them to be used in demand-side management applications. Depending on the application and the payment methods, a variety of meters exists. The extended possibilities include power measurement and the opportunity to set a certain energy limit (IRENA, 2016a).

A large effort in standardisation is still required. Some of the relevant technical committees and standards that currently exist for metering and monitoring are described in Appendix B. The importance of standardised monitoring in mini-grids is further detailed in Section 2.6.

Example of smart metering in mini-grids: SparkMeter

The SparkMeter system consists of a base station and meters that communicate data to a cloud-based server. A dedicated software allows utilities or operators to monitor system operations and set controls for load limiting demand response and pricing from a distance. If needed, the base station can also be used to access the software on-site (no internet connection needed) (SparkMeter, 2019b).

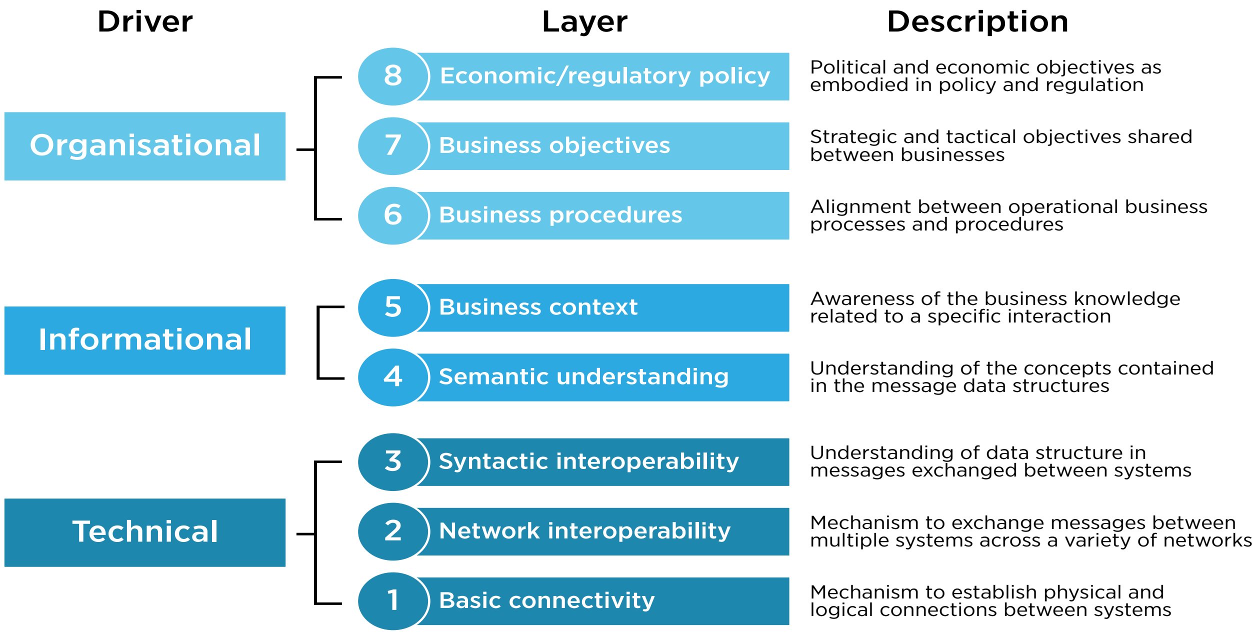
Interoperability

Interoperability is the ability of different components and pieces of equipment, from same or different manufacturers, to operate together in a controlled manner.

In a number of functionality standards previously proposed, interoperability has already been implemented (*e.g.* IEEE P2030.7 and IEEE P2030.8). However, interoperability is applicable on a number of levels and to a number of components. Currently, one of the main issues is the vendor lock-in on the main components of the entire mini-grid, making it complex to integrate multivendor solutions. Developers have expressed difficulties with adding PV and battery inverters supplied by the same company to production units on a plug-and-play basis, and making them communicate with other assets. For low-cost, remote off-grid systems, interviewed experts indicated that main components' being able to operate independently on a main busbar is adequate and often more cost-effective than trying to achieve interoperability.

The eight layers shown in Figure 23 demonstrate the various levels of interoperation that make various interactions and transactions in a mini-grid possible. This was initially developed for smart grids by the GridWise Architecture Council, but is equally applicable for mini-grids, depending on the level of complexity and communication required (NIST, 2014a).

Figure 23 Different layers of interoperability (NIST, 2014a)



Based On: (NIST, 2014a).

There are few systemic standards covering all of these aspects, but each of them should be integrated in the different aspects of a mini-grid. The SCC21 IEEE 2030 Smart Grid Interoperability Series of Standards provides a series of standards addressing some smart grid interoperability requirements that are directly relevant to the development of a mini-grid functional specification, particularly from the information and communication perspective (CIGRE, 2018).

Interconnection

Mini-grid interconnection refers to its ability to connect to a main grid in a point of common coupling (PCC). This could be for support services to the grid such as voltage and reactive power control or for economic benefits. This requires quality assurance to make sure the mini-grid fulfils the requirements of the main grid. QI also has to establish the framework within which interconnected mini-grids can work "off-grid" or in so-called (intentional) islanded mode. This is useful in a grid of low power quality or in the event of a natural disaster or grid disturbance.

Interconnection standards and regulations are dependent on the national grid code and the demands set by grid operators with respect to power quality and safety. There are a number of standards describing various aspects of grid interconnection of a local power generation source. For national grid code case studies and connection requirements, refer to the IRENA report "Scaling up variable renewable power: The role of grid codes" (Ackermann, et al., 2016).

Interconnection standards and codes in various countries

Europe

In Europe, the requirements for grid interconnection are partly covered by a region-wide regulatory framework, including some non-exhaustive requirements that have to be defined on a national level.
As this regulatory framework covers only a part of the identified standardisation needs, CENELEC developed the first standards in the **EN-50549 series** covering the **requirements for generating plants to be connected in parallel with distribution networks**. Publication of these documents is expected soon, as they were approved in July 2018. These standards are expected to promote a further alignment of the connection requirements among various European countries. Indeed, in the past, the requirements varied from country to country. As a result, in some nations, the DER and mini-grid installation costs are rather high.

The European Distributed Energy Resources Laboratories (DERlab), made up of testing facilities in 11 European countries (Austria, Bulgaria, Denmark, France, Germany, Greece, Italy, Poland, Spain, the Netherlands and the United Kingdom), are active in pre-standardisation activities regarding interconnection requirements of DER, among other DER-related topics. In some nations, such as Germany, clear interconnection schemes are present due to the enhanced deployment of distributed renewable generation.

Japan

Due to its location and seismic activity, the development of distributed generation and mini-grids in Japan is quite advanced. As a result, the regulatory and normative framework for their operation was implemented quite early. Japan generally has consistent technical requirements for grid connection nationwide. Three main regulations are adapted to microgrids:

- guideline on technical requirements for grid interconnection to ensure quality of electricity
- grid interconnection code
- harmonics restraint guideline.

United States

In the majority of states in the United States, **IEEE 1547 Standard for interconnecting distributed resources with electric power systems** has been adopted, referenced or used in some manner for the development of own interconnection standards. This national uniformity has enhanced the development a number of new distributed resource projects due to faster and easier interconnection processes. One of the first states to set a standard interconnection policy for distributed generation was California, which enacted Rule 21 for combined heat and power and other distributed generation systems up to 10 megawatts. All three major investor-owned utilities have adopted it as a model, and it meets the IEEE 1547 interconnection standard (ACEEE, 2018).

Traditionally, mini-grids were equipped with a single generation source, but with multiple renewable energy sources reaching maturity different topologies may emerge. This increases the importance of the way distributed generators interact with the distribution system, especially during outages. In an interconnected or grid-connected system, there are safety measures that have to be taken into account in the event of an outage. Grid operators demand that local power to the grid be turned off so the required repairs can be performed. This is called anti-islanding, meaning that it is not beneficial to have a local energised island in a non-energised grid situation.

For grid operators, unintentional islanding is something to be avoided as it can be hazardous to line workers who might assume the lines are not energised during a failure; it obstructs central control over power quality and can damage utility or customer equipment when reconnected. Intentional islanding would mean that the grid-connected mini-grid intentionally switches to an off-grid state and therefore does not feed the main grid and is also not subjected to power quality issues faced by the main grid. A significant barrier to the wideapread implementation of distributed generation has been utility companies' concerns about unintentional islanding. These concerns have largely been addressed through anti-islanding features in grid-interactive inverters and provisions in standards such as UL 1741, IEEE 1547 and IEC 62116 (Greacen, et al., 2013).

In the event that mini-grids are to be integrated into a central grid that is prone to reliability issues, it might be interesting to design the mini-grid interconnection such that it can operate in intentional island mode during failures and provide service to local consumers (uninterrupted revenue to mini-grid operators).

Examples of relevant standards for interconnection and interoperability are included in Appendix B.

Protection

The protection design of mini-grids strongly depends on the type of mini-grid and the operational mode of the mini-grid (islanded, interconnected or transition between modes). The protection designs that are commonly used in traditional networks, whether distribution or residential, are generally speaking not sufficient to meet the requirements of mini-grid internal protections. Mini-grids that can transition between islanded and grid-connected mode in particular have to pay special attention to mini-grid protections. For these types of mini-grids, protection-setting values have to be reconfigured, as power flow, neutral earthing, short-circuit current values, etc. will alter upon transition. There are few standards, specifications and guidelines available or under development:

- The IEEE P2030.12 – Guide for the Design of Microgrid Systems is an active project that will cover the design and selection of protective devices and the co-ordination among them for various modes of operation of a mini-grid. These include grid-connected and islanded modes and transitions between modes (IEEE, 2018b).
- The design of mini-grid protections is also mentioned in the technical specification IEC TS 62898-1:2017: Microgrids – Part 1: Guidelines for Microgrid Projects Planning and Specification (IEC, 2017a).
- For rural electrification projects, the technical specification IEC TS 62257-5:2015: Recommendations for Renewable Energy and Hybrid Systems for Rural Electrification – Part 5: Protection against Electrical Hazards, can be consulted (IEC, 2015).

Gaps

- **Data communication**: The incompatibility of communication protocols is an issue faced by a number of developers and manufacturers who are active in the conversion of existing diesel mini-grids to fully or partly renewable mini-grids. These protocols need constant updating as assets evolve. At the same time, existing assets need to remain compatible with new ones.
  - **Metering**: Further standardisation efforts are required, especially for metering in DC mini-grids. The accuracy of consumption metering in DC mode has to be exactly right when a utility looks to charge and bill customers.
  - **Grid extension:** In certain regions there is a lack of national standards, codes and regulations concerning the possible integration of mini-grids into a larger grid in the event of a grid extension. The resulting uncertainty discourages future investments. The integration of a mini-grid often causes technical difficulties due to discrepancies in design standards. In some cases, custom metering and billing systems will have to be replaced and fitted to national standards. An ideal situation is one in which a previously autonomous mini-grid uses the grid as "battery" (net metering), but national regulations and tariffs have to be put in place to enable this interconnection scheme.
  - **Distribution systems:** In certain regions the regulations imposed for distribution system operators (DSOs) and transmission system operators (TSOs) may be too strict to include smaller (autonomous) systems, and consequently provide too much of a cost barrier.

    Furthermore, in Europe, DSOs and TSOs have expressed **discrepancies in regulatory responsibilities** between themselves and equipment manufacturers. A DSO is considered an operator and could thus be considered responsible for the performance of a mini-grid system authorised to connect to the grid, while responsibility for mass-market equipment compliance rests on equipment manufacturers. DSOs demand a harmonisation of norms for grid operators and equipment manufacturers, in which equipment performance in a system should be the responsibility of the manufacturer.
  - **Protections:** For DC mini-grids particularly, there is a rather large need for protection standards and overall design guidelines and standards. More on this in Section 4.2. For AC mini-grids there is still a need for comprehensive documents that can assist equipment vendors, utilities, microgrid developers and owners to specify and configure protection systems for mini-grids of all types.

Recommendations

- **Data communication**: Current communication protocols and standards should be drafted with future evolution of assets in mind so mini-grids can easily be expanded when needed.
- **Metering**: International metering standards for DC energy are being drafted (*i.e.* IEC 62053-41 Electricity Metering Equipment [DC Direct Current] – Particular Requirements – Part 41 – Static Meter for Active Energy [Class 0.5 and 1]). Metering standards will see an enhanced development with the roll-out of more commercial DC mini-grids.
- **Grid extension:** The prime focus of standards and regulations regarding grid interconnection will have to be the assurance of a return on investment in the case of a grid extension. There are a number of ways of doing so; in Sri Lanka, off-grid electrification was implemented in places that the utility said could not be reached by the grid within at least the next five years (Sarangi, et al., 2015). Concession systems, such as the PERMER programme in Argentina, grants investors the exclusive rights to undertake off-grid electrification (Best, 2011).

Other examples of grid extension policies can be found in India and the United Republic of Tanzania, where the utility can buy either the energy or the entire system for a negotiated rate. In Indonesia, the current law states that, a licensed private power utility can have exclusivity in a region the national utility (PLN) does not serve and sell electricity to customers at negotiated rates. These markets are still in fairly early stages of project development, so there are few, if any, examples of how and how often this process will play out (Bhattacharyya & Palit, 2016).

- **Distribution systems:** There should be a discrepancy between the regulations and standards imposed by the grid regulator for the public grid and those imposed for mini-grids with regard to electricity distribution. In certain cases it is useful to require mini-grids to comply with grid regulations concerning factors such as power quality. This is primarily the case in more developed markets, as mini-grid operators have to take into account limitations of the appliances/equipment connected to the mini-grid. Note that standards regarding the safety of all stakeholders (end users, installers and maintenance personnel) should be maintained in any case (IFC, 2016).
- **Protections:** International best practices about mini-grid protection and fault analysis should be included in regional and national design guidelines and adapted to the local circumstances. Depending on the type of mini-grid deployment in the region, one of the aforementioned international documents can be used as reference. For more information on DC mini-grid protection issues, refer to Section 4.2.

Conversion

Available standards

The relevant standards related to grid interconnection are given in the interconnection functionality above. Other technical committees and standards relevant for energy conversion within a micro-grid are described in Appendix B.

Gaps

- Depending on the source of generation, complexity, power and required resiliency of the system, the requirements for conversion technologies may differ, making it difficult to establish comprehensive standards.

Recommendations

- Guidelines describing mini-grid-specific converter requirements should be defined. Based on their experience with mini-grid projects, such as the advanced mini-grid system at US Marine Corps Air Station Miramar, NREL has created a fact sheet with upfront considerations to be added to a request for proposal that will help ensure that PV systems are built for future mini-grid connection (NREL, 2017). This contains a set of requirements for inverters such as the capability to curtail PV output via control set point(s) if PV generation needs to be reduced in order to help balance generation and load in a mini-grid. Inverters also have the capability to "ride through" frequent minor disturbances, log real-time data, report alarms, etc.

Consumption

Available standards

Energy consumption is often overlooked as an active element in energy systems. Renewable mini-grids are mostly small energy systems in which the delicate balance between consumption and generation is hard to maintain due to its variable behaviour. Previously, energy storage equipment was discussed as a means to balance this variability, but load management also plays an important role in the energy balance of mini-grids. The standards that are relevant to load management and end-user safety are mentioned in Appendix B.

Gaps

- **Household wiring**: Since a significant portion of currently developed mini-grids are situated in areas that were not planned for electrification, attention has to be given to customer safety issues. In many cases, houses are not in accordance with fire safety standards, creating dangerous situations in case of short circuits or faulty wiring. As is the case in certain electrification projects, mini-grid developers and operators are also responsible for the wiring services, so guidelines must be set in place to ensure safety (Danley, 2017).

Recommendations

- **Wiring management and maintance:** In most basic residential installations, a prewired electrical panel (ready board) will suffice. If this is not an option, licensing systems could require that only certified technicians may install, perform maintenance and inspect installations. A utility could also provide the wiring services for an additional fee on top of the interconnection charge or provide plans, materials and inspections to ensure uniform, safe and reliable installations and maintenance (Danley, 2017).

Although in most countries, an abundance of household wiring standards exist, it may be beneficial to bundle these in a comprehensive standard for low-tier mini-grid applications.

A summary of the standardisation needs is illustrated in Figure 24. A significant takeaway is that major standardisation work is mainly oriented to each functionality or sub-technology (*e.g.* standards for batteries or solar PV panels), and not to the overall mini-grid system. Further efforts are needed to elaborate standards at a mini-grid system level. To achieve this, current gaps in each one of the mini-grid's functionalities have to be fulfilled, and Figure 24 gives initial recommendations on how to alleviate these standardisation gaps.

Figure 24 Standardisation gaps and recommendations by mini-grid functionality

Functionality	Gaps	Recommendations
Planning and Design	Lack of standardised project planning and forecasting	Framework to specify the level of service, predicted load/generation and configuration
	Lack of uniform or mini-grid adapted terminology	Mini-grid terminology/configuration standard for all service tiers
	EHS regulations and standards required, especially for lower tier mini-grids	Standardised EHS procedure containing a land utilization assessment, essential safety standards and a decommissioning plan
Storage	Insufficient or unclear safety standards for new battery technologies	Provide codes of conduct and installation guidelines with a focus on end-user safety and hazards
CMM	Incompatibility of communication protocols	Standardised communication protocols facilitating mini-grid extensions
	A lack of national standards, codes and regulations concerning the possible integration of mini-grids in a larger grid	Grid extension QI has to assure a return on investment in the case of a grid extension. Several schemes are possible
	Grid regulations not adapted to mini-grid service levels	Grid regulations and standardisation adapted to operational demand of the end users.
	Discrepancies in regulatory responsibilities between grid operators and mini-grid suppliers	
	Lack of standards regarding DC network protection	Provide frame and guidelines regarding mini-grids protection scheme
Conversion	Unclear conversion requirements for mini-grids	Guidelines stating conversion requirements depending on the level of service
Consumption	Household wiring safety aspects for low-tier mini-grids in electrification efforts	Prewired panels or certified personnel to assure safe installation of wiring and circuit breakers

System-level standards

A system-level standard is a document or set of documents which comprehensively describes the development and/or operation of a renewable mini-grid in its totality. Evidently these standards refer to other aspects such as safety, design and operation standards, but by bundling these in a single set of documents, the complexity of quality assurance for a mini-grid drastically decreases.

Examples of such efforts are:

- **Subcommitee 8B of TC 8, Decentralized Electrical Energy Systems,** seeks to bundle a lot of the aspects mentioned above:

"It provides standards (guidelines) enabling the development of secure, reliable and cost-effective systems with decentralized management for electrical energy supply, alternative/complement/precursor to traditional large interconnected and highly centralized systems" (IEC, 2020b).

- The **IEC 62257** series aims to do the same for rural electrification purposes by providing guidelines describing the development process from inception through decommissioning, while focusing on quality.

Some other standards/technical specifications which offer a more systemic overview are described in Appendix B.

General recommendation

- **Regulation of mini-grids based on system size and demand requirements**: Requirements concerning the regulations and standardisation of mini-grids should be assessed by looking at the operational demand of the end users. In doing so, cost barriers due to overregulation or overly strict regulations for small (autonomous) systems can be prevented. Standardisation remains key in these systems as small-scale (lower-tier) mini-grids can be profitable only with economies of scale. In order to obtain scalable systems, they have to be designed according to some sort of standard and be subject to consistent regulation. The adjustment of standards should focus on the system voltage and power handling capabilities. This means that low voltage systems may be subject to less formal requirements, but minimum requirements regarding safety, grounding, clearances and insulation should remain (*e.g.* IEC 62257-9) (IFC, 2016). Guidelines made available by the National Association of Regulatory Utility Commissioners can be used as a reference for the development and implementation of national mini-grid standards (Meister Consultants Group, Inc., 2017).

National and regional standards

The previous section primarily focused on international standards. As detailed above, there are also national and regional efforts to standardise various aspects of mini-grids. A few examples of these efforts are detailed in Appendix C.

Technical regulations

Technical regulations define minimum conditions to allow, for example, the connection of a mini-grid to the utility grid. Therefore, they must be taken into account at all stages of mini-grid deployment, from planning to construction and dismantling. The compliance with technical regulations will mainly be controlled during the commissioning phase, before permission to connect to the main grid is given.

These technical regulations are crucial in the development of the mini-grid sector. They determine the legal framework to ensure quality on a component and system level, but must avoid becoming a barrier instead. The IEC TC 82, photovoltaic off-grid systems, including decentralised rural electrification and hybrid systems Working Group JWG1 has expressed the intent to arrange and adjust standards to the tiers of service defined by the World Bank in its "Multi-tier framework for measuring household electricity access" This would clarify at which point in the mini-grid market development certain regulations should be put in place.

Technical regulations and regulatory instances in developed markets

European Union

In certain cases, regulatory framework is not provided nationally but on a regional level. This is, for example, the case in the European Union, where EUR-Lex is the official journal giving access to European Union legislative documents. When a mini-grid is to be connected to the main grid, the most relevant regulations are the EUR-Lex Commission Regulation 2016/631 concerning the connection of diverse generators to the grid and 2016/1388 concerning the connection of demand units or distribution systems, including closed distribution systems.

United States

For technical regulations concerning renewable energy grid connections in the US, refer to "U.S. laws and regulations for renewable energy grid interconnections" published by NREL. It offers an overview of the stakeholders and the institutional framework under which interconnection policies are established and implemented in the United States (Chernyakhovskiy, et al., 2016).

Regulatory instances operating in markets where mini-grids for rural electrification are rapidly increasing

India

Through the Central Electricity Regulatory Commission, the Central Electricity Authority and each of the State Electricity Regulatory Commissions, a set of regulations were put in place to ease the deployment of mini-grids and provide sufficient quality infrastructure for customer protection and safety. They provide clarity concerning tariffs, quality of supply and interconnection, although uncertainty among developers still exists with regard to the long-term perspective in the case of *e.g.* a grid extension. There's an increasing interest in DC mini-grids and appliances, and regulatory efforts are being made, but interconnection remains an issue.

Nigeria

The Nigerian Electricity Regulatory Commission has provided a number of technical regulations based on IEC standards ensuring quality and protecting consumers. Efforts are still required to ensure that these standards and regulations are well communicated among the different parties to make sure all equipment fulfils the required norms. Experience in the field has proven that quality issues have caused a certain degree of consumer mistrust in the past, so information-sharing policies are crucial.

2.3 Mini-grid testing

Once standards cover the relevant requirements to ensure safe and reliable operation of a mini-grid system, the conformity of the different mini-grid components (PV inverter, battery inverter, protection equipment, etc.) should be tested, as well as the entire system. For technologies with well-developed QI, this testing is generally done in accredited laboratories. A physical testing process is established to determine the operation of an element or system compared with the standards requirements. For a mini-grid, however, testing the whole system requires a well-developed testing infrastructure and sufficient funding, and may sometimes not be possible with conventional physical testing infrastructures. The focus in this section is on system testing rather than the individual components, as these have largely been discussed (see *Boosting Solar PV Markets: The Role of Quality Infrastructure* (IRENA, 2017c)).

Testing methods

Today, mini-grid system-level testing is often done through physical tests during system building and commissioning or in expensive mini-grid test labs. For less advanced mini-grids, with smaller budgets, control integration and system physical tests are mostly performed only at the end of mini-grid deployment. This results in a higher risk perception by stakeholders. More flexible and cost-effective testing methods will reduce this risk perception.

A testing practice that has been used in the automotive and aerospace industries for quite a while is the hardware-in-the-loop (HIL) simulation (Lampert et al., 2017). This method allows testing of the control functionality of a mini-grid without having to construct the complete mini-grid, thereby limiting the cost of the testing process and facilitating easy adjustments. The controller is identical to the one in the actual mini-grid but (some of) the mini-grid hardware is simulated based on information from existing mini-grid projects, such as load and generation profiles. HIL simulation is able to add the complexity of the whole system to the test platform with a limited number of hardware components, and standardised test sequences can help to thoroughly test all edge cases. HIL simulations are divided into two types: control HIL (CHIL) and power HIL (PHIL). CHIL interfaces a simulator with the control device undergoing testing and exchanges signals at low voltage, while PHIL interfaces the simulator to power devices in order to simulate variations in load and generation at actual power. Only a handful of HIL test facilities currently exist, due to the high degree of complexity and skill required to operate them (Limpaecher, et al., 2017).

Testing standards

With regard to controller and system testing, standardisation efforts are ongoing; some relevant standards concerning general testing requirements are described in Appendix D.

Gaps

The main barriers for test implementation are costs of establishing testing facilities, dealing with varying operational circumstances and the unique characteristics of each system.

Recommendations

The main goal of mini-grid testing should be to facilitate a mini-grid system that can easily and safely be repeated in varying circumstances. Standardised testing procedures that allow mini-grid CMM equipment to be tested in varying circumstances and in different (simulated) configurations are key to do this. There are a number of active mini-grid test beds evaluating various aspects of mini-grids in Asia, Australia, Europe and the United States. In Section 4.1, another prominent mini-grid testing facility from China is discussed.

Examples of prominent testing facilities around the globe

Asia

- Nanjing University of Aeronautics and Astronautics microgrid test bed – China
- Test microgrid at the Institution of Engineering and Technology – India
- Experimental Power Grid Centre – Singapore.

Australia

- Microgrid test bed of Queensland University of Technology – Australia.

Europe

Other relevant laboratories for mini-grid testing associated with the DERlab active in research and pre-standardisation are:

- Fraunhofer Institute for Wind Energy and Energy System Technology – Germany
- Institute of Communication and Computer Systems at the National Technical University of Athens – Greece
- Centre for Renewable Energy Sources and Saving – Greece
- Institute for Energy & Environment at the University of Strathclyde in Glasgow – Scotland
- KEMA microgrid laboratory in Arnheim – Netherlands.

United States: Energy Systems Integration Facility

In the Energy Systems Integration Facility (ESIF) test bed of NREL, manufacturers and integrators can do a preliminary run-through of their technology or configuration at actual power before it is implemented.

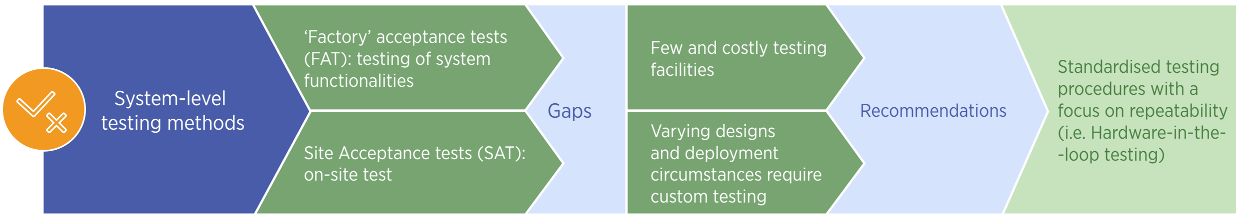
The testing done in the NREL ESIF testing facility and several others includes:

» Pre-certification testing according to IEEE 1547, *e.g.* mandated power disconnection tests using grid simulators. The mini-grid is configured as a whole at the PCC to comply with IEEE 1547, with relaxed inverter settings within the mini-grid to avoid nuisance shutdowns.

» Testing according to IEEE 2030 to assess islanding (intentionally/unintentionally), reconnection to the utility (re-synchronisation of voltage, frequency and phase), and grid support when grid tied.

Economic operations: peak demand shaving, power factor improvement, dispatch of battery storage, etc.

Figure 25 Summary of gaps and recommendations: Testing



Mini-grids on islands
Image credit: Shutterstock

2.4 Licensing

A mini-grid's quality of operation depends on the quality of its components and design, but also on its installation and maintenance. In many countries, installers must be licensed to install equipment such as PV, and consumers cannot benefit from governmental subsidies if they have no certificate from a licensed or certified installer. This is needed for mini-grids as well, to ensure quality is respected and security is guaranteed. Training of local installers and service technicians, whether to obtain a certification or not, is also deemed critical in the deployment of mini-grids for rural electrification.

Installer certifications

European Union

The installer certification database of the Renewable Energy System Schemes of the EU (RESEU) offers a collection of certification schemes in place for the different European Union member states. These certifications are required for small-scale renewable energy installers to operate in countries across Europe and are applicable for many of the mini-grid components (RESEU, 2018).

United States

- The International Brotherhood of Electrical Workers and the National Electrical Contractors Association offer a training and certification programme called the Energy Storage and Microgrid Training and Certification programme (ESAM-TAC) supported by the National Science Foundation. This training programme will be certified through the Electric Power Research Institute (Riley & Kotlier, 2017).

- The North American Board of Certified Energy Practitioners offers a Solar PV Installer Certification. Solar Energy International offers training in preparation for this certification called "Solar training-advanced PV multimode and microgrid design (battery-based)", which focuses on stand-alone battery/PV mini-grid installation and design (Solar Energy International, 2018).

Installer licences

United Republic of Tanzania

According to the new Electricity (Electrical Installation Services) Rules, any person who conducts electrical installation activity must apply to the Energy and Water Utilities Regulatory Authority (EWURA) for a licence. This applies to the installation and servicing of essential equipment of mini-grids as well. For secondary appliances such as light bulbs and switches, a licence is not required (Mini-grids Information Portal, 2018).

Installer qualifications

Nigeria: Clean energy qualifications

The Nigerian Energy Support Programme introduced a set of relevant qualifications for people working in renewable energy. This consists of seven qualifications with curricula developed by practitioners and international experts to comply with relevant competency standards (updated in 2020). To ensure quality, a nationwide certification is being introduced. From 2018 an independent third party conducted examinations of trainees and qualified professionals against relevant competency standards and market needs. The clean energy qualifications include:

- solar PV installation (technicians)
- solar PV installation supervision (electricians)
- mini-grid design (engineers)
- rural hydropower civil engineering (engineers)
- energy management (engineers)
- energy audit (engineers)
- energy-efficient building design (engineers).

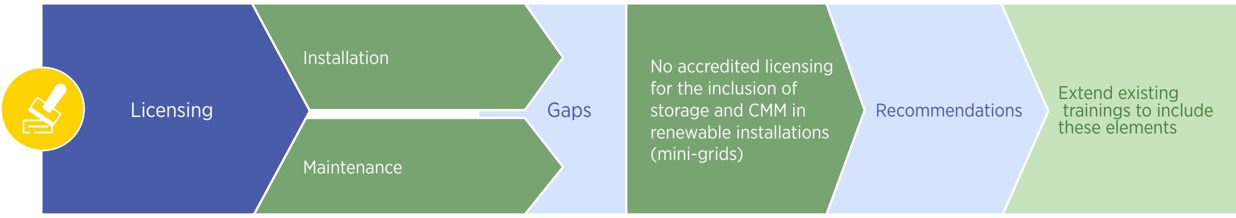
Gaps

There are no accredited certification bodies for mini-grid installers (and operators) yet, as there are for PV installations and other renewable energy resources, mainly due to the absence of relevant standards.

Recommendations

Where licensing requirements for *e.g.* PV installers already exist, the extension of existing licence training to include storage and system control could be a solution. Certain organisations already offer training and (non-accredited) certifications to mini-grid installers and operators, focusing on storage and control.

Figure 26 Summary of gaps and recommendations: Licensing



2.5 Accreditation and certification processes

Certification is the independent and impartial evaluation performed by certain conformity assessment bodies by means of a set of generally recognised standards. This means that groups performing tests, doing calibrations, providing certifications and performing inspections according to a certain standard have to be accredited by an accreditation body or registered by an international conformity assessment system based on peer assessment. As such, there is impartial and expert supervision assuring the conformity and correctness of the activities performed by said bodies. The standards by which accreditation bodies are evaluated are listed in Appendix B (IRENA, 2015a).

ISO/IEC definition of accreditation

"Accreditation refers to third-party attestation related to a conformity assessment body conveying formal demonstration of its competence to carry out specific conformity assessment tasks" (ISO, 2017).

One of the main national actors in the accreditation process is the national accreditation board (NAB), an institution securing the independence of accreditation decisions. NABs are private entities that work with governments, operating within a legally determined framework. Although this doesn't exist in certain countries it is definitely desired. In developing economies, interviewed experts have identified this as a gap in QI.

There is a form of evaluation hierarchy associated with these different QI activities, as illustrated in Figure 27. For a mini-grid these activities can be seen on a component level (generators, storage, control, etc.), but also on a system level, when considering the installation and operation of several components in a system.

Figure 27: QI evaluation hierarchy

Accreditation is related to bodies such as laboratories or conformity assessment bodies, while certification concerns the product or system itself. Certification formally asserts that an organisation's product, service and management system, or a person's competence, meets a standard's requirements (IRENA, 2015a).

Due to the perception of uncertainty associated with mini-grids in the early market stage and the relatively limited QI currently in place, it is essential that components and services be certified. The certification of products has proven to lower the market barrier for suppliers and installers.

The certification processes of components are realised by several conformity assessment bodies. A list of the certification bodies relevant in the mini-grid field can be found in Appendix E (IRENA, 2015a).

A quality management system (QMS) is a formalised system that documents several aspects in the assurance of quality objectives. It aids in meeting customer and regulatory requirements and improving effectiveness and efficiency. Standard ISO 9000:2015 is usually used in the general approach to establishing a QMS. For mini-grids, system requirements often specify a certain quality of the power delivered. In this regard, a certified power QMS can reduce upfront uncertainty (Fullelove, 2017).

A quality management system according to ISO 9000:2015

"QMS is a collection of business processes focused on consistently meeting customer requirements and enhancing their satisfaction. It is aligned with an organisation's purpose and strategic direction" (ISO, 2015).

Listed components

In addition to proof of certification, a mini-grid component can also be listed or rated, meaning that the component in question has displayed an acceptable level of quality for independent certified laboratories that are acceptable to the authority with jurisdiction in the area.

Another example of identification of (limited) product quality is the European conformity marking. This marking indicates that the quality has not been ensured by an outside agency, but that the manufacturer declares that the product meets the requirements detailed in relevant European health, safety and environmental protection legislation.

A list detailing several examples of institutions that are active in certification and listing of mini-grid components can be found in Appendix E.

Relevant mini-grid component certifications

UL 1741

There is not yet a system-level mini-grid certification, but there are a number of component-level certificates. An important one for the role of mini-grids in the future electricity market is the compliance certificate for advanced utility interactive inverters. There are several institutions that issue such a certificate, depending on the regionally relevant standards. An example of such a certification programme is the **UL 1741 Supplement A Advanced Inverter Testing and Certification programme**.

Some of the minimum testing requirements stated in UL 1741 SA (UL, 2017b) concern:

- anti-islanding
- low/high-voltage ride-through
- low/high-frequency ride-through
- must trip test
- ramp rate (normal and soft-start)
- specified power factor
- volt/var mode
- frequency watt
- volt watt.

Advanced inverter certification will allow policy makers to include quality requirements in regulations facilitating (smart) grid support function by mini-grids and DERs. These advanced functions provide:

- elaborate monitoring and communication of grid status
- set point and other operation instructions from a centralised location
- "smart" decision-making to support grid stability and power quality, and provide ancillary services.

IECRE

The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System) seeks to further international trade in the equipment and services used in renewable energy sectors while ensuring required safety levels. While the focus of certification, testing and inspection bodies is currently on the marine, solar PV and wind energy sectors and not mini-grids themselves, the certifications apply to the generation and conversion functionalities described in Chapter 1. The applicability of the certification for mini-grid PV power plants, for example, is specifically mentioned in the "Rules of procedure for the certification of photovoltaic systems according to the IECRE-PV schemes" (IECRE, 2016). Such a global certification system or a global quality management standard could be the next step in international QI.

A national QMS, based on certificates or conformity markings, is important when importing electrotechnical components for use in mini-grids. This does not mean that imports should be (re)tested; however, there should be a clear policy on import quality (Chapter 5) and a management system to manage import certification and conformity to quality standards.

2.6 Inspection and monitoring

Inspection in a QI usually refers to the inspection of components and/or processes to ensure they comply with standards and technical regulations.

Inspection according to ISO/IEC 17000

"Inspection is the examination of a product, process, service or installation or their design and determination of its conformity with specific requirements or, on the basis of professional judgment, with general requirements" (ISO, 2004).

Defining procedures for the monitoring and reporting of the operation of technical elements is an essential step in the quality evaluation of a mini-grid. Expert opinions show that the lack of a standardised monitoring process for mini-grids is often one of the major impediments in the improvement of system operation. Due to the varying working conditions and system requirements, data acquisition and analysis are not only useful to troubleshoot problems, but also to evaluate overall performance, reliability and quality of the system. This can subsequently be used to improve the system design and to instil a certain level of confidence in investors and end users of similar projects.

Monitoring devices include dedicated power quality monitors, revenue meters with power quality functionality, statistical survey/compliance monitors and system protection relays.

Once these devices are set up, the monitoring process can start. This consists of four main stages (Baring-Gould, et al., 2016):

» **Data acquisition**: combining hand-recorded specific values and an automated data acquisition system, this is likely to include local data storage; more on this in Section 2.7

» **Data summation**: raw plant data collected are analysed and summarised and depending on the stakeholder needs, the reporting requirement should be adapted.

» **Summary information**: information about the system's operation can be relayed to the stakeholders.

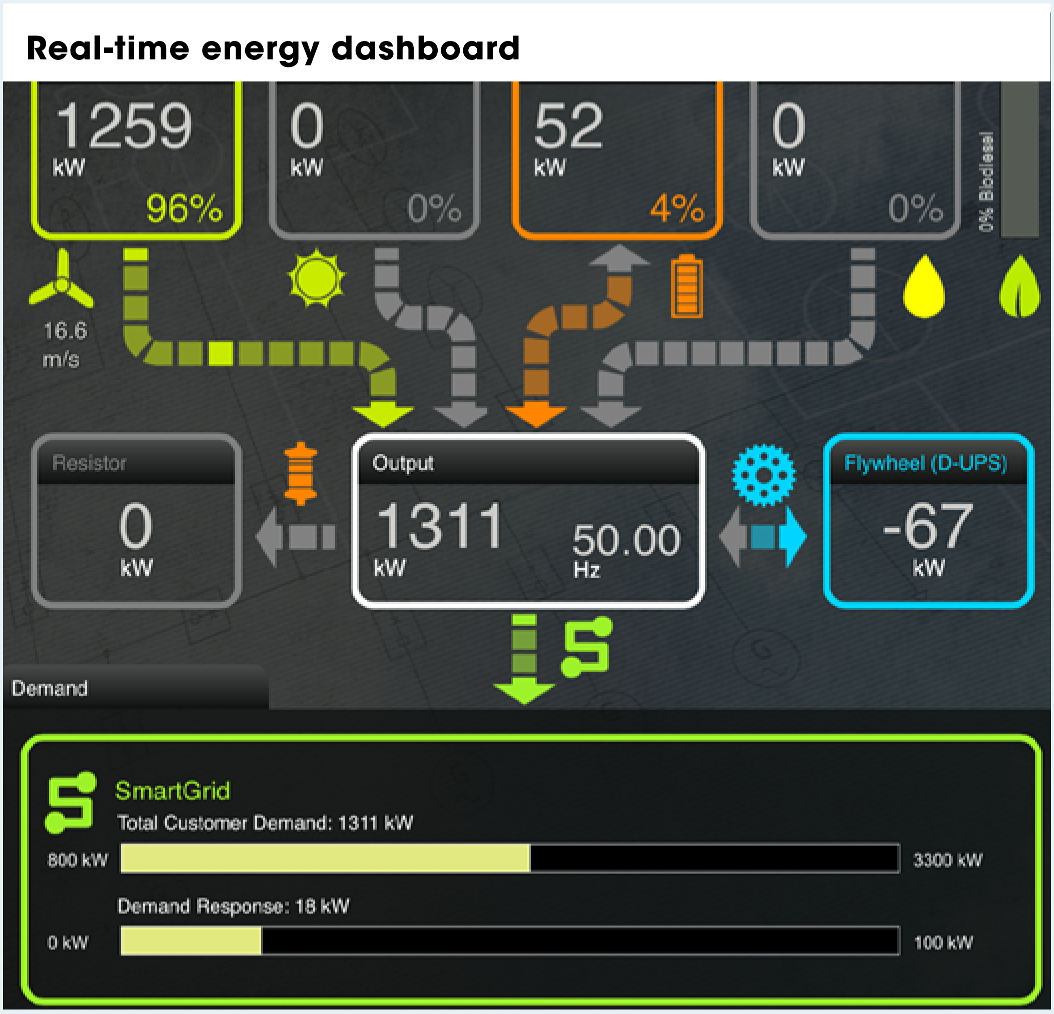
» **Aggregation of data**: for multiple sites, for example, expanded analysis is performed.

Mini-grid monitoring

Hydro Tasmania

On King Island in Tasmania, Australia, Hydro Tasmania has aided in the transition from a diesel to renewable-based electricity system, in which 65% of the current electricity need is delivered by renewables. To enable this high degree of renewable energy, the utility monitors customer energy use and generation in real time using smart meters with switching capability. This allows for the control of a number of interruptible loads in participating homes and businesses. It also provides the end users and parties of interest an overview of the system performance and the contribution of renewables, enabling technologies, etc. This was partly initiated by the Australian Renewable Energy Agency to instil goodwill and have a clear overview of operational issues.

Figure 28 Real-time energy monitor



Notes: kW = kilowatt; Hz = hertz; D-UPS = diesel uninterruptible power supply.
Source: (Hydro Tasmania, 2019).

2.7 Metrology

The previously discussed QI-elements (standardisation, testing, certification and accreditation) all depend on accurate measurements and data, so it is crucial to properly define metrology requirements.

Metrology has a scientific, industrial and legal aspect:

- scientific: defines proper measurements units
- industrial: uses calibration to validate tests and industry measurements
- legal: uses verification to provide accurate measurements (IRENA, 2015a).

Metrological and calibration activities are typically performed by a country's national metrology institute (NMI). The formation of guidelines leads to an easy interaction among power supply companies, testing laboratories and research offices, which subsequently facilitates commercial collaboration. New standards can then be established, resulting from a collaboration of all the stakeholders. The main function of metrological and calibration bodies is to provide impartiality and integrity in measurements.

The European Association of National Metrology Institutes offers metrology development support through NMIs and co-ordinates European metrology research. Its projects include research aimed at providing accurate and traceable measurements to control the additional demands of future power grids. This research is mainly motivated by the need for an accurate understanding of a mini-grid operation at any point, which is often quite complex due to the number of distributed resources and two-way energy flows. An approach to solve this problem is the integration of micro phasor measurement units, which are able to measure the state throughout the entire system, providing an actual overview of the mini-grid operation. The synchrophasor measurement data gathered by these units can be used for faster control of components, and to optimise grid synchronisation, identify anomalies and monitor stability.

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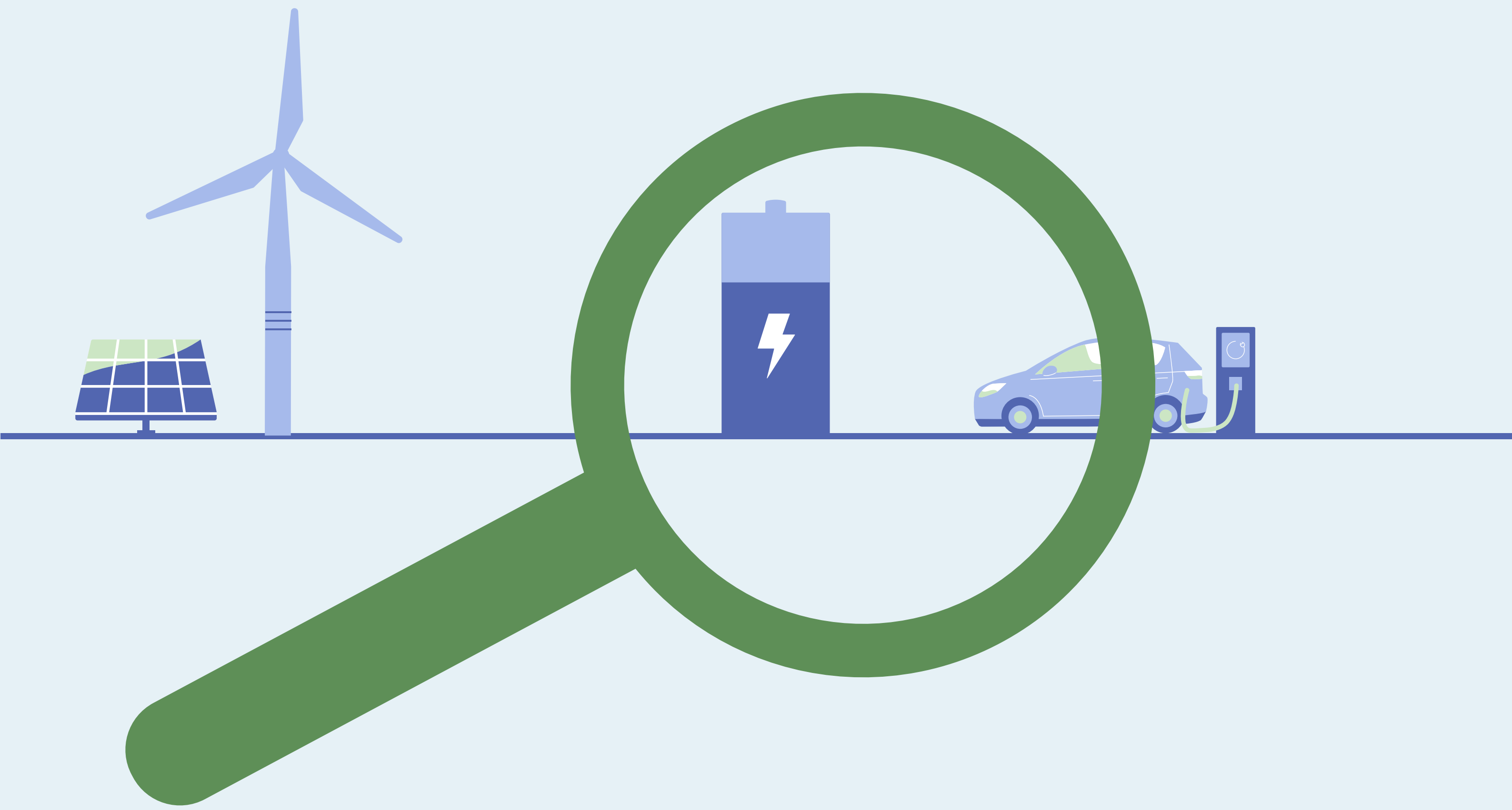


3. IMPACT OF QUALITY INFRASTRUCTURE IN RENEWABLE MINI-GRIDS: CASE STUDIES, COSTS AND BENEFITS

Chapter 3 illustrates the importance of quality infrastructure (QI) in the deployment and operation of various mini-grids around the world.

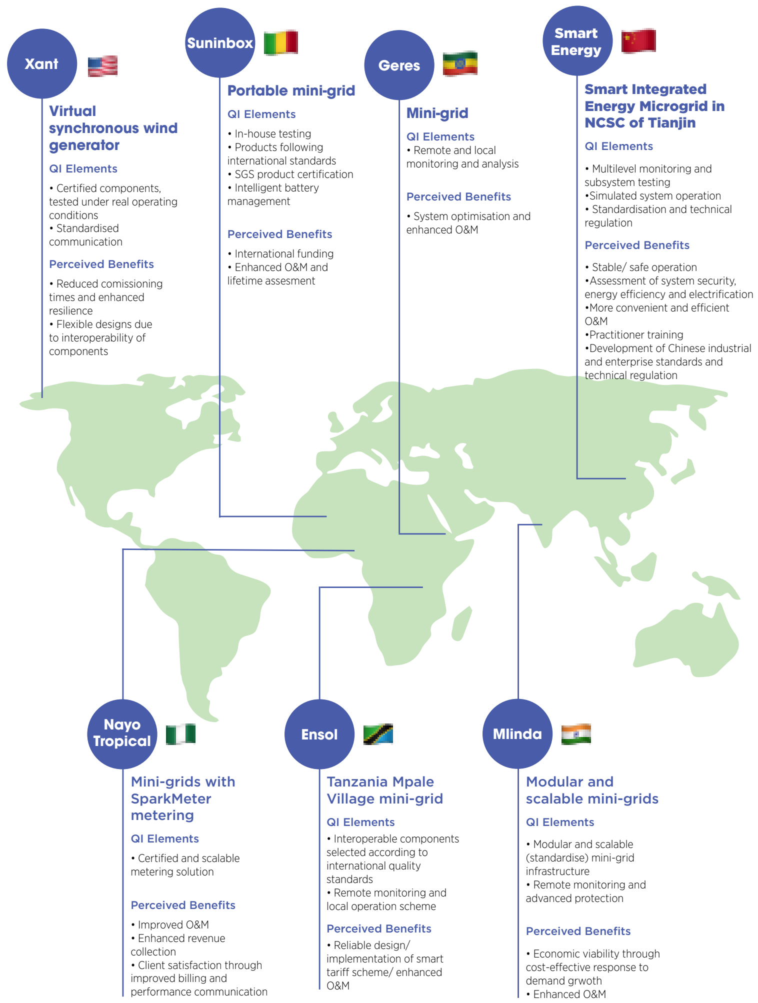
Key information in this chapter:

» real applications of quality elements in mini-grids

» benefits of quality infrastructure.

In each of the case studies the stakeholder indicated that the presence of QI elements (*e.g.* standards, testing, monitoring and technical regulation) has proven to increase the quality of the installation leading to benefits for mini-grid developers, operators and end users.

Figure 29 Summary of the mini-grid cases with QI elements and perceived benefits



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.1 India: Mlinda modular and scalable mini-grids

Context

Gumla, a rural district of Jharkhand state in India, is one of the poorest in the country with most of the population falling in the lowest 20% by wealth based on the National Family Health Survey framework. The villages there depended on kerosene for lighting and charging services for devices such as mobile phones, spending significant portions of their income for these basics. For farming, they used fossil fuels, which were not only polluting, but emitted poor-quality light, affecting education and economic activities. The community has now transitioned to solar PV-based mini-grids commissioned by the organisation Mlinda. These systems are ground mounted, with a distribution network and smart prepaid metering. They provide power for domestic, productive and commercial needs.

Mini-grid technical details

The mini-grid supplies alternating current (AC) power, single-phase 230 volts at 50 hertz and three-phase 415 volts for domestic, commercial and productive loads generated by 30 kilovolt ampere (kVA) inverters. Energy storage is through lead acid gel batteries (see Figure 30). A diesel gen-set is provided for peak load management and as a back-up. The Mlinda mini-grids range from 20 kilowatts peak (kWp) to 30 kWp in size.

Figure 30 Battery bank and maximum power point tracker (MPPT) in Phori village

Source: (Mlinda, 2018).

Quality infrastructure elements

1. Standardisation in plant modularity: In order for the mini-grid utility business to be economically viable, the capital infrastructure must be capable of being expanded at a cost that is a fraction of the original cost per kilowatt. All the mini-grids have identical prototype and design; the components used are the same across systems. This helps increase the speed of scaling and replication.

Figure 31 show an Mlinda mini-grid built in a modular manner; it is designed for incremental growth, of up to three expansions each of 5 kWp of capacity. The scope of adding capacity depends upon the space available, *i.e.* the size of the control room and the land needed to set up the panels as well as the demand for electricity generated by the community.

Figure 31 Gumla plant; the land can accommodate an additional capacity expansion of 15 kWp

Source: (Mlinda, 2018).

In Mlinda the below modularity guidelines are followed:

1. The grids should be scaled up every 24-30 months
2. The capacity addition is 5 kWp[2]
3. The cost should be not more than 25% of original cost per kilowatt peak
4. The direct current distribution board (DCDB), displayed in Figure 32, is designed to allow for three to four increases in capacity over ten years
5. The space for the grid control room and modules should cater for additional land of 450 square metres for expansion.

Modularity is based on the fact that village energy demand will grow at 25% per annum for the first three years and 15% per annum thereafter up to ten years.

Figure 32 Mlinda-designed DCDB: Catered to allow for three increases of capacity from 23.6 kWp to 38.6 kWp

Source: (Mlinda, 2018).

2. Control, manage and measure

2.1 Remote monitoring system: The system facilitates grid utilisation and performance; it flags repair and maintenance needs, safeguarding the system from major failures. This translates to better revenues for the grid. Monitoring systems are already incorporated in the inverter software. The Victron Color Control device provides monitoring, and works as a communication centre of the installation. Monitoring can be carried out locally or remotely using the open-source Victron Management Portal to track health of the grid. It shows the real-time load, consumption pattern, generation and battery usage. Victron Systems conforms to the NEN-EN-ISO 9001 standard from the Royal Netherlands Standardisation Institute.

2.2 Smart prepaid metering: Adds transparency to the system; now customers have information about their consumption profiles.

2.3 Lightning protection: Gumla is a lightning-prone area. A very high level of lightning protection system has been incorporated in all Mlinda mini-grids, with the help of global leaders in lightning protection. The system includes a sophisticated earthing matrix, electrodes, air terminals, lightning arrestors and surge protection devices on both AC and direct current (DC) sides.

Impact and benefits

By 2019, 17 mini-grids had been commissioned in villages in the Gumla district of Jharkhand. Through the use of **standard modularity practices**, these mini-grids permit a three- to fourfold increase in capacity over ten years, reacting faster to energy demand increases. In the two years of operation, the mini-grids represented about 42% of the village electricity generation, while revenues were also increasing. These mini-grids systems power 2 106 houses and 452 productive and commercial loads. The mini-grid powers three productive areas such as oil expellers, wheat pulverisers and irrigation pumps (the latter is illustrated in Figure 33).

Figure 33 5 horsepower pump powered by the mini-grid used for construction material manufacturing

Source: (Mlinda, 2018).

The implementation of a **remote monitoring system** has proven to be an important information and control tool as it meets the power needs of the village, helps to assess demand and assists in load scheduling. Costs are around USD 150 per grid per annum; this includes only the activation with the help of a data card. In terms of monetary benefits, remote monitoring has enabled an **OPEX reduction by USD 2 400 per grid per annum.**

3.2 China: Smart Integrated Energy Microgrid in NCSC of Tianjin

Context

The Northern Customer Service Center (NCSC) located in Tianjin, China, is responsible for providing online customer service 24 hours a day, seven days a week, for half of the service area of the State Grid Corporation of China (SGCC), which covers 13 provinces and affects over 500 million people. The NCSC has a total construction area of 143 000 square metres including the call centre, two public service buildings and five dormitories, which can accommodate 2 600 employees' working and living. As a result of high population density and work schedules, the variety and high level of energy demands pose new challenges for energy supply solutions of electricity, heat, cooling and hot water. Thus, the Smart Integrated Energy Microgrid (SIEM) was built in NCSC (Figure 34).

Figure 34 **SIEM in NCSC - Overview of Northern Customer Service Center (left) and energy management platform (right)**

Source: (Li, 2018).

Mini-grid technical details

The energy facilities of SIEM include photovoltaic (PV) units, electric storage, a solar water heating system, an electric boiler with heat storage, a ground-source heat pump, ice storage and electric cooling devices. The energy supply frame of SIEM is shown in Figure 35 and the energy subsystems capacities are shown in Table 4 (Li, 2018).

Figure 35 Frame of SIEM

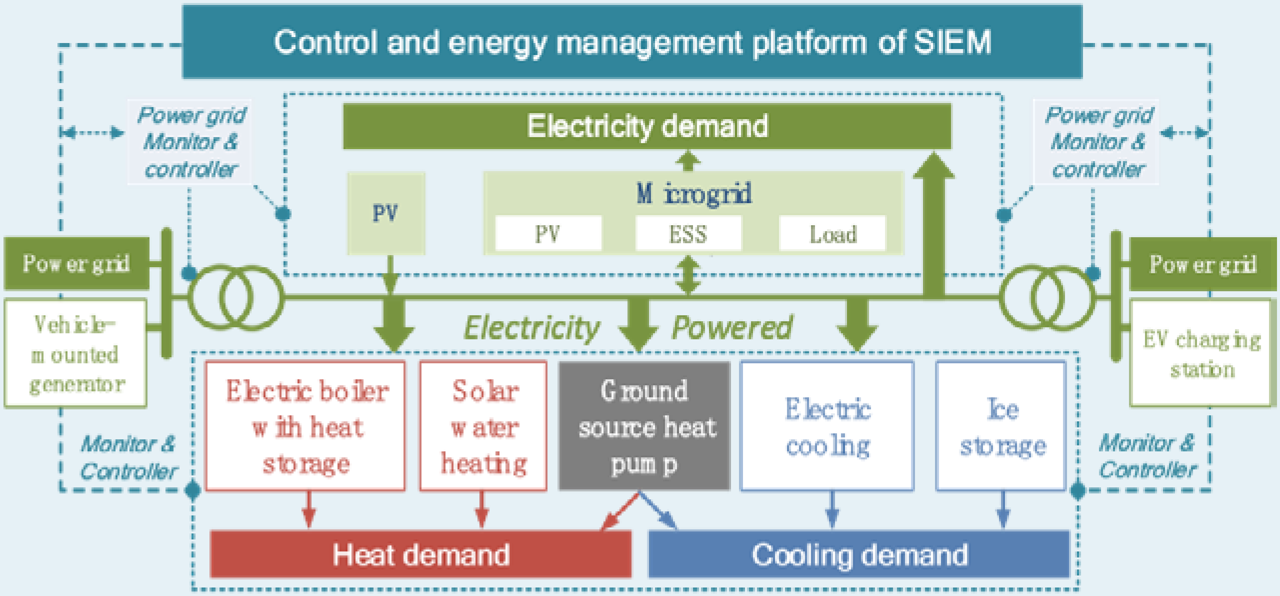


Table 4 Capacities of energy subsystems

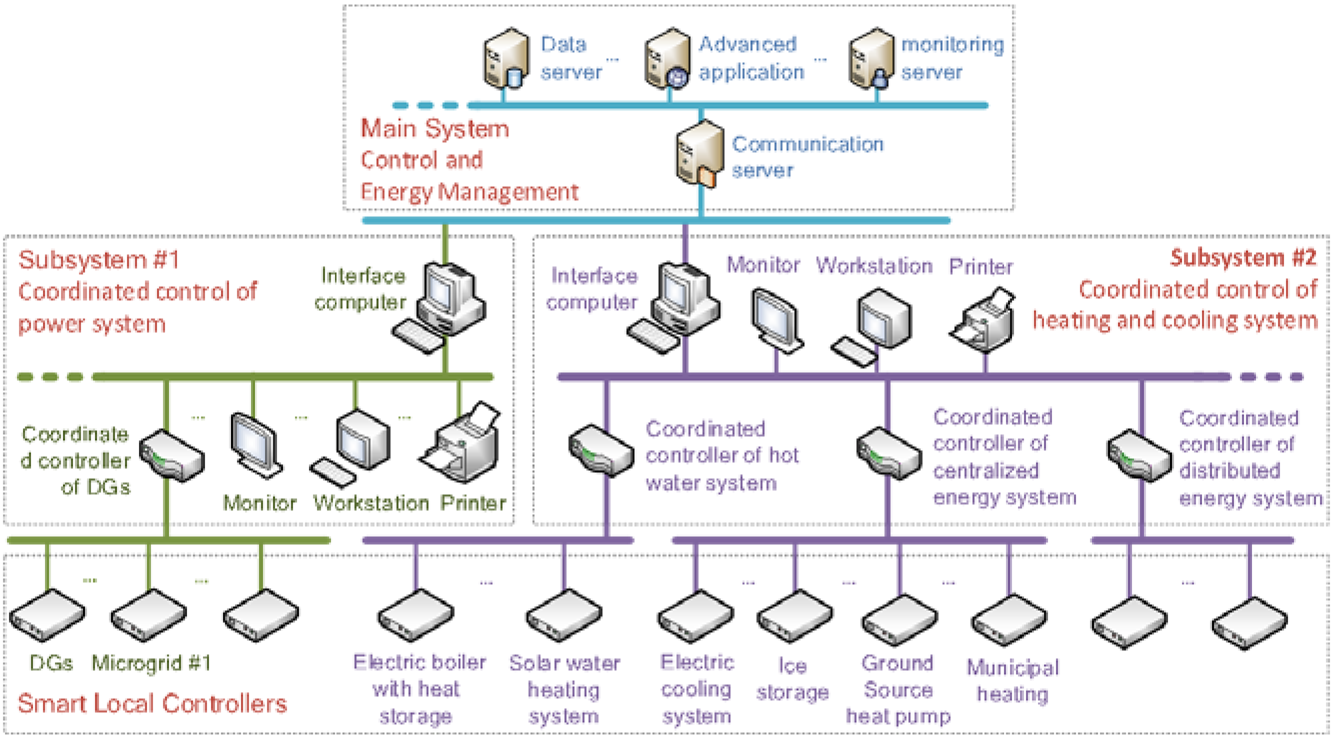
Subsystem	Capacity
PV system	823 kWp
Electric storage	200 kilowatt-hours (kWh)
Solar water heating system	1 007 kilowatts (kW)
Electric boiler with heat storage	8 200 kW
Ground-source heat pump	Cooling: 3 690 kW/Heat: 4 065 kW
Ice storage system	Cooling: 6 328 kW/Icing: 4 680 kW
Electric cooling system	6 328 kW

The total construction investment of energy facilities in SIEM was approximately USD 27 million. And the cost of the energy management platform was about USD 1.5 million. The integrated energy solution proposed in SIEM is highly scalable and replicable. It can be applied in many scenarios such as towns, industrial parks, business districts, public facilities and islands.

Quality infrastructure elements

1. Monitoring: An energy management platform (presented in Figure 36) realises the intelligent dispatching of SIEM. It considers an optimal strategy that combines day-ahead and real-time scheduling. It helps to improve penetration of renewable energy and flexibility when dealing with uncertain energy demand, while lowering operation costs.

Figure 36 Structure of control and energy management platform of SIEM



Note: DG = distributed generators
Source: (Li, 2018).

As the brain of SIEM, the control and energy management platform has provided many quality assurance solutions for the operations and maintenance (O&M) of the system. It ensures a stable and safe operation **by monitoring the operation status of energy subsystems and equipment** in SIEM. A unified measurement guideline is applied in the module. The measurement data consist of three levels: region monitoring, energy system monitoring and equipment monitoring. The representative data are given in Table 5 (Li, 2018).

Table 5 Representative measurement data

Module	Measurement data
Region monitoring	Climate data
	Energy demand
	Emissions reduction indexes
Energy system monitoring	Energy production
	Energy consumption
	Operation efficiency
	System failure rate
Equipment monitoring	Operation status
	Operation parameters
	Failure information
	Maintenance information

2. Testing: The control and energy management platform supports operational testing of the SIEM. It can generate energy production schedules for each energy subsystem and subsequently track their performance. Using these test results, the platform provides decision makers with a comprehensive assessment of system security indices, energy efficiency indices and electrification indices.

- System security indices include the ratio of safe operation, equipment operation status, energy supply balance and cost of maintenance.
- Energy efficiency indices include the analysis of energy consumption, energy utilisation level, energy conservation, emissions reduction, and economic and social benefits.
- Electrification indices include electricity alternatives, peak load shifting and ratio of self-sufficiency.

The **production training module** in the platform can provide online courses, study plans and simulated operation to help new practitioners learn safety production skills and understand the actual operation process according to the real test data.

3. Standardisation and technical regulation: The successful experience of the operation of SIEM has prompted the Chinese government to introduce “Guidance on Promoting the Development of ‘Internet Plus’ Smart Energy” (NDRC and NEA [2016] No. 392), “Notice on Organizing and Implementing ‘Internet Plus’ Smart Energy (Energy Internet) Pilot Project” (NEA [2016] No. 200), etc. Moreover, relevant models, methods and technologies of this project have been referenced by formulating Industrial Standards of China and enterprise standards of SGCC. These standards are listed in Table 6**.**

Table 6 Industrial and enterprise standards used in the SIEM project

Identifier	Type	Title
NB/T 33010-2014	Industrial Standard of China	Specification of Operation and Control of Distributed Generator Integrated to Power Grid
NB/T 33011-2014	Industrial Standard of China	Technical Specification of Test on Distributed Generator Integrated to Power Grid
Q/GDW 11565-2016	Enterprise Standard of State Grid	Guidance on Construction of Smart Park
Q/GDW 11566-2016	Enterprise Standard of State Grid	Technical Specification of Plug and Play Equipment of Distributed Generator Integrated to Distribution System below 10 kV Level

Note: kV = kilovolt; NB/T = Industrial Standard of China; Q/GDW = Enterprise Standard of State Grid.

Impact and benefits

Attributed to the energy monitoring module, SIEM has realised a combination of day-ahead scheduling and hour-level control. It can have significant energy savings and improve energy efficiency by integrating distributed energy resources and using energy management strategies such as peak load shifting, optimal scheduling and co-ordinated control. In 2016, **SIEM saved USD 1.3 million on energy costs.**

The production training module in the platform can provide online O&M lessons for the practitioners, and makes the O&M of SIEM more convenient and efficient. **The training period of new practitioners has been reduced by three months.**

3.3 Nigeria: A smart metering solution for mini-grid development

Context

Nayo Tropical is a mini-grid developer, operator, and engineering, procurement and construction company based in Abuja, Nigeria, that built two 30 kW solar mini-grids for the United Nations Development Programme/Anambra State Ministry of Environment in 2010 and 2014. Between 2010 and 2017, prior to the deployment of the SparkMeter smart meters, Nayo Tropical Technology relied on suboptimal billing approaches with its customers. Without smart meters, the company was using both inaccurate and non-transparent estimated billing procedures and, later, more expensive post-paid meters to track and bill customers' electricity consumption.

These methods and equipment caused several problems for Nayo Tropical Technology, including:

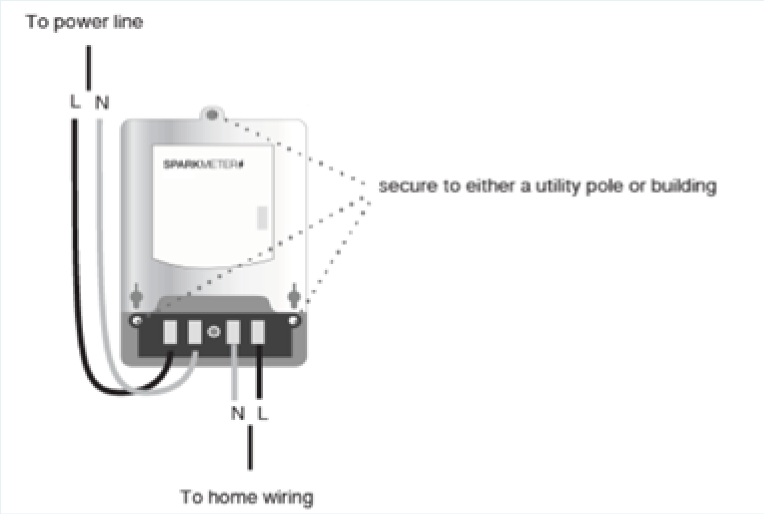
- Revenue loss as a result of under-billing
- High collection costs from manual bill collection with a large customer base (120 connections)
- 20-30% revenue loss due to power theft
- Overall risk to the company, including security-related risks from handling large amounts of cash
- Irregular electricity pricing. It was impossible to accurately measure energy consumption, making it impossible to create a structure/block tariff
- Frequent customer service complaints as a result of billing methods
- Exposure to electricity theft. Because the power consumption of their customers could not be accurately analysed, it was difficult to detect, correct and prevent power theft.

Mini-grid smart meter technical details

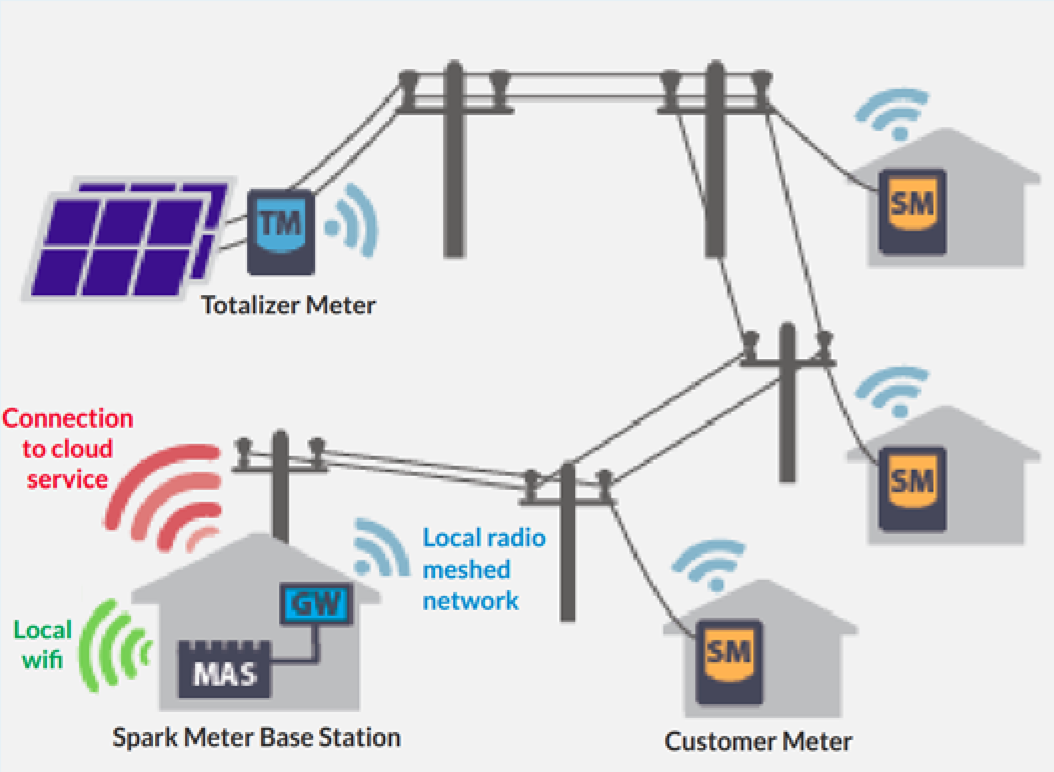
The SparkMeter system consists of smart meters that communicate via a mesh network, which allows for reliable communication even when there is no clear line of sight. When connection to the internet is possible all data are routed to and from SparkMeter's cloud application (*i.e.* Thundercloud). When connection to the cloud is not possible, as is often the case in rural mini-grids, the SparkMeter base station contains a mirrored local instance of the application (*i.e.* Groundbolt) which allows the metering system to continue operating without interruption. SparkMeter also utilises a number of software features to perform functions fulfilled by hardware features in other metering systems – this enables access to smart metering by mini-grid operators who require a lower-cost system. These functions are as follows:

- In lieu of reading a display on the meter, the SparkMeter system utilises an update to a web interface or text message updates, which allow the customer to view the performance of their meter and their energy consumption. In communicating to the consumer in these ways, the SparkMeter **can provide the consumer with other information as well** (i.e. account balance, consumption trends) more conveniently than with a display on the meter.
- Instead of interfacing with an optical pulse output to calibrate or verify the meter energy reading, the SparkMeter system allows the operator to directly **query the meter wirelessly** in order to obtain the energy reading of the meter. In querying the energy in this way, **the SparkMeter system allows for quicker calibration and verification,** thus saving on costs since the operator does not have to convert pulses into energy or use special pulse counting equipment.

Figure 37 SparkMeter smart meter



Note: N = neutral; L = load.



Note: TM = totaliser meter; MAS = SparkMeter base station; SM = customer meter.
Source: (SparkMeter, 2019a).

Quality infrastructure elements

1. Interoperability: The implementation of SparkMeter's application programming interface in the mini-grids provides the flexibility to build out data flows for other enterprise operations, whether mobile money integration, text message communications, customer relationship management tools, custom software or work order management.

2. Standards: SparkMeter meters have been designed to meet the varied needs of mini-grids and central grids and the numerous countries they are deployed in. In order to achieve this, the SparkMeter has focused on key areas of compliance that are common for revenue meters. The SparkMeter SM60R, which can be used for both mini-grids and central grids, has been tested and certified to **IEC 62053-21 to class 1** (*i.e.* 1% active energy accuracy). Compliance to this standard is essential for electricity meters used for revenue collection to ensure the equitable exchange of services and revenue. Additionally, to ensure that the meter does not adversely interfere with other electronic devices, the SM60R is compliant for electromagnetic interference and electromagnetic compatibility per **IEC 61000.** Lastly, to ensure that the meter does not present any safety or environmental hazards for importation, the SM60R has been tested by SGS to the key elements of **IEC 69050** pertaining to general safety, necessary for pre-shipment inspections in markets where SGS has been designated the import inspector. Compliance to these standards reduces the risk to the operators deploying the SparkMeter system.

3. Communication reliability and scalability: SparkMeter's communications protocol allows for strong meter communications in areas with intermittent power and internet access. The meters communicate over a 100% local mesh network, allowing for data transmission regardless of internet access. By relying on a wireless mesh network rather than a hub-and-spoke system, adding new connections is easy, as complex networking is not necessary.

4. Remote monitoring: The SparkMeter application provides the utility operator with remote access to meter data, control of the meter, the ability to set tariffs and a multitude of other software features needed to manage a grid as soon as the system is turned on.

Impact and benefits

Nayo Tropical Technology has experienced several benefits as a result of the implementation of quality metering and monitoring:

- **lower O&M costs**
- **reduced revenue loss** through innovative payment options and capabilities
- **lower electricity theft** after introducing real-time customer consumption monitoring
- more **accurate load monitoring and forecasting**
- **better customer service** through documented events and follow-up investigations
- **robust communications to remotely monitor the site**
- business model flexibility through **limitless tariff options** for time-of-use, block and monthly plans
- **demand management through load limits**, which can be assigned to individual tariffs
- **easy deployment of new connections** as more customers request to join the network
- ability to **conduct performance benchmarking** to understand the actual performance of its assets in order to raise funds for future mini-grid projects.

3.4 United States: Wind mini-grid testing

Context

The village of Pilot Point, Alaska, in the United States, has relied on diesel for its electricity, using almost 1 000 barrels (120 000 litres) of oil per year. The average electricity cost for a residence is about USD 0.35/kWh. Now the village is undertaking a hybrid system that runs on wind and batteries (XANT, 2018).

Mini-grid technical details

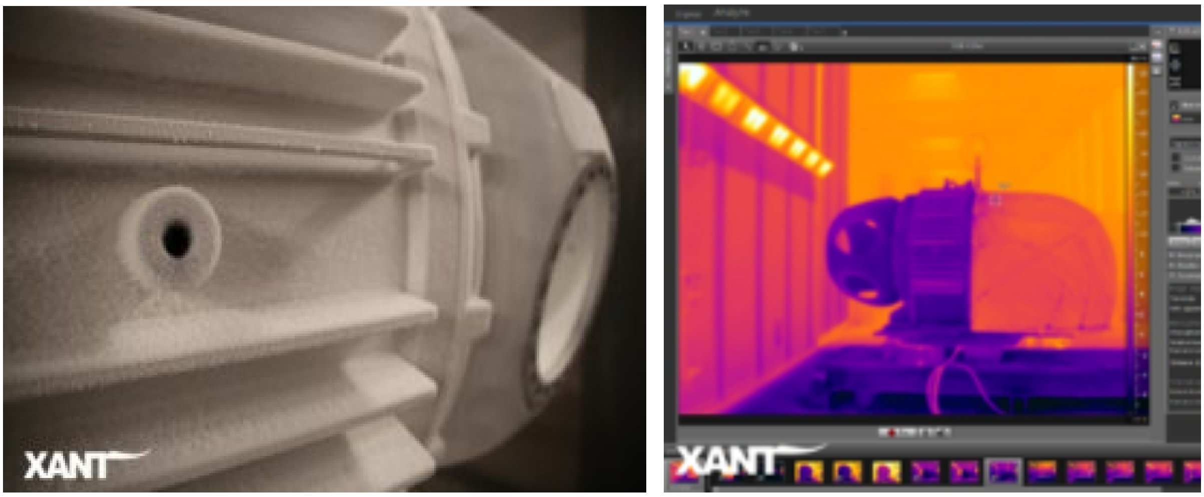
This mini-grid has the XANT Control System, which interfaces with the mini-grid energy management system (EMS) to continuously indicate the level of active and reactive power that can contribute to the grid. The turbine will be able to operate in island mode (being the only grid-forming unit on the mini-grid) or as a "virtual synchronous generator" and operate in conjunction with other grid-forming units on the mini-grid.

As the mini-grid has to be able to operate under extreme weather conditions, system quality is of the essence

Quality infrastructure elements

1. Testing: Provides details on the simulations carried out by XANT for the nacelle operating conditions at temperatures down to -40°C. The blade heating system has been tested and works under real operating conditions (XANT, 2018).

Figure 38 XANT M cold-climate testing



Source: (XANT, 2018).

2. Standards: XANT turbines are certified according to the **IEC 61400-1 standard** and testing methods for its components adhere to these guidelines.

3. Standardised communication/scalability: Standardisation of the data exchanged between the turbine control system and the mini-grid EMS is a contributing factor for cost-effective mini-grid replication.

Impact and benefits

According to the developers, the benefits of implementing QI in this mini-grid is threefold:

- **Speedier commissioning of the mini-grid:** the wind turbine can be integrated even without setting up communications with the EMS.
- **Better interoperability of components from different original equipment manufacturers** and thus more optimal (lowest levelised costs of electricity) design.
- **Higher resilience of the mini-grid** as unpredictable power sources are converted into intelligent devices contributing to grid stability. An outage of one single unit or even interruptions of the communication with the EMS will not necessarily take down the complete system.
- **Increased renewable penetration** on the mini-grid: a better management of the wind turbine will lead to a higher utilisation rate of the wind power.

3.5 United Republic of Tanzania: International standardisation and component interoperability in Mpale village mini-grid

Context

Fossil fuels such as kerosene and diesel generators had always provided lighting and electricity to the 3 000 inhabitants of remote Mpale, a village in the Korogwe district. Now the 730 households use a hybrid solar mini-grid for sustainable, reliable and cleaner energy.

A **centralised mini-grid with solar PV** was implemented by Ensol Tanzania, a local developer working with international partners such as TTA and Studer. Together they ensure the quality of the project, and the commissioning, start-up and training activities. They helped to solve some pending issues before the start of the service and ensured a reliable operation.

Mini-grid technical details

The mini-grid has battery storage, a PV generation of 48 kW and a 50 kVA diesel generator as back-up. It has DC-coupling architecture for ensuring the battery lifetime, including a back-up generator. The renewable energy system combines inverter/chargers MPPT solar charge controllers working on the same communication bus as displayed in Figure 39, therefore synchronising the battery charge. The inverter system is programmed to give priority to the use of solar over the use of other generators.

Figure 39 Inverters and MPPT solar controllers

Source: Ensol Tanzania, Studer and TTA, 2019.

A 2-kilometre aerial line distributes the electricity generated by the PV system to the village. Each user's residence has an electricity dispenser, which allows the system to control how much energy is dispensed and limit the current.

Quality infrastructure elements

1. Standards: The main equipment was selected taking into account conformity to international standards. The design followed European regulations with a strict supervision of the implementation, making sure that the equipment sourced locally fulfilled the specifications.

2. Interoperability: Component interoperability and standardised communication protocols have allowed the set-up of a smart tariff scheme in which the tariff varies according to the energy state in the system:

- tariff increase when the energy available is low (restriction)
- tariff decrease when the energy available is high (bonus).

3. Remote monitoring: A remote monitoring system and a local operation scheme, which includes standardised O&M protocols, have been set up to follow up the mini-grid performance, as well as to manage and solve operational issues that may arise.

Impact and benefits

Equipment that complies with international standards and proper interoperability of the mini-grid components have allowed the system to provide a service tariffs scheme. This helps to match the deferrable demand with the generation profile (solar) for maximising energy utilisation. In addition, this model ensures a secure use of the equipment within its operating range, and it comes along with a financial model (tariffs) to ensure O&M during the project lifetime. The system is flexible, allowing future expansions if required, in case of demand growth.

Figure 40 Mpale village

Source: Ensol Tanzania, Studer and TTA, 2019.

3.6 Mali: Konseguela village mini-grid monitoring system

Context

In Mali, only 18% of the people in rural areas have access to electricity. The recent development of decentralised solutions offers promising perspectives towards a more universal access to energy. However, these solutions and their business models are designed to serve domestic customers: standard systems copy-pasted from site to site with low voltages, frequent outages or limited operating hours are not fitted to the needs of microbusinesses. Their pricing schemes are also inadequate, favouring connection over consumption fees. Therefore, these rural micro, small and medium enterprises (MSMEs), the vehicles of local economic development, had to rely on their own energy sources, often at a cost (equipment, fuel, maintenance) hampering the profitability of their operations. In addition to a lack of reliable access to energy, rural MSMEs often meet issues related to managerial or technical capacities and lack of training/ coaching resources, as well to inadequate access to finance to support business development (Geres, 2019a).

The Green Business Area (GBA) has been developed and tested in Mali by the French non-governmental organisation Geres, with the aim to allow MSMEs to access electricity 24 hours a day through mini-grids. A GBA with a 100% renewable energy mini-grid has been installed in the village of Konseguela.

Mini-grid technical details

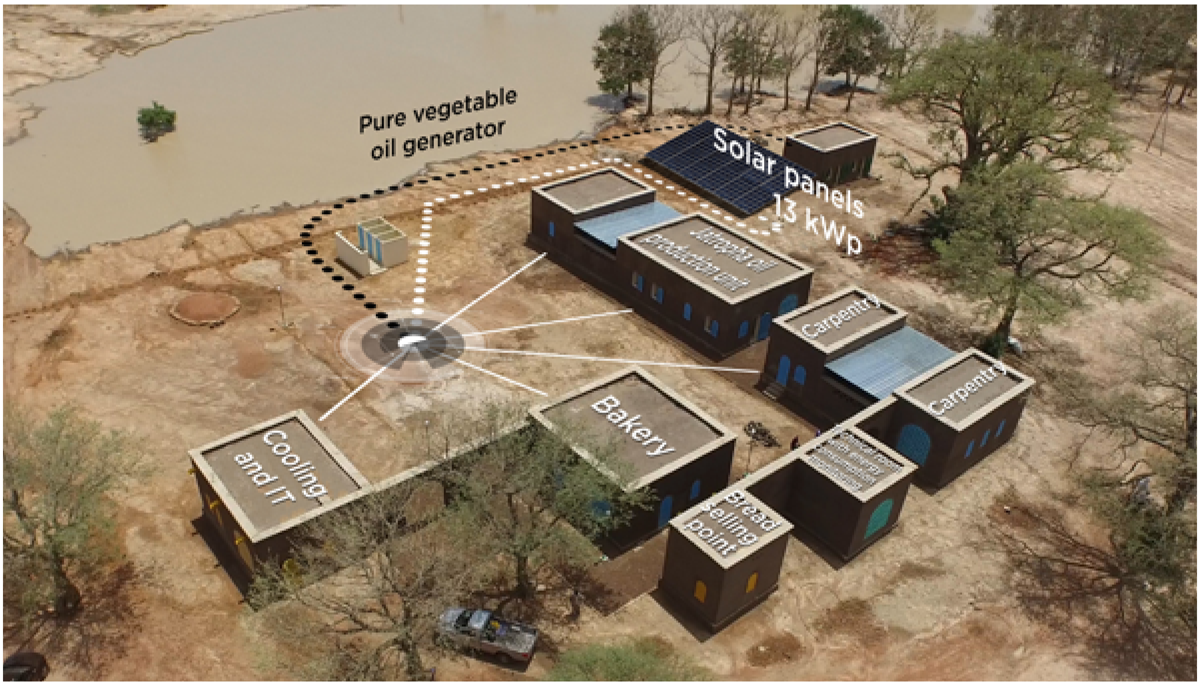
» A **hybrid solution** with solar and thermic energy (90%/10%), refer to Figure 41.

» 12.5 kWp of **solar panels** and a generator of 16 kVA allowed production of 6.5 megawatt-hours of clean electricity the first year.

» Either connected or not to an existing micro-grid (can work as a stand-alone system or as an add-on to a grid).

» Decreases the technical constraints related to the provision of electricity to MSMEs, by gathering/grouping the electric demand on one single location.

Figure 41 Mini-grid solution



Source: (Geres, 2019a).

Quality infrastructure elements

Remote/reliable monitoring: As an experimental project, strong technical monitoring has been implemented to follow up the energy production and consumption on a daily basis. The task is particularly challenging in remote areas, where network access is not always reliable, but essential for the village. It provides a set of data that the managing team analyses in order to overcome any possible flaw.

The current monitoring is based on the measurement tools integrated into all the high-quality inverters or regulators. Battery voltage, temperature or state of charge are closely watched. Moreover, detailed figures and charts on power consumption are available. Other criteria, impacting solar power production and MSMEs consumption, are also taken into account (*e.g.* weather conditions).

Data are accessible locally on Secure Digital (SD) card or via the constructor's online platform for remote access. This allows continuous monitoring of the systems. The analyses are then realised manually based on the data collected, by developing specific tools.

Impact and benefits

The monitoring system has made possible several cost savings as a result of system optimisation (*e.g.* electricity production) and prevention of heavy breakdowns. However, it also entails additional human resources costs, necessary to internalise the skills to manage this type of tool.

Figure 42 Productive uses of the energy generated by the mini-grid

Source: (Geres, 2019b).

3.7 Ethiopia: Portable solar mini-grid

Context

Suninbox is a complete mini-grid with lithium batteries; it is a portable solution, as the whole system can be transported in a container. This mini-grid is produced by the organisation GFM Fotovoltaica. Once the container is opened, the mini-grid can easily generate electricity and supply it to the community.

Suninbox has served as a power generation unit for a community of refugees and nomads in Ethiopia, close to the border with Somalia. This unit is also used to power water pumps.

Figure 43 Suninbox container (left) and Suninbox solar panels (right)

Mini-grid technical details

Suninbox is a portable solar PV energy solution that includes, in a certified container, all the necessary components to generate electricity autonomously, and is portable and easy to install (plug and play). This solution is ready to arrive and start to work. The mini-grids use lithium iron phosphate batteries.

Quality infrastructure elements

1. Monitoring: With the monitoring system, one can remotely check the status and behaviour of every subsystem, see instant consumptions, apply configuration changes to the devices, analyse alarms, etc.

2. Testing methods and certification: Each Suninbox is tested before being sent to the consumer. GFM has a laboratory where its own technical solutions are developed and tested. All their products have the SGS product certification. All the components used in Suninbox follow relevant IEC standards and other certifications.

Impact and benefits

According to GFM, certification and standardisation have been key aspects to strengthen their proposal when participating in international funding programmes. Technical standards help demonstrate to financial institutions that the solution will comply with specifications.

04

4. QUALITY INFRASTRUCTURE FOR RENEWABLE MINI-GRIDS OF THE FUTURE: GAP ANALYSIS, EMERGING TRENDS AND MARKET CHALLENGES

Chapter 4 undertakes a forward-looking analysis and studies the required quality infrastructure (QI) for future and smart mini-grids, which incorporate breakthroughs such as electromobility, digitalisation, prosumers and others. In the next pages, quality gaps of smart mini-grids are identified and a set of recommendations guide the way to assure high quality for this new generation of mini-grids.

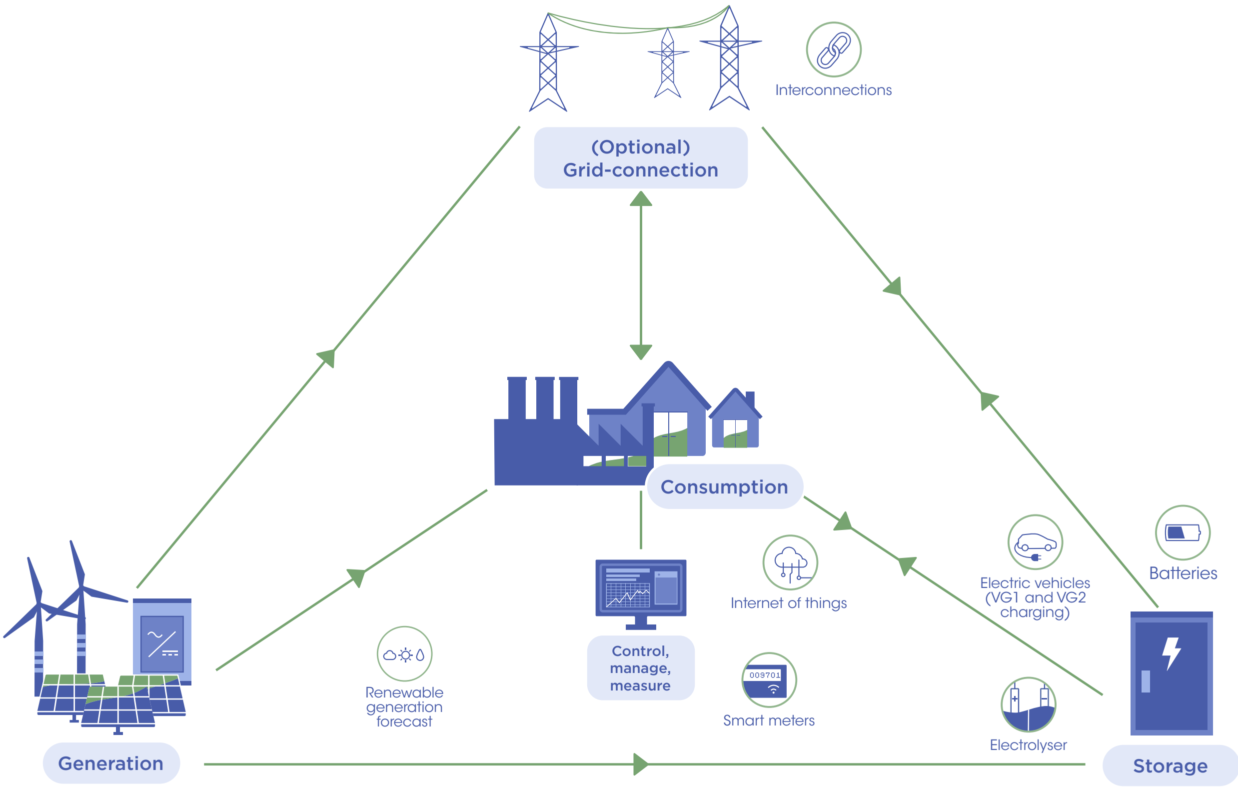
Key information in this chapter:

- QI for energy forecasting
- smart meter control and monitoring
- cybersecurity standards
- QI for electromobility
- interconnection standards
- low-voltage direct current (DC) mini-grids
- quality gaps.

4.1 Smart mini-grids and QI gaps analysis

Renewable mini-grids of the future, also called smart renewable mini-grids, will have more advanced control, management and measurement (CMM) operations, due to the development and wide spread of digital applications, such as smart meters and internet of things (IoT) solutions, as well as improved data availability and forecasts of renewable energy generation. Innovations in storage technologies will also impact the mini-grids of the future, with storage technologies ranging from batteries to electrolyser technologies. In addition, the integration of electric vehicles (EVs) will also be crucial in these mini-grids, where higher electrification rates in the transport sector are expected over the next years. On the consumer side, the traditional consumers-to-prosumers transition is accompanied by a variety of technological innovations such as peer-to-peer electricity trading, which facilitate a better use of the locally generated electricity between consumers. Figure 44 illustrates the smart renewable mini-grids concept.

Figure 44 Renewable mini-grids of the future

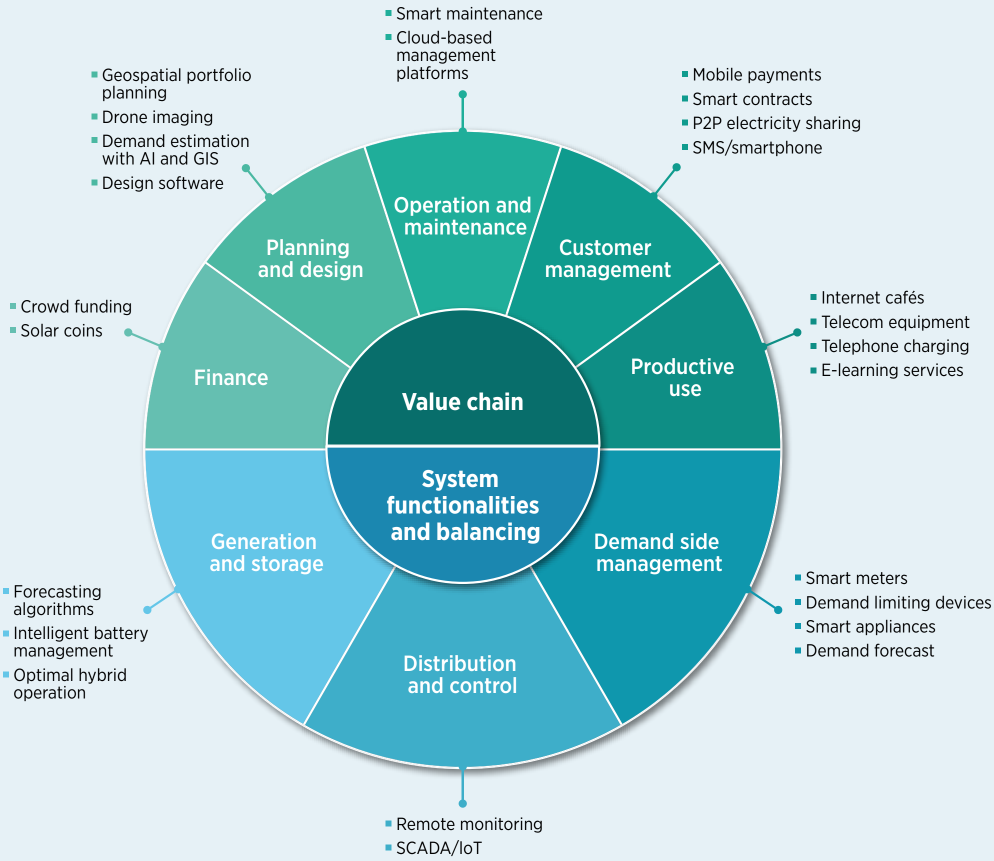


In order to accommodate the mini-grid of the future, further evolution of QI is necessary. Technical and business model innovations introduce a number of challenges and opportunities, and the anticipated development of QI can fulfil performance gaps in mini-grid systems. In this section, gaps are again described by following mini-grid functionalities.

Smart mini-grids and digitalisation

Digitalisation is spurring the development, control and monitoring of mini-grid systems. Digital technologies are growing at a fast pace, and they provide solutions for mini-grids that make the processes more efficient and time-saving, cut costs, and provide better services to the consumer. In Figure 45, the Institute for Advanced Sustainability Studies (IASS Potsdam) studied the application areas where digital innovations may provide added value for mini-grids, specially at value chain and system functionalities level (IASS Potsdam, 2019).

Figure 45 Digital technologies in mini-grids



Based on: (IASS Potsdam, 2019).

Digital applications are at the core of smart and intelligent mini-grids and consequently, early QI development is key to guarantee robust and reliable technologies.

Control, manage and measure

CMM is the functionality that will possibly see some of the more drastic technological advancements in the future. These innovations will introduce gaps in QI. Some examples of technologies, models or innovative applications that will see wider application in the next few decades are detailed in the next subsections; these can aid in proactive development of QI.

Renewable generation forecast

Due to the intermittent behaviour and low inertia of mini-grid renewable generators, and a lack of load diversity characterising larger geographical regions, forecasting of consumption and generation is an important aspect in the efficient and cost-effective operation of mini-grids. Through the use of short-term forecasting methods in mini-grids, generation and consumption can be adjusted accordingly, limiting the required buffers and subsequently the cost.

Up until recently the main focus of forecasting research was on nationwide or region-wide forecasting, but methods are being developed to adapt these models to the more irregular and dynamic load curves of mini-grids. These methods can make use of artificial neural networks, autoregressive integrated moving average, etc. (Dutta, et al., 2017).

All of these models need large amounts of input data, ranging from numerical weather predictions to consumption and generation data.

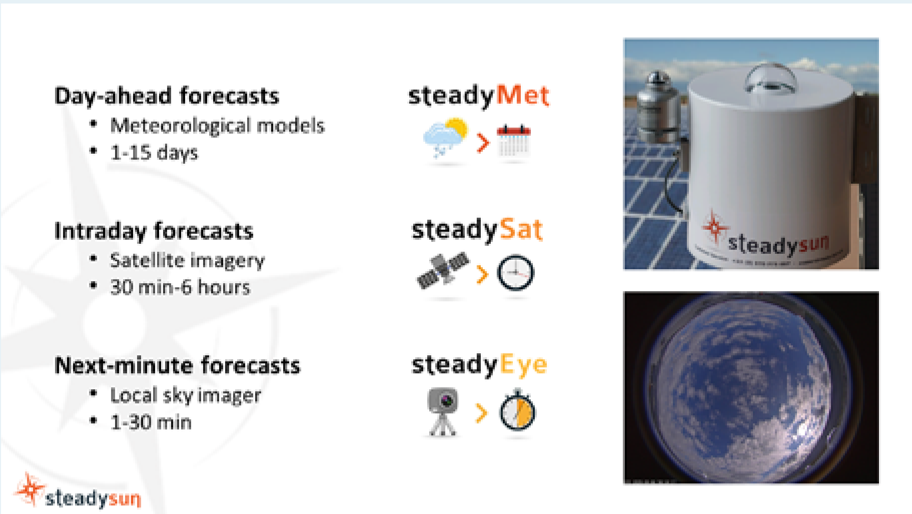
QI gaps that will arise: A regulatory framework specifying the means and limits of data collection (*e.g.* consumption data) will be needed. As these methods evolve, testing and performance determination will have to be adjusted. Furthermore, a minimum reliability will have to be specified, demanding *e.g.* a certain amount of local data collection to assure functionality in the case of a data breach or malfunction.

There is an uncertainty associated with forecasting. The confidence level of (short-term) forecasts will have to be taken into account in mini-grid operation and design, to assure that a minimum service reliability is always maintained.

Solar generation forecasting provided by Steadysun

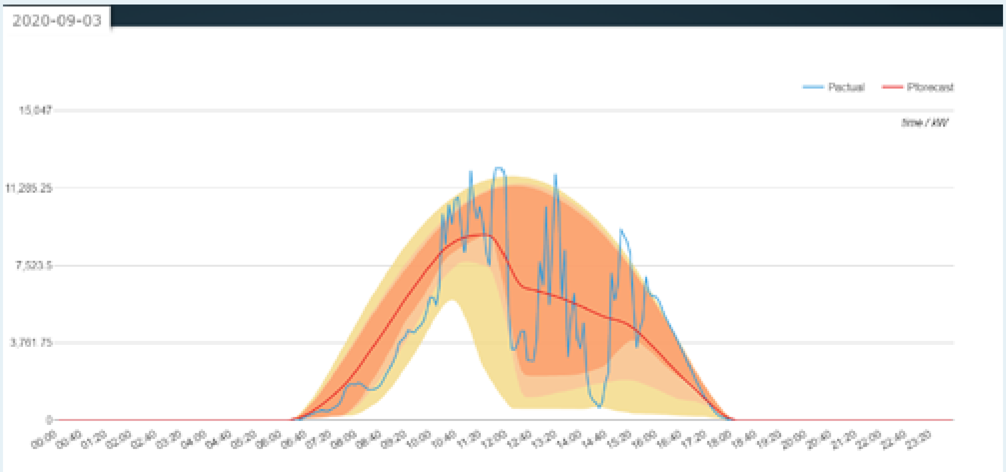
Figure 46, Figure 47 and Figure 48 illustrate real-life cases justifying the need for short-term forecasting in a mini-grid in Germany (Steadysun, 2017). These forecasting methods have to be combined with accurate load forecasts and short-term controls to be of valuable use for mini-grids.

Figure 46 Solar forecasting methods



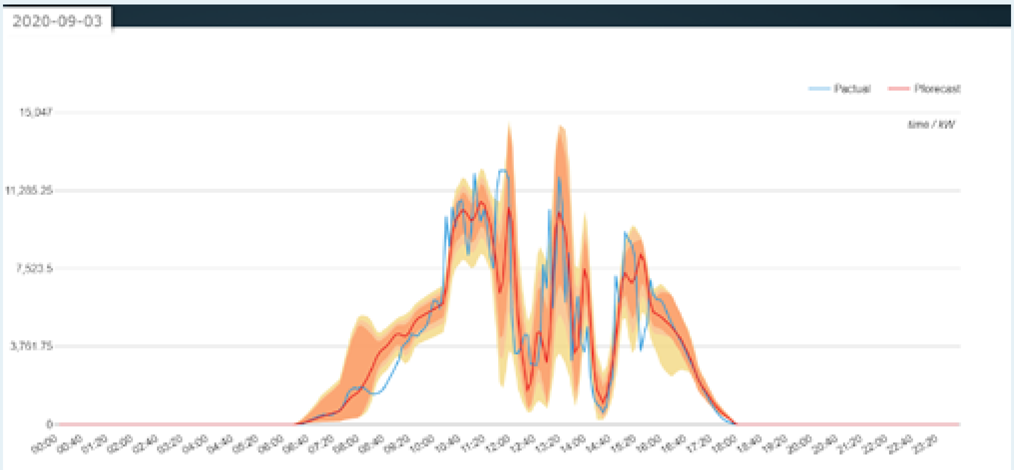
Source: (Steadysun, 2017).

Figure 47 Actual (in blue) versus forecasts of the day before



Source: (Steadysun, 2017).

Figure 48 Actual (in blue) versus intraday forecasts – 60 minutes in advance



Source: (Steadysun, 2017).

Smart meters

Smart meters have seen increased deployment in the last years, due to the perceived benefits to utility companies (payment assurance, anti-tampering, etc.), rising demand for energy efficiency measures, and an increasing number of prosumers and intelligent devices. There is still a lot of room for innovation, however, especially considering the way in which the measured and monitored data are used. The future of mini-grid operations and maintenance (O&M) relies strongly on the collection and analysis of data that allow remote management of mini-grids. Smart meters also allow for innovative pricing methods, such as time-of-use energy pricing, which allows customers to use energy when it's cheaper and provides opportunities for demand control through pricing incentives.

QI gaps that will arise: As with forecasting, standards and regulations concerning data collection will be required. Furthermore, regulations concerning new pricing schemes and privacy issues will need to be clearly communicated before roll-out. There has been a promotion of standardisation efforts in past years (i.e. the European Committee for Standardization, the European Committee for Electrotechnical Standardization [CENELEC] and the European Telecommunications Standards Institute [ETSI]) Smart

Meters Coordination Group), but experts consulted for this study indicated that further standards and clarity will be required.

Internet of things

Mini-grids are ideal for the implementation of internet of things due to their inherent level of intelligence and data collection. IoT-based platforms will form the backbone of the CMM functionality in the future. According to expert opinions, the issue with QI for IoT is not that there is too little, but instead that there is too much (hardware standards, cloud standards, security standards, industry standards, privacy standards, etc.). Many of these are competing proprietary standards.

QI gaps that will arise: The development of open, comprehensive and preferably international standards, solving the pain points that hinder current adoption, will be crucial.

Some benefits of open instead of proprietary protocols (standards):

- used by multiple manufacturers, installers and developers, not just the owner of the proprietary standard
- easier communication with other mini-grid systems (interoperability)
- community-wide support, freeware and actualisation efforts.

There is a lack of collaboration among the different stakeholders defining IoT requirements. Therefore the International Electrotechnical Commission (IEC) has clearly outlined the roles of each of them in Table 7.

Table 7 Roles of IoT QI stakeholders

Government	» Should focus exclusively on requirement s for public sector IoT such as smart city » Should collaborate on sharing requirement with each other and with the open standards bodies and industry consortia » Should align with private sector and push for greater alignment between competing organizations and initiatives » Should not define standards or dictate statutory use of standards » Should avoid dictating regional policies on data ownership, data stewardship and data use
Private sector	» Should push for maximized development and use of international, open standards » Should, with public sector, push for alignment between competing standards bodies and consortia » Should coalesce around key standards bodies and consortia
Standards bodies and consortia	» Should replicate good relationships with other organizations such as IIC/14.0 partnership as much as possible » Should focus on their core standardization competency and not develop competing requirements or standards for the sake of organizational survival or expansion

Source: (IEC, 2016b).

Innovative CMM in residential systems:

Sonnen

An example of advanced metering, forecasting and control, using IoT, can be found in the Sonnen battery system (Sonnen, 2018). Data from energy usage, photovoltaic (PV) generation, weather predictions and grid tariffs are used to control the charging and discharging cycle of the battery.

Compliances and certifications of Sonnen battery system:

» UL 9540 compliance

» Certified to UL 1741 (inverter)

» UL 1973 (batteries)

» US Federal Communications Commission Part 15 Class B compliant.

Schneider

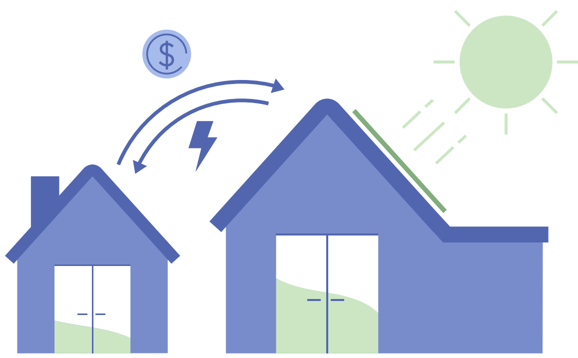
Schneider's EcoStruxure Microgrid Advisor is a cloud-based software as a service and hardware platform that offers a wide array of innovative CMM functionalities, from autonomous generation and distribution optimisation using predictive algorithms to communication using an interactive web interface (Schneider Electric, 2018a).

Compliances and certifications of Schneider EcoStruxure:

» All connections from the gateway to the cloud are validated using an industry standard (2 048-bit RSA) certificate and data are encrypted in transit using 128-bit AES encryption

» It is designed to use only HTTPS TLS 1.2 encrypted outbound connections on port 443 and cannot be contacted from the outside

» Data are stored at a cloud provider in the United States, which is EU-US Privacy Shield self-certified (Schneider Electric, 2020).



Cybersecurity

- Any communication and control system in a modern mini-grid is vulnerable to cyberattacks. Whether cellular payment services in rural mini-grids, customer data gathering, IoT applications or any other computer-based remote controlled application, mini-grid cybersecurity must address inadvertent damage to the electric infrastructure due to user errors and equipment failures, along with threats from natural disasters and deliberate attacks.

  QI gaps that will arise: Although this is an issue faced in critical infrastructure today and has been addressed to a certain degree, it is considered as a future gap since cybersecurity is an ever-evolving commitment that requires ongoing vigilance, especially with rapid technological advancement in the CMM functionality of mini-grids.

  In order to avert cyberattacks, a systematic and proactive approach must be available, tailored to an evolving set of mini-grid-related characteristics, risks and vulnerabilities. These efforts could be co-ordinated within a national agency responsible for the protection of critical infrastructure.

- As mini-grids for military purposes are early adopters of cybersecurity processes, these can be used to benchmark the cybersecurity guidelines of other projects. An example of such a guideline is the US Department of Defense Risk Management Framework (DoDI 8510.01) and the Army Office of Energy Initiatives cybersecurity requirements (O'Neil, n.d.). There are also testing facilities that can validate cybersecurity measures to tackle evolving threats (*e.g.* Electric Power and Intelligent Control [EPIC] test bed at Singapore University of Technology and Design).

Relevant guidelines, reports and standards for the development of the cybersecurity aspect of mini-grids

- National Institute of Standards and Technology Guidelines for Smart Grid Cybersecurity developed by members of the Smart Grid Interoperability Panel and Smart Grid Cybersecurity Committee (NIST, 2014b)
- ISO 27000 (International Organization for Standardization standards series for Information Security Management Systems)
- North American Electric Reliability Corporation Critical Infrastructure Protection Standards
- IEC 62351: defines cybersecurity for the communication protocols defined by standards IEEE P2030 (Institute of Electrical and Electronics Engineers), ANSI C12.22 (American National Standards Institute), ISA100.11a (International Society of Automation), and ITU-T G.9955 and G.9956 (International Telecommunication Union) (Güngör, et al., 2011)
- IEC TR 62351-12:2016/-90-1:2018: technical reports concerning resiliency and security recommendations for power systems with distributed energy resources (DER) cyber-physical systems/Guidelines for handling role-based access control in power systems (IEC, 2007)
- A comprehensive overview of the relevant standards for cybersecurity and privacy is given by the Coordination Group on Smart Energy Grids, Cyber Security and Privacy in light of the M/490 smart grid mandate (CG-SEG, 2016).

EPIC test bed from Singapore University of Technology and Design and iTrust Centre for Research in Cyber Security

» Operational since 22 May 2017, EPIC allows cybersecurity researchers to experiment to check the effectiveness of new cyber-defence tools. EPIC is one of the three critical infrastructure test beds at iTrust that researchers in cybersecurity work on for applied research. The other two test beds simulate Secure Water Treatment (SWaT) and Water Distribution (WADI).

» On demand, EPIC supplies power to run both SWaT and WADI test beds concurrently. This connection is useful for research into the cascading effects of cyberattacks on a power plant to downstream infrastructure. EPIC supports experimental investigation into the cybersecurity aspects of the distributed cyber components controlling the physical components such as generators and transformers (iTrust; SUTD, 2018).

Storage

Innovations in storage technologies will provide a challenge to existing QI to establish relevant standards and regulations. Each of these technologies has different testing, operational and safety requirements. Standardisation and regulations concerning the different aspects of these storage technologies and their implementation in mini-grids are bound to fall behind due to their rapid evolution.

Electrolyser technologies and other power-to-gas applications are increasingly used as storage solutions. However, few commercial applications in mini-grids exist at the moment. Power-to-gas technologies convert water and electricity to chemical raw materials using electrolysis. Siemens' Mainz Energy Farm is leading an initial 6 megawatt pilot project on hydrogen generation. The facility has the capacity to produce enough hydrogen for around 2 000 fuel-cell cars. In addition to electrolysis-based hydrogen, Siemens is examining the feasibility of methane. Both hydrogen and methane can be stored in the natural gas network and be used for reconversion into electricity. Siemens experts are also working on conversion processes using carbon-neutral fuels such as methanol.

QI gaps that will arise: A framework recognising the different storage types and how to formally describe them should be available at the time a new technology reaches the market. Experience has shown that the biggest issue in innovative storage implementation is often a wrong interpretation of the demand or specifications required for the project. For example, standards and guidelines of new battery technologies should include the following formal descriptions: a method to describe the usable capacity, round-trip-efficiency and cycling capability, a description of deterioration and capacity at end-of-life, fire safety and mitigation of hazardous material, and decommissioning/recycling at end-of-life (Danley, 2017). Uncertainty regarding the integration of new storage technologies can thus be reduced. The Energy Storage Lexicon published by the National Rural Electric Cooperative Association can be seen as a dictionary explaining battery specifications and requirements, partly eliminating costly miscommunications between vendors and operators or project developers (NRECA, 2016).

For implementation in a mini-grid, testing should focus on the performance of these storage technologies, particularly on energy supply rates, energy storage rates and ramp rates. In doing so, they can be more effectively designed to meet the demands of future projects.

Additionally, electrolyser technologies and power-to-gas systems will have to be tested in mini-grid environments with a high penetration of renewables. QI will have to develop to accommodate:

- intermittent operation (low degradation)
- black-start capability
- customer-friendly installations (safety standards)
- robustness and reliability
- grid connection (power quality).

Electric vehicles

QI has to be adjusted to the integration of EVs in a mini-grid. Clearly, the integration of EVs has many benefits for mini-grids as they can be seen as storage for intermittent renewable generation. However, the integration of EVs in mini-grids also poses a set of challenges that are rather different as compared with their integration in a national grid infrastructure.

QI gaps that will arise: Unregulated clustered charging could lead to local overloading in mini-grids, especially if no charging management is present to mitigate peak loads. This could damage transformers and other technical equipment, drastically reducing their lifespan.

Standards and test procedures of EVs and EV supply equipment (EVSE) should be harmonised and updated with advanced communication capabilities in order to enable controlled charging and meter electricity flows from grid to vehicle and from vehicle to grid (V2G). A further harmonisation of these standards would ease the use of EVs in grid stabilisation. For this purpose interoperability centres have been set up in Europe and the United States to harmonise standards, technology and test procedures (Hardy, 2015). Some of the standardisation efforts by the Society of Automotive Engineers that could serve as inspiration are presented in Appendix B.

Consumption

Consumer to prosumer

The transition from traditional consumers to prosumers will be accompanied by a variety of technological innovations ranging from local generation, storage and controls to innovative transaction technologies.

QI gaps that will arise: Some of the QI aspects required for a smooth transition have been discussed in previous functionalities (CMM, storage, etc.). One gap that remains to be discussed is the regulatory discrepancy concerning transaction, self-generation and self-consumption. This includes QI aspects such as performance, cost reporting and transaction safety to ensure that prosumers maintain consumer protection.

There are a number of showcase projects worldwide that are demonstrating the prosumer concept and can be considered as use cases in the development of regulations, policy guidelines and QI. Common definitions and specific legislation on prosumers are needed. The European Parliament has called for one definition of prosumers throughout the European Union and for measures in new energy legislation to that will encourage investment into self-generation capacity. The level of QI and regulatory framework strongly varies from region to region and depends on the number of project implementations and government incentives. Many innovative projects that are currently deployed rely on proprietary technology standards and bilateral regulatory agreements with the concerned governments.

Interconnection/interoperability/conversion

Once again, these functionalities will evolve as a result of technological innovations in control and converter technologies, requiring QI to ensure a wide deployment of mini-grids that are a) able to transition between grid-connected and islanded mode seamlessly (black start, system restoration, resynchronisation, shedding of non-critical loads, etc.); and b) able to scale easily, exhibiting modular, plug-and-play functionalities, with communication and control protocols determined by a comprehensive set of standards.

QI gaps that will arise: Manufacturer interviews have shown that the required technology is perceived as mature and component standards will follow (multiple-input/multiple-output converters; dual-mode inverters; high-gain, high-power converters; etc.), but mini-grids with advanced functionalities have mostly been implemented. The indicated gaps in QI that might inhibit a future mass deployment are recurring ones: a lack of clear national standards (significant progress has been made in international standardisation in recent years, *i.e.* IEEE 1547 and IEEE 2030 series) and interconnection regulations that are applicable in actual use cases, and proprietary QI-elements inhibiting optimal interoperability (little customisation required). There are a limited number of companies/developers currently capable of developing a (hybrid) system that allows a seamless transition from grid-connected to islanded mode, due to in-house testing, research, and proprietary standards and quality protocols. The technical capabilities and proprietary QI are present, as demonstrated by the ABB Longmeadow facility. To support further market maturity and reduce the market entrance barrier for smaller players, the return of experience on these projects should be translated in a further QI development.

ABB Longmeadow facility demonstrating islanding capabilities

The ABB Longmeadow facility was plagued by frequent voltage dips and power disruptions, requiring four diesel generators as a back-up (high fuel cost + slow ramp-up times). To address this, ABB installed a 380 kilowatt-hour PowerStore battery based on lithium-ion (Li-ion) technology and a Microgrid Plus Control System, as well as a 750 kilowatt peak rooftop solar PV system in addition to two remaining 600 kilovolt-ampere diesel generators. According to in-house standards, the PowerStore battery system forms the grid and provides power to the load while maintaining utility-grade power quality for the site. A cloud-based monitoring system enables remote O&M of the mini-grid, in keeping with ABB's industrial IoT approach.

Source: ABB, 2017

Case demonstrating the design and operational challenges of an innovative renewable mini-grid with grid-forming capabilities

REIDS

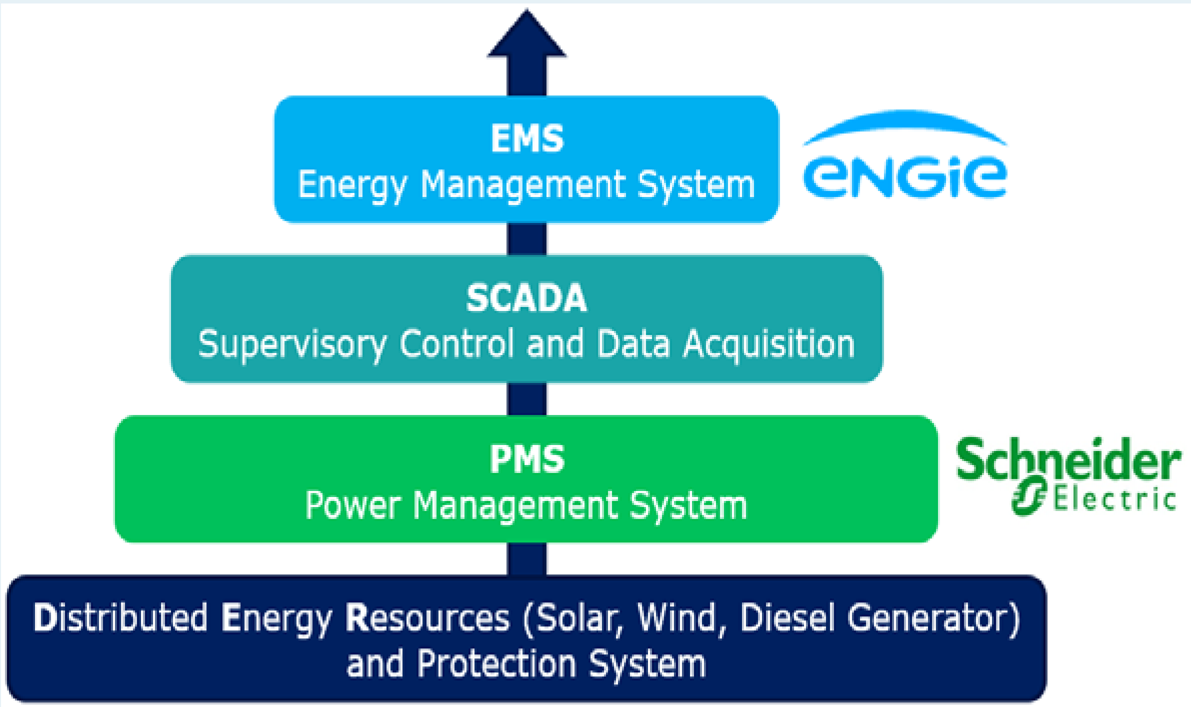
Nanyang Technological University Singapore (NTU) launched the Renewable Energy Integration Demonstrator Singapore (REIDS) initiative, a mini-grid demonstrator in a tropical environment. NTU, ENGIE and Schneider Electric have joined forces to set up a research mini-grid solution.

This mini-grid consists of different grid-following assets: PV panels, wind turbines, Li-ion batteries and a hydrogen system; and also several grid-forming assets: diesel generators, a virtual synchronous generator and a simulated bio-genset. The virtual synchronous generator is creating virtual inertia, making this asset a grid-forming one.

Interoperability is one of the major challenges in this project. It entails:

- The integration of different technologies, from different manufacturers, in one coherent functional system
- As the levels of the management system of the mini-grid are developed by different entities (*i.e.* Figure 49), these have different objectives and proprietary algorithms. This requires an agreement on concrete input/output exchanges in order to successfully build an interface for the systems to communicate.

Figure 49 SPORE management system



The objective of the project is to study the behaviour of the mini-grid for different configurations, and thus assessing the technical limits. A large number of tests are planned in order to ultimately extrapolate general trends and possible quality issues for similar mini-grids. As Belgian and French experts are notably working on this project, the EN 50160 standard is currently used to indicate the targets of the mini-grid in terms of stability. The use of standards will be validated during tests and adjusted to fit the Asia-Pacific context. Some of the tests are:

1. Black start

Black start is the process of establishing the electric power of the microgrid without relying on any external electric power transmission network. Gensets are able to perform this but the virtual synchronous generator could allow it without the use of fossil fuel.

2. Synchronisation

Synchronisation of any assets is tested; the behaviour of the microgrid is recorded and then studied.

3. Step load

Step loads are performed for any asset combinations by using the load bench of 400 kW set up on the island. The impact on parameters such as frequency and voltage is monitored.

4. N-1 situations

The loss of an asset is also studied for any asset combination and different load set points. The loss of an asset can be related to a default or simply because of a sudden cloud over the PV panels.

5. Production fluctuations

Power fluctuations are likely to happen while using renewable energy, notably as a result of a cloud or a wind gust. This use case is thus really important.

6. Energising the medium-voltage matrix

One of the most interesting aspect of mini-grids is that they can possibly connect and disconnect to the main grid or other mini-grids. Energizing the medium-voltage/low-voltage transformer will require a sudden high demand of reactive energy and will cause perturbations on the mini-grid. This behaviour will be studied.

7. Protections

The protection scheme will also be assessed if a defect occurs. The defect will be created on purpose to study this phenomenon.

8. Power quality

Harmonics, unbalances or flickers are measured to assess the robustness of the grid. The EN50160 standards can be taken as a reference in this case.

9. Optimisation

The objective is to assess the optimisation performed by the energy management system by letting the microgrid run on its own for several weeks.

Test bed for the mini-grids of the future

To bridge some of the aforementioned gaps, new technologies and prototypes will have to be tested before being implemented in commercial mini-grids, new standards and technical regulations will have to be drafted, mini-grid operators and other personnel will have to be trained, and stakeholder acceptance has to be developed to demonstrate the advanced capabilities of innovative mini-grids. The challenge lies in the development of mini-grid test beds that fulfil the variety of future needs for the different mini-grid applications.

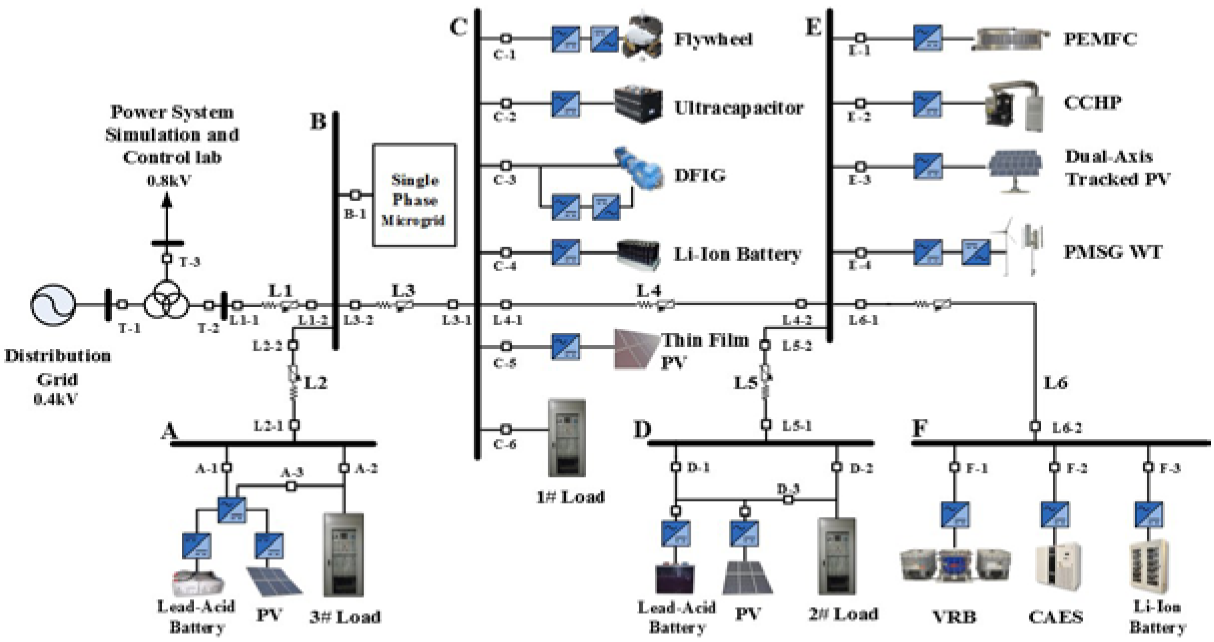
Besides some of the cases mentioned above, the **Tianjin University microgrid test bed (TUMT)** will serve as example to demonstrate how this can be accomplished in a mini-grid test bed.

Configuration

The TUMT is a low-voltage alternating current (AC) mini-grid test bed, coupled to a local low-voltage grid (0.4 kilovolts [kV]). It consists of multiple distributed generation sources such as PV installations; wind turbines; a combined cooling, heating and power system (CCHP); a proton-exchange membrane fuel cell (PEMFC); and different kinds of energy storage systems, including Li-Ion batteries, ultra-capacitors, flywheels, etc. It incorporates multiple energy carriers such as electricity, hydrogen and natural gas. The interface converters are specifically designed such that the control strategies of the converters are open to researchers, which enables them to develop innovative strategies and algorithms.

The reconfigurable and versatile character of the test bed and the opportunity to change the network topology allows it to test the customised needs of a variety of existing and future mini-grid technologies (*e.g.* stand-alone and grid-connected mini-grids with multiple energy carriers). To further extend the capability of modelling realistic microgrids operation, the physical equipment is complemented with hardware-in-the-loop real-time simulation platforms. The layout of the test bed is demonstrated in Figure 50.

Figure 50 Layout of the TUMT



Note: DFIG = doubly fed induction generator; PMSG WT = permanent magnet synchronous generator wind turbine; VRB = vanadium redox battery; CAES = compressed air energy storage.
Source: (Li, 2018).

Quality elements

The manner in which this test bed facilitates the deployment of innovative mini-grid technologies and the development of associated quality elements (*e.g.* standards, test protocols and safety guidelines) is the following:

1. Prototype testing for mini-grid projects: a number of influential industrial microgrid projects use TUMT in the early-stage testing of their prototypes, where system designs (from equipment specification to controls and management systems) are validated in a range of studies. Examples of practical mini-grid tests are: Dongfushan microgrid, Yongxing Island microgrid and some island microgrids in the Maldives.

2. Standardisation and technical regulation: the practice of using TUMT in industrial and research microgrid projects has contributed the formulation of standards in various levels, as summarised in Table 8.

Table 8 Examples of contributions to standards and guidelines from the TUMT

Identifier	Type	Title
P2030.9	IEEE Standard	Recommended Practice for the Planning and Design of the Microgrid
GB/T 36274-2018	National Standard	Technical Specification for Energy Management System of Microgrids
T/CEC 5005-2018	China Electricity Council Standard	Design Code for Microgrid
T/CEC 106-2016	China Electricity Council Standard	Evaluation Guides of Planning and Designing for Microgrid

3. Personnel and practitioner training: TUMT currently hosts two undergraduate courses and one graduate course in the electrical engineering curriculum of Tianjin University. On average 100 students graduate each year with a good understanding of microgrid technology and enter the power system industry.

4. Stakeholder acceptance: TUMT routinely holds demonstration tours for practitioners from utility companies, conference attendees and the general public including middle school students.

Impact on market development

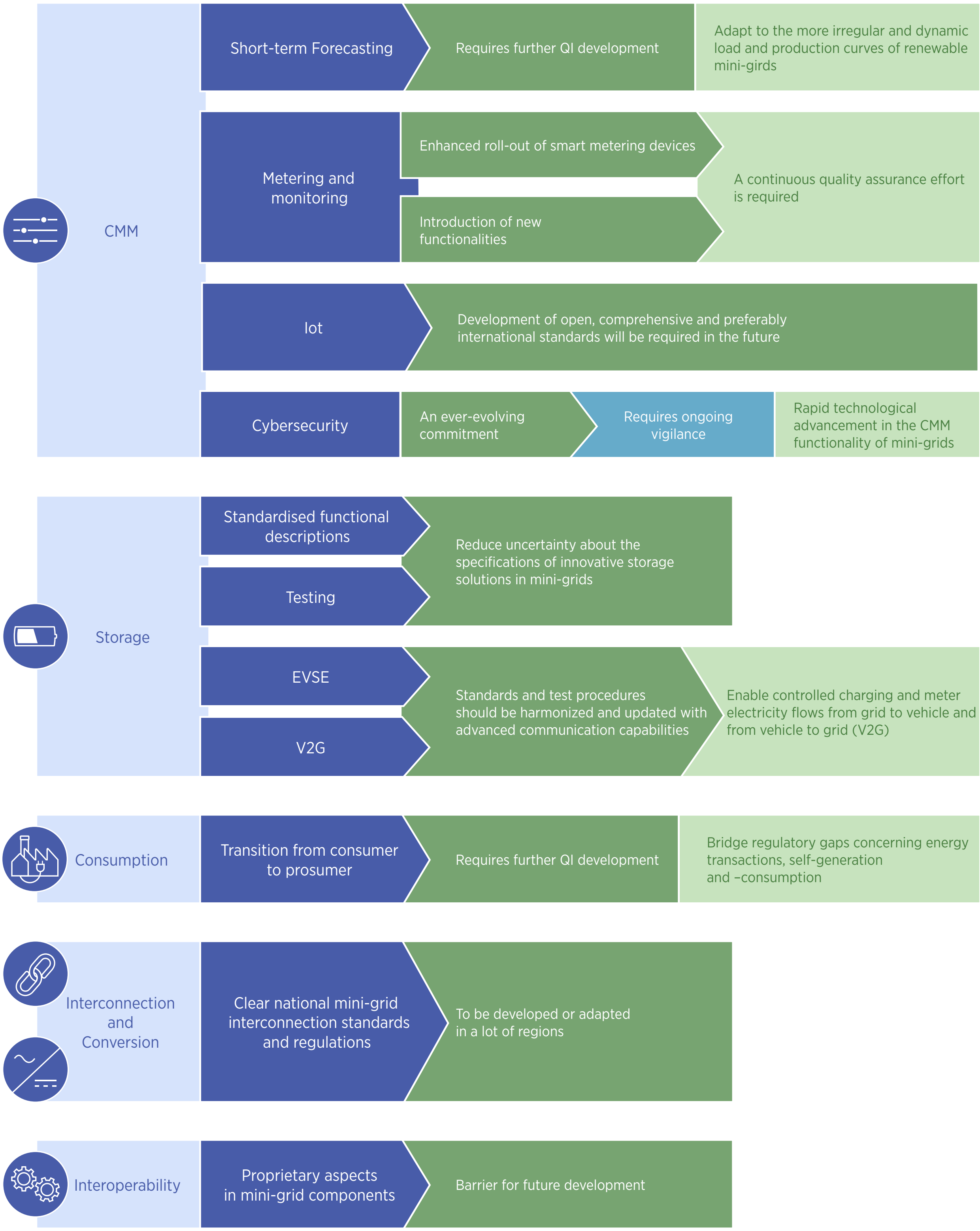
TUMT has been used as the laboratory prototype for a number of influential and innovative mini-grid demonstrations and commercial projects in China (*e.g.* the world's first water desalination mini-grid). The presence of this testing facility within the national QI has contributed to the development of new standards and has instilled confidence in both commercial and innovative mini-grid projects.

The cost of implementing these testing procedures is minimal and compensated by the accelerated iteration process, thanks to the deliberate design of TUMT where flexibility and openness is stressed. Mini-grid project developers are encouraged to conduct laboratory testing in different stages, and for newly founded test laboratories to adopt a similar design philosophy as TUMT.

Summary of gaps in standards and quality control

A list of the domains in which QI efforts are still required is summarised in Figure 51.

Figure 51 Summary of gaps in standards and quality control for future mini-grids



4.2 Emerging trends: Low-voltage direct current mini-grids

The characteristics of renewable mini-grids (DC power generation, limited system size and user profiles) also enable the introduction of "new" means of distributing energy to the end user to make its consumption more efficient and cost-effective. Low-voltage DC (LVDC) mini-grids and appliances are essential to mention in this regard.

DC distribution is a key enabling technology to improve the future connection of more distributed renewables that are more efficient and better controlled. LVDC mini-grids exhibit several benefits over conventional AC mini-grids with regard to power quality, reliability, expandability, and especially energy and cost efficiency, due to a reduced number of components and conversion steps. LVDC grids can be used in data centres and commercial buildings, but also show great promise for use in renewables-based mini-grids as they eliminate the need for inverters working at part load, which diminishes efficiency.

Most homes and appliances are designed to operate in AC, and most electricity delivered by utilities is AC, mainly due to the fact that the transformer allowed for an easy transition between AC voltages. Many of the advantages that AC distribution used to have are slowly diminishing, due to the rapid development of power electronics and the enhanced use of renewable DERs. The specific technical issues that used to limit the adoption of LVDC grids have been largely resolved, although some remain (Beheshtaein, et al., 2015):

» **Grounding/bonding/earthing:** There is still a lack of information concerning the appropriate design of grounding/bonding/earthing systems for DC mini-grids.

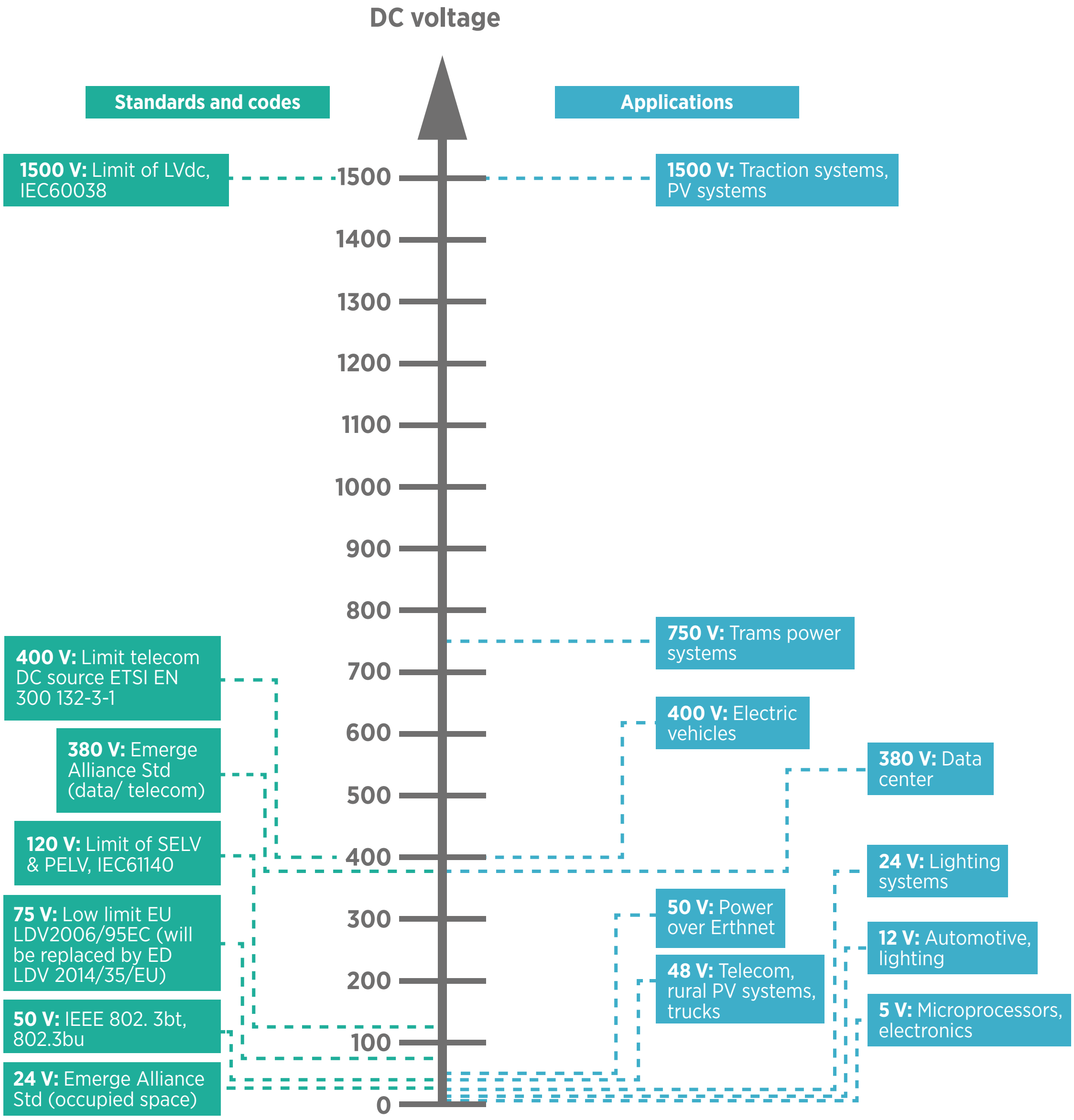
» **Protection and safety:** One of the fundamental challenges of DC protection is that there are no zero-crossing currents, making faults more difficult to interrupt with fuses and circuit breakers. This makes the provision of a good level of protection and safety for an active LVDC last-mile distribution network difficult. There are other protection challenges for DC mini-grids (*e.g.* arcing and high fault clearing times of DC circuit breakers, stability during faults and restoration process, etc.), but these will not be detailed in this report. For more information on these issues refer to (Augustine, et al., 2018).

Probably the largest drawback of DC distribution is that it limits the appliances that can be used, as these are still mostly designed for use with AC grids (IRENA, 2016). However, many appliances used today are more efficiently used with DC power or even require an extra AC-DC adaptor for their functioning (LED lighting; electronics found in TVs, mobiles and computers; brushless DC motors; variable frequency drives). The market for DC appliances is growing, both for productive use applications (*i.e.* GIZ "Photovoltaics for productive use applications: A catalogue of DC-appliances" [Mundt, 2016]) and non-productive (*e.g.* M-Kopa solar TV or SunDanzer DC refrigerators), but further QI development is needed for the enhanced deployment of LVDC appliances.

Standardisation efforts

Although it is considered a novel segment in the mini-grid market, DC distribution systems are already being used (and standardised) for various other applications. Figure 52 shows some existing standards, codes and applications of DC distribution systems.

Figure 52 Voltages, codes and standards of various DC distribution applications



Note: SELV = safety extra-low voltage; PELV = protected extra-low voltage; LDV = laser Doppler vibrometer.
Based on: (Rodriguez-Diaz, et al., 2016).

Despite the aforementioned standards and codes, there is still a lot of ground to cover to come to comprehensive standards for LVDC mini-grids. Interesting efforts to mention in this regard are:

- IEC System Committees SyC LVDC: Low Voltage Direct Current and Low Voltage Direct Current for Electricity Access (IEC, 2018)
- IEEE 2030.10: Standard for DC Microgrids for Rural and Remote Electricity Access Applications (IEEE SA, 2018).

For a more complete list of standardisation efforts, refer to Appendix B.

Arrangements are being made (*i.e.* IEC) to combine several standardisation efforts into a comprehensive set of standards, enabling easier implementation and adaptation to technological advancements.

International and national standardisation bodies (*e.g.* Bureau of Indian Standards [BIS] LVDC Committee) acknowledge the enhanced need for DC-compatible appliances and have amended certain standards in order to accommodate this need, but many provisions and requirements still should be added to existing AC standards.

As an example, India is one of the leading nations in the implementation of DC mini-grids for electrification purposes. Its national policy for renewable energy-based micro- and mini-grids includes specifications concerning DC configurations. Some active organisations on this matter are Mera Gao Power, which owns and operates microgrids in Uttar Pradesh, in around 900 villages; and Balance of Storage Systems (BOS), a German start-up that installs smart DC mini-grids in the north of India and provides training to local technicians for on-site support and quality control.

QI gaps

The lack of standards and guidelines for DC mini-grids is one of their major challenges. This gap in QI combined with a relative lack of practical experience means that for DC mini-grid stakeholders, there is little to depend on for safety and functionality.

As shown in Figure 53, despite some differences in future perspective there is a general consensus concerning the identified (general) QI gaps that will need solutions for the successful deployment of DC mini-grids in the future. Some of these solutions include:

» New standards or adjustments of AC appliance standards to accommodate differences with LVDC applications (plugs, sockets, earthing, overvoltage/current, fault detection, etc.)

» Development of new standards and testing specifications specifically targeting system safety, protection design (see Figure 53), grounding, communication protocols and power quality.

» Standardisation of DC system voltages (12 volt [V], 24 V, 48 V, 110 V, 350 V, 380 V, etc.), installation guidelines and certifications. This will reduce uncertainty and barriers for contractors.

» Co-operation among the various stakeholders to obtain a comprehensive and universally applicable QI:

    o standardisation development and compliance: IEC, ITU, International Organization for Standardisation (ISO), IEEE, African Electrotechnical Standardization Commission, CENELEC, etc.

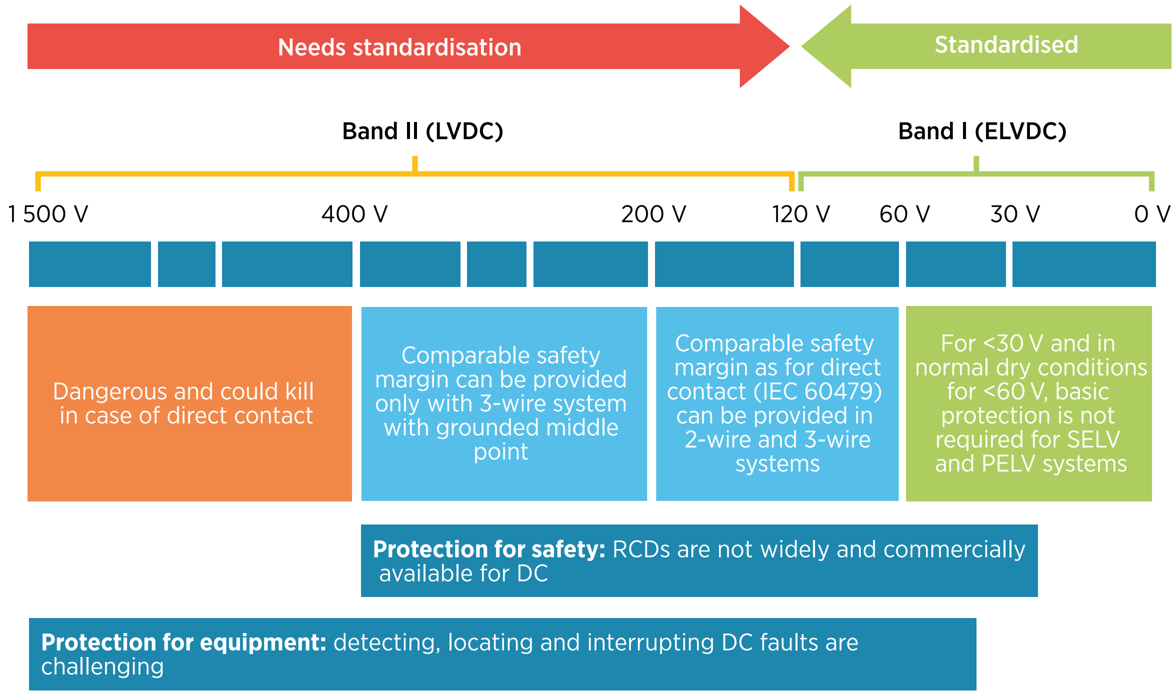
    o testing and certification bodies

    o research and development: academia, component developers and utilities

    o compliance: contractors, utilities and operators

    o integration in various QI bodies of experts and stakeholders familiar with the challenges faced in electrification efforts: United Nations, International Finance Corporation, IRENA, World Bank, mini-grid installers ,etc.

Figure 53 DC mini-grid standardisation needs by nominal voltage level[3]



Note: ELVDC = extra-low voltage DC; RCDs = residual-current devices; SELV = separated or safety extra-low voltage; PELV = protected extra-low voltage.
Based on: (Augustine, et al., 2018).

3 SELV = safety extra-low voltage: an electrical system in which the voltage cannot exceed extra-low voltage (ELV) under normal conditions, and under single-fault conditions, including earth faults in other circuits (IEC 61140).
PELV = protected extra-low voltage: an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, except earth faults in other circuits (IEC 61140).

05

5. POLICY FRAMEWORKS FOR QUALITY INFRASTRUCTURE

Chapter 5 illustrates the importance of a defined mini-grid policy and more specifically, the reference to quality infrastructure (QI) in policy will be demonstrated through a number of cases that can be viewed as exemplary for policy frameworks for mini-grids of the future.

Key information in this chapter:

- countries that have included QI in their policies and guidelines
- summary of recommendations for policy makers.

5.1 The role of policy frameworks influence of QI

Policy plays a key role in the growth of renewable energy mini-grids.[4] The solar PV market has shown that a favourable investment climate, through incentives and regulations, is essential for rapid market uptake. One of the biggest difficulties is to formulate clear policy goals that can catalyse mini-grid implementation, taking into account demographic changes, industrial evolutions, urban development and the electrical infrastructure required to facilitate these.

In theory, the development of QI follows the market, as it benefits all industry stakeholders to establish a quality market, with satisfied end users and regulations that are based on the needs of the market. Unfortunately, the complexity of mini-grids and their disruptive character with regard to grid operation has led to decision-making inertia. This has sometimes led to situations where mini-grid policy, or the lack thereof, is a bottleneck, rather than a stimulant for development. On the other hand, policy reforms that aim to develop a market (too) quickly without a sufficiently developed QI can also be harmful for sustainable development.

Examples of both are:

1. Policy inertia leading to development bottlenecks

» **Example:** Mini-grid value stream limitation: The inherent control functionality of mini-grids makes it possible to control production and demand within a mini-grid. In the future this could allow mini-grids to participate in grid balancing services (*e.g.* ancillary services) for a connected grid. This would open up new revenue streams for mini-grids, by allowing them to make an economic optimisation between auto-consumption and grid support. Ancillary service markets and wholesale markets would have to implement reform policies to allow mini-grids (and other flexible loads and renewable generation) to participate. This could happen in the form of dynamic pricing (time-of-use) or tailored mini-grid tariffs.

  Some of these mini-grid policy reforms are faced with decision-making inertia, or a very slow transition, as policy is traditionally focused on conventional generation/consumption patterns and interests.

  The policies would have to refer to QI (standards, testing, etc.) to specify and control the requirements for market participation, as is the case for traditional generators (and increasingly for variable renewable energy sources). As long as policy frameworks with referral to QI are not sufficiently present, these innovations cannot take place on a larger scale.

Recommendations: Instead of instituting premature policy frameworks, **pioneer projects** could be used as proof of concept, and involve policy makers, developers and utilities. Examples of projects that are trialling innovative market configurations are the Brooklyn mini-grid project or the LO3 Landau mini-grid project backed by EnergieSudwest and co-owned by Enovos and the City of Landau, with support of the Karlsruhe Institute of Technology. The approach involves establishing an innovative mini-grid using blockchain to develop a transactive energy market with residential and commercial participants. The participant data and return of experience could serve as inspiration for policy reforms, market model development and further QI development (new standards, tariff schemes, inspection organs, certification bodies, etc.).

2. Policy disconnected from QI development

» **Example: PV system failures in Nigeria:** Although Nigeria has recently implemented a number of QI aspects in its regulatory and policy framework, in the past they were severely lacking. A study has shown that many PV systems failed within two to three years of deployment, whereas the lifespan of most PV systems of good quality ranges from 20 years to 25 years (Akinyele, et al., 2018). This has led to scepticism among solar PV mini-grid developers and development funds about the viability of a mini-grid market.

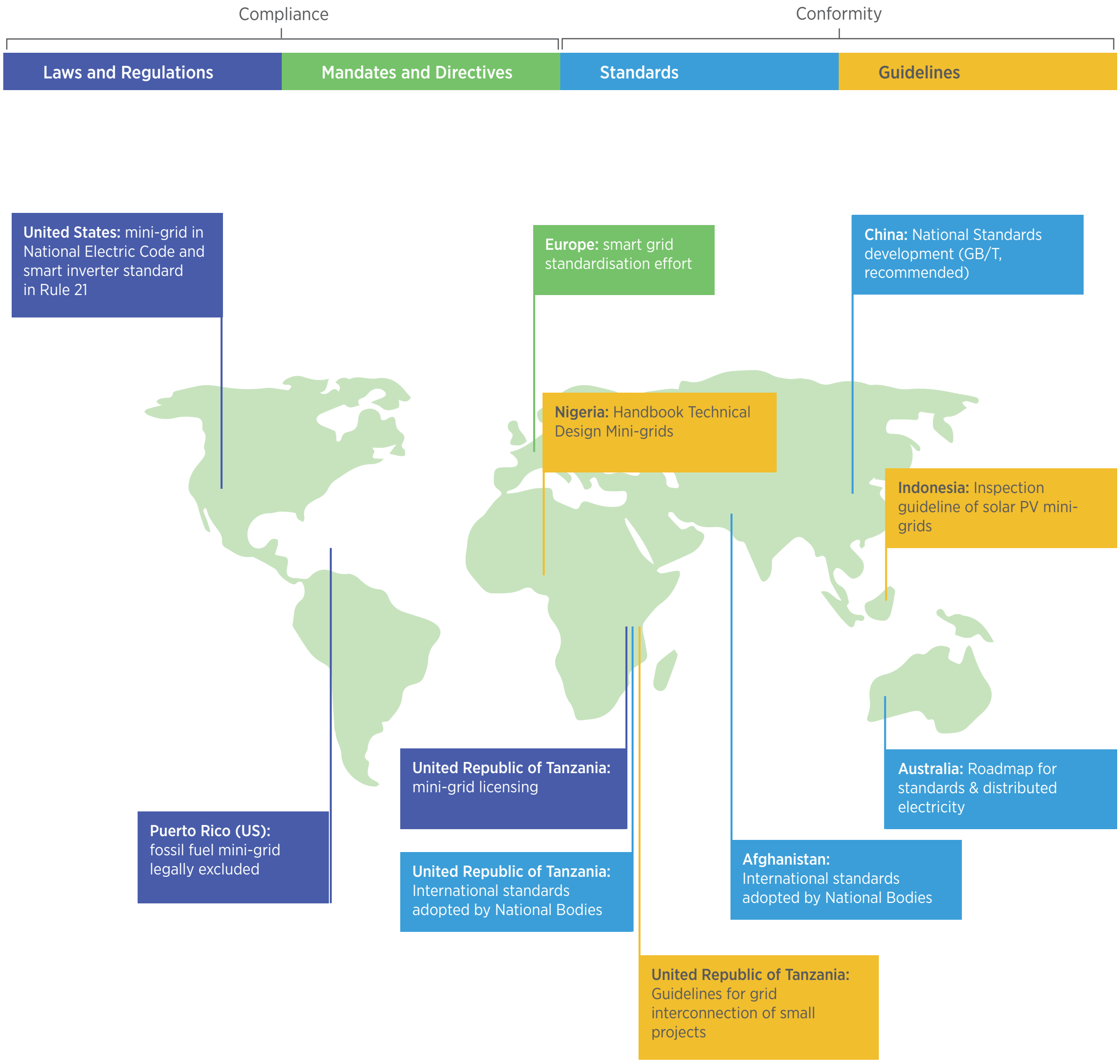
Recommendations: Referring to quality guidelines or requirements in policy that aim to stimulate market development is sometimes considered inhibiting. The aim of this section is to demonstrate that mini-grids need a certain level of national and international QI for a sustainable market and that policy should refer to **different levels of QI** at **different times of market development**.

5.2 How to integrate QI into policy frameworks

Conformity and compliance

There are different means of integrating QI into mini-grid policy (*e.g.* national mini-grid policy), which are partially dependent on the market stage. In an incipient mini-grid market it might be easier and more effective for policy makers to issue safety and design guidelines than to integrate QI into legislative actions (laws, mandates and technical regulations). Figure 54 illustrates the different levels in which QI can be enforced or implemented, and illustrates cases from different countries that have included QI in their policies and guidelines.

Figure 54 Different aspects of policy referring to QI



Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

The different aspects of QI in policy have been divided into two main categories:

1. Conformity

Policy frameworks can facilitate the conformity of mini-grid systems to (international and national) standards and codes. This can happen in the form of standards and guidelines defining which technical considerations are relevant in the design, operation and testing on a national or regional level. In the early stages of mini-grid markets, policies will mostly refer to voluntary (international) standards and guidelines with few enforced safety regulations. In a further stage, policy frameworks can include the development of national standards by a statutory body such as a governmental agency, and the participation in international standard formation.

2. Compliance

The legal framework in policy determines which regulations, laws, codes, mandates and directives must be complied with and how compliance will be inspected and enforced. This also includes licensing and mini-grid enlisting procedures. The first step in the development of a clear legislative framework for mini-grids is to provide a legal definition of a mini-grid, to which regulation will apply. This will relieve developers from the maze of legal and technical issues currently faced in practically every mini-grid market and provide them with easily accessible compliance requirements.

Challenges for QI integration in mini-grid policy

A recurring phenomenon that makes it difficult to develop a mini-grid policy or establish a legal framework that consistently refers to mini-grid QI is the fact that there are various types of mini-grids, each with its own requirements and characteristics.

The solution to this issue is twofold:

1. An apt policy "design" for all mini-grids: Lessons from previously deployed mini-grids can be used to develop a legal and policy framework that differentiates between the different tiers of service.

- Complex large-scale systems have a high market entry barrier. As such, QI for these systems is mostly developed by private companies (proprietary QI), with the required know-how. Initially these systems will operate in a regulatory grey zone that will allow policy makers to implement the return of experience in clear public policy to lower the market barrier.
- In lower-tier mini-grids, the market barrier is lower due to a lower system complexity. For these mini-grids, policy incentivised QI and regulations are essential to protect the market from substandard installations. In a first stage, policy should proactively refer to QI, established in more developed markets.

2. Standardised mini-grids: Policy should incentivise the development of standardised mini-grid configurations instead of tailored projects, where possible. This will not only benefit the commercial viability of mini-grids but will also enable development of a more comprehensive QI policy. An example of such an incentive is the grant funding opportunity and roadmap by the California Energy Council (CEC) to stimulate standardised repeatable mini-grids (down to a finite number of configurations). The CEC sees the grant and its project outcomes as a goal to possibly answer open policy questions (CEC, 2018).

The difficulty of QI policy implementation due to mini-grid variety is summarised in Figure 55.

Figure 55 Market barriers that can be solved by policy-integrated QI

Best practices

To demonstrate how mini-grid policies have addressed the challenges above, a number of national best practices are given, starting with policy aimed at incipient markets and ending with mandatory implementation of mini-grid QI. In addition, Appendix F presents numerous strategies and actions that countries have taken in order to develop and enhance QI in their markets.

Guidelines and handbooks

Indonesia (Guidelines)

An example of a guideline specifically addressing the steps to be taken in the inspection of solar photovoltaic (PV) mini-grids is given in the EnDev2 Indonesia "Inspection guide for photovoltaic village power (PVVP) systems" (Schultz & Suryani, 2013). The different steps that are described in this guideline are given in Figure 56.

Figure 56 Different steps in the inspection of solar PV mini-grids in Indonesia

Based on: (Schultz & Suryani, 2013)

In Indonesia the mini-grid service package (MSP) methodology was used. The MSP methodology inspects the quality of the installation and later technical performance of solar PV mini-grids. It is made up of technical inspection, socio-economic survey, on-site training for operator and village management teams, photographic documentation, technical reporting, and a feedback mechanism between EBTKE (the Directorate General for New and Renewable Energy and Energy Conservation) and the engineering, procurement and construction companies. For an extensive case review please refer to the IRENA International Standards and Patents in Renewable Energy (INSPIRE) platform case studies (IRENA, 2017d).

Nigeria (Guidelines)

TFE Energy, with the support of the African Development Bank, adapted and widened the Quality Assurance Framework (QAF) for Mini-grids, developed by the US Department of Energy and the National Renewable Energy Laboratory. This tailored version supports mini-grid developers in Nigeria in delivering high-quality energy access services, including national regulatory compliance, project financial viability indicators and end-user safety guidelines. Its comprehensive set of standards covers power quality, reliability and availability, and a protocol for reporting performance is based on these standards.

With the use of the Odyssey web-based platform, the developers use a designated dashboard to ensure compliance with the regulations and monitor the mini-grid's important performance metrics (Odyssey Energy Solutions, 2019). The data are secure and accessible only to the developers themselves; however, where appropriate, aggregated and anonymised data can be shared with other parties such regulators (for example in order for them to check developer regulatory compliance) or investors (for example to allow them to track their investments). This ability to aggregate data and projects and provide common indicators for comparison is key to the value this framework offers donors, industry support groups and investors. This initiative is done in close consultation with the Africa Mini-Grid Developers Association, the Nigerian Electricity Regulatory Commission, the Rural Electrification Authority of Nigeria and individual mini-grid developers (ESI Africa, 2019).

United Republic of Tanzania (Guidelines)

As a response to regulatory uncertainties concerning possible grid extensions, the Tanzania Energy and Water Utilities Regulatory Authority (EWURA) has developed the *Guidelines for Grid Interconnection of Small Power Projects in Tanzania* (EWURA, 2011). The technical guidelines of this document contain a comprehensive description of the recommended standards and engineering recommendations to be taken into account when designing a system capable of grid connection.

The complete document consists of three parts:

» Part A: Guidelines for Grid Interconnection of Small Power Projects in Tanzania

» Part B: Guidelines for Grid Interconnection of Small Power Projects in Tanzania – Technical Guidelines

» Part C: Appendices – Studies to Be Conducted, Islanding and Protection.

Example of a guideline concerning harmonics:

> "To avoid excessive harmonic distortion on the DNO [distribution network operator] system, the EG [embedded generator] installation shall be designed and operated to comply with the criteria specified in UK Engineering Recommendation G5/4-1" (EWURA, 2011).

Nigeria (Handbook)

The mini-grid design course handbook with a focus on solar PV and micro-hydro, issued by the Nigerian Energy Support Programme in pursuit of conformity with the Nigerian Competency Standards for Clean Energy, provides an introductory look at the technical design aspect of mini-grids for rural electrification. It also provides an overlook of the different legislative players and the licensing institutions for mini-grids (generation, distribution, transmission licence) (GOPA Consultants, 2017).

There are a number of other national and international guidelines and handbooks referencing relevant standards and QI aspects related to the various tiers of service of mini-grids. As mentioned before, the higher the complexity of the mini-grid, the higher the degree of customisation, so comprehensive guidelines are not possible.

An interesting platform to find renewable energy standards that are commonly used on the international stage is the previously mentioned IRENA INSPIRE platform (IRENA, 2020). It also provides guides on mini-grid components such as small wind turbines and reports aiding in the integration of QI in public policy. The Technical Brochures of Study Committee C6 of the Council on Large Electric Systems (CIGRE) can be used to inform policy makers on the current developments in the field of distributed energy and aide them in the development of guidelines.

Standards

Standardisation efforts can be incentivised by policy in order to stimulate a robust market. While the development or adoption of standards for PV equipment, small wind turbines, combined heat and power, and other generation components are more advanced on both national and international scales, there are few countries currently developing national mini-grid standards related to the other core mini-grid functionalities (China, Germany and the United States are the most active).

Standard adoption

There are a number of countries that adopt international standards under a national reference, which is often sufficient to prevent substandard systems. However, interconnection standards such as UL 1741 and IEEE 1547 (from the Institute of Electrical and Electronics Engineers) often set excessive requirements for certain mini-grid markets at early stages of their development. The need for nationally developed interconnection standards (possibly based on UL 1741, IEEE 1547, E DIN EN 62909-2 VDE 0558-909-2: 2018-02, etc.) is seen as a necessary step to further develop national mini-grid QI in the future.

Mini-grid international standards adopted by national and continental standardisation bodies

Afghanistan

AS 423, AS 424, AS 425, AS 523, AS 462, AS 524, AS 526, AS 525, AS 426, AS 468 (IEC/TS 62257-1, 2, 3, 4, 5, 6, 7, 7.1, 7.3, 9.1): Recommendations for small renewable energy and hybrid systems for rural electrification parts 1 to 7.3 and 9.1.

Africa

The African Electrotechnical Standardization Commission (AFSEC) is very active in adopting appropriate standards for its members to promote the use of common electrotechnical standards and a conformance system in Africa. AFSEC/International Electrotechnical Commission (IEC) technical committees (TCs), relevant for mini-grids:

- AFSEC TC 8: system aspects for electrical energy supply
- AFSEC TC 13: electrical energy measurement and control
- AFSEC TC 57: power system management and associated information exchange
- AFSEC TC 64: electrical installations and protection against electric shock
- AFSEC TC 82: solar PV energy systems.

United Republic of Tanzania

TZS 1911-1(IEC 61427-1): Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 1: Photovoltaic off-grid application

TZS 1628-2(IEC 62053-11): Electricity metering equipment (a.c.) – Particular requirements – Part 11: Electromechanical meters for active energy (classes 0.5, 1 and 2)

TZS 1628-1(IEC 62053-21): Electricity metering equipment (a.c.) – Particular requirements – Part 21: Static meters for active energy (classes 1 and 2)

TZS 1951-9-5 (IEC TS 62257-9-5): Recommendations for renewable energy and hybrid systems for rural electrification – Part 9-5: Integrated systems – Selection of stand-alone lighting kits for rural electrification

Source: (IEC, 2020a).

Standard development

Policy frameworks for the development of standards are needed as a response to quality gaps in a developing market. For policy makers, these standards will eventually form the technical basis for mini-grid regulation. In a first step, most standards will be voluntary or recommended, to enable the industry to provide feedback and adjust where needed.

Mini-grid standard development efforts

Australia

An aid for detecting QI gaps and future standardisation requirements is the "Roadmap for standards and the future of distributed electricity" (Standards Australia, 2017) as developed by Standards Australia. However, Standards Australia is not a government body, but the government tasks it with meeting Australia's need for modern, internationally aligned standards and related services. It uses input from a number of industry stakeholders (in this case Standards Australia, Energy Networks Australia and the Commonwealth Scientific and Industrial Research Organisation) and determines which actions are to be taken. For policy makers it is a useful tool to establish appropriate regulation, since it allows them to identify which national and international standards to refer to and which will become relevant in future development for proactive legislative actions and incentives.

Some conclusions concerning mini-grids from the roadmap:

» Australia should work with the IEC Systems Evaluation Group 6 (non-conventional distribution networks/microgrids), led by industry and government stakeholders. This may require a separate roadmapping exercise.

» To help line up Australian terminology with that golbally, industry and government stakeholders should submit a propsal to create a committee that mirrors IEC TC 1 Terminology.

» Australia needs better coordination of standardisation in terms of data frameworks and privacy related to electricity networks (Standards Australia, 2017).

China

National standards development in China is governed by the Standardisation Administration of the People's Republic of China and is legislated through the Standardisation Law of the People's Republic of China. There are few mini-grid specific (controls, grid connection, etc.) standards that have mandatory compliancy. China is quite active in the development of recommended national mini-grid standards, prefixed GB/T (mandatory standards are prefixed GB), such as:

- GB/T 33589-2017 : technical requirements for connecting microgrid to power system
- GB/T 34930-2017: operation and control specification for microgrids connected to distribution network
- GB/Z 34161-2017: technical guide for smart protection equipment of microgrid
- GB/T 34129-2017: specification for test of microgrid connected to distribution network
- GB/T 36274-2018: technical specification for energy management system of microgrids
- GB/T 36270-2018: technical specification for monitoring and control system of microgrids
- GB/T 34866-2017: vanadium flow battery – safety requirements
- NB/T[5] 31093-2016: technical specification for main controller of wind turbine generator system with microgrid
- NB/T 31092-2016: performance and safety technical specification of wind turbine generator system with microgrid.

Codes and regulations

Mini-grids in electrical codes

United States

The National Electrical Code (NEC), or NFPA 70 NEC (from the National Fire Protection Association), is not legally binding but often serves as a de facto guide for state and municipal regulations. The 2017 edition of the NEC (in effect in 19 states) addresses some of the regulatory gaps identified in the development of existing mini-grids. Although most of the newer articles are relatively short, allowing them to be amended by local regulators, they will further evolve in the future when more standardised mini-grid solutions come to market. Some mini-grid articles are:

- Article 705 Interconnected Electric Power Production Sources
- Part IV. Microgrid Systems
- 705.150 System Operation
- 705.160 Primary Power Source Connection 705.165 Reconnection to Primary Power Source 705.170 Microgrid Interconnect Devices (MID)
- Article 706 Energy Storage Systems (ESS) (New Article 706) governs ESS installation, disconnection, shutdown and safety labelling.
- Article 710 Stand-Alone Systems covers power production sources that are not connected to the grid, including PV and wind-powered systems.
- Article 712 Direct Current Microgrids concerns independent energy distribution networks that allow the utilization of power from sources to direct-current loads. Refers to UL 489 H: Molded-Case Circuit Breakers, Molded-Case Switches, and Circuit-Breaker Enclosures.

Inverters installed in the states of California and Hawaii have to comply with ruleRule 21 grid interconnection requirements and Hawaiian Electric Company (HECO) Rule 14H requirements, stating that new installations require inverters that can provide grid support or smart inverter functions, preparing them for the future. UL 1741(SA) (see Chapter 2) is used as the test standard to certify that inverters comply with the aforementioned requirements. In other words, Rule 21 and HECO 14H are Source Requirement Documents to be used with UL 1741 (UL, 2017a).

These regulations demonstrate how advanced mini-grid markets such as the ones in California and Hawaii can be encouraged by legislation to enhance smart grid functionalities in their systems and secure a pole position in the development of a regional mini-grid market. As mentioned in Chapter 2, there has been some concern from developers that such compliance requirements could reduce the amount of choice regarding inverter suppliers, although an increasing number of suppliers offer certified equipment.

Puerto Rico (US)

Puerto Rico's proposed rules for the Regulation on Microgrid Development (CEPR, 2018) are unique in that they exclude brownfield mini-grids (fossil fuels can make up a maximum of 25% of energy production)[6] as being legally recognised as a mini-grid. The proposed text can be considered exemplary legislation with regard to QI referral as it states:

- A legal mini-grid definition.
- Mini-grid classification, differentiating by size, ownership structure and the level of grid services provided.
- Procedural requirements, depending on the classification (*e.g.* certification, registration and reporting).
- A clear referral to QI elements where needed.
- Examples:
    - Section 3.05. – "Codes and Standards Microgrids shall be compliant with existing safety standards; namely, IEEE Standard 1547 for design; UL Standard 1703, UL Standard 1741, or IEEE Standard 1547 for equipment; and the National Electric Code, or any successor code or standard, as such code or standard may be revised, amended or updated from time to time" (CEPR, 2018).
    - Registration application, inspection certification from a licensed electric engineer and other quality enforcing measures are cited.
- Grid interconnection regulations.
- Clear non-compliancy penalties.
    - Section 1.16. – "Penalties: Any person who fails to comply with any of the requirements set forth in this Regulation may be subject to a Notice of Non-Compliance pursuant to Chapter IV of Regulation 85431 and may, as a result of such non-compliance, be subject to the imposition of a penalty, as provided in Article 6.36 of Act 57-2014 or any other administrative sanction deemed appropriate by the Commission" (CEPR, 2018).

Several interest groups, such as the Puerto Rico Solar Energy Industries Association, the Advanced Energy Management Alliance and the New York Smart Grid Consortium, were included in the legislative procedure to assure that the legislation has a broad support among stakeholders and is prepared for future mini-grid developments. One of those future visions is the networking of mini-grids to a smart grid to create systems large enough to service entire cities. This requires systems that are capable of interconnection and that comply with a similar set of standards. To facilitate this vision these standards are incorporated in legislation.

6 "Use of any grade of fuel oil or natural gas by a microgrid may not, in the aggregate, exceed twenty-five percent (25%) of the total energy input of the system during the 12-month period beginning with the date the facility first produces electric energy and any calendar year subsequent to the year in which the facility first produces electric energy."

Mini-grids in regulation

United Republic of Tanzania

The third generation of mini-grid regulations from EWURA have an interesting addition to their licensing procedure that can be seen as exemplary for other policy makers that find themselves in a similar market.

- » Mini-grids can acquire a single licence (>1 megawatt [MW]) or a single registration (<1 MW) if the mini-grids use the same technology. This reduces the regulatory burden and stimulates the repeatability of mini-grids.
- » Grid-connected mini-grids are legally allowed to operate in islanded mode when power supply from the main grid is not available.
- » The text provides clarity and credibility as to what happens with distribution assets when the main grid is available for interconnection, as well as the associated tariffs.

In other countries with similar markets, such as India, Kenya and Nigeria, mini-grid regulations have seen recent updates stating the differentiation in licensing requirements according to installed generation power and enhanced quality requirements. Evidently, the concerns of developers over a possible main grid extension have been taken into account as both regulations state compensatory measures to instil some sort of confidence in local developers as well as facilitate the repeatability and scalability of projects.

Mandates and directives

Mandates that stimulate mini-grid QI

Europe

The mandated smart grid standardisation effort of the European Commission to stimulate smart grid deployment is an effective strategy to secure regional QI. This is a policy effort that is unique due to its scale. It considers a number of directives (*e.g.* Directive 2004/108/EC on Electromagnetic Compatibility, Regulation (EC) No 2006/2004 on co-operation among national authorities responsible for the enforcement of consumer protection law) and required the European Committee for Standardization, the European Committee for Electrotechnical Standardization and the European Telecommunications Standards Institute to develop a framework to enable European standardisation organisations to perform continuous standards enhancement and development.

Although this is an exemplary QI effort from policy makers, market regulatory inertia has so far limited the deployment of mini-grids and smart grids in Europe. The Clean Energy Package is another policy effort that attempts to stimulate market innovation, mandating consumer generation, community energy schemes, and the adoption of new technologies and associated QI, among many other things.

International measures to control the quality of imports

There are currently very few quality-based import controls for mini-grid components, mainly in order to maintain international trade relationships and to avoid over-regulation on a state or provincial level. In some cases it is quite important that import controls be present, especially in incipient markets focused on cost reduction that are vulnerable to substandard or counterfeit components.

Incentives

For renewable energy systems, quality has been coupled to policy incentives in a number of cases, such as feed-in tariffs, renewable energy certificates and tax credits (IRENA, 2017a). Due to the incipient state of most mini-grid markets, most incentives focus on the bankability of projects rather than quality. In Appendix F, the Bangladesh Infrastructure Development Company Limited strategy is mentioned as a means to enhance the perceived benefits of QI through incentives when few statutory quality bodies or limited QI are present. In doing so, a quality culture is built up among developers, boosting QI development on a national level.

Recommendations:

- » Tax breaks could be offered to developers or operators that design and operate their system according to quality standards. One option is to exempt licensed or approved mini-grids from value-added tax. Another possibility is to use tax holidays, reduced tax rates or adjusted depreciation timelines to reduce the tax on corporate profits on mini-grids.
- » Licensing or registration processes could include quality incentives (next to the compliant safety and operational requirements discussed earlier). If the design includes accessible performance monitoring, pre-emptive compliance to grid interconnection codes (for off-grid systems) or the development of training facilities, this should be rewarded in the licensing procedure.
- » Incentives could be put in place in the form of governmental funds, to support the trial of new breakthroughs in mini-grids and validate their impact on the project feasibility, planning and regulatory requirements. The lessons learned from these projects can be used to draft new regulations, quality requirements and support initiatives. An example of such an innovation incentive is the New York prize administered by the New York State Energy Research and Development Authority. It can be used to fund mini-grid feasibility studies, audit-grade engineering design and business planning, and project implementation and monitoring once in operation.

Key recommendations

Refer to the available international and national quality infrastructure when drafting mini-grid regulations and policy. When doing this, it is crucial to consider the current level of market development and to adjust quality requirements accordingly. The predominant focus should be the end-user safety and reliability of supply.

Include the various stakeholders (utilities, investors, developers, regulators, grid operators, users and academia) in the drafting of mini-grid policy and regulations and make use of **pioneer projects** to establish quality requirements and to support QI development.

Represent national interests in international technical standardisation committees and possibly establish mirroring national committees to be in line with international standardisation efforts. International standards have the goal to provide standards that are globally applicable (*e.g.* to refer to in policy/regulations). However, the application of mini-grids serves different purposes for different areas, so standards and other QI elements should be adjusted to the local needs.

Make use of the international return of experience to **draft guidelines and handbooks** that limit the administrative and technical barriers for mini-grid developers and investors.

Provide a **dedicated mini-grid regulation** or include mini-grids in the national electric code. Regulatory texts should provide:

- a **clear legal definition** of what is considered a mini-grid
- a **mini-grid classification**, differentiating by size, ownership structure and/or the level of grid services provided. Mini-grid policy and legislation/regulation should differentiate between various types of mini-grids (see Table 2) and refer to quality requirements or guidelines accordingly
- **procedural requirements**, depending on the classification (*e.g.* certification, registration, commissioning and reporting)
- a clear referral to **QI elements** where needed.

Couple incentives to mini-grid quality elements or reward mini-grid developers that develop systems following international best practices. This can be done in the licensing procedure, by providing financial incentives or in the form of funds and support for innovative mini-grids that monitor and communicate their performance.

Control the quality of imported components to avoid substandard components that could lead to malperformance. A clear national regulatory framework for mini-grids that is based on national and international quality control systems will facilitate international trade and development.

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Annex A. Standards organisations

The most well-known and active international standards organisations include:

- **the International Organization for Standardization (ISO)**
    - composed of national standards bodies (NSBs), one for each member economy
- **the International Electrotechnical Commission (IEC)**
    - composed of national committees, one for each member economy
- **the International Telecommunication Union (ITU)**
    - treaty-based: composed of governments and other organisations based on a treaty within the United Nations
- **Institute of Electrical and Electronics Engineers (IEEE)**[7]
    - membership is open to qualified parties that have an interest in developing standards according to IEEE by-laws.

Some regional standards bodies that are taking the lead in the development of mini-grid standards include:

- **the European Committee for Standardization (CEN)**
- **the European Committee for Electrotechnical Standardization (CENELEC)**
- **the European Telecommunications Standards Institute (ETSI).**

NSBs also play a role in the development of mini-grid standards whether through their membership in international bodies or on a national level. Examples of such NSBs include:

- **American National Standards Institute (ANSI)**
- **British Standards Institution (BSI)**
- **German Institute for Standardization (DIN).**

Annex B.
Key standards and technical committees

General electrical standards

IEC 61970 series	Energy and power management
IEC 61508 series	Functional safety of electrical/electronic systems
EN 50160	Local standards on voltage characteristics in public distribution systems as mini-grid systems comply with the standards of public distribution grids, guaranteeing that typical consumer appliances are not at risk
ANSI C84.1	Voltage Ratings for Electric Power Systems and Equipment
IEC 60038	Standard voltages (similar to the previous one)
IEEE 1159	Recommended Practice for Monitoring Electric Power Quality, for guidance on the electrical output of power systems and how to monitor them
IEC 61000-2	Environment – Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems
IEC 61000-3	Electromagnetic compatibility – Limits for Power Quality
IEC 61000-4	Electromagnetic compatibility – Testing and measurement techniques
IEC TS 62749	Assessment of power quality – Characteristics of electricity supplied by public networks
IEC TS 61200-101	Residential electrical installation in direct current not intended to be connected to Public Distribution Network
IEC TS 61200-102	Application guide on Low Voltage direct current electrical installation not intended to be connected to Public Distribution Network
IEC 62087-3	2015: Audio video, and related equipment – Determination of power consumption – Part 3: Television sets
IEC 62087-6	2015: Audio, video, and related equipment – Determination of power consumption – Part 6: Audio equipment
IEC 60050 series	Illuminance of an elementary surface
IEC 62257-12-1 ed 2 (2015)	Selection lamps and lighting appliances for off-grid electricity systems
IEC 60068-2-6	Environmental testing – Part 2-6: Tests – Test Fc: Vibration (sinusoidal)
IEC 60598-1	Luminaires – Part 1: General requirements and tests
IEC 60598-2-1	Luminaires – Part 2: Particular requirements. Section One: Fixed general purpose luminaires
IEC 62257-13-1 (ED1-CDV)	Quality for solar lanterns and off grid systems
IEC 60364-7-712	Electrical installations of buildings – Part 7-712
VDE-AR-N 4105	2011-08: Power generation systems connected to the low-voltage distribution network

Standards for conversion and interconnection to the main grid

IEC TC 22	Power electronic systems and equipment
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems – ensures that renewable mini-grid operation is safe and prevents power exportation into a grid where there are line workers
IEC 62116	Utility-interconnected Photovoltaic Inverters – Test Procedures of Islanding Prevention Measures provides safety requirements internationally used for mini-grids
IEC 60870	Telecontrol Equipment and Systems
IEC 61850	Power Utility Automation – this communication protocol defines and regulates exchanges and events among power system substations
IEC TS 62786	Distributed energy resources connection with the grid
CLC EN 50549 series	Requirements for generating plants to be connected in parallel with distribution networks
UL 1741	Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
CAN/CSA-C22.2 NO. 257-06 (R2015)	Interconnecting Inverter-Based Micro-Distributed Resources to Distribution Systems

Standards for photovoltaic and solar power-related components

IEC 61215	Crystalline Silicon Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval
IEC 62116	Utility-interconnected Photovoltaic Inverters – Test Procedures of Islanding Prevention Measures – provides safety requirements internationally used for mini-grids
IEC 60904	Photovoltaic device general specifications
IEC 60730	Automatic electrical controls (solar energy)
IEC 62548	PV design and installation
IEC 60364 series	PV design and installation
IEC 62446	PV commissioning
IEC 61724	PV Performance and Operations
IEC 62446-2	PV Performance and Operations
IEC 62257 series	Off Grid Specifications and rural electrification
IEC 62738	Utility Scale Specifications
IEC 62103	Common solar PV inverter
IEC 61727	Photovoltaic (PV) systems – characteristics of the utility interface

IEC 62910	Utility-interconnected photovoltaic inverters – Test procedure for low voltage ride-through measurements
IEC 62920	Photovoltaic power generating systems – EMC [electromagnetic compatibility] requirements and test methods for power conversion equipment
IEC TS 62862 series	Solar thermal electric plants
IEC 60529	Degrees of protection provided by enclosures (IP [Ingress Protection] Code)
IEC 60891	Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics
IEC 62109-1	Safety of power converters for use in photovoltaic power systems Part 1: Requirements for special installations or locations – Solar photovoltaic (PV) power supply systems
IEC 62109-2	Safety of power converters for use in photovoltaic power systems Part 2: Particular requirements for inverters
ISO 9806	2013: Solar energy – Solar thermal collectors – test methods
ISO 9459	Solar heating systems

Standards for wind turbines

IEC 60076-16	Power transformers – Part 16: Transformers for wind turbine applications
IEC 61400-21-series	Measurement and assessment of electrical characteristics
IEC 61400-1	Design Requirements
IEC 61400-2	Small wind turbines
IEC 61400-27	Electrical simulation models – Wind turbines
IEC 61400-12	Power performance measurements of electricity producing wind turbines
IEC 61400-22[1]	Conformity testing and certification
IEC 62257-7-2	Small wind turbines

Standards for fuel cells

TC105	Fuel cell technologies
IEC 62282-3-200	Fuel cell technologies – Stationary fuel cell power systems – Performance test methods
IEC 62282-3-300	Fuel cell technologies – Stationary fuel cell power systems – Installation
IEC 62282-3-400	Fuel cell technologies – Stationary fuel cell power systems – Small stationary fuel cell power system with combined heat and power output

8 IEC 61400-22:2010, Wind turbines – Part 22: Conformity testing and certification, is withdrawn and replaces, effective 31 August 2018, with the IECRE [IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications] conformity assessment system
This has become possible with the creation of the IECRE Conformity Assessment (CA) System and the deliverables for the wind sector contained therein.

Standards for batteries

General battery standards

IEC 60050	International electro technical vocabulary. Chapter 486: Secondary cells and batteries
IEC 60086-1	Primary batteries – general specifications
IEC 60086-2	Primary batteries – Physical and electrical specifications
IEC 61427-1	Secondary cells and batteries for renewable energy storage – Photovoltaic off-grid application
IEC 61427-2	Secondary cells and batteries for renewable energy storage – On-grid applications
IEC 60050	International electro technical vocabulary. Chapter 486: Secondary cells and batteries
UL 2054	Safety of Commercial and Household Battery Packs – Testing
USNEC Article 480	Storage Batteries
IEC 62257-8-1	Selection of batteries and battery management systems for stand-alone electrification systems – Specific case of automotive flooded lead-acid batteries available in developing countries
IEC 62509:2010	Battery charge controllers for photovoltaic systems – Performance and functioning
IEC 62933-5-2 ED1	Electrical energy storage (EES) systems Part 5-2: Safety requirements for grid integrated EES systems – electrochemical based systems

Lithium battery standards

IEC 60086-4:2000	Primary batteries. Safety standard for lithium batteries
IEC 62281	Ed.1. Safety of primary and secondary lithium cells and batteries during transport
UL 1642	Safety of Lithium-Ion Batteries – Testing
ST/SG/AC.10/27/	United Nations recommendations on the transport of dangerous goods

Nickel metal hydride battery standards

IEC 61436:1998	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-metal hydride rechargeable single cells
IEC 61808:1999	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-metal hydride button rechargeable single cells
IEC 61951-2:2003	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Portable sealed rechargeable single cells. Nickel-metal hydride
IEC 1808	Sealed nickel-metal hydride button rechargeable single cells (IEC Document 21A/207/CD)

Nickel cadmium battery standards

IEC 60285:1993	Alkaline secondary cells and batteries. Sealed nickel-cadmium cylindrical rechargeable single cells
IEC 60622:1996	Sealed nickel-cadmium prismatic rechargeable single cells
IEC 60622:2003	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium prismatic rechargeable single cells
IEC 60623:1990	Vented nickel-cadmium prismatic rechargeable single cells
IEC 60623:2001	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Vented nickel-cadmium prismatic rechargeable single cells
IEC 60993:2002	Electrolyte for vented nickel-cadmium cells
IEC 61150:1992	Alkaline secondary cells and batteries. Sealed nickel-cadmium rechargeable monobloc batteries in button cell design
IEC 61440:1997	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium small prismatic rechargeable single cells
IEC 62259:2004	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Nickel-cadmium prismatic secondary single cells with partial gas recombination
BS EN 60285	Ed.4. Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium cylindrical rechargeable single cells
BS 5932:1980	Specification for sealed nickel-cadmium cylindrical rechargeable single cells
BS 6115:1981	Specification for sealed nickel-cadmium prismatic rechargeable single cells
BS 6260:1982	Specification for open nickel-cadmium prismatic rechargeable single cells
BS 3G 205:1983	Specification for lead-acid and nickel-cadmium rechargeable batteries

SAE standards for electric vehicles

SAE J2293	Requirements for Electric Vehicles (EV) and Electric Vehicle Supply Equipment (EVSE). It standardises the electrical energy transfer from electric utility to EVs
SAE J2836	Use cases for communication between plug-in electric vehicles and the power grid for energy transfer and other applications
SAE J2847	Communication messages between PEVs [plug-in electric vehicles] and grid components

Standards for diesel generators

NEMA MG1	Practical information concerning performance, safety and testing of AC and DC motors and generators
IEC 60034	Rotating electrical machines
ISO 8528	Reciprocating internal combustion engine driven alternating current generating sets
NFPA 110	Standard for Emergency and Standby Power Systems
ISO 3046	Reciprocating internal combustion engines

Standards for mini-grids in general and mini-grid controllers

IEC 60287	Ratings of electrical cables that interconnect equipment
IEC 60364-7-712	Electrical interconnection of a building
IEC 62357	Interaction between systems such as power system control and associated communications
IEEE 2030.7-2017	Interoperability of the different controllers and components needed to operate the Mini-grid Energy Management System through cohesive and platform-independent interfaces
IEC TS 62898-1	Guidelines for mini-grid projects planning and specification
IEC TS 62898-2	Mini-grids Guidelines for Operation
IEC TS 62898-3-1	Mini-grids – Technical/protection Requirements
IEEE P1547-REV	Mini-grid Connection to Distribution Utilities
IEEE P2030.9	Recommended Practice for the Planning and Design of the Mini-grid
IEC 2005 - TS/62257	Recommendations for Small Renewable Energy and Hybrid Systems for Rural Electrification
IEEE P2030.7	Standard for the Specification of Mini-grid Controllers
IEEE P2030.8	Standard for the Testing of Mini-grid Controllers
IEC 61131	Programmable controllers: programmable logic controllers (PLCs), programming and debugging tools (PADTs); human machine interfaces (HMIs) etc.

Standards and technical committees (TCs) for metering, monitoring and data exchange

TC 13	Electrical energy measurement and control: a.c. and d.c. electrical energy measurement and control
EN 13757	Communication systems for meters
IEC61968-9	Application integration at electric utilities – System interfaces for distribution management – Part 9: Interfaces for meter reading and control
IEC TC/SC 57	Power systems management and associated information exchange

IEC TR 62357-1:2016	Power systems management and associated information exchange – Part 1: Reference architecture
IEC 61850	Communication networks and systems for power utility automation
IEC 60870	Telecontrol equipment and systems
IEC 62056	Data exchange for meter reading, tariff and load control
Modbus	Communication protocol
DNP 3	Communication protocol

Standards for direct current (DC) mini-grids

IEEE P2030.10	Standard for DC Mini-grids for Rural and Remote Electricity Access Applications
IEEE DC@Home (IGCC)	DC use in residential dwellings and LVDC [low-voltage direct current] Micro-grid systems
IEEE 946-2004 / IEEE P946	Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Systems
IEC SEG 4	Standardization of LVDC systems up to 1500V [volts]
IEC SyC LVDC	Low Voltage Direct Current and Low Voltage Direct Current for Electricity Access
IEC 62040-5-3:2016	Uninterruptible power systems (UPS) – Part 5-3: DC output UPS – Performance and test requirements
Pika Energy REbus™	REbus™ is a DC energy network standard that operates alongside the existing AC infrastructure, enabling customers to build cost-effective, scalable renewable energy systems
ETSI EN 300 132-3-1	Part 3: operated by rectified current source, alternating current source or direct current source up to 400 V; sub-part 1: direct current source up to 400 V
ITU-T L.1202 (2015-04)	Methodologies for evaluating the performance of an up to 400 VDC power feeding system and its environmental impact
ITU-T L.1201 (2014-03)	Architecture of power feeding systems of up to 400 VDC
ITU-T L.1202 (2015-04)	Methodologies for evaluating the performance of an up to 400 VDC power feeding system and its environmental impact
YD/T 2378-2011	240 V direct current power supply system for telecommunications
YD/T 2556-2013	Maintenance requirements of 240 V direct current power supply system for telecommunications
YD/T 3091-2016	Communication with 240/336 V DC power supply system evaluation requirements and methods of running

Standards by which accreditation bodies are evaluated

- **Testing and calibration laboratories** (ISO/IEC 17025:2005 “General requirements for the competence of testing and calibration laboratories”)
- **Certification bodies for quality management systems** (ISO/IEC 17021 “Conformity assessment – Requirements for bodies providing audit and certification of management systems”)
- **Certification bodies for products** (ISO/IEC 17065:2012 “Conformity assessment – Requirements for bodies certifying products, processes and services”)
- **Certification of proficiency test providers** (ISO/IEC 17043:2010 “Conformity assessment – General requirements for proficiency testing”)
- **Inspection bodies** (ISO/IEC 17020:2012 “Conformity assessment – Requirements for the operation of various types of bodies performing inspection”)
- **Persons** (ISO/IEC 17024:2012 “Conformity assessment – General requirements for bodies operating certification of persons”).

Annex C. Examples of national and regional code and standard development

Africa

The African Electrotechnical Standardization Commission (AFSEC) was established among other things to promote the application of common standards on the entire continent in order to improve access to electricity and hence the well-being of African populations in support of the Sustainable Development Goals and Agenda 2063. AFSEC, through development and harmonisation of standards, could contribute to the broad ambitions of African Continental Free Trade Area initiative.

Recognising the need for appropriate standards for electrification of rural areas in Africa, AFSEC Technical Committee (TC) 82, mirroring the work of International Electrotechnical Commission (IEC) TC 82, was tasked to develop a guide, "Guide for application of standards for rural electrification in Africa", taking into account publications from recognised standardisation bodies, notably the IEC, and other specifications developed by stakeholders in Africa.

Europe

The Smart Energy Grid Coordination Group of the European Committee for Standardization, the European Committee for Electrotechnical Standardization and the European Telecommunications Standards Institute continuously works to provide relevant standards, identify standardisation gaps and provide best-practice examples on smart energy grid specific use cases in order to show the applicability of existing and upcoming standards (CEN CENELEC, 2018).

India

As a leading player in the regional and global mini-grid market, India is increasingly developing mini-grid standards focused on national needs. An example of a relevant effort in this regard is the work of the Bureau of Indian Standards Low-Voltage Direct Current (LVDC) Committee focused on:

- LVDC system requirements, safety and installation guidelines
- LVDC products including electrical wiring accessories and applications
- integration of DC infrastructure
- non-traditional distribution networks/mini-grids.

United Republic of Tanzania

The United Republic of Tanzania, one of the leading players in the African mini-grid (energy access) market, has also enhanced standardisation efforts in recent years. The Tanzania Bureau of Standards is a crucial partner in the development and adoption of standards and other quality infrastructure (QI) aspects. It works together with regulatory instances and international partners to establish an enabling QI to support mini-grid penetration.

United States

In the 2017 edition of the US National Electric Code, four new articles were added addressing recent developments in the area of renewable energy systems, of which three are of direct significance to mini-grids (NEC, 2020).

» Energy Storage Systems (Art. 706) – permanently installed energy storage systems operating at over 50 volts (V) alternating current (AC) or 60 V direct current (DC) in stand-alone mode or interactive with other electric power production sources

» Stand Alone Systems (Art. 710) – covers electric power production sources operating in stand-alone mode

» DC Microgrids (Art. 712) – a DC power distribution system consisting of one or more interconnected DC power sources, DC-DC converters, DC loads, and AC loads powered by DC-AC inverters.

These codes often refer to standards such as the aforementioned UL 1741 and IEEE 1547.

Annex D.
General testing standards

ISO/IEC 17025:2017: General requirements for the competence of testing and calibration laboratories

- "Specifies the general requirements for the competence, impartiality and consistent operation of laboratories" (ISO, 2017).

ISO/IEC 17043:2010: Conformity assessment – General requirements for proficiency testing

- "Specifies general requirements for the competence of providers of proficiency testing schemes and for the development and operation of proficiency testing schemes. These requirements are intended to be general for all types of proficiency testing schemes, and they can be used as a basis for specific technical requirements for particular fields of application" (ISO, 2010).
- The testing stage starts during the manufacturing process, with some tests in quality control according to the standard ISO 9001, until the installation and commissioning processes. Then, qualification steps such as gathering samples from a production line to test them in a laboratory takes place.

Examples of specific mini-grid testing standards or technical specifications are:

- IEC 62257-9-5 ED ED4 (2018), Integrated system – Laboratory evaluation of stand-alone renewable energy products for rural electrification
- IEC 62257-13-1 (ED1- CDV), Quality for solar lanterns and off-grid systems
- IEC 62257-13-2 (ed1 - NWP), Solar home systems test method.

Annex E.
Active institutions in certification and listing of mini-grid components

» **BSI Group:** British Standards Institution, the national standards body of the United Kingdom, provides certificates and other activities related to standardisation.

» **CSA Group** is a non-profit standards organisation, previously known as the Canadian Standards Association. CSA develops a wide range of standards covering 57 areas and provides training and advice.

» **DIN** - German Institute for Standardization is also involved in certification.

» **Electrical Test Laboratory of Intertek Group** focuses on electrical product safety testing, electromagnetic compatibility testing and benchmark performance testing.

» **JET**, Japan Electrical Safety & Environment Technology Laboratories, is Japan's testing services body, advancing safety in electrical equipment and facilities.

» **SWCC**, the Small Wind Certification Council, is a certification body for wind turbines. SWCC has established a standardised system for reporting wind turbine energy and sound performance in North America.

» **UL,** previously Underwriters Laboratories, drafts safety standards for electrical devices and components and serves as an independent safety science company.

» **VDE Testing and Certification Institute**: one of Europe's largest technical-scientific associations active in standardisation, testing, certification, consulting, etc.

» **CGC**, China General Certification Center: a third-party testing and certification institute that has been active in standardisation, testing and certification of mini-grid components.

» **Certification bodies for quality management systems** according to ISO/IEC 17021 "Conformity assessment – Requirements for bodies providing audit and certification of management systems".

» **Certification bodies for products** according to ISO/IEC 17065:2012 "Conformity assessment – Requirements for bodies certifying products, processes and services".

» **Certification bodies for persons** according to ISO/IEC 17024:2012 "Conformity assessment – General requirements for bodies operating certification of persons".

Annex F. Strategy to develop and implement quality infrastructure for renewable energy mini-grids

Stepwise quality infrastructure development strategy

The main idea behind this approach results from the experience that the most durable and effective method of QI implementation is one which goes hand-in-hand with market development and country context. Indeed, the QI needed (or that could sensibly be expected to be implemented in-country in terms of cost-benefit) will vary according the development stage of the market.

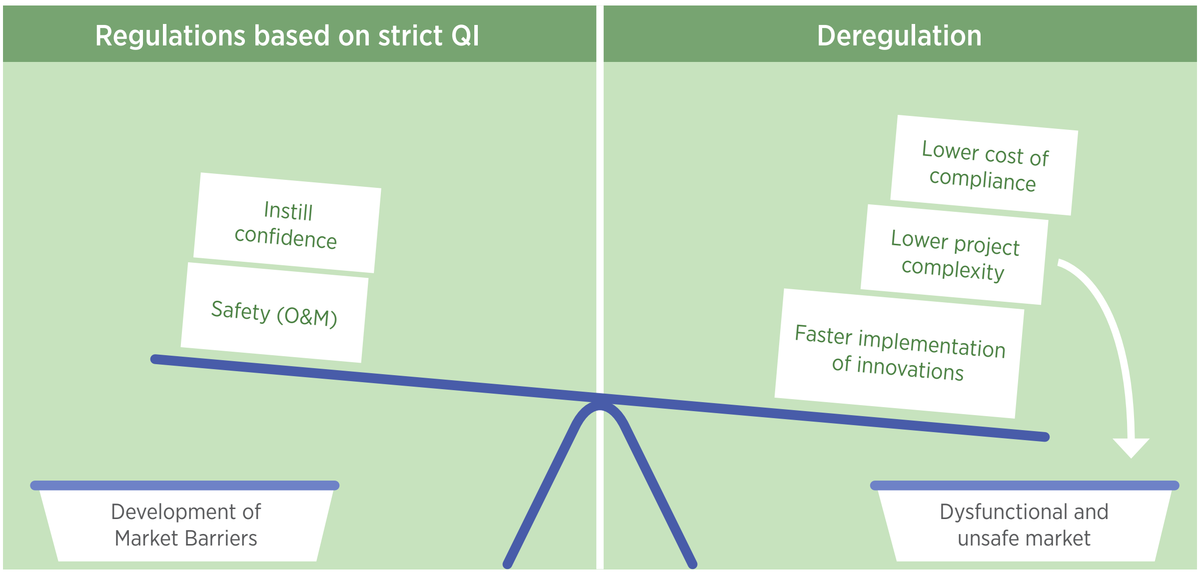
Mini-grid markets exhibit such a variety, ranging from different implementation circumstances to diverse economic and political situations, that a universal strategy for QI would fail to provide advice to different countries. Therefore, best practices are given and supported, if convenient, with country cases.

General remarks

Some aspects that are key in the development of QI and mini-grids in general are:

» **QI balance:** QI needs to be developed in close co-operation with all stakeholders. In doing so, the balance between stringent regulation (based on QI) and low market barriers can be protected, as depicted in Figure 57. Expert interviews have shown a range of opinions regarding the level of QI that should be in place at each point. Some claimed that minimal QI signifies minimal market barriers for developers in the short term. Others stated that lacking QI posed the biggest threat to commercial mini-grids. One issue that remains constant is the need for clarity. If one wants to develop QI that safeguards trust and quality and enables the market to grow, the QI plan has to be clear and "future-proof", supporting and encouraging innovations in technologies and business plans.

Figure 57 QI development balance



Note: O&M = operation and maintenance.

- **Market incentives coupled to QI:** the inclusion of stakeholders is crucial, but to speed up the process of QI implementation and the development of a reliable mini-grid market, quality efforts in market incentives are recommended.

In some cases, a specific market at a given moment could be positioned in more than one stage. Indeed, some aspects of the market and QI in place might correspond to a more advanced stage, while other aspects might still be at an early stage of development. For instance, there may be a strong presence of certification bodies and testing facilities (as they were already developed for other industries) in a country still lacking any specific national standards or regulations for mini-grids, while other countries more advanced in the definition of such national standards and regulations may still have fewer developed certification and testing facilities.

QI development for market assessment stage

At this stage there is no or little mini-grid-specific QI in place. There is a need to bundle efforts of industry and government as well as financing institutions to promote the market and to plan the implementation of QI in time.

These efforts can often build on existing markets. In the case of rural electrification, for example, the solar home systems or grid-tied solar market can be considered as inspiration, and mini-grids can be seen as the following step. This bottom-up approach has worked well with mini-grids in United Republic of Tanzania through the Rural Energy Agency, which initially focused electrification efforts on solar home systems and has pivoted to more extensive mini-grids. There is also the top-down approach, where utility grid regulations and QI are adapted to mini-grid systems. The ideal situation is a QI plan with elements of both approaches.

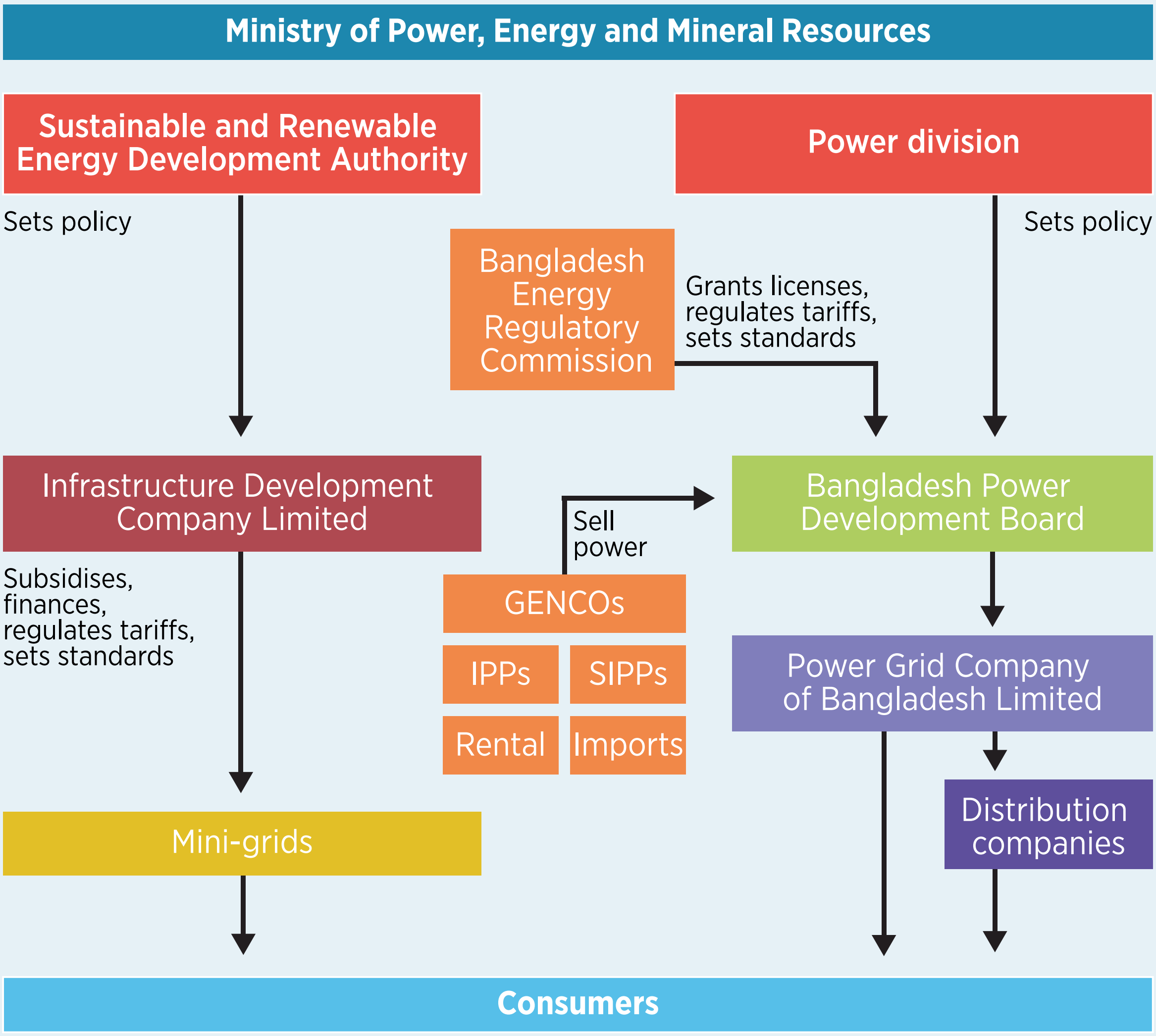
A country case that exhibits the importance of a systemic approach of QI implementation in an incipient market through an interest group of stakeholders is **Bangladesh.**

Country case

Bangladesh

Bangladesh currently has seven operational mini-grids, connecting around 2 243 households in rural areas, with many more projects in the process of being developed. In order to show the systemic approach to the quality oversight of mini-grids, the structure of the Bangladesh power sector is detailed in Figure 58.

Figure 58 Mini-grid situated in power sector



Note: GENCOs = generation companies ; IPPs = independent power producers; SIPPs = small independent power producers.

Based on: (ESMAP, 2017).

The Infrastructure Development Company Limited (IDCOL) is a state-owned financial institution. It integrates inputs from various stakeholders (government, private sector, non-governmental organisations, multilateral and bilateral institutions, academics) and is managed by government and private-sector representatives.

Most of the international standards that are currently mentioned in the Supplier Enlistment Process under IDCOL Solar Mini-Grid and Rooftop Projects (IDCOL, 2017) are related to photovoltaic (PV) modules (*e.g.* IEC 61215:2005, IEC 61646, IEC 61730). IDCOL allows only low-maintenance lead-acid type batteries in its projects, most likely because operational safety standards of Li-ion batteries are too costly and complex to comply with.

Bangladesh has recently surpassed what is defined as the market assessment stage, so current IDCOL QI strategies will be presented in the next section as well.

Bangladesh's IDCOL was crucial in the development of mini-grids as it identified the areas where grid expansion was unlikely and provided incentives and financing to private project developers. These incentives were accompanied by QI requirements, provided in a set of documents clearly stating the international standards that equipment had to comply with, among other specifications. Although IDCOL's requirements are often seen as too strict considering the current market state, they illustrate a strategy to assure the quality of mini-grids in a system where systemic national regulations and QI are in an early stage.

At this market stage, the best strategy to ensure the level of quality of equipment on the market is to require imports to be certified based on international or foreign component standards *(e.g.* Europe's "CE" mark, the International Electrotechnical Commission [IEC], UL). If there is a lack of knowledge to assess compliance to standards (metrology and testing methods) and to facilitate import controls, universities or national research institutions with prior research activities can serve as assessment bodies.

The example given above focuses on off-grid systems of low complexity. These systems are mostly installed by developers with previous international experience, and as a result the technical risk is small. On the other hand, mini-grids meant for on-grid purposes or consisting of more complex functionalities (demand-side management, peak shaving, etc.), face more challenges, *e.g.* complying with grid codes. There are currently very few country cases where the interconnection requirements for mini-grids are completely comprehensive. The prevalent QI implementation strategy currently deployed in these types of projects is a stepwise approach:

1. Demonstration projects are set up in close co-operation with regulators. These operate in a regulatory grey zone, functioning as proof of concept and demonstrating market viability. They are mostly developed by experienced suppliers; engineering, procurement and construction companies (EPCs); or research institutions. Standards developed in more advanced mini-grid markets can be used as guidelines for these demonstration projects.
2. QI can be developed based on the knowledge gained from these projects, encouraging local industry and addressing the barriers faced during development. The adaptation of international standards to local requirements will depend on the input from academia and on the data and operational experience obtained from these demonstrations.

The government cost of QI development in the assessment stage should be held to a minimum. This could be done by limiting cost-intensive measures (*i.e.* use of international standards in national standards development). In this respect, Bangladesh has accepted aid from institutions such as the World Bank, the Asian Development Bank and the Islamic Development Bank to set up initial QI systems and limit the barrier for private investors to participate in these efforts.

Summary of recommendations for market assessment stage :

- » require certified imports based on international component standards
- » use universities or national research institutions as assessment bodies if there is a lack of knowledge to assess the technical aspects of requirements
- » develop a QI plan combining a bottom-up approach (integrating mini-grids in national development plans) and top-down approach (adapting utility regulations to mini-grids)
- » for interconnected mini-grids, authorise some initial pioneering projects in co-operation with the regulator (using standards of more advanced mini-grid markets as guidelines), then use these as a basis to develop a QI plan.

QI development for market introduction stage

Projects in the market assessment stage can rely on developer know-how for installation and O&M, and rely on imports for components. If the market is to grow, the development of national capacity is crucial. The first step for developing QI in this stage should always be training. **Training** consists of two elements:

Practitioner training: A mini-grid system is complex and requires skilled technicians for operation and servicing. Furthermore, the successful operation of these systems requires an extended expertise of all power-sector stakeholders. These trainings can initially be accommodated by private entities, such as private EPCs, but with the risk of practitioner lock-in when the training is solely focused on the company system. Existing expertise in technical universities and institutions can also be used to start training development.

Examples of different training levels

» ENGIE's PowerCorner installed a mini-grid in Ketumbeine, United Republic of Tanzania (16 kilowatts [kW] PV, 45 kilowatt-hour Lithium batteries, back-up genset). To assure quality in operation and a fast response to servicing issues, someone from the area receives extensive training to master operational protocols and be responsible for the O&M.

» An example of a more advanced method of training specifically focused on improving the capability of technicians to install and service high-technology mini-grids is the Energy Storage and Microgrid Training and Certification. Its development is led by the Pennsylvania State University in the United States, with the support of National Industry Standards Bodies and the Electric Power Research Institute. It was mentioned in Chapter 2 as the training is concluded with a certification exam. In the market introduction stage of mini-grid development, certification is not yet of the essence, but the sharing of knowledge is.

» The National Power Training Institute (ISO 9001 and ISO 14001 certified) operating under the Ministry of Power of the Government of India, offers workshops dealing with mini-grid standards and technical comparisons, battery testing, quality analysis, and battery management systems for all power-sector stakeholders (NPTI, 2018).

Training of end users and supply channels: There is a continuous need to assess any quality issues that arise both from the end-user perspective and the supply chain perspective. In the absence of quality management systems or advanced quality monitoring systems, a feedback control system might help at this stage. An example of such a mechanism can be found in **Uttar Pradesh, India**.

Example of mini-grid feedback control system

Uttar Pradesh

The mini-grid quality infrastructure of Uttar Pradesh is based on a laissez-faire point of view in that operating permits are not issued, but there are still stringent technical and safety standards in place (>50 kW). However, the system depends on ad hoc inspections, grievances and feedback from end users. If a project displays a lack of safety or operational quality, a complaint can be reported to the Uttar Pradesh Electricity Regulatory Commission. The Uttar Pradesh New & Renewable Energy Development Agency can then inspect the site and possibly blacklist or cancel the project, depending on the severity of non-compliancy to service standards.

Note that this is only a viable solution until formal procedures are put in place (Castalia, 2017). This requires quality assessment capabilities from end users, but also from custom officials, installers, etc.

In this stage international or foreign standards will still form the basis of a nation's QI. A **national standards committee** or institution that is responsible for mini-grid standards and quality must be established following the successful deployment of the first mini-grids. The activity of this committee will vary with market stage. In this stage the main goal is not to develop comprehensive national (or regional) standards but to safeguard project quality.

A successful demonstration of an incipient QI is the partnership between United Republic of Tanzania, National Renewable Energy Laboratory in the United States, Global Lighting and Energy Access Partnership (Global LEAP) and the US Agency for International Development (USAID). The quality assurance framework (Baring-Gould, et al., 2016) as used as a common technical standard for classifying service from mini-grids and serves as a basis for the development of national standards and regulations.

Another example of a co-ordinated effort towards the incipient development of QI is the Standardisation Mandate (M/490) to European standardisation organisations to support European smart grid deployment from the European Commission (European Commission, 2011). This is a region-wide plan to prepare the market for the deployment of smart/mini-grids. One of the aspects of this plan is that the developed (or adjusted) standards should be flexible enough to allow future developments in technologies and markets.

Example of a mandated report aimed at the facilitation of system interoperability in smart grids

"Methodologies to facilitate Smart Grid system interoperability through standardisation, system design and testing + interoperability tool" (SG-CG, 2014).

This report focuses on:

» creation of use cases and design of systems

» creation of interoperability profiles based on use cases, standards and specifications

» compliance, conformance and interoperability testing.

The interoperability tool (checklist) helps the user identify the necessary standards for specification, profiling and testing in terms of interoperability. It also supports identifying related standardisation gaps.

To mandate standards development is an effective strategy that ensures the conformity of standards across a region and allows for shared knowledge among the participating standards bodies. The benefits of co-ordinating such a mandated effort among different standards bodies include the reduced risk of non-interoperability (proprietary standards) and a certain QI uniformity across boundaries, allowing large-scale and cost-efficient deployment of mini-grids. The latter is an aspect that is crucial to the bankable deployment of small-scale mini-grids (especially in developing economies).

In this stage the framework to enable **grid interconnection** should be put in place, using international standards and operator experience as a basis for agreements with grid operators. As seen in Chapters 2 and 4, there are interconnection standards (*e.g.* IEEE 1547, UL 1741) under continuous development that form the basis for a number of interconnection cases in Europe, Japan and the United States.

The difficulty lies with mini-grid markets that were originally aimed at off-grid systems, but could be interconnected in the future. Developers should be made aware of the grid requirements that they need to take into account in order to design their system for possible interconnection. This must be distinct from the national grid code, as *e.g.* power quality requirements will differ depending on the tier of service, and existing standards are hard to comply with due to the lack of resources and testing facilities. These agreements must be made early on in QI development and in close co-operation with interest groups. There are two elements that should be part of the QI strategy in places where grid extension is possible:

1. **Access to QI elements**: the utility can facilitate a grid extension to include mini-grids by making its standards and testing facilities freely available for mini-grid developers.

2. **Clear statement of safety and operational provisions**: in order to reduce the complexity of an "extension"-proofed design some conformance changes should be highlighted. These can include:

   » conductor sizes and composition

   » cable cross-section

   » insulation and line accessories

   » switch gear

   » grounding

   » conductor configuration.

An example of efforts to make connectivity compliance requirements clear and accessible is India's Central Electricity Authority's Technical Standards for Connectivity to the Grid (Central Electricity Authority (India), 2010). It provides a single document referring to relevant standards and systematically amends policy to include innovative developments (*e.g.* prosumers and electric vehicle charging (CEA, 2018)). The influence of policy on QI is discussed further in Chapter 5.

Lastly, **safety and reliability tests** of mini-grid components are often deemed the most crucial step in the development of QI in emerging markets. This does not mean that these have to be executed in formally certified and accredited testing labs. A strategy could be to have components tested in university laboratories following international standards (or equivalent to international safety and reliability standards). In Bangladesh, universities were engaged by IDCOL to provide basic mini-grid testing services, and accreditation for more mature technologies is under way (*e.g.* ISO/IEC 17025, Bangladesh University). Testing could once again be co-ordinated on a regional level to build up know-how, mitigate costs and facilitate scalability for developers.

Summary of recommendations for market introduction stage:

- develop training for mini-grid practitioners: it is possible to initially rely on private entities for such training, but it is better to develop training by independent parties such as technical universities and institutions to avoid practitioner lock-in
- develop training for end users and supply channel players
- adopt a feedback system until formal procedures for quality management and monitoring can be set in place
- set up a national standards committee or institution in charge of mini-grid standards and quality, with the safeguard of project quality as the initial focus. Ideally, the development of national standards and regulations should be consistent at the regional level, *e.g.* by the adoption of common basis for development such as the Quality Assurance Framework for Mini-Grids
- create a framework to enable grid interconnection, based on international standards and operator experience. The case of interconnection of mini-grids initially established as autonomous systems (typically in the event of main grid extension) must be addressed, both regarding the access to QI elements (*e.g.* utility standards and testing facilities) and the definition of clear safety and operational provisions
- initiate the development of basic component safety and reliability testing capabilities in unaccredited labs (*e.g.* university labs) following international standards. Establishing co-ordination of testing capabilities at a regional level can be beneficial.

QI development for market growth stage

This is the development stage that the early adopters of mini-grids have currently reached. As of today, the most developed mini-grid markets (*e.g.* Australia, China, Japan and the United States) contain very few commercial mini-grids, so these markets cannot yet be considered consolidated or mature. These markets instead mainly consist of niche mini-grids such as mining or military facilities, although commercial community mini-grid projects are under way.

The market size in certain regions is now capable of handling an established mini-grid QI. This includes:

- certified or licensed mini-grid installers and practitioners
- certified training facilities
- equipment and system certification
- system testing (reliability, hardware tests, control testing, performance ratings).

Evidently, certification has to be accompanied by a testing standard. Certifications and standards for equipment and system testing have to be developed based on international standards and adapted to the deployed market and stakeholder interests. Many of the components currently used in renewable mini-grids have reached a more advanced market stage in grid-tied systems and can subsequently be tested and certified accordingly (*e.g.* solar PV: IEC 61215/61646, IEC 61730 for European CE certification; PV inverters: EN 50524, EN 50530, UL 1741, IEC 61683, IEC 62109-1 and IEC 62109-2). However, as mentioned in Chapters 2 and 4, there is a need to accommodate testing of advanced batteries and to assess the control functionality of the system in greater detail. A number of testing labs capable of doing this are mentioned in Chapter 2. It might be difficult to develop a standard describing the system functionality test in *e.g.* a PHIL[9] test environment. An international guideline describing the different testing options, their scope and functionality could be a first step.

9 A PHIL (power hardware-in-the-loop) environment can be used to test the operation of a complete system thanks to a combination of software-simulated system components with actual hardware components, in a set-up enabling the exchange of electrical power among the components. Thereby a loop of interaction is created as the components will react to the conditions at each timestep, creating new conditions for the next timestep.

Experts have expressed scepticism about system certification according to a standard series, simply because there is such a variety and complexity to mini-grids. Certification of functionalities as is done for grid interconnection according to IEEE 1547 has wider support. A strategy that is deployed in Kenya, the United Republic of Tanzania and other early adopters of mini-grids for electrification purposes is the issuing of project licences, assessed case by case. Of course, this is only necessary for projects above a certain size (*e.g.* 1 megawatt). The licensing procedure could contain tests of the system reviewing its compliance with the requirements specified by the regulator. These can later evolve into certification requirements, following international standards.

Example of interconnection protection and testing procedure

United Republic of Tanzania

Consists of:

» verification of construction/installation diagrams and information regarding the proposed protection coordination done by the small power producer (SPP) co-ordinating unit.[10]

» testing and certification of interconnection and relay settings in accordance with the SPP developer *Guidelines for Grid Interconnection of Small Power Projects in Tanzania* (Mini-grids Information Portal, 2018).

Sub-Saharan Africa is currently seen as the testing ground for small off-grid mini-grids for international developers; however, it lacks dedicated testing facilities for a sustainable growth of its internal market. More advanced markets such as those in Nigeria and the United Republic of Tanzania should be used to develop dedicated testing, training and certification facilities. This could jump-start regional QI efforts.

Testing laboratories provide test results to certification bodies, and should normally be separated (conflict of interest) to be accredited. However, in this stage it may prove easier to combine testing, certification and training in one facility. Note that this applies to system-wide testing and certification. Although component testing and certification could very well take place in the same laboratory, there are already established labs and certification bodies for most mini-grid components.

10 The distribution network operator (DNO) establishes an SPP co-ordinating unit to serve as a single point of contact for SPPs in interacting with various divisions within the DNO's organisation.

Example of an innovation centre focused on regional QI development

The Microgrid Systems Laboratory (MSL) (MSL, 2018) in Santa Fe, New Mexico, United States, is a collaboration among several national and international laboratories, utilities and mini-grid experts with the goal of acting as a regional mini-grid development facilitator in order to:

- conduct sponsored research
- support projects for prototype, pilot and demonstration
- advance its agenda for applied research and development and innovation, including human, social and community factors
- train qualified workers in the **Microgrid Education Center (MEC)**
- provide testing and certification at the systems level in the **Microgrid Certification Center (MCC).**

The **MCC** will conduct testing and certification for components, modules, subsystems and whole mini-grid systems. It will focus on testing and certifying systems to ensure they work properly and have plug-and-play interoperability, under a wide variety of conditions and types of connection to the utility grid, and will also be a leader in developing applicable international standards. Furthermore, its goal is to develop a system certification standard and to provide an official certification for components that meet the standard. The combination of these efforts in one centre shows the impact of QI on cross-vendor interoperability, acceleration of implementation, encouragement of competition, and promotion of modularisation and innovation.

The **MEC** will provide technical training, continuing education for industry professionals, specialised training for industry, and – via university partnerships – upper-level courses and advanced degrees, along with "train the trainer" courses for global implementation.

The international member institutions of the MSL collaborate in reaching these objectives by:

- sharing the results of any work that is not proprietary
- joining teams that collaborate on projects or programmes
- serving as local experts and affiliates in the communities where they are based
- engaging in transferring and commercialising joint technology
- helping MSL to set up international standards
- participating in conferences, colloquia and workshop held by MSL.

The growth stage is when international standards are translated into national standards, or new national standards are developed, depending on the needs of developers and regulators. Many of the mini-grid markets studied in this report depended on international standards or foreign standards as guidance, without clear national requirements. Project developers were expected to translate these standards to the needs of a certain project. To resolve this, national standards committees could work within a regional (*e.g.* sub-Saharan Africa) or international scheme for clear standards development.

Regional standard development has several benefits compared with national development:

- reduced cost of QI development
- concentration of technical skill and know-how
- clear region-wide standards enable repeatable and regionally scalable projects
- easier international co-operation
- reduced barrier to international standards co-operation.

The last point is especially important for developing economies. Many of the international standardisation working groups drafting standards for mini-grids are made up of suppliers, academics and other stakeholders that are on the forefront of mini-grid technical development. However, experts noted that stakeholders from developing economies could have a stronger presence in the international standardisation groups. A regionally co-ordinated effort to contribute to international standard development would drive down costs and allow input of mini-grid stakeholders that face different needs (*e.g.* the co-operation of the African Electrotechnical Standardization Commission with IEC TC 8).

The role of national QI development depends on the need of the market. In the previous chapters a number of challenges and gaps were cited. It is clear that QI development concerning innovative technologies such as internet of things (IoT) and advanced inverters and control should be led by regions that are leading in its development (China, Europe, Japan, United States). Countries where mini-grids are mainly used for electrification purposes are to focus national or regional QI development on the adaption of international standards to regional needs and the facilitation of new business models (*e.g.* standards concerning pre-paid energy meters).

Example

Kenya is the first African country that is an (associated) member of ISO/IEC Joint Technical Committee 1/SC 41, which is occupied with standardisation in the area of IoT and related technologies. There is still little need for standards or regulations in this area at the moment, as important applications in industry are yet to be discovered. Once meaningful applications are identified, regional standards could be put in place based on the developed international standards.

In mini-grid markets such as Australia, China, Europe, India, Japan and the United States, technological and supply chain challenges are no longer considered an issue: the know-how is present, there are sufficient research and development facilities where testing and certification capabilities exist, and national standards committees are developing standards that can serve as inspiration for international standards (*e.g.* UL 3001: a system-level standard, intended to reflect integration of different equipment in varying combinations, blending testing and certification for a broad spectrum of electrical products and components). The development of QI to support innovations will come organically; however, there needs to be a clear regulatory framework stating mini-grid requirements based on the accessible standards. Some examples of actions:

- combine interconnection requirements according to *e.g.* IEEE 1547 with rules stating grid support functions (*e.g.* voltage-reactive power support)
- while there are guidelines and standards for single grid connections, provide clear guidelines concerning multiple grid connections
- as mentioned in the MSL goals, clearly state interoperability requirements for mini-grid-based systems and subsystems.

This can be summarised as follows: QI should be organised so that customisation is reduced to a minimum and where necessary, QI is present to facilitate it. This will have to be done with support from utilities, component suppliers and EPCs.

Summary of recommendations for market growth stage:

Establishing QI:

- certification (non-accredited) or licensing of mini-grid installers, practitioners, training facilities, systems and equipment
- advanced testing: systems, controls, performance in various circumstances
- development of national/regional standards
- participation in international standardisation efforts
- provision of a clear system-wide QI or guideline combining the various aspects of mini-grid design and operation in a single document or easily accessible series of documents.

Market consolidation and market maturity stage

As there are no mini-grid systems currently operating in consolidated or mature markets, there are no cases yet to describe QI development strategies for mini-grids. The development of renewable energy technologies in a mature market demonstrates that before the mini-grid market is to reach this stage, mini-grid associated costs have to decrease and private investments have to increase. The QI present in the previous stage is sufficient to assure quality while costs remain relatively low.

An example that demonstrates the difference in QI between these stages is system-wide certification. Whereas during the growth stage testing and certification (unaccredited) can be combined, and is mostly focused on solving existing quality issues based on different technology and functionality standards, the consolidated and mature markets will require certification and testing to occur independently and according to established standards. This is no longer a supporting QI but a QI that is focused on protecting the market from poor quality inputs. The market will have reached a maturity that will no longer tolerate quality issues. At the same time, it will be able to bear the cost of installing QI that prevents quality issues.

This will require the following actions:

- independent institutional structures for testing and certification
- increased testing and certification capacity to handle a larger number of suppliers and EPCs
- established national and international standards, describing all system functionalities and facilitating adjustments with future developments
- stakeholder protection schemes, providing reliable performance data to stakeholders based on testing and certification
- if the latter is to be done reliably, accreditation of training, testing, certification and inspection bodies is needed.

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