IRENA
International Renewable Energy Agency

OFF-GRID RENEWABLE ENERGY SYSTEMS: STATUS AND METHODOLOGICAL ISSUES

WORKING PAPER

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. 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.

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LIST OF ABBREVIATIONS

AC	Alternating current
CES	Collective Electrification System
CHP	Combined Heat and Power plant
DC	Direct current
DOE	Department of Energy (United States)
EPIA	European Photovoltaic Industry Association
ESAP	Energy Sector Assistance Programme (Nepal)
ESCO	Energy Service Companies
GDP	Gross Domestic Product
GSMA	Groupe Speciale Mobile Association (in sub-Saharan Africa)
GW	Gigawatt
IEC	International Electrotechnical Commission
IES	Individual Electrification System
IS	Isolated Systems (Brazil)
JNNSM	Jawaharlal Nehru National Solar Mission
kVA	Kilovolt-amperes
kW_p	Kilowatt-peak
LED	Light Emitting Dioide
MW_p	Megawatt-peak
NIS	National Interconnected System (Brazil)
PV	Photovoltaics
REA	Rural Electrification Agency (Tanzania)
REDP	Rural Energy Development Programme (Nepal)
REMP	Rural Electrification Master Plan (Laos)
SHP	Small Hydropower and also Small Hydro Plants
SHS	Solar Home System
SIDS	Small Island Developing States
SREP	Scaling Up Renewable Energy Programme
SWT	Small Wind Turbines
UPS	Uninterrupted Power Supply
WHR	Waste Heat Recovery
WSHDR	World Small Hydropower Development Report

EXECUTIVE SUMMARY

Renewable energy deployment in off-grid systems is growing steadily in both developed and developing countries, but there are only limited data available on their scope and extent. With declining costs and increasing performance for small hydro installations, solar photovoltaics (PV) and wind turbines, as well as declining costs and technological improvements in electricity storage and control systems, off-grid renewable energy systems could become an important growth market for the future deployment of renewables (IRENA, 2013a). In the short- to medium-term, the market for off-grid renewable energy systems is expected to increase through the hybridisation of existing diesel grids with wind, solar PV, biomass gasification and small hydropower, especially on islands and in rural areas. Furthermore, renewables in combination with batteries allow stand-alone operations and batteries are now a standard component of solar PV lighting systems and solar home systems. The impact of off-grid renewable energy systems will not only be measured in terms of their usage or reduced costs for electricity consumption in rural areas, but also in the context of their effect on the lives of the some 1.16 billion people who today are totally without access to electricity.

Off-grid renewable energy systems are not only urgently needed to connect this vast number of people with a source of electricity, but are also most appropriate due to geographical constraints and costs for grid extension. At the same time, off-grid systems could become an important vehicle to support the development of renewables-based grids. In developed countries, mini-grids are increasingly considered an option to improve energy security, power quality and reliability, as well as to avoid power blackouts due to natural disasters (*e.g.,* hurricanes) or even deliberate attacks. Furthermore, declining costs for solar PV and wind, together with reduced costs for battery storage, make this option attractive for households and small communities to intentionally disconnect from the grid and start producing and consuming their own electricity. The ability to cover residential electricity demand with local renewables is already commercially interesting in some regions of the world and could become more widespread in the next five years. Australia, Denmark, Germany, Italy, Spain and the US (Hawaii) are expected to be comprise the most promising early markets (RMI, 2014).

Despite the growing attention and market opportunities, there are to date only limited data available and only inadequate definitions of what exactly constitutes an off-grid renewable energy system. Furthermore, data sources are scarce and inconsistent across countries and regions. To address this challenge, IRENA has identified a number of key areas where methodological improvements are needed. These methodological improvements include: 1) an overview of systems; 2) a categorisation of off-grid renewable energy systems based on their application and system design; 3) consistent indicators to differentiate, evaluate, compare and aggregate data on off-grid renewable energy systems, including hybrid systems; and 4) measures to compile existing data sources, identify their limitations and create consistency.

Based on these methodological suggestions, the key results of this status update are summarised below:

- A significant number of households—almost 26 million households or an estimated 100 million people in all—are served through off-grid renewable energy systems: some 20 million households through solar home systems, 5 million households through renewables-based mini-grids, and 0.8 million households through small wind turbines.
- There is a large market to replace diesel generators with renewable energy sources in off-grid systems. Currently, there are ca. 400 gigawatts (GW) of diesel capacity (>0.5 megawatts (MW)) in operation, either in the form of industrial facilities and mines operating remotely, as back-up units where electricity supply is unreliable or as community mini-grids. Some of the diesel generators are single machines with more than 10 MW capacity. 50 to 250 GW of the total installed diesel capacity could be hybridised with renewables, of which around 12 GW is located on islands.
- China has led the development of renewables-based mini-grids in recent decades. However,

Chinese mini-grids are meanwhile mostly integrated into the centralised grid, while generation still takes place on a decentralised basis. There are about 50 000 such decentralised production units, mainly small hydropower (SHP). Total global SHP capacity amounted to 75 GW in 2011/12, complemented by 0.7 GW of small wind turbines (SWT).

- There are a few thousand mini-grids in operation that are not connected to the main grid. Bangladesh, Cambodia, China, India, Morocco and Mali are among those countries with more than 10 000 solar PV village mini-grids. India has a significant number of rice husk gasification mini-grids.
- More than six million solar home systems are in operation worldwide, of which three million are installed in Bangladesh. Moreover, nearly 0.8 million small wind turbines are installed.
- A significant, but not precisely quantified, number of solar street lights and other electronic street signs are in operation.
- More than 10 000 telecom towers have been fitted with renewable electricity systems, especially with solar PV.
- In 2013, Africa had around eight million solar lighting systems installed to provide outside (public) lighting.

1 INTRODUCTION

Interest in off-grid renewable energy systems is on the rise, both in developed and developing countries. A decentralised system requires less land than a utility-scale renewable project, experiences less distance-related transmission losses (as it serves only a local customer or area), and provides electricity like a traditional grid connection. Furthermore, off-grid systems are able to support the integration of decentralised renewable power generation into the grid and provide power reliability and stability, evidenced in reduced outages and their respective massive economic impacts[1] upon related economic activities.

For *developing* countries, providing and maintaining energy access is an important driver for off-grid renewable energy systems (Sovacool, 2012; IRENA, 2013a). An estimated 1.16 billion people (17% of the world's population) currently live without access to electricity; an estimated 615 million of them in Asia and the majority of those in India (306 million), Indonesia (66 million) and the Philippines (16 million). Off-grid renewable energy systems are in many cases the most economical solution for these population groups (Szabo, *et al.,* 2011; Breyer, 2012). The energy access industry, excluding grid extension, is currently estimated as a USD 200-250 million annual industry (Sierra Club, 2014). However, fewer than five million households (*i.e.,* 25 million people) had energy access through off-grid solutions in 2013 (Sierra Club, 2013). Rapid expansion is projected with 500 million households being provided with access to electricity through mini-grids and solar home systems by 2030 (Sierra Club, 2014). Until recently, mini-grids have been a stepping stone towards grid expansion.[2] However, with improved control systems and declining renewable energy technology costs, it is currently not clear whether this evolution will continue or if mini-grids can become an alternative to main transmission grid extensions.

For *developed* countries, off-grid systems consist of two types: 1) mini-grids for rural communities, institutional buildings and commercial/industrial plants and buildings; and 2) self-consumption of solar PV power generation in residential households. The latter category is relatively small and most residents still rely on the grid for part of their load, but Germany and Japan are currently providing subsidies for electricity storage technologies for renewable self-consumption. In Germany, ten thousand rooftop solar PV systems are already coupled to battery storage systems. With increasing grid parity of solar PV systems expected in a number of countries, this could be an important development. Furthermore, in a number of countries businesses have entered the market and are leasing solar PV systems coupled to battery storage technologies.

Mini-grids are particularly relevant for island states, both developed and developing. It is estimated that there are more than 10 000 inhabited islands around the world and an estimated 750 million islanders. Canada, USA and Chile are the countries with the largest number of islands, while Indonesia, the Philippines and China are the countries with the largest population of islanders (Howe, *et al.,* 2013). Many of these islands, especially those in the range of 1 000 to 100 000 inhabitants each, rely on diesel generators for their electricity production and spend a considerable percentage of their gross domestic product (GDP) on the import of fuels. In most cases, renewables are already a cost-effective replacement for these diesel generators (IRENA, 2013a), creating an important market for off-grid renewable energy systems.

Although off-grid renewable energy systems are not new, there is still only limited information on them. Some overviews exist for solar home systems or mini-grids, but data sources are inconsistent or difficult to compare and aggregate. As renewables increasingly become cost-effective resources for off-grid systems, it is important to have a clear picture of their current

1 According to Eaton's Blackout Annual Report: "With electrical power outages, surges and spikes estimated to cost the US economy USD 150 billion, it is more important than ever for companies of all sizes to invest in reliable power backup solutions." (EATON, 2013)

2 Since the 1950s China has pursued the development of small hydro mini-grids, first operated in stand-alone mode and afterwards integrated into the central grid as it expanded into the rural areas, mainly due to government initiatives (Deshmukh, *et al.*, 2013). Similarly, in India mini-grids are seen as stepping stones towards a full grid (Palit, 2012).

status, their future prospects and the methodological improvements required to track their progress (World Bank, 2013).

The aim of this working paper is to identify key methodological challenges for data collection and analysis of the current status of off-grid renewable energy systems. Section 2 lists these challenges, and proposes some definitions and classifications to improve data collection. Furthermore, this working paper provides a global overview of available data organised by country and statistical resources in Section 3. Section 4 concludes with a number of steps to improve methodology development and data collection in the future.

2 METHODOLOGICAL ISSUES

The aim of this working paper is to identify key areas where methodological improvements are needed to provide a global status update on off-grid renewable energy systems. Four broad areas can be identified where improvements are needed. *First,* there is only a limited understanding of what aspects and designs comprise an *off-grid renewable energy system* and what applications, renewable energy resources and technologies should be considered under this broad topic. *Second,* the definition of what constitutes an 'off-grid system', including its application, users, and system components, is incoherent and inconsistent. *Third,* the indicators used to quantify and report off-grid systems differ, depending on the specific organisation and country, so it is difficult to compare and aggregate data across the world. *Fourth,* data on renewables used in off-grid applications are often not captured in national energy statistics and they often do not distinguish between installed capacity and operating capacity, especially considering that many off-grid systems have been in place over long periods of time or are used as back-up systems.

Methodological improvements are therefore necessary to increase the accuracy and comprehensiveness of data on renewable mini-grids and off-grid systems. Based on the broad overview of existing data sources (in Section 3), this Section discusses these four categories of challenges and provides proposals for improvement in more detail.

2.1 What are off-grid renewable energy systems and why do they matter?

There is broad agreement that off-grid systems are different from centralised grids in two ways. *First,* centralised grids are larger in size. They can include several hundred megawatts (MW) or even a thousand gigawatts (GW) of central generation capacity that can cover countries or even continents. Such grids include transmission at medium and high voltage (above 11 kilovolt, kV) to transport electricity over large distances. In contrast, off-grid systems are smaller in size and the term 'off-grid' itself is very broad and simply refers to "not using or depending on electricity provided through main grids and generated by main power infrastructure. *Second,* off-grid systems have a (semi)-autonomous capability to satisfy electricity demand through local power generation, whilst centralised grids predominantly rely on centralised power stations. The term "off-grid systems" covers both mini-grids (serving multiple customers) and stand-alone systems[3] for individual appliances/users. Customers of off-grid systems can be residential users or they can be used solely for commercial purposes.

Despite this broad agreement on the definitions of off-grid systems, the first question that need to be addressed in the context of this global status overview is when off-grid systems should be defined as "off-grid renewable energy systems". Open questions are:

- To what extent should hybrid diesel-renewable systems be counted as off-grid renewable energy systems?
- If a diesel generator is occasionally operated with vegetable oil, does it count as a component of an off-grid renewable energy application?

Thus, the first step is to precisely define the extent to which off-grid systems are actually *renewable*. For off-grid systems that are based 100% on renewables, the capacity of the system can be taken to evaluate the capacity of renewables, but for hybrid systems, different indicators would be required, such as the capacity of the renewable power generation sources connected to the off-grid system. In off-grid systems that are partly sourced by renewable energy, the capacity or renewable energy production share can be taken to represent the ratio of renewables. Through recent smart grid technology developments, it is becoming easier to monitor and track the production of each component of hybrid systems (IRENA, 2013b).

3 The International Electrotechnical Committee (IEC) refers to stand-alone systems as Individual Electrification Systems (IES).

Figure 1: Renewable mini-grid and off-grid systems, status 2012/13

	Grid connected	Minigrid <50 MW/own consumption	Stand-alone systems/ Individual electrification systems	Productive use
Gas	~ 1500 GW			> 1 GW Gas-fired CHP systems
Diesel		5–10 GW 50 000–100 000 systems		
Hydro	Large >10 MW 10 000– 50 000 systems >1 000 GW	Small < 10 MW 100 000–150 000 systems 75 GW	Micro-hydro 0.1– 1 MW Pico-hydro <0.1 MW	
Wind	310 GW 250 000 turbines	Diesel-wind hybrid <1 000 village/mining systems	Small wind turbines 0–250kW 806 000 turbines	Wind pumps > 500 000
Solar PV	50 GW/0.5 mln large systems >50 kW 80 GW/10-20 mln rooftop systems 1-50 kW	Diesel-PV hybrid <10 000 village systems	SHS <1 kW 5–10 mln systems	Solar lighting 5 mln; Telecom towers 10 000; Solar water pumps; PV Fridges/refrigeration; Street lighting systems; Traffic signs; Phone recharging stations;
Biogas/ biodiesel to power	14 GW 30 000–40 000 systems	< 100 kW biogas plants > 1 million biogas systems Gasification/rice husk etc 1 000–2 000 systems		Livestock farms Back-up biodiesel generators
Biomass cogeneration	20 GW pulp, sugar/ethanol 1 000–2 000 systems 20–30 GW steam cycles/CH 1 000–2 000 systems 5–10 GW cofiring coal plant 250–500 systems			

Considering these questions and based on the overview and insights from Section 3, Figure 1 provides an overview of the possible areas for renewables-based mini-grids and off-grid deployment. The information is organised into two "dimensions": resource type and application. The application areas include mini-grids, including systems for owner consumption only, off-grid residential systems, and systems for productive use. Renewable resources available for mini-grids and off-grid systems are biomass, hydro, solar photovoltaics (PV) and wind. In a number of cases, geothermal energy is also used to provide base-load power generation to off-grid systems, mainly on (volcanic) islands. Ocean energy technologies could also provide base-load power generation, especially to islands, as they are scalable (1-10 MW plants exist today), but so far they have not been deployed commercially. This overview reflects a very diverse market that is not yet well-documented. Figure 1 also compares renewables mini-grids and off-grid systems to grid-connected renewable energy resources and to fossil fuel-(mainly diesel) driven mini-grids and off-grid systems. For each category, the figure summarises existing data on the number and/or total installed capacity of renewables.

The data in this table are collected from various sources and are explained in greater detail in Section 3 of this paper. The table shows that hydropower is the largest source of renewables and that most hydropower is grid-connected. However, small hydropower systems (1-10 MW) constitute the largest source of renewables for mini-grids (75 GW). The second largest energy source for mini-grids is diesel generators (23 GW). Diesel generators are used as back-up power for renewables-based mini-grids and also as back-up for unreliable grids. Around 500 GW of diesel generators are used in industrial applications (ARE, 2013). With declining costs for renewable energy and electricity storage technologies, the replacement of diesel generators could become an attractive market for accelerated renewables deployment. Solar PV and wind turbines are increasingly used as an energy source for mini-grid and off-grid systems; however, their total installed capacity is fairly limited.

Looking forward, three markets are projected: 1) the replacement of existing diesel generators, usually through hybridisation of existing diesel grids[4]; 2) the

4 So far the cases of complete island conversion from diesel to renewable energy are few and far between. The Pacific island of Tokelau has proven that ambitious plans can work by co-installing 4 032 solar panels and 1 344 batteries to generate 100% renewable electricity. As battery technology costs fall, more remote communities are likely to follow this island's example.

The IRENA questionnaire for off-grid renewable energy

IRENA collects data for off-grid systems based on the following definition: "Off-grid electricity is generated in plants that are off the main grid; that is to say, in stand-alone systems and mini-grids. Off-grid capacity refers to the capacity of these stand-alone systems and mini-grids." In a first round, nineteen countries submitted data. These are split by resource (*i.e.,* biomass, small hydro, oil, wind, PV) and by some specific systems (*e.g.*, communication towers, PV streetlights/traffic lights, PV water pumps)

supply of electricity to consumers who were previously without it; and 3) the 'islanding'[5] of existing grids and/or extension of existing grids through mini-grids and off-grid systems. In the latter two categories, mini-grids might remain independent but could also at some point be integrated into the grid while maintaining island operation capability on a community, industrial plant or cluster level.

2.2 Where are these systems used, and what are their components?

Off-grid systems are not new: there are millions of diesel and gasoline generators in use worldwide. These provide electricity where there is no grid or where the existing grid is unreliable. What has changed is that new renewable solutions have emerged that are cheaper, cleaner and better able to produce electricity locally without reliance on imported/transported fuels. Due to this development, off-grid renewable energy systems are now seen as a potential replacements for both traditional diesel-based off-grid systems and for existing grid systems.

Ideally, off-grid renewable energy systems would need to be characterised in a systemic way in order to compare and aggregate the applications and to provide a global perspective on the scale of deployment. However, in reality, as Figure 1 shows, there are many different kinds of off-grid renewable energy systems, ranging, for example, from single-home rooftop PVs with and without battery storage, to solar lanterns, to PV street lighting and traffic lights, to PV pumping systems, to PV telecom towers, small wind turbines, wind pumping systems, off-grid fridges/refrigeration systems to mobile phone recharging systems. Other questions that need to be addressed are:

- Do systems connected to the main grid, but able to operate independently, still count as off-grid systems?
- At what scale does an island electricity system cease to be a mini-grid?
- Are mining operations and industrial operations that do or do not connect to the main grid included in the definition of off-grid systems?

At this point, however, there is no universally agreed definition of what constitutes an off-grid system, mini-grid system, or stand-alone system.[6] For example, Lilienthal (2013) defines mini-grids very broadly as "local producer networks that use distributed energy resources and manage local electricity supply and demand". There are, however, a number of more formal characterisations for micro-grids. At an international level, the International Electrotechnical Commission (IEC) (2006a) defines micro-grid as *"grid that transfers a capacity level less than 50 kilo volt-amperes (kVA) and is powered by a micro-power plant*" (Note that the IEC, 2006b sets the boundary to 100 kVA). Furthermore, the IEC has established a number of standards for micro-grids for decentralised rural electrification purposes. These standards cover micro-grids with low voltage AC (three-phase or single-phase) with rated capacity less than or equal to 100 kVA (*i.e.,* less than 50-100 kW), which are powered by a single micro-power-plant and do not include voltage transformation.

5 According to Greacen *et al.* (2013), islanding refers to the condition in which a portion of the grid becomes temporarily isolated from the main grid but remains energised by its own distributed generation resource(s).

6 see *e.g.*, *http://blog.homerenergy.com/how-to-classify-micro-grids-setting-the-stage-for-a-distributed-generation-energy-future/* and *http://der.lbl.gov/micro-grid-concept* and *www.cleanenergyministerial.org/Portals/2/pdfs/A_Guidebook_for_Mini-grids-SERC_LBNL_March_2013.pdf).*

Furthermore, the IEC differentiates between individual electrification systems (IES home systems) and collective electrification systems (CES mini-grids) by their sub-systems. IESs consist of only two sub-systems:

- an electric energy generation sub-system; and
- the user's electrical installation.

Collective electrification systems (CES mini-grids), however, consist of three sub-systems:

- an electric energy generation sub-system, which can include several electricity generation units (*e.g.,* PV and diesel generators);
- a distribution sub-system, also called a micro-grid; and
- the user's electrical installations, including interface equipment between the installations and the micro-grid and metering.

At the national level, there are different definitions for micro-grids. The United States Department of Energy (DoE) had a micro-grid exchange group that defined micro-grids as *"a group of interconnected loads and distributed energy sources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid"* (DoE, 2010). According to this DoE definition, micro-grids can be connected or disconnected from the grid and operate in both grid-connected or island-mode; however, this definition does not specify a precise size or scale. The defining characteristic of a micro-grid is, from the DoE perspective, the fact that it has a semi-autonomous capability and can control its loads and supply. Interestingly, US states have their own definitions of micro-grids, which differ again from the Federal Department of Energy.[7]

Based on the available definitions of off-grid systems provided by international and national sources, Table 1 proposes an overview to categorise different off-grid renewable energy systems in terms of their applications, users, and system components. Stand-alone systems tend to either be small and/or exist where the owner has no intention to connect them to a wider grid. These include residential solar home systems (SHSs) without grid connection, small wind turbines (SWTs), as well as solar lighting systems. Pico-, nano-, micro- and mini-grids are in many cases semi-autonomous and can operate in island mode, but are also often connected to larger grids. Finally, there are the off-grid systems for productive use: telephone towers, water pumps, street lighting, etc. Mechanical wind-driven water pumps could also theoretically be included as they offer the same function as solar PV-driven pump sets.

2.3 How can off-grid renewable energy systems be compared?

The categorisation provided in Table 1 allows for differentiation of off-grid renewable energy systems into different applications and system components; however, it does not provide guidance on how to compare and aggregate the scope and scale of different off-grid renewable energy systems.

A starting point for comparing and aggregating off-grid systems requires a common indicator for measuring their size and/or impact. However, different international, national, and local organisations use different indicators for measuring and reporting mini-grids or stand-alone systems. Furthermore, mini-grids are subdivided into 'micro-grids', 'nano-grids', and 'pico-grids', although the relationship and size differences between 'micro-', 'nano-', and 'picogrids' does not correspond to their mathematical equivalents. Furthermore, the term mini-grid is often used inter-changeably with the term micro-grid (Lilienthal, 2013).[8]

Another issue is the appropriateness of the indicator. As highlighted in Figure 1, the total renewable power generation capacity in off-grid systems might be small compared to grid-connected systems; however, they can have important implications for the livelihood of people in rural areas. Therefore, it might be more appropriate to use other indicators than capacity. Possible

7 For example, definition of a microgrid for the U.S. State of Connecticut differs from the definition for micorgrids for the U.S. Federal Department of Energy (EPRI, 2013).

8 In some documents, mini-grids and micro-grids mean the same thing (*i.e.,* stand-alone grids that are not connected to the main grid). Mini-grids are generally understood to be larger than micro-grids. However, there is no firm and consistent definition of the dividing line between them. Moreover, there is no fixed definition of what constitutes the "main grid." This becomes relevant in cases where the national grid is relatively small (*e.g.,* small island states where the entire national grid has a generation capacity of less than 10 MW). In other documents, a mini-grid is defined as a stand-alone AC grid (of undetermined size) while a micro-grid is a smaller stand-alone grid that deals exclusively with DC power (*e.g.,* see *http://www.nrel.gov/docs/fy12osti/55562.pdf*, footnote #1).

Table 1: Proposed categorisation of off-grid applications

	Stand-alone			Grids		
	DC		AC	AC/DC		AC
System	**Solar lighting kits**	**DC Solar home systems**	**AC Solar home systems; single-facility AC systems**	**Nano-grid Pico-grid**	**Micro-grid, Mini-grid**	**Full-grid**
	Off-grid					
Application	Lighting	Lighting and appliances	Lighting and appliances	Lighting, appliances, emergency power	all uses	all uses
User	Residential; Community	Residential; Community	Community; Commercial	Community; Commercial	Community; Commercial; Industry	
Key component	Generation, storage, lighting, cell charger	Generation, storage, DC special appliances	Generation, storage, lighting, regular AC appliances. Building wiring incl. but no distribution system	Generation + single-phase distribution	Generation + three-phase distribution + controller	Generation + three-phase distribution + transmission

characterisations are cumulative capacity operating, the annual production/consumption/sales of renewables-based electricity, persons/households/service organisation (*e.g.,* hospitals) served or investment volumes. Based on these issues, the open questions that are addressed in this Section are:

- What is the minimum and maximum size of off-grid systems, and in how far is this consistent across countries and organisations?
- What is the appropriate indicator to examine the impact of off-grid renewable energy systems?

Comparing different sources, there are a number of indicators that can be used to separate and compare different off-grid systems, such as generation capacity, transmission voltage levels, AC versus DC systems, the geographical distance between generator and consumers, and the level of grid redundancy.

Classification according to generation capacity. Different sources use a maximum generation capacity ranging from 3-15 MW[9] to separate off-grid systems from grid systems while other sources use the maximum voltage level (11 kV) or, in the case of AC systems, maximum voltage-ampere levels to distinguish different sizes of off-grid systems (SDC/TARA, 2014).

However, the 15 MW capacity cut-off point is relatively arbitrary. Many island countries and islands operate mini-grids although their installed capacity is often more than 1 GW. For example, island systems range from 6 MW (Nauru) to 15 MW (Tonga) (IRENA, 2013d), expanding to larger island systems ranging from 1 GW (Cyprus) to 5 GW (Cuba and the Dominican Republic). Similarly, industrial users often produce their own electricity and can run their electricity systems semi-autonomously. The typical size for an energy-intensive industry (*e.g.,* pulp mill, cement kiln) is 5-100 MW, equivalent to a city with 25 000 – 250 000 inhabitants. Some recovery boilers generating power in pulp mills can have capacities as large as 400 MW. Worldwide, more than 850 waste heat recovery (WHR) systems are installed with power system sizes ranging between 5-25 MW per installation.

The terms 'micro-grid', 'nano-grid' and 'pico-grid' are used to differentiate different kinds of mini-grids with size thresholds, capability and complexity as some of their defining characteristics (Nordmann, *et al.,* 2012). For example, Navigant classifies nano-grids in the range

9 The United Nations Convention on Climate Change (UNFCCC) uses an upper range of 15 MW to define mini-grids within their Clean Development Mechanism (CDM), while the Global Village Energy Partnership (GVEP) uses 3 MW as an upper range for their definition of mini-grids.

from 5 kW for remote systems not interconnected with a utility grid to 100 kW for grid-connected systems (Navigant, 2014b).

Classification according to project data. Another possibility is classifying different kinds of off-grid systems by evaluating their project data. A global evaluation of 155 mini-grid systems (*i.e.,* 79 for powering remote villages, 59 for public amenities, 14 for islands and eight for powering telecommunication[10]) showed that grids designed for electrification of villages had an average power of 69.9 kW (Werner and Breyer, 2012). This is consistent with national data on mini-grid systems in Sri Lanka (*i.e.,* 268 off-grid systems ranging between 3-50 kW) or Cambodia (*i.e.,* 150 kW average installed generation capacity) (World Bank, 2014). In another study, hybrid mini-grid systems supplying remote islands have an average power of 379 kW (Breyer, 2012), although this range is still far below the 100 MW of installed capacity for some island states. In the Philippines, where diesel-based mini-grids are also used to support commercial and industrial activities, capacities may reach more than 20 MW (Bertheau, *et al.,* 2012). In comparison, industrial users of mini-grids often have generation capacities in the tens of MWs.

Classification according to generator size. A third option is to examine the size of the generators in off-grid systems, although definitions and use vary across countries. For example, some African countries define small hydro plants (SHPs) as those with a maximum capacity of 15 MW, while Vietnam and China in comparison have higher limits of 30 MW and 50 MW, respectively. In Italy the maximum capacity is 3 MW and in Bosnia and Herzegovina, 5 MW. Diesel generators for off-grid systems can be up to 10 MW,[11] while biomass systems can be up to 15 MW if connected to an industrial facility like a sugar factory.

Based on both formal definitions and case study material, Table 2 proposes a categorisation of off-grid systems based on *size, capability and complexity*. Hybrid diesel-renewable mini-grids constitute a sub-category of their own. The share of capacity or the share of TWh generated during a typical year can be applied as a measure of the share of renewables in the system.

Classification according to financial, social and disease-burden criteria. Besides capacity, there are a number of other indicators that can be used to evaluate the impact of off-grid renewable energy systems. For example, the World Bank has evaluated its financial support to off-grid renewable energy systems at the residential level by calculating expenditure increases per capita due to energy cost savings or increased productivity, evening study hours for children, reduced respiratory diseases and mobility and entrepreneurial ambitions among women (World Bank, 2014).

For off-grid renewable energy systems connected to the grid, indicators can be expanded to include contributions to power quality and reliability, economic and even security benefits of off-grid renewable energy systems.

2.4 What data sources are available for off-grid renewable energy systems?

Finally, there are a large number of different data sources available for off-grid renewable energy systems. However, the data in these sources is often inconsistent and out of date. In this Section, we provide a brief overview of the different sources available followed by suggestions for improvement.

Energy Ministries and/or Agencies. In developing countries, data sources for off-grid systems are often found in agencies or ministries dealing with rural electrification or in international development agencies. However, statistics offices often exclude data on sub-MW installations in their data sets, although these comprise the majority of off-grid systems. Many development agencies are involved in the development of mini-grids but do not necessarily collect and supply data back to the ministries or statistical offices.[12] Furthermore, renewable

10 There is an overlap among the different categories.

11 There are cases where diesel generators for off-grid systems achieve greater capacities in order to fulfill different purposes; for example, in order to supply remote mining sites, Peru relies upon a diesel generator in an off-grid system that generates 16 MW of electricity.

12 For example, Schnitzer *et al.* (2014) collected data from seven different agencies, local utilities and rural power producers involved in the development of mini-grids in Haiti, India and Malaysia. Development agencies in India included the Chattisgarh State Renewable Energy Development Agency (CREDA), Orissa Renewable Energy Development Agency (OREDA) and the West Bengal Renewable Energy Development Agency (WBREDA), but at the same time rural power producers like DESI Power and Husk Power Systems are also developing mini-grids.

Table 2: Proposed grid categorisation

	Size (kW)	Capability	Complexity
Stand-alone systems	0 – 0.1		
Pico-grid	0 – 1	• Single controller	
Nano-grid	0 – 5	• Single voltage • Single price • Controllers negotiate with other across gateways to buy or sell power	• Both grid-tied and remote systems • Preference for DC systems • Typically serving single building or single load • Single administrator
Micro-grid	5 – 100	• Manage local energy supply and demand • Provide variety of voltages • Provide variety of quality and reliability options • Optimise multiple-output energy systems	• Incorporate generation • Varying pricing possible
Mini-grid	0 – 100 000	• Local generation satisfying local demand • Transmission limited to 11 kV	• Interconnected customers

power production produced at residential level does not appear on the meter, and is therefore difficult to track by local utilities. In official statistics, off-grid electricity generation is therefore often estimated and only partially included into the national energy balances (IRENA, 2013e). To augment data from ministries and agencies, there are also international development organisations and technology providers, like Trama TecnoAmbiental (TTA) in Spain that implement renewable mini-grids in developing countries. They have often sales figures that can provide accurate data on installed capacity, although this does not mean that the technologies are actually used.

Regulatory institutions. Another important potential data source are the regulatory institutions. In both developed and developing countries, mini-grid and off-grid systems are often connected to the grid although they are able to operate independently if required. In this case, regulators might have an overview of what percentage of the grid constitutes mini-grid and off-grid systems, because in many countries specific interconnection procedures apply to independently owned grids. For example, in Tanzania only power producers with a maximum capacity of 10 MW are allowed to operate isolated mini-grids. For distributed generators above 1 MW, licensing is required. Below one MW, generators are exempted on distribution, transmission and generation segments (Deshmukh, *et al.,* 2013).

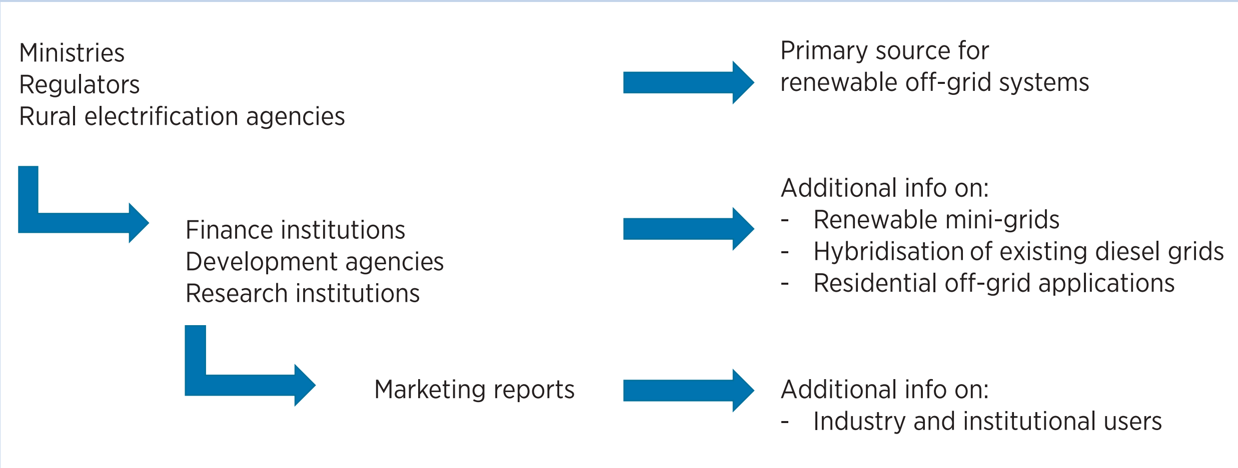
Financial and Research Entities. Yet another data source for mini-grids and off-grid systems are financial institutions and research institutes. Financial institutions like the World Bank have been providing financial support to off-grid systems since the 1980s (IEG, 2008). For example, the World Bank financed the installation of almost 320 000 solar home systems in 14 countries through the year 2008 (IEG, 2008). Research institutes have been collecting data in two ways. First, research programmes (*e.g.,* European framework projects) have been providing funding to demonstration projects. Furthermore, academic institutions and research institutes have been collecting data on off-grid systems to evaluate their performance and/or the effectiveness of policies that have supported the deployment of off-grid renewable energy systems. However, the latter resources do not supply consistent data, given that they are case study-specific and often cover only a particular geographic or application area and timeframe.

Marketing Reports. A fourth source of data are marketing reports, such as the Micro-grid Deployment

Tracker or the Nano-grid Global Market Analysis of Navigant Consulting, or the North American Micro-grids 2014 report of GTM Research. These reports are often based on bottom-up data collected through interviews and surveys to technology providers. For example, many large international firms like ABB, Alstom, Bosch, GE, Schneider Electric and Siemens supply micro-grid controllers and thus have a fairly good grasp of the number of projects and their size. However, there are also a large number of smaller and more local companies that supply such technologies, but these data are more difficult to collect and track. Furthermore, the reports often collect data based on the capacity of the micro- or nano-grids with only limited data on the resources used or the operational state of the micro-grid. For example, according to Bloomberg New Energy Finance (BNEF) most micro-grids in the US use gas as a fuel for base-load onsite generation (BNEF, 2014) and according to Navigant, only half of the installed capacity of micro-grids is operational (Navigant, 2014).

Considering the different data providers, each with different sources for their data, consistency of data can be improved by cross-checking of multiple source. Figure 2 provides a possible sequence of steps for data collection. For renewables deployment in mini-grid systems, ministries for energy and regulators are primary sources for data. Such data should be augmented with data from finance institutions, development agencies, and research institutions in those cases where primary statistics are lacking. This is particularly the case for the use of renewables in providing rural electrification. Marketing reports are good data sources for usage of renewables in industrial applications and off-grid systems that do not need to report their energy consumption to local authorities.

Figure 2: Data sources for off-grid renewable energy systems



3 STATISTICAL DATA ON OFF-GRID RENEWABLE ENERGY SYSTEMS

This Section provides a global overview of the available statistics for off-grid systems based on data from countries and other sources. The results of this overview has been used to identify the key areas for methodological improvement as discussed in Section 2. Detailed statistics on off-grids systems are lacking, mainly due to the lack of generally accepted definitions but also because of the fragmented and small-scale markets. Some information can be gathered from trade statistics, associations of manufacturers and sellers of equipment, etc. In the case of mini-grids, some countries keep statistics. The following discussion uses available statistical information from a number of different sources.

3.1 Global statistics

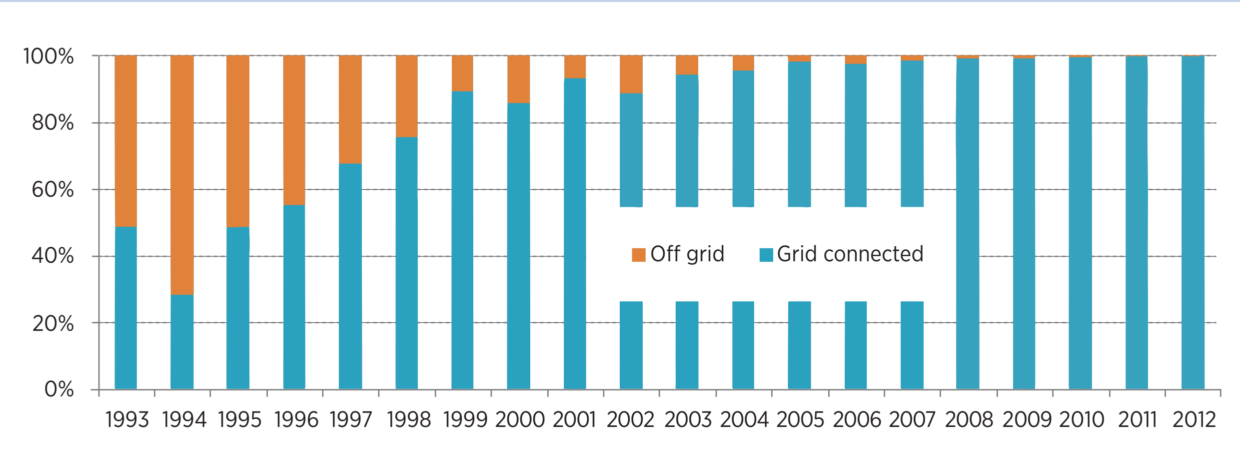
Off-grid systems are not new. For decades they have been used to supply remote areas (*e.g.,* rural villages, islands and even small cities) that are not connected to any national electricity grid. For renewables, in particular solar PV, applications in off-grid systems were more common than grid-connected systems until 1995 (see Figure 3).

Furthermore, mini-grids are used to supply remote industrial sites, telecommunication facilities or public applications (*e.g.,* lighthouses, national parks, schools or mountain shelters) (Werner and Breyer, 2012). The market can be divided into six categories (adjusted from Schnitzer, *et al.*, 2014, which is also the categorisation used by a number of market reports):

- Islands;
- Remote systems;
- Commercial/industrial – to ensure energy security (99.99% reliability) or provide cheap energy sources, especially if connected to heat production;
- Community/utility – often demonstration projects in the case of developed countries;
- Institutional/campuses – includes hospitals, government buildings and other institutions with access to cheap capital and no short payback requirements; and
- Military – US-specific market for 500 military facilities within and outside of the US.

Global analyses of off-grid renewable energy systems are scarce, but some data on global overview of micro-grids, off-grid systems and diesel generators do

Figure 3: Ratio of off-grid versus grid-connected solar PV deployment between 1993-2012



Source: IEA PVPS, 2013a

exist. Many of these overview reports are from market research companies.

Navigant Consulting, one of these market research companies, distinguishes between micro-grids and mini-grids. Its latest micro-grid report identified 4 393 MW of total installed micro-grid capacity in mid-2014 (Navigant, 2014a). Only 53% of this capacity is actually in operation and an additional two GW of micro-grids are in the planning or proposal stage. Furthermore, the majority of micro-grids in the United States are run on gas. In addition to the micro-grid capacity, an additional 8 900 MW of nano-grid capacity (from 5 kW remote systems to 100 kW grid-tied systems) was identified in 2014 (Navigant, 2014b). In comparison, BSIA identified a total of 3.5 GW of global installed capacity in 2012 (BSIA, 2012). The major difference is the installed capacity in Europe (1.2 GW vs 0.54 GW). Similarly, GTM research (2014) identified a total micro-grid capacity in North America of 355 MW in 2014, while Navigant's data suggest a widely disparate capacity of 2 874 MW.

In general, North America is the world's leading off-grid market, with an additional planned or proposed capacity of 1 363 MW_e or 66% of the global total. The largest growth took place in the Asia-Pacific Region with 134 of the 155 micro-grids being built during 2013 alone (Navigant, 2014a).

Islands and remote systems are an important market and opportunity for off-grid renewable energy systems. For islands or rural areas where the mini-grid infrastructure is already in place, there is the economic case to displace – or ensure more efficient use of – diesel generators (ARE, 2011). The 37 Small Island Developing States (SIDS) had a total installed capacity of 28.4 GW at the end of 2012 (IRENA, 2014a). This included 10.2 GW for Singapore, around 5 GW each for Cuba and the Dominican Republic. This left around 8 GW for all other SIDS. But there are also other island power systems that are not part of SIDS. Worldwide, there are 2 056 islands with 1 000 – 100 000 inhabitants each, with an average electricity demand of 25.6 GWh. That equals around 12 GW of capacity (Blechinger *et al.*, 2014). Many of these island systems are hybrid mini-grid systems with some level of renewable energy.

Beyond islands, global statistics on rural electrification through off-grid systems (either based on diesel or renewables) are limited, although a number of countries are collecting or reporting national data. Recent estimates suggest a current market potential for upgrading existing diesel-based, off-grid systems with renewables in the range of 40-240 GW (Breyer, 2012).

3.2 Country statistics

The market for off-grid systems is mainly located in developing countries, although there are also niche markets in developed countries. In Europe solar PV installed in off-grid systems account for less than 1% of the installed PV capacity. In the US, solar PV off-grid systems accounted for 10% of the overall market in 2009, but the share has declined since then. In Australia and South Korea, solar PV off-grid capacity ranges in the dozens of MW per year (EPIA, 2014).

In developing countries, the market for off-grid renewable energy systems is mainly related to improvements in electrification[13] rates. From 1990-2010 worldwide access to electricity in urban areas increased by around 1.1 billion people, while the total global population increased by 1.27 billion; in rural areas both total population and people with access to electricity increased by around 0.3 billion people during that two-decade period. In other words, rural electrification has increased in line with population growth, but the number of people without electricity access has not changed. In India, Indonesia and the Philippines, annual growth rates for grid electrification have reached 2% per year. This expansion rate suggests that universal electrification can be achieved within the next few decades, assuming that technical, physical and financial barriers can be overcome. Unfortunately, however, the simple arithmetic of expanding centralised grids is misleading since the geographic realities of mountain ranges (*e.g.,* northern India) and archipelagos (*e.g.,* Indonesia and the Philippines) with limited electricity access means that large numbers of households and enterprises in Africa and Asia are unlikely to *ever* be connected to a large centralised grid.

Most country data are, however, reported on a case-by-case basis. For example, a global survey of rural electrification activities in 87 developing countries

13 "Electrification" in this instance means access to electricity. The same term is commonly used to explain the increased use of electricity-based technologies, such as heat pumps or electric vehicles.

reviewed 48 renewables-based initiatives, although not all initiatives used off-grid systems (UN DESA, 2014). The countries addressed below in this report are but a sample of statistics by country as this compilation does not include all countries with ongoing mini-grid development. The countries are categorised by continent and in sequence of population.

Asia

Since the 1950s, ***China*** has pursued the development of renewables-based mini-grids. Many of these mini-grids were initially stand-alone configurations based on small hydro. By 2002, there were 42 000 small hydropower plants in China with a total capacity of 28 GW to provide distributed energy. From 2003-2005, China's Township Electrification Programme constructed 721 solar PV and PV/wind hybrid systems (20 Megawatt peak (MW_p) each), along with 146 small hydro stations (264 MW) to provide electricity to 1.3 million people (LBNL, 2013). The 2005-2010 Village Electrification Programme connected another 3.5 million people to renewable sources, including more than 400 000 off-grid solar home systems. Many of the mini-grids have now been integrated into the expanding national grid. In 2013, China had roughly 60 000 diesel and hydro mini-grid systems, most of them connected to the centralised grid. Furthermore, China has installed 11.8 GW of solar PV systems, of which 500 MW was installed in off-grid systems (EPIA, 2014). By the end of 2015, China aims to address the challenge of providing power to another 2.73 million people without electricity, 1.54 million of them through grid extension and 1.19 million through the utilisation of independent solar PV power supplies (IRENA, 2014d). However, to date only limited data are available on the progress of this programme.

India is a leading country in the area of mini-grids and off-grid applications. The Jawaharlal Nehru National Solar Mission (JNNSM) is its main policy initiative to promote solar energy, including off-grid power development. Furthermore, it has a number of programmes for other renewable energy technologies. As of May 2014, India had 17.5 MW of biomass gasifiers for rural off-grid applications and 147.2 MW for industrial ones, 174 MW of solar PV, 2.25 MW of small wind turbines/hybrid systems, 13.2 MW of SHPs (2 643 units) and 3.77 MW of biogas mini-grid systems (MNRE, 2014). Schnitzer, *et al.* (2014) identified around 750 mini-grid systems in India, including 135 biomass rice husk gasification systems and 599 solar photovoltaic mini-grids, with a total capacity of 8.2 MW and typically 10-400 customers each.

In ***Indonesia***, the Directorate General of New, Renewable Energy and Mineral Resources has goals of increasing rural electrification from 70-90% by 2020 and decreasing diesel power generation from 21% down to only 3% by 2015. The state-owned electricity company, PLN, is initiating a distributed solar PV development programme called "1 000 Islands" and plans to install a total of 620 MW of solar PV (through integration of diesel, biomass and other renewable energy sources on remote islands) by 2020 (CIF, 2014; Gerlach, 2013). With regard to total hydropower investments from 1992 to 2012 by the People Centered Business and Economic Initiative (IBEKA), out of 2 260 kW there were 57 off-grid systems. Today 47 000 people benefit from these off-grid systems that range in size from 0.5-170 kW.

Bangladesh is another country where significant progress has been made through off-grid renewable energy systems. A programme for SHS installations started in 2003 and implemented 50 000 installations by 2005, thus exceeding expectations. In July 2014, the figure had risen to 3.2 million installations benefiting 14 million Bangladeshis and contributing around 132 MW of renewable energy generation. The programme is currently carrying out more than 50 000 installations per month and is targeting a total of six million SHSs by 2017 (IRENA, 2013c; IDCOL, 2014; World Bank, 2014). Furthermore, initiatives have been developed in terms of solar mini-grids, solar irrigation programmes, solar-powered telecom towers and biogas-based electricity projects (see Table 3).

In the ***Philippines*** there are about 375 MW of installed capacity in diesel mini-grids. National Power Cooperation-Small Power Utility Group (NPC-SGUP) operates 279 MW of this capacity in 221 areas (*i.e.,* a total of 534 generating units). The majority of these systems are operated between 6-8 hours/day; other areas are supplied between 10-24 hours/day. Operating capacity in most cases is below 500 kW.

In ***Nepal*** between 1996 and 2011, the Rural Energy Development Programme (REDP) provided 317 villages (58 000 households) with micro-hydro installations with a cumulative capacity of 5.8 MW. Simultaneously, the Energy Sector Assistance Programme (ESAP) provided local support structures, quality standards and

Table 3: Off-grid renewable energy projects in Bangladesh (IDCOL, 2013; IDCOL, 2014).

Project/Programme	Target	Achievements as of July 2014
SHS Programme	6 million by 2017	3.2 million
Solar Irrigation Programme	1 550 by 2017	149
Solar mini-grids	50 (average 100 kW) by 2017	8
Solar powered Telecom towers	As per demand	138
Biogas-based electricity projects	130 by 2017*	8
Rice husk-based power plants	30 (average 200 kW) by 2016	

*Initial target of 450 (average 20 kW) plants by 2016

guidelines. Since 2012, Nepal operates a restructured rural and renewable energy programme (LBNL, 2013).

Tracing back to 1940s, ***Sri Lanka*** had over 500 micro-hydro facilities to provide energy services for tea plantations, although village systems were only installed since the 1990s. Two programmes, the Energy Services Delivery Programme in 1997 and the Renewable Energy for Rural Economic Development Project in 2002, provide electricity through micro-hydro mini-grids and solar home-based systems to 22 000 and 6 000 households, respectively (LBNL, 2013). Off-grid generation is a diminishing component on the supply side. This is a result of the fast expanding national grid, which now serves more than 90% of all homes.

Cambodia launched the Renewable Electricity Action Plan (REAP) in 2003 to coordinate and grow the existing 600 diesel-based mini-grids and 1 000 battery-charging stations so that they can cover 70% of domestic electricity demand by 2030. However, there are only a few renewable energy mini-grid projects so far (LBNL, 2013). One biogas-based mini-grid provides electricity to around 1 100 households (ARE, 2013).

In **Laos**, where nearly 70% of the population lives in rural areas, the government promotes the development of renewable energy in these areas by funding and supporting the construction of off-grid systems. Moreover, several policies are in place to foster rural electrification through off-grids systems (*e.g.,* governmental encouragement of private investors to undertake the construction and installation of renewable energy off-grids themselves and later to transfer control of the facility to the province) thus raising the national electrification rate from 30% in 2000 to 78% in 2012. Furthermore, the rent-to-own Solar Home System project led the installation of 15 000 SHSS by 2009. Laos' Rural Electrification Master Plan (REMP) aims at achieving 94.7% of residential electrification by 2020, 90.9% by on-grid systems and 3.8% by off-grid systems using mini/micro-hydropower and SHSs (ASEAN, 2013).

Africa

The global Market Outlook of the European Photovoltaic Industry Association (EPIA) for 2013-2017 estimates new PV off-grid installations in Africa to be between 70-100 MW per annum (PV Magazine, 2013). A comprehensive tool has been developed to explore and compare off-grid solar PV versus diesel generators in Africa (EC, 2014). In 2014, the US Government launched a new framework focused exclusively on unlocking investment and growth for off-grid and small-scale energy solutions on the African continent (The White House, 2014). The programme, called "Beyond the Grid", partners with over 36 investors and practitioners committed to investing over USD one billion into off-grid and small-scale solutions to this underserved market. The framework is part of a larger initiative called "Power Africa", which aims is to provide access to 20 million new connections for households and commercial entities before 2020 (PV Tech/Solar Media, 2014).

Nigeria has been identified as one of the countries with a high potential for mini-grids (IED, 2013), and the Nigerian government has announced plans in 2014 to fast track rural electrification projects with wind, solar, biomass and hydropower. So far, only 64 MW out of 3 500 MW of small hydropower resources has been exploited, and most other renewables-based pilot projects have been small scale. Only 40 small scale solar off-grid plants were installed in rural communities in the period between 2007 and 2012 (5 solar home systems, 6 mini-grids, and the rest street lighting systems) (Julius, *et al.,* 2014). 700 residential households have been connected to a mini-grid to provide lighting (ARE, 2013).

Tanzania is another country with a high potential for renewable of-grid systems (IED, 2013). Tanzania's Rural Electrification Agency (REA) perceives hybrid technology as one of the solutions to provide reliable and affordable electricity to isolated areas. Private developers presently manage the development of hybrid systems while REA provides support to them through capacity building, technical assistance, promotion of the technology and awareness raising. REA is planning to use various financing schemes to further develop Tanzania's hybrid technology.

In Tanzania, off-grid electricity is mainly supplied by diesel generators, and in 2010 a total of 22 projects (42 MW of grid-connected and 17 MW of isolated projects using small hydro and biomass power) were in various stages of development. Furthermore, more than 60 projects were being planned (LBNL, 2013). Bertheau, *et al.* (2013) identified a potential for at least 22 MW of diesel-based mini-grids that are available for upgrading to hybrid grids. Table 4 provides an overview of diesel generators operators.

Solar home systems constitute around 75% of the installed solar PV capacity in Tanzania (or around 4 MW), and around 4 000-8 000 systems are sold annually (Hansen, Pedersen and Nygaard 2014). Tanzania also has plans to implement systems that include wind energy.

Kenya is the third country that has been identified as having high potential for off-grid renewable energy systems (IED, 2013). Kenya has 18 operational mini-grids with 19 MW of capacity, including seven that have been in operation for more than 30 years. All have diesel generators, two have wind and six have solar hybridisation (IRENA, 2013a). In 2011, a PV/diesel hybrid power plant was implemented (10 Kilowatt peak (kW_p) PV, 80 kVA diesel) and managed by Kenya Power and in 2013 a 13 kW solar PV-based mini-grid was installed (E4D, 2013). The residential solar home system market corresponds to around 6-8 MW_p (Hansen, Pedersen and Nygaard, 2014).

In ***Algeria***, there is also a rural electrification programme with about 20 plateau and steppe villages electrified with PV (MEM, 2013).

As of late 2014, ***Uganda*** has hybrid systems in the 5 kW_p range implemented at rural district headquarters and in a few industries. The deployment of this technology is still at the "infant" stage. The Rural Electrification Strategy and Plan established in 2011 aims to connect over 500 000 new electricity customers to the main grid, independent grids and solar PV systems, with the support of local institutions (Rural Electrification Fund, Rural Electrification Board and Rural Electrification Agency). These institutions are willing to promote this promising PV/diesel hybrid technology. REA has budgeted for feasibility studies in 2011-2012 for hybrid solutions on Koome and Buvuma Islands (*i.e.,* hybrid systems using wind, solar and diesel sources). Around 15 000 solar home systems were installed in 2013, amounting to around 300-400 kW_p (Hansen, Pedersen and Nygaard, 2014).

Morocco is an African leader in electrification through its development of village-scale mini-grids with 3 663 villages with nearly 52 000 households electrified with solar by 2010. Around one in ten villages that were electrified used renewable mini-grid solutions (Benkhadra, 2011).

Table 4: Overview of isolated diesel grid operators in Tanzania (Bertheau, et al., 2013)

Operator	Number of plants	Installed capacity (MW)	Type of Organisation
TANESCO	21	11.05	State-owned
ZECO	5	10.33	State-owned
Urambo Coop.	1	0.11	Private
Mbinga Coop.	1	0.29	Private

In ***Madagascar,*** two hybrid systems based on PV were implemented in 2010: one funded by the government (*i.e.,* 7 kW_p PV, 12 kW diesel) and one by the African Development Bank (*i.e.,* 8 kW_p PV, 100 kW diesel).

Cameroon has over 23 MW of mini-grids installed, consisting of some over 30 installations varying in size from a few dozen kW to 13 MV.

Burkina Faso's Fund for the Development of Electrification initiated a project in 2012 to add a solar PV components to existing diesel power plants in the Sahel region. A previously installed PV array at the diesel plant in a remote locality in the Sahel will soon be connected to the main grid.

Mali has 60 000 energy service companies with 74 000 clients. Access to electricity in rural areas has jumped from only 1% in 2006 to 17% in 2012. Mali has the largest installed PV/diesel hybrid mini-grid in Africa: a 216 kW_p system implemented in 2011 thanks to cooperation between the national utility EDM and a private operator with funding from the Malian Bank for Commerce and Industry. Presently, the World Bank and the AfDB are funding the Scaling Up Renewable Programme (SREP), including a hybrid component that plans to erect PV arrays in existing diesel power plants in 40 localities comprising a total of 5 MW_p PV and a total investment budget of USD 58 million (USD 11 600/kW_p PV). Another programme managed by the rural electrification agency AMADER is currently hybridising 17 localities for a planned total of 1 MW_p PV power. Several private operators plan to add PV capacity to diesel power plants (Kama SA: 300 kW; SSD Yeelen Kura: 300 kW_p planned in addition to the existing 72 kW_p hybrid plant and Tilgaz: 22 kW_p).

In 2002, ***Senegal*** published the Senegal Poverty Reduction Strategy Paper setting out the government's strategy to provide energy services to off-grid areas (ADB, 2013). So far, Senegal has been one of the most active African countries in implementing this hybrid technology. With a EUR 20 million fund from the Spanish government, the company Isofoton has installed nine hybrid power plants in remote areas and islands in the Saloum Delta to provide electricity to 5 000 households and several productive activities. Furthermore, Dutch and German development agencies provided EUR 1 million for the installation of 16 hybrid power plants (5 kW_p PV and 11 kVA diesel each) and an extension of this programme plans to add 50 more hybrid systems. Two larger hybrid power plants are planned on islands in Casamance (*i.e.,* 30 kW_p PV and 50 kVA diesel each).

Rwanda is the fourth "high-potential" country for off-grid renewable energy systems (IED, 2013). Rwanda has an electrification rate of 5%, and has a plan to increase its total installed capacity from 90 MW in 2011 to 1 000 MW in 2017. In terms of renewables, Rwanda has installed PV/diesel hybrid systems in 50 remote health centres (typically with diesel generators rated at 16-20 kVA and 3-6 kW_p PV arrays). Diesel generators are used as a back-up to PV supply. Hybrid systems are owned by the beneficiaries and are financed through grants from different international development partners working with through Ministry of Health. These systems have reduced fuel consumption and enabled the use of new medical equipment, but maintenance remains a challenge for the beneficiaries.

In 2013, with 2.3 million Euro funding from the European Union, ***Mauritania***'s Agency for the Development of Rural Electrification started implementing six hybrid PV/diesel power plants spread across the country. Three of them will consist of an addition of 15-20 kW_p PV to existing diesel power plants, and the other three will be new power plants, each equipped with 25 kW_p PV and two diesel generators (IEA PVPS, 2013b).

The Americas

In the ***USA***, it is estimated that around 10% of total installed PV capacity—which equates to 100 MW—was in off-grid systems in 2009. Around 40 MW of additional off-grid capacity was installed in 2009, but since then the use of off-grid systems has declined (IEA PVPS, 2013).

The ***Brazilian*** electrical system is formed by both the National Interconnected System (NIS) and the Isolated Systems (IS). NIS has a transmission network covering 89 200 km^2 and is responsible for 96.6% of the full transmission capacity of electricity production in that country. The high costs of the national grid expansion in northern regions of the country, due to its geographical characteristics and low population density, make the IS the major supplier of energy in this region. These systems cover an area equivalent to 45% of the national territory but supply energy for only 3% of the population, with 8.7 TWh of electricity generated from fossil fuels in 2009. In 2009, nearly 1000 power plants used diesel oil to supply electricity for isolated cities and villages in the Amazon. so full sentence: Some 700 of these plants have an installed power capacity below 500 kW (Coelho, 2009). Brazil has ambitious plans, supported by an 85% capital subsidy, to connect more than 250 000 households in rural regions through renewables-based mini-grids but by 2010, only 15 small hydro-based mini-grids and one solar PV-based mini-grid had been established (LBNL, 2013). In 2012, around 45 MW of solar PV was installed in Brazil, mostly in off-grid systems (IEA PVPS, 2012).

In ***Mexico***, around three million people live without any electricity access but around 500 systems have been installed to provide local communities, schools and solar water pumping systems, at least aiding around 3000 people (ARE, 2013). Clearly, much remains to be done.

In ***Canada***, around 300 remote communities are served with mini-grids with a total capacity of 453 MW, mostly diesel power plants and gasoline generators. Eleven mini-grids are hydro-based (153 MW). The 2011 survey identified four small solar PV systems (30 kW in total), three wind turbines (600 kW in total), five biomass and wood pellet systems and five solar thermal systems integrated into existing Canadian mini-grids (Government of Canada, 2011).

Chile has a six GW solar pipeline with most of the projects planned in the north directed towards power mining companies. These mining operations are remotely located and currently operate largely based on diesel generators. However, at the end of 2013, only 8.4 MW of solar installations were connected to the grid with a further 69 MW were under construction (Renewable Energy Center Chile, quoted in PV Magazine, 2013).

Oceania

Only 2% of ***Australia***'s population lives within the off-grid electricity market – the area not covered by the main grid – which currently consumes over 6% of the country's total electricity output. Off-grid energy consumers include agricultural processing facilities, outstations, off-grid mines, small communities and off-grid infrastructure, such as telecommunications and desalination facilities. This group is currently supplied with electricity from both off-grid interconnected systems and islanded power stations. Australia's off-grid electricity market sources 74% of its energy from natural gas and the remainder mostly from diesel fuel. Statistics indicate that 15812 GWh of electricity was produced by off-grid generation in Australia in 2012 from a total installed capacity of approximately 5 GW (BREE, 2013). The off-grid industrial sector consumes approximately 12.4 TWh per annum or 79% of the total off-grid electricity produced, of which the majority is consumed by the mining industry. So far only 1% (56 MW) of the off-grid market is supplied by renewables but the economic case is convincing and rapid growth is expected (AECOM, 2014).[14]

Many of the Pacific islands have ambitious plans to increase their shares of renewables (IRENA, 2013d). Their total generation capacity in 2012 was approximately 712 MW with 78% of power generation derived from fossil fuels. The other 22% was based on hydropower, with Tokelau having transformed to 100% renewable energy through solar PVs (927 kW). Since many Pacific Island states are composed of numerous islands, the mini-grids are supported by diesel generators in the range of 25 kW to 10 MW.

3.3 Statistics by resource

The diesel generator market and its relevance for mini-grids

According to Werner and Breyer (2012), at least 42 countries and regions had mini-grid systems in operation as of 2012. Looking at the existing diesel generator market in financial terms, about 60% is accounted for by machines below 20 kW and 15% above 220 kW (PV magazine, 2013). However, the bulk of this capacity is in the larger units. Around 40 GW (31696 units) of diesel generators larger than 0.5 MW were sold in 2012 (Diesel and Gas turbines, 2013), half of them for permanent operation and half as stand-bys. In 2012 there were around 13.5 GW sales of diesel generators in the 0.5-1 MW size class, 16 GW between 1-2 MW, 5.5 GW between 2-3.5 GW and around 3.5 GW above 3.5 MW.

Assuming a growing market and a 15-year life span, world installed capacity of diesel generators >0.5 MW is on the order of 400 GW (Diesel Gas Turbine, 2013).

14 The PV in Australia 2013 Report (*http://apvi.org.au/pv-in-australia-2013/) mentions an off-grid PV capacity of 132 MW in 2013.*

Adding to that figure, machines below 0.5 MW capacity suggests a global total installed capacity of diesel generators in the order of 1000 GW.[15] Especially for the smaller generators, no detailed statistics exist. Worldwide, more than 22.5 GW of installed power capacity in isolated diesel-based power systems can, however, be detected and more than two-thirds of these systems are located in developing and emerging countries. Island states and large territorial states have the highest installed diesel capacities (Bertheau, 2012). The majority of such diesel energy systems have a capacity of less than 1 MW.

A key point here is that hybrid mini-grids account for just 2-3% of total diesel capacity. Thus, there is a huge global development potential for incorporating renewables into mini-grid systems.

An alternative option is to replace imported diesel with biodiesel producted at location. In the Pacific islands, for example, biodiesel from coconut oil is produced. This biodiesel could be used in a dual tank system connected to a diesel generator, such that the engine burns pure coconut oil when at high loading and switches back to diesel fuel at low loading (IRENA, 2013d).

Table 5: Small Hydropower Operational Capacities below 10 MW for 2011/2012 (ICSHP/UNIDO, 2014)

Region	Capacity [MW]
Eastern Africa	209
Central Africa	76
Northern Africa	115
Southern Africa	43
Western Africa	82
Caribbean	124
Central America	599
South America	1 735
North America	7 843
Central Asia	184
East Asia	40 485
South Asia	3 563
South-East Asia	1 252
Western Asia	489
Eastern Europe	2 735
Northern Europe	3 643
Southern Europe	5 640
Oceania	310
Pacific islands	102
Total	~ 70 000

Small hydropower

The findings of world small hydropower development report (WSHDR) from 2013 show that small hydropower potential is almost 173 GW. As around half of this potential has already been developed; the operational small hydropower capacity (up to 10 MW) was estimated to be 75 GW in 2011/2012 (ICSHP/UNIDO, 2014) (Table 5). A significant share of these systems is grid-connected, notably in China, Europe and North America.

Solar home systems

Solar home systems (SHSs) have enjoyed sustained growth in many developing countries, with installations now surpassing more than six million (up from 1.3 million in 2002) (Table 6). In Bangladesh, the government has played an important leadership role in off-grid renewables, having deployed more than three million SHSs. Unfortunately, other Asian nations have yet to replicate this success. According to the International Finance Corporation (IFC) (2012), total sales in Asia in 2011 reached 2.2-2.4 million systems, nearly half of which was located in India (IFC, 2012).

Despite some commercial success in Kenya—Africa's leader in solar home systems with 320 000 units cumulative installed capacity at the end of 2010 and a market growth of around 10% per year (Ondraczek, 2011)—Africa's solar industry faces numerous challenges to growth and job creation. As in other developing regions and countries, these include: domestic financing (*e.g.,* SHSs are primarily only within the reach of the wealthiest segments of the rural populations); the quality of imported solar PV panels; and lack of technical training. There are skill gaps in many developing countries, particularly for the key occupations of electrical engineers and technicians (IRENA, 2014e).

Solar lanterns

Asia's solar lantern sales amounted to 2.3-3.2 million systems per year in 2011. Nearly all of this was in India, with about 10 000 systems in Cambodia and

15 Platts database accounted for 90 GW operational capacity until the end of 2012.

Table 6: Global status of off-grid solar home system markets (IRENA, 2013c)

	Year	Solar Home Systems
Bangladesh	2014 (July)	About 3 200 000
India	2012 (March)	861 654
China	2008	>400 000
Kenya	2010	320 000
Indonesia	2010	264 000
Nepal	2012	229 000
South Africa	Est.	150 000
Sri Lanka	2011	132 000
Morocco	Est.	128 000
Zimbabwe	Est.	113 000
Mexico	Est.	80 000
Tanzania	Est.	65 000
Total		~ 6 million

NB: The information is only indicative; data gaps prevent reliable analysis of the number of SHSs deployed globally.

3 000 systems in the Philippines (IFC, 2012). In Africa cumulative sales amounted to 8 million systems in 2013. Cumulative sales could grow to 20-28 million solar lanterns in Africa by 2015 (sales of 6-10 million lighting systems per year). This suggests that up to 140 million people may have access to better lighting by 2015 (Lighting Africa, 2013).

PV systems leasing

There is increasing use of the systems leasing option for supply solar electricity. Such contracts can also provide valuable information on installed capacity. The Groupe Speciale Mobile Association, an association of mobile network operators known as GSMA, found that 60 000 pay-as-you-go solar services were sold in sub-Saharan Africa in 2013 alone (Sierra Club, 2014).

Small wind turbines

As of the end of 2012, a cumulative total of 806 000 small wind turbines were installed worldwide, equal to about 0.68 GW of capacity. This is an increase of 18% over the previous year (WWEA, 2014). China accounts for 39% of installed capacity (570 000 turbines), the US, 31% (*i.e.*, 155 000 turbines) and the UK, 9.4%. The average installed size has increased from 0.66 kW in 2010 to 0.84 kW in 2012. In 2009, approximately 34.4 MW of SWTs sold were connected to the main grid, making up 92% of the market, and leaving only 7.6 MW of off-grid systems (*i.e.,* individual consumers or mini-grids). The trend is towards ever larger grid-connected turbines.

Biomass power systems

Various biomass-to-power technologies can be detected. Small-scale biomass gasification is deployed where residues are available (*e.g.,* rice husks). Straw-based power plants tend to require a larger logistical efforts and are generally limited to grid-connected power (*e.g.,* in China). Biogas to power makes economic sense for large livestock farms.

Chemical pulping yields a "black liquor" residue that is generally combusted for co-generation. Bark residue can also be deployed for power generation. The majority of electricity generated is usually for private consumption; sometimes surpluses are fed into the local grid. The same applies to bagasse residue from sugar cane processing.

Biomass-based power systems are being promoted *inter alia* in India where a handful of companies are installing them. One such company, Husk Power Systems, started in 2007, operated around 80 rice husk-based mini-grids in 2013, ranging from 32-100 kW in capacity, providing electricity to over 200 000 people across 300 Indian villages and hamlets (ADB, 2013). Bangladesh also uses biomass and has a target of 450 biogas-based power plants (average 20 kW) and 30 rice husk-based power plants (average of 200 kW per plant) by 2016 (IDCOL, 2013).

Industrial off-grid systems

Many large-scale industrial plants and complexes produce their own electricity for two reasons: 1) local electricity production is cheaper than electricity from the grid; and 2) reliability and the need for uninterrupted power supply is a priority. In many cases, electricity is produced in a combined heat and power plant (CHP). CHP systems are concentrated in the paper and pulp industry (20%), chemical industry (40%) and petroleum and refining industries (15%). CHP plants are sourced by waste streams (*i.e.*, paper and pulp industry) and often gas as well. The total capacity is unknown, but large chemical complexes like Chemelot or the BASF site in

Ludwigshafen, Germany are able to generate a great deal of their own electricity through gas-fired CHPS with capacities of 231 MW and 390 MW, respectively.

Several African countries, such as Tanzania, Kenya, Uganda and Cameroon, have significant technology knowledge and agro-industry experience in CHP co-generation and gasification technologies and their utilisation in agro-industries for power self-generation and sales of excess power to the grid or surrounding mini-grid area. Selling the leftover power to the grid could be attractive, given extra investment and a good Power Purchase Agreement (PPA), as is the case in India, Thailand and Brazil (IED, 2013). At the same time, solar PV systems are integrated into existing industrial plants to mitigate power outages, as is the case for a one MW solar PV system for an Indian cotton mill and a MW-scale PV system for a chrome ore mine in South Africa (ARE, 2013).

Individual Electrification Systems (IESs for productive use)

In *India,* which currently has about 650 000 telecom base stations (averaging 3-5 kWe each and requiring 1-3 GWe of capacity in total), some 40% of the power needed comes from the grid and 60% from diesel generators. The government has mandated that 50% of rural sites be powered via renewables by 2015. In 2013, 9 000 towers were operating with renewable electricity. By 2020, 75% of rural and 33% of urban stations will need to run on alternative energy (Scientific American, 2013). *Bangladesh* has 138 solar power telecom towers (IDCOL, 2014).

In *Africa,* there are currently more than 240 000 telecom towers of which an estimated 145 000 are located in off-grid sites. Only 4 000 of these sites deploy renewable energy sources (*e.g.,* solar, wind or hybrid combinations). In 2020, these numbers are expected to grow to 325 000 and 189 000, respectively (GSMA, 2014). Furthermore, many of the grid-connected sites suffer from black-outs and unreliable electricity supply and thus have to rely on back-up diesel generators. Renewables-based power generation could significantly improve the economics of these sites, as diesel fuel often costs as much as USD 1.6 per litre.

Renewables can help to reduce fossil fuel expenses and reduce outages at industrial sites. Projects are being developed in Western Australia (15 TWh needed in the coming years), northern Chile and Western Africa. A wind-diesel hybrid system has also been developed for a mine in Mauritania.

Remote, secure, independent, flexible, non-flammable power generation is ideal in a military context. For example, in addition to field deployment, more than 40 United States military bases now have mini-grids, either in operation or planned.

Africa has had wind-driven water pumping systems for decades. Around 400 000 such systems are in operation across Africa (IRENA, 2014b). Some systems use the wind force directly to drive a mechanical pump while others work with electricity as intermediate energy carrier. *India* installed 1 417 wind-driven water pumps in the fiscal year 2013/2014 (MNRE, 2014b). *Bangladesh* had 150 solar PV-driven water pumps installed in July 2014 and targets 1 550 pumps by 2017 (IDCOL, 2014). However, the use of wind pumps has stalled with the emergence of low cost solar PV pumping systems.

Lighting is another sector with high potential and already enjoys a rapidly growing deployment of renewables. The size of the overall commercial outdoor lighting market is estimated at USD 11 billion. Within this sector, there has been a pronounced shift to LED technologies. In 2012, for example, 54% of the two million luminaires installed along roadways and tunnels around the world used LED lights for outdoor area and street lighting (Strategies Unlimited, 2014). Another forecast from Navigant Research predicts shipments of smart, LED-based street lights will top 17 million by 2020 (Navigant Research, 2013). It should be noted that these figures are not consistent. A single US company had installed more than 60 000 systems in 60 different countries, representing more than 10 MW of solar capacity as of November 2013 (Clancy, 2014).

In the health sector, two million domestic gas and kerosene refrigerators are operational worldwide, plus 100 000 vaccine coolers. The average consumption is 300 litres of kerosene per year. PV systems have been designed to replace these systems (IRENA, 2013a).

4 CONCLUSIONS AND NEXT STEPS

This working paper has sought – based on an overview of existing literature on off-grid renewable energy systems – to identify a number of methodological challenges, and propose methodological improvements. The results show that renewables deployment in off-grid systems are only a small percentage of the total installed renewable power generation capacity. In terms of off-grid systems, especially in mini-grids electrification systems, diesel generators still dominate. However, there are a number of areas where the rapid growth of off-grid renewable energy systems is expected. A significant market exists to hybridise or replace existing diesel grids, on a scale of *hundreds* of GW. This includes community mini-grids and industrial plants. The rapid growth of individual electrification systems, both in developed and developing countries, is also feasible, but will be starting from a very small base.

This round-up of data suggests that significant work is needed to develop a single accurate dataset. Given the growing market size, this effort is seen as warranted. There is also an urgent need to improve the statistical basis for off-grid systems, including more insight into available definitions and improved data consistency and comparability. This includes both mini-grids and individual electrification systems. Until that happens, it will not be possible to adequately track progress in off-grid systems for electricity access and other applications. In addition to data collection on the capacity of off-grid systems, data on their investment and operational costs will also remain limited. Efforts should also focus on collecting such data that would facilitate the creation of a robust business case. For example, the Rocky Mountain Institute (RMI) has used a software programme called HOMER to evaluate when off-grid, solar PV deployment of renewables will become economically more advantageous than staying connected to the grid (RMI, 2014). The Reiner Lemoine Institut has also developed some techno-economic optimisation models to evaluate hybrid mini-grids (Huskens and Blechinger, 2014), and the IEA Photo-voltaic Power Systems Programme (IEA PVPS) has developed some life cycle cost assessments for solar-based water pumping (IEA PVPS, 2012).

This working paper also listed a number of key methodological issues in the development of better statistical data for off-grid applications with renewable energy.

To effectively address these issues, this working paper proposes a number of concrete methodological improvements. The following are needed:

1. A consistent categorisation of off-grid renewable energy systems across all **application and resource areas**. Such a categorisation allows for a more consistent assessment of what kind of off-grid systems should be included, how they relate to one another and how they differ from grid-connected, renewable power generation.
2. The categorisation of off-grid renewable energy system by **uses, customers, system components and size** to differentiate the different systems.
3. The identification of a number of **key indicators** to evaluate, compare and aggregate global data on off-grid renewable energy systems. This paper also proposes a categorisation of mini-grids, micro-grids, nano-grids and off-grids with associated, clearly defined indicators and upper limits. The renewable power generation capacity connected to such off-grid systems could be the primary indicator for tracking progress; however, it is important to use additional indicators to provide a clearer understanding of the impact of off-grid renewable energy systems for individual users, grid services and productive use.
4. **Country statistics** on off-grid renewable energy systems need to be improved but will require the engagement of local development agencies, utilities, end-users and technology providers. Furthermore, they should be augmented with marketing reports to ensure coverage of industrial/commercial applications of renewables in off-grid systems.

Despite more than twenty years of renewable energy deployment in off-grid systems, the future prospects for such systems are not yet evident. However, based on previous experience and research, certain key barriers have been identified and both technological and economical solutions are being developed to overcome them. Furthermore, the declining cost and increased performance of off-grid renewable energy systems is gradually rendering them more cost-competitive compared to alternatives, especially on islands and in rural areas. While there is rapid growth in many places, some mature markets have actually seen a *reduction* of off-grid systems due to their integration into the main grid. Further cost declines for renewable energy generation and electricity storage technologies, including the development of dedicated control systems for mini-grids, may change this situation in the near future. From this perspective, it is important that methodological improvements to collect, aggregate and track progress are developed before the expected rise in deployment in the next decades.

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