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Evaluation of the reliability of solar micro-grids in emerging markets – Issues and solutions

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A R T I C L E I N F O

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A B S T R A C T

One of the most important technical features of a power system is its ability to deliver electricity reliably to the customers. Based on interviews with 12 energy service companies (ESCO) currently operating solar micro-grids in northern rural India, this study identified important factors related to technical design, customer behaviour and operations and management (O&M) that may result in contingencies in service. In addition, the study presents companies' innovative solutions to overcome these problems. Initially, the interview method allowed only a rough qualitative comparison of different reliability levels as the availability of comparable data was limited. We found that a more descriptive method for reliability assessment would create equally valuable information on renewable off-grid energy projects. We propose a simple framework for assessing reliability that highlights the particular features of off-grid areas in developing countries.

Introduction

Advances in technology and reductions in solar photovoltaic (PV) panel prices have been important drivers for the expansion of the micro-grid sector worldwide. In the developing world, the high number of people without access to electricity is still considerable and an attractive statistic for various market players. For example in India, 239 million people were without electricity in 2016 (IEA, 2017), though this number is rapidly decreasing as a result of combined actions by the Indian government (Government of India, 2017) and commercial market actors. The Indian government aims to provide electricity to each household by 2019 mainly by extending the central grid (Government of India, 2017). On the other hand, the number of micro-grid operators and other off-grid energy service companies (ESCO) in India have quadrupled from 2006 to 2014 (The Climate Group, 2015) and some 30 private companies have micro-grids as their key business area (Singh, 2016). In Uttar Pradesh (UP) only, which is the most populous state in India, solar micro-grid operators had installed 37,000 connections by 2017 (ESMAP, 2017).

From a technical point of view, micro-grids are independent electricity delivery systems, in which the power is produced near the point of consumption. Therefore, they can be more energy efficient than traditional power transmission and distribution which always involve long lines with energy losses. Furthermore, the existing grid suffers from frequent power outages due to technical and governance reasons. The situation is the worst in rural Uttar Pradesh (Min, O'Keeffe, & Zhang, 2017), where the average number of daily supply hours was 16 in 2017 (Prayas Energy Group, 2018). The reliability was not better for the recently electrified villages (Thomas & Urpelainen, 2018).

Therefore, in spite of the expansion of the centralized power grid, there is clearly still scope for services offered by micro-grid operators and other off-grid energy companies, in particular as Indian consumers are willing to pay for improved reliability of electricity delivery (Graber, Narayanan, Alfaro, & Palit, 2018). Consequently, the reliability of micro-grid systems would also be highly relevant. Unfortunately, technical reliability studies are rare (Terrapon-Pfaff, Dienst, König, & Ortiz, 2014; Pachauri, 2011) even though service quality analyses would be important to help in capturing the full potential of these systems in the future.

This study addresses this evident gap of information by investigating how current micro-grid providers In India are in practise able to meet customer expectations for reliable power. Previous studies provide evidence of some reliability problems in micro-grids in rural India (Numminen, Lund, Yoon, & Urpelainen, 2018). Another study found that quality problems had led to customers dropping the micro-grid

Abbreviations: PV, Photovoltaics; ESCO, Energy service company; UP, Uttar Pradesh; LOLP, Loss of load probability; LOLH, Loss of load hours; MDT, Mean down time; MTTR, Mean time to repair; MTSR, Mean time to start repairing; MTR, Maximum time to repair; SAIDI, System average interruption duration index; SAIFI, System average interruption frequency index; ESMAP, Energy Sector Management Assistance Program of the World Bank; SHS, Solar home system; PAYG, Pay-as-you-go; O&M, Operation and maintenance; AC, Alternating current; DC, Direct current.

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service (Aklin, Bayer, Harish, & Urpelainen, 2018). Our study provides a unique analysis of the current state of service quality of micro-grids in northern India based on data collected from 12 Indian Energy Service Companies (ESCOs) currently operating micro-grids. We believe this kind of information would be valuable for improving the reliability of solar micro-grids in the developing world.

Reliability estimation in renewable off-grid power systems

Reliability is an important technical indicator when assessing the success of an off-grid electrification project in developing countries (Ilskog, 2008; Bhattacharyya, 2012; Mainali & Silveira, 2015). The system's reliability should remain the same or even improve throughout the working lifetime of the system because if customers are not satisfied, their interest in making payments and using the system appropriately may be threatened and sink the whole project into a "vicious circle" (Schnitzer et al., 2014). By definition, the reliability of an electric system covers the ability to supply the energy required by the customers at all times, and to withstand sudden disturbances (Rausand & Høyland, 2008, pp. 6–7). The accurate reliability estimation of any complex system requires information of the failure probability of each technical component that comprises the system. A closely related term is power availability, which refers to the probability of the system being in an uninterrupted state (Brown, 2009, p. 42).

The term reliability in our context can be divided roughly into two parts: energy reliability and technical reliability. To cover the energy requirements of the customers, the energy system need to be optimally sized, i.e. the system should always have a sufficient capacity of power generation and storage to avoid power insufficiency related reliability problems. In particular with variable renewable power systems, it is important to understand the intermittent nature of these energy sources. In terms of optimal and cost-efficient system sizing, Kumar et al. (2018) provides a profound presentation of available software and optimization possibilities. A widely used measure for energy reliability is the Loss Of Load Probability (LOLP) which indicates the number of hours that a system must curtail loads annually due to inadequate generation (Brown, 2009, p. 5). However, as accurate load estimation is often complex and requires detailed data on load, a related indicator is the Loss Of Load Hours (LOLH) which is simple to use (Lorenzo & Navarte, 2000). LOLH indicates the fraction of time when power is not available divided by the total time when power is required. Apart from installation problems that reduce the energy yield (Posadillo & López Luque, 2008), the LOLP and LOLH and related indicators do not directly reflect technical or practical failures.

Therefore, the technical reliability that represents the time needed to overcome component failures should be evaluated in parallel. For its detailed assessment, it is necessary to know failure rates, maintenance distribution functions or their mean time equivalents such as Mean Down Time (MDT) (Rausand & Høyland, 2008, pp. 1–8). Díaz, Egido, and Nieuwenhout (2007) highlighted that the MDT in off-grid areas consists of both the actual repair of broken equipment (Mean Time to Repair, MTTR) as well as the waiting time before the actual repair work can start after the identification of a failure (Mean Time to Start Repairing, MTSR). For example, the logistics of importing equipment have resulted in long delays in Africa (Louie, Dauenhauer, Wilson, Zomers, & Mutale, 2014), and geographically inaccessible areas in Brazilian Amazon (Fuso Nerini, Howells, Bazilian, & Gomez, 2014).

In addition to the above considerations of the energy reliability (loss of loads) and technical reliability (failures), Díaz et al. (2007) also highlighted the need to separately consider component degradations over time as several studied off-grid systems performed sub-optimally in real environments in comparison to their nominal values. They recommended incorporating correction factors for the PV generator, storage capacity, and charge controller (the latter telling how well the charge regulator is configured to protect the battery).

Generally, power system performance assessment is a complex activity and the performance indicators may vary even in seemingly similar technical systems if there is no sufficient agreement on the measurement and reporting practises (Kueck, Kirby, Overholt, & Markel, 2004; CEER, 2016). Traditional utility reliability indices, such as System Average Interruption Duration Index (SAIDI) or System Average Interruption Frequency Index (SAIFI) are listed by the IEEE (2004). The World Bank's Energy Sector Management Assistance Program (ESMAP) developed a new framework for evaluating reliability, power quality, and other energy access metrics offered by smaller energy systems in developing countries (Bhatia & Angelou, 2015). However, the imprecision on how to measure these metrics has been criticized of being prone to subjectivity (Groh, Pachauri, & Narasimha, 2016; Pelz, Pachauri, & Groh, 2018). Sometimes customer surveys are used for this purpose. In South Africa, the customers reported outage durations twice as long as the distribution utilities, because the utilities had not measured the interruptions in low voltage lines (Tait, 2017). However, customer surveys should also be treated with caution as customers have a tendency to overestimate supply problems (Küfeoğlu & Lehtonen, 2015).

In practise, the reliability is also a result of the prevailing expectations. In developed countries, power systems are assumed to function completely without interruptions and the consumers receive compensation if the power is switched off, e.g. for longer than 12 h (FINLEX, 2013). On the other hand, ESMAP estimates sufficient reliability in energy systems with power levels below 2000 W if there are at maximum 14 weekly disruptions. In rural Venezuela, when 65% of end-users had perceived the duration of interruptions as "short", the micro-grid was considered to perform with a sufficient level of reliability (López-González, Domenech, & Ferrer-Martí, 2018). Nevertheless, whichever assessment method is chosen, it is important to separate the realized values (assessed reliability) from the theoretical ones (company promise for reliability) as unexpected problems may occur due to design faults or externalities in any technical system that operates in a new environment.

Method

Our approach is based on comprehensive interviews with micro-grid service providers (see Appendix A for questions dealt with) which was preceded by field-trips in an earlier (Numminen et al., 2018) and later stage to understand the underlying reliability problems.

Thirteen semi-structured interviews were conducted with CEOs and CTOs of energy service companies (ESCO)s currently operating in the northern India. The technology was limited to PV, as it is the most commonly used technology (~80%) by off-grid utilities in the Indian market (The Climate Group, 2015). Through excluding other technologies such as pico-hydro, mini-wind and biomass systems, the comparison of different micro-grid systems is more straightforward as the energy source specific aspects do not require attention. In addition, rooftop or other grid-connected solar technologies were excluded, as they serve other power levels and customer groups than off-grid companies.

The study was limited to power systems that necessitate a communal maintenance service. Thus, small consumer products such as solar home systems (SHS) or solar lanterns, were excluded even though they technically comprise of a similar set of components (PV panels, batteries, control units and cabling) than micro-grids. However, one company offering pay-as-you-go (PAYG) solar home systems was invited to the study. PAYG vendors maintain the ownership of the equipment right after their installation and have similar interest in protecting the systems and delivering reliability in supply than the micro-grid providers.

The interview method was chosen because discussions would allow better understanding of different factors in the business ecosystems. The interviews were semi-structured and took one to 4 h on the following topics: energy service, power availability, O&M, quality assurance, and technical challenges (see Appendix A for more details). Half of the interviews were made in person and half of them over telephone. After critical analysis, missing information was requested per email or in a second call.

Initially, the target was to gather a statistically significant amount of data on reliability, system downtimes, and technical failures of all installed grids. However, it was soon discovered that the analysis will be only qualitative for a few reasons. Firstly, most of the companies had no records on the technical failures in their grid installations. Secondly, the micro-grid industry is rather young as all except one of the companies were established in 2011 or later, and most of them had not held records on service downtimes from the onset. In some cases, companies having multiple donors were less keen on sharing information due to confidentiality agreements with the donors.

Companies were approached directly per emails and telephone calls. To increase openness of the study, visibility for the study was given on the website of the lead author and in social media. Kind support from the Indian off-grid industry association Clean Energy Access Network (CLEAN, 2018) facilitated the contacting of the companies.

The invitations to interviews were accepted positively. The respondents were curious in participating as they believed that the general technical problems are shared in the industry. Furthermore, studies that are technically-oriented are rather rare, and therefore companies had decided to participate. Many of the companies had earlier contributed in a quality assurance study of the industry (CLEAN, 2015). Anonymity with answers was guaranteed, so the companies could openly share their experience and insights. Respondents were not compensated for participating in this study.

Visits to six different micro-grid sites were made by the lead author, installed by four different companies in north India between 2015 and 2018. Visits allowed observations of technical installations and interviewing technicians to verify the objectivity of the data. Other secondary data were technical documentation, such as maintenance manuals, provided by the companies.

Interviews were structured similarly for all companies, but not all questions were applicable for all companies, depending on their size, technology, service and business models and financial structures. The interview data collected consists of measurable data such as number of installations, system capacities and topologies, as well as qualitative data such as customer information and service descriptions. The installations set up by the interviewed companies widely vary in capacity, service offer, and system configuration so their comparisons in purely numerical terms were not meaningful.

An additional 10 personal and semi-structured interviews were conducted with people working at the companies being studied, in other off-grid energy companies, in consultancy, universities, and in the system component assembly sector.

Results

Firstly, we give an overview of the interviewed companies and their service offerings, in particular in terms of power availability and reliability. Then, reasons for deviations from the maximum reliability are analysed. Finally, we present design and operation and maintenance (O&M) related constituents of reliable supply, based on the interviews.

Overview of the micro-grid companies and the energy systems

The interviewed companies were for-profit companies or social enterprises in the formal market. The micro-grid project sizes varied from larger (up to 60 kW) to pico-scale (the smallest grid had the capacity of 0.2 kW). The grids served the last mile including the most remote off-network areas, as well as villages in semi-urban settings where national power distribution lines had already been installed. The majority of customers was living in rural areas and had lower income than the country average. The grids had mainly household customers. However, also productive loads and private entrepreneurs were served.

The offered services represent a wide variety of loads, ranging from small lighting and mobile phone charging only to service packages up to unlimited energy access both in time and in amount of energy (up to the system limitation). Some companies had constructed a variety of different grids, but in this study only one type of a power system (the highest number installed) was analysed as the representative type for the company.

In total, the companies had installed over 1800 micro-grids or mini-grids, ranging from one to 1500 installed grids per company. The number of systems sold by the single PAYG SHS vendor interviewed is not included in this number. Half (6/12) of the companies offered only alternating current (AC) systems, 3 companies only direct current (DC) systems and 3 companies both. Out of the installed micro-grids, 95% were still operational. Reasons for non-operation were mainly economical, typically low demand on the customer side. Sometimes ending of a research project or a pilot had been the reason that the company was no longer operating in a village, and the grids had been handed over to the local communities.

Most companies had no legally binding contracts with their customers. Sometimes everything was settled orally, particularly if the customers were illiterate. Sometimes a light “end-user subscription agreement” was signed, where the names of subscribers, the energy price, and the conditions when the power could be cut were written.

Power availability and reliability – customer promise and reality

The majority of the companies (7/12) offered 24/7 access to their customers. The rest (5/12) limited the number of daily access hours (see Fig. 1). Sometimes different loads were served differently, for example, a school was supplied only in the daytime and households from dawn till dusk. The majority (7/12) of the companies limited the energy levels. Typically, a maximum instantaneous power limit was set to save the produced solar energy of the small power system. To adhere to the anonymity promise made to the companies, the service offerings are not described here in more detail.

While companies generously described their theoretic offerings, they could only crudely estimate the service uptime or the number and the duration of supply interruptions. The variety of descriptions was broad and sometimes inconsistent. Examples of answers:

- “Maybe 10 h [or] 9 h per month [the grids are not operating]” (Interviewee 6, personal communication, June 19, 2018)
- “[Number of days of delivery is] 360 or so. [—] If the solar is generating every day, we can deliver every day. I'm counting those 5 days [of decrease] for basic maintenance and checks. However, this is not considering some accidents [—] that can cause the system to break down” (Interviewee 5, personal communication, 7 September, 2018);
- “We expect to very occasionally have downtime (typically in January/February) during one week in the cloudy season” (Interviewee 10, personal communication, April 24, 2018);
- “We believe we are maintaining our systems with 98% uptime, [based on] smart inverter [data]” (Interviewee 3, personal communication, 26 June, 2018).

The maximum uptime estimations were given by the two interviewees who operated grids which had diesel generators as backup supplies. The given answers were 99.95% uptime (0.05% downtime)

Fig. 1. Electricity availability of the twelve types of power systems offered.

and “an average shutdown time of 2 hours per plant per year” (Interviewee 8, personal communication, 18 July, 2018), which equals to a downtime of 0.02%. Similarly calculated[1] for 6 companies, the median value of all downtimes was 4% and the average was 5%. Downtime estimations varied between 0.02% and 17%. The remaining 5 companies could not provide a numeric estimation.

Only a couple of companies based their answers on measured data. If a company had measured supply and consumption values, they rather analysed other metrics such as the energy balance which is an indicator of the system health. Some companies held technical failure records only manually.

Companies also treated their systems as single units. Interviewees did not specify when only a fraction of customers had been affected in a case of a power cut.

Reasons for supply interruptions

Table 1 presents possible problems that effect reliability, based on the interviews and field observations. Problems can be categorized due to their origin to seasonal, component related and human related issues. Table 1 also shows the number of companies that mentioned that a particular problem had occurred (N).

It is noticeable that company representatives tended to emphasize issues that were not so much in their own control (component quality, weather, customer behaviour). Therefore, the number of mentions (N) in Table 1 may give a biased picture of the importance of each problem from a customer perspective. For example, no company mentioned installation work as a problem. In visual inspections, however, sometimes the distribution lines were connected loosely (Fig. 2c). Such situations could eventually result in a disconnection of a fraction of household customers without appropriate preventive measures. Lack of protection also makes the lines more vulnerable to power tapping.

Low availability of renewable energy on a seasonal basis in PV only systems

Seasonal lack of produced energy was mentioned most often as the reason for interruptions. Most (10 out of 12) companies had at least once per year a period when power is not available for customers due to seasonal variation in the weather (November–January, typically). The two companies that had a diesel backup, did not have this problem. Solar irradiation levels in Uttar Pradesh are significantly lower during winter (December–February) (Srivastava, Singh, & Pandey, 1993), and not sufficient to satisfy a 356 days/year supply with PV energy only and thus a backup is needed. However, as no company had solar irradiation sensors, accurate identification of underperformance between component failure or weather conditions is not possible (Nordmann, Clavadetscher, van Sark, & Green, 2014).

As earlier mentioned, an important indicator for describing energy sufficiency is the number of days (or hours) of system autonomy. This indicator describes the ability of the backup storage (in days or in hours) to be able to cover the village load during no or very low solar input. After this number of hours, the regular power supply would discontinue. Depending on the battery capacity, interviewees estimated 2–3 days of autonomy.

Low quality of system components and related maintenance issues

The low quality of inverters was a frequent reason for system failures mentioned by most AC system providers (Fig. 3). Various technical problems with the inverters affected reliable supply especially due to the long repair times. Sometimes the inverter vendor company refused to deliver a spare part to remote areas. Sometimes the repair times were up to 15 days. In hard-to-access off-grid and off-network areas, getting even a message of the failure to the ESCO technical staff may have taken several days. To solve the situation, companies had and stored extra inverters in the village and trained villagers for more difficult repair tasks. AC inverters manufactured mainly in India and Bangladesh were reported to last 6–7 years after which frequent malfunctions were likely to occur.

As a solution, high-tech inverters primarily of western origin could theoretically be used to solve the problem, but they could be up to 10 times more expensive, according to an interviewed company representative. They also contain unnecessary and complex technical functions that are not needed in modest micro-grid systems (Buluswar, Khan, Hansen, & Friedman, 2016). Simpler DC system providers avoided this problem, and also highlighted the maintainability and less complex reparability, which is also acknowledged in literature (Hossain, Kabalci, Bayindir, & Perez, 2014; Patrao, Figueres, Garcerá, & González-Medina, 2015). The key benefit was that also less educated villagers could be trained to various repair tasks of DC systems.

Quality problems were reported also for control electronics and smart meters (Fig. 3). Batteries were found robust and a lifetime of 4–5 years was assumed, if maintained properly; in areas with cooler ambient temperature even up to 7 years could be feasible.

The findings are supported by the literature. Laboratory tests by the Institute for Transformative Technologies (ITT) concluded similar technical problems with Indian inverters, having led to severe performance problems and system downtime (Buluswar et al., 2016). Low component quality in Indian off-grid systems has been a key technology barrier for Indian off-grid companies from extending their energy business (CLEAN, 2015). In some countries, low component quality has even damaged the trust of people with the whole renewable energy sector (Akinyele, Belikov, & Levron, 2018).

The set of national regulations for component quality is still going through a development phase. A quality control order in India (MNRE India, 2017b) was issued to be in force in January, 2018, for ensuring that all renewable energy system components sold in India are complying a definite set of standards, and tested in certified national laboratories according to a testing policy (MNRE India, 2017a). The programme has capacity problems and is delayed (Prateek, 2018). However, the quality control order requires only safety standards to be complied in PV power inverters (according to IS 16221(Part 1):2016, and IS 16221 (Part 2):2016, identical to IEC 62109-1: 2010 and IEC 62109-2: 2011), not setting requirements for the power quality, e.g. according to IEC 61000-3-2, which would be recommendable e.g. for better electromagnetic compatibility.

As there are actors currently in the market that may be attracted to sell products with lower quality, it was thus important for the interviewees to underline that they purchase their components from “reliable vendors”. The importance of the existence of component quality standards was acknowledged, but there was not a full awareness of all details.

On the other hand, many companies mentioned PV panels as both the most breakable (fragile) and the most durable component in their system. This is understandable, as PV panels constitute the highest share of the initial system cost and the economic loss due to, for example, extreme weather event or an animal or human intervention induced accident may be substantial. Innovative practises in PV panel protection and maintenance could be witnessed (Fig. 2b).

Improper behaviour of people

Trying illegally to use power system equipment for one's own benefit is an unfortunate but tangible reality for Indian grid operators (Upadhyay, 2017; Depuru, Wang, & Devabhaktuni, 2011). Neither are micro-grid operators free from such problems (Henry Louie, 2018, pp. 461–462). The issue of power theft was raised surprisingly often in the interviews. One interviewee said that a new attempt is discovered daily.

The most frequent method applied by the actual micro-grid customers was attempting to bypass a critical component, such as a distribution box or an energy meter. This kind of behaviour typically causes problems only

[1] The percentages were calculated as follows. For example, if an operator delivers electricity for 8 h per day and estimates that there are ten no supply hours per month, the downtime would be (10 h/month) / (8 h × 30 h/month) = 4%.

Table 1
Design, installation and management problems effecting service reliability in micro-grids, and suggested solutions. N = number of companies that mentioned the problem having occurred either once or more times.

Reliability problem	N	Width of the outage	Nature of the occurrence	Duration of the outage	Possible design solutions (non-exhaustive) to keep up power supply
Electrical design aspects					
Capacity not sufficient for 365 days a year due to alternating local weather conditions	10	All village	Abrupt during low irradiance seasons	Depends on the number of days of system autonomy	Hybrid energy solutions; seasonal frugal use or energy; load prioritization
Unexpected failure of a critical component e.g. inverter due to low quality	5	All village	Abrupt	Depends on the availability of spare parts and technical workforce	Choosing system units with sufficient quality; buying critical components or their spare parts to storage; systems requiring simpler maintainability
Unexpected power losses due to internal inefficiencies of electrical equipment	0	All village; a node	Covertly in the background[a], then abrupt	Depends on repair buffer investment among other things	Choosing energy efficient system units; careful installation work
Practical design aspects (installation)					
Low quality installation work	0	All village; a node; household only	Abrupt	Depends on technician availability	Careful installation work; well-chosen mounting elements and fasteners
Accidental human/animal intervention with crucial components	4	All village; a node	Abrupt	Depends on how ESCO handles the situation	Prohibiting or complicating access
Plant management aspects					
Overloading with high-consuming appliances	9	Household only (or a node supplied from a distribution box)	Covertly or abruptly (depending on load limiter configuration and supply capacity)	Depends on customer agreements (if household only), otherwise maintenance rules	User education; load limiters; DC distribution (less loads available); higher system capacities; system topologies that build peer pressure against theft
Experimenting with critical components such as control units, distribution boxes or energy meters	8	All village, a node, or a household only	Abrupt	Depends on how ESCO handles the situation	User education; consumer satisfaction; safety stickers for visual inspections; placing system intelligence in inaccessible places; tamper-proof devices, for distribution boxes see e.g. (Patel & Mishra, 2016)
Power tapping directly from supply components (battery)	6	All village	Background or abrupt (depending on supply capacity and the mode of discharge)	Depends on the quality of the protective installations	Prohibiting access (metal boxes, not wooden); user education
Power tapping from distribution lines	3	All village (or a node)	Covertly or abrupt (depending on supply capacity)	Depends on how ESCO handles the situation	DC distribution; protecting cables with rubber bands; underground cabling; load limiters in distribution cables; system topologies that build peer pressure against theft
Exceptional events					
Extreme weather conditions (heavy rain, storms etc.)	6	All village (or a node)	Abrupt		Weather monitoring; back-up supplies

[a] The effect takes place in the background, even unnoticed by the operator and the users, until one day may be demonstrated as a blackout.

for a limited number of households. Tapping distribution lines and using central battery storage directly for operating private appliances affect the long-term power sufficiency covertly, but these do not necessarily cause immediate blackouts. Whether or not a blackout occurs depends on the system capacity, the season and on how quickly the problem is recognized. Tapping and the direct use of the central battery could be perpetrated by both customers and non-customers.

Only five operators stated that they have not experienced any misuses. They proudly portrayed their systems as theft-proof by design. They had invested in thorough protection, including sealed and locked

Fig. 2. a–c (from left to right). Placing of a central battery bank up on the loft of a storehouse (a); Technician attached a row of nails on top of the PV panel to prevent birds from landing there as bird leaves, dirt and shadowing reduce the solar energy output (b); Faulty cable installation dangling over a village alley (c). Photos: Sini Numminen, 2016–2018, various micro-grid sites.

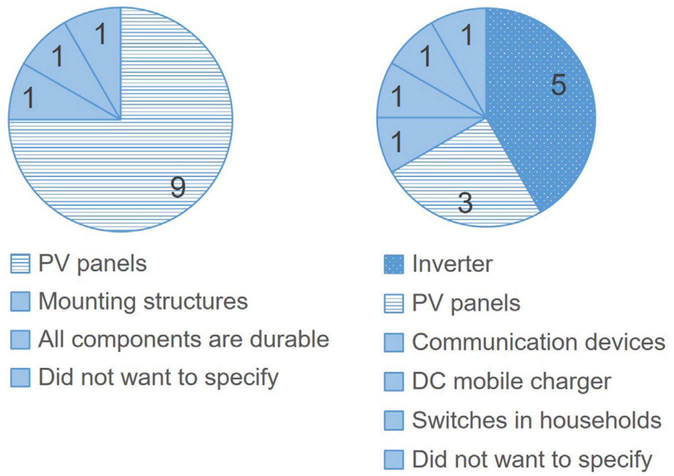

Fig. 3. Most durable (left) and most fragile (right) components in the micro-grid systems according to the entrepreneurs (12 companies interviewed).

cases for all system units. However, these companies had taken precautions as well. An interviewee mentioned that they conduct regular surprise inspections with a team of engineers, focusing especially on those villages that have least revenues collected.

Overloading is a mode of behaviour in which the customer exceeds the allowed instantaneous consumption limit, often accidentally. Eight companies which limit their customers' power levels mentioned that overloading had caused problems, resulting in various component damages. Many had, therefore, taken precautions, for example by connecting extra fuses or load limiters to their systems. Depending on grid configurations and protection schemes, overloading may cause problems also for neighbouring grid customers.

Companies had elaborate practises to hinder undesirable behaviour. Education campaigns helped to spread awareness on the collective consequences of the improper use of the systems. Micro-grid companies are sometimes the first to introduce their customers to solar energy. One company sent a technician to a village to stay there for the first month to monitor operations. Warnings, disconnecting the service and setting charges for reconnection were used to punish the culprits.

The neat positioning of components in the village was another smart tool for theft prevention. One company had purposefully hidden the system intelligence unit behind a PV panel. The villagers do not experiment with panels, possibly because they know its crucial role for the complete electricity supply. Sometimes component protection requires particular relationships with villagers. Batteries, for example, are sometimes better placed in a room of a private house where the ambient temperature is cooler. In such a case the company should maintain a particularly trustworthy relationship with the inhabitants who can best ensure that the battery is well protected from unnecessary damage and interactions with outsiders (Fig. 2a). Actually, central supply stations where all components are locked inside are not common. Micro-grid units (PV panels, cabling, batteries, controllers etc.) are often placed in rather accessible places, where they may be exposed to undesired interventions from people and environment.

Peer pressure was another socially effective method used against power theft by at least three companies. As typically 5–10 households were connected in the same distribution box, so whenever somebody tries to tap power, the load limiter cuts power and all households connected face a blackout. Neighbours will report the situation and will also put pressure on the culprit to discontinue such activities. The method was evaluated as efficient, but only to a certain extent, because social status may define the acceptable behaviour of villagers.

The improper treatment of the equipment generally reflects social-behaviour and cultural factors which obviously require proper attention. Several studies (Kumar et al., 2018; Sovacool, 2012; Javadi et al., 2013; Hirmer & Cruickshank, 2014; Gollwitzer & Cloke, 2018) emphasize that cultural factors have been the fundamental reason for failures of off-grid electrification projects. But a "gatekeeper approach" may ensure proper operation. An external expert interviewed for this study described that a landowner and a hirer of land was chosen by a micro-grid entrepreneur to also run the micro-grid. The respected status of the landlord ensured efficient payment collection; on the other hand, he had a sufficient level of ownership in the grid and a personal interest to sustain a failure-free electricity supply.

Discussion

Providing maximum constancy in supply may not have been the most important target for the majority of the companies interviewed in this study. In practise, a completely interruption-free power supply can sometimes even be unachievable. A serious obstacle is the general market unavailability of affordable and robust PV system components. Various technical, financial and operational challenges of the micro-grid sector in India (Tongia, 2018; Safdar, 2017) force the companies to prioritize their activities. Companies balance between the initial costs of purchasing equipment and repair frequencies. In particular, as a large share of their customers has irregular incomes, the sporadic cash flows may periodically deter companies from accomplishing all repair requests.

Under-emphasizing reliability may also be due to a lack of insistence by various stakeholders, such as investors and customers. Firstly, there is a general belief that micro-grid power per se is "reliable", as it is often compared with the unreliability of the national grid supply service. Secondly, the current political climate in India does not encourage the micro-and mini-grid sector and its technical development (Comello, Reichelstein, Sahoo, & Schmidt, 2017). Uttar Pradesh was the first state imposing a micro/mini-grid policy, but the numeric requirements for supply consider only the service hours,[2] and only such grids that are subsidized by the state (UPNEDA, 2016). Most off-grid companies do not seek subsidies.

Thirdly, the study shows that neither customers themselves require measurable levels of reliability for their electricity access nor demand high reliability levels (compared to people in industrialized countries that can use established 24/7 power infrastructure services). People at the bottom of the economic pyramid are experience uncertainties in several sectors of life, including access to sufficient energy levels for their daily routines. Even entrepreneurial customers, such as farmers, were once described by an interviewee as being satisfied if solar water pumping was available only "whenever the sun [was] shining, which [could be] any day of the year" (Interviewee 10, personal communication, April 24, 2018). The mutual flexibility is clearly demonstrated by the lack of legally binding contracts between the energy companies and customers.

Nevertheless, a few studies have investigated how off-grid micro-grid customers really experience the various short and longer power outages in their daily lives. For example, a company serving a rural village may have scheduled a weekly maintenance break of 30 min for Mondays. According to an interviewee, it is fully acceptable if the technician switches the power off for half an hour any time before noon on Mondays. To our knowledge, there are no studies confirming how rural customers tolerate such a deviation. This example raises a fundamental question on the definition of "reliability" and the notion of time. According to the most rigorous definition of reliable power, even a one-second-long deviation from the allocated supply timetable decreases the reliability level. Further studies on the different perceptions in this context would be useful.

On the other hand, requiring elaborated and uniform monitoring practises from low-income companies may not be justified. Any extra sensor, Wi-Fi server, monitoring software or phone application would require

[2] A mandatory 3 h in the morning and 5 h in the evening, total at least 8 daily supply hours for domestic customers and a daily 6 h supply for production and commercial needs.

Table 2
Reliability assessment framework for renewable off-grid power systems.

Reliability aspect	Note	Unit
Energy service description (company promise)		
Supply schedule	Start and end of power supply in daily cycle per customer group	Daily schedule (hours and minutes)
Power and energy levels	Power amount per customer group	Watts (W) or Watt-peak (Wp)
Maintenance schedule	Schedule of no-supply hours due to regular maintenance	Dates or weekdays and schedule (hours and minutes)
Load prioritization functions	Priorities set between customer groups during energy insufficiency or technical failure	(Descriptive)
Energy reliability		
Loss Of Load Hours LOLH	Number of hours of no supply due to energy insufficiency divided by the number of hours promised	%
Number of lost customers	Percentage of customers disconnected during low power	%
Schedule of low supply seasons	Seasonal periods when renewable supply does not meet the load	Dates. share of no-supply days per year (%)
System autonomy	Storage ability to supply in periods of low power	Number of hours
Technical reliability		
Mean downtime MDT	Total time of no supply due to component breakup, repair or system maintenance divided by the total time promised	%
Mean time to start repairing, MTSR	Speed of repair personnel to arrive after first notice (also first-aid service rapidity)	Number of hours
Mean time to repair MTTR	Speed of repair operations	Number of hours
Maximum time to repair MTR	Replacement or repair time of components with lowest availabilities	Number of hours
Protection measures	Anti-theft and other measures implemented against illegal behaviour and exceptional external events	(Descriptive)
Component degradation and system lifetime		
Battery lifetime (nominal and real)	Nominal and an estimation of the real lifetime in the actual use environment	Number of days
Vulnerable components	Description of vulnerable blocks in the energy system installed	(Descriptive)
Total reliability		
Total estimated system downtime	Approximate annual time of no power out of the scheduled supply = LOLH + MDT	%

further financial and O&M resources. Technical experts would be needed to field work and data analysis for monitoring efforts to be meaningful. The interviewees acknowledged the difficulty in finding talented workforce. The more educated the technician is, the more reluctant he/she is to stay and work in remote villages. In addition, as system capacities often are low, each additional monitoring component would consume a relatively high share of the total amount of energy produced.

Therefore, we propose here a new method for the reliability assessment in renewable off-grid systems that relies on the existing reliability-related facts and figures that the low-income companies already possess (Table 2). For example, the duration of system autonomy is a natural feature of a battery-based energy system that the system design engineer should provide. It is a relevant piece of information describing the ability of the system to continue service to the customers during seasons of low availability of the renewable source. The total energy reliability is represented by the lost number of service hours (LOLH), because evaluating temporal unavailability is simpler than evaluating lost loads (LOLP). This also applies to data gathered using parallel customer surveys whenever such surveys are conducted. When the percentage of hours not served is counted in relation to the offered service, differently scheduled micro-grid offers can also be compared.

A further off-grid-specific reliability-related piece of information is the prioritization of different loads and customer groups, which needs to be highlighted in this context. Sometimes the anchor load (such as an agricultural building) was supplied with electricity even if the majority of household customers were disconnected during power insufficiency.

In terms of the technical reliability, the companies should be requested both the total technical downtime MDT as well as the information on the Maximum Time to Repair of any single component as MTR may dominate the total reliability level in systems that are installed in remote areas. The inherent component degradation may deserve more attention (Díaz et al., 2007), but the battery operation often defines the system lifetime. The engineering and operational design should have the necessary measures to minimize degradation. Other vulnerable system parts should also be described, as well as all implemented anti-theft measures.

To validate the accuracy of the given data, companies should report how they collect or measure the data, or whether it is just an estimation. Of course, some of these details can only be approximated. Companies cannot, for example, forecast the low supply seasons in the way the meteorologists can, but they are expected to have an adequate understanding of the renewable power resource base in the locations where they are operating.

This set of reliability-related information can serve as a convenient discussion framework between the company, the customers, the donors, and other stakeholders involved in an renewable energy project. These features are also understandable for people without a technical background, which would facilitate the discussion about various practical reliability-related aspects.

Conclusions

All energy suppliers should be encouraged to be as accurate as possible in their service quality descriptions, irrespective of their customer background, because any unplanned power interruption is disturbing to the user and diminishes the usability and attractiveness of the electricity service provided. In India, the quality of the national power supply is occasionally so substandard that people keep their lights on all the time, because they know that power may be switched off at any moment, which is very inefficient use of electricity. Micro-grids and other off-grid energy systems serve the purpose of bridging this service gap. To evaluate the significance of the sector, it is important to understand how companies are finally able to meet customer expectations of reliable power.

Initially, this study intended to compare numerically the reliability levels in the rural Indian solar micro-grids. However, it was quickly realized that this would be a too complicated undertaking because the energy service companies interviewed had rather non-uniform and often irregular data collection routines. The companies did not possess the specific measured data to make a comparison of the performances meaningful.

However, this study identified important design-related, installation-specific and O&M factors that diminish the reliability in supply. The most critical design aspect was the instability and the low quality of certain system component units. Secondly, the seasonal variation in solar irradiation reduced the annual availability of power. If an all-year-round supply is desired, the companies should be prepared to these variations with secondary supply or storage units. Naturally, such options are more costly and complex and would not be realistic for the smallest systems (Numminen et al., 2018).

A somewhat surprising factor that contributed to the reliability of the micro-grid system was the neat positioning of system units in the village. Actually, the micro-grid systems are far from being just black boxes. Due to practical and cost-efficiency reasons, PV panels, cables, batteries and control units are often installed in places where they are exposed to undesired interventions from people and nature. Companies demonstrated many innovative practises in dealing with the consequent problems, such as power theft. Additionally, there is a specific sensitivity involved when dealing with low-income customers with irregular wages (GSES, 2016) which adds to the complexity in managing the whole business. Above all, trustworthy relationships with customers played an important role in the total success of the project.

This paper contains a new analytical framework for assessing the reliability of off-grid systems which is useful for private companies and other stakeholders interested in providing energy for people with insufficient access to electricity. Importantly, most of the off-grid energy companies already possess the information on their energy systems proposed in this framework despite their often low economic resources. Necessitating a specific monitoring technology to be installed for recording reliability levels on an hourly basis, for example, may not be justified, unless the required economic and O&M burden for running such monitoring systems can be covered. Using data recovered from the field is typically a sustainable starting point for creating a more reliable system.

As a further step, the new reliability assessment method could be tested in interviews with energy system operators in other counties, for example in Africa where the off-grid energy sector is currently booming. In parallel, the customer input on evaluating this framework would be useful, because we know too little about what customers think about various reliability aspects, such as the timing of the supply interruptions. Benchmark levels for these reliability aspects could also be elaborated. In this way, reliability could become a tangible and measurable indicator in the micro-grid power systems in the developing countries.

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Declarations of interest

None.

Appendix A. Topics discussed with interviewees

Basic technical information

- System capacities
- Distribution type, grid voltage and topologies
- Control methods and system protection
- Number of installed and number of operational grids

Energy service

- Power availability per day (0–24 h) and per year (0–365 days)
- Power availability per moment (Wp)
- Energy price and payment methods
- Customer promise and contracting

Component qualities

- Most durable system part
- Most delicate/fragile system part
- Component procurements and warranties
- Estimations for lifetimes of micro-grids

Power interruptions

- Examples of exceptional events
- Duration and frequency of interruptions and their reasons
- Occurrence of undesirable behaviour and preventive measures
- Insurances coverage

Operations, maintenance and quality assurance

- Regular maintenance procedures
- Testing practises of installed components
- Education and training of staff
- Relation with international or national standards and guidelines for installation, operations and quality assurance

Future

- Future plans and prospects on the company and the industry

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