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Power availability and reliability of solar pico-grids in rural areas: A case study from northern India

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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

Solar micro-grids are receiving increasing interest in the electrification in emerging economies. On-site performance studies of these systems have become more important as the global market is being supplied with an ever-greater variety of solar power equipment with inconsistent quality. We studied the reliability of seven small identical low-power DC solar grids installed in real settings in villages in rural northern India. A detailed analysis of measurement data, interviews and field visits over a whole year showed that solar electricity was available to the households for 87% of the time. Along with technical problems, a share of the power shortages was an indirect cause of an illegal behaviour of users. The study draws attention to quality recommendations for energy access for consumers with modest energy needs.

Introduction

Micro-grids are feasible options for electricity provision especially in developing countries with large populations without access to electricity [1]. India inhabits most of the people without electricity [2], or some 239 million persons, but this number is rapidly decreasing [3]. By definition, micro-grids involve small-scale electricity generation, which can function apart from the main grid and serve a limited number of customers [4]. Their capacity varies from small pico-scale systems below 1 kW up to several MW. Technically, micro-grids are able to use intermittent renewable sources such as photovoltaics in a way which does not jeopardize the reliability of local electricity supply [5,6]. In literature, micro-grids are considered as a reliable alternative to an erratic central power grid supply [7,8]. In the state of Uttar Pradesh (UP), which is the most populous state in India, centralized grid power in rural areas was available for 11 h per day in 2016 [9]. Power quality problems persist in the state, but the situation is improving [10]. Meanwhile, customers have reported notable satisfaction with micro-grid services in Uttar Pradesh [11,12].

The reliability of micro-grid services in low-income countries has received little attention in the past. A reason for this may be that micro-grids have been on the market for a short time, e.g. in Uttar Pradesh the first micro-grids were installed less than 10 years ago [13]. However, components with poor quality have been found e.g. in solar controllers, protection, and metering, but also the quality of installing work has sometimes been lacking [14,15]. Most of the technical literature on off-grid electricity actually focuses to the system planning phase [16,17], reporting on system simulations or on energy balance calculations. Ex-post analyses of off-grid energy projects mainly focus on the societal outcomes, but they rarely address real-life technical problems in detail, which would be important for improving such systems.

In this paper, we focus on investigating the reliability of small pico-scale micro-grids in rural Uttar Pradesh in India. Our study provides a unique analysis of real off-grid solar electricity systems, based on actual measurement data over a whole year. We assessed how well the engineering design managed in delivering uninterrupted electricity to the customers in the villages and analysed the technical and social reasons for the malfunctions and interruptions in electricity supply. We focus on the continuity of supply [18] and calculate the number and duration of the power outages. We also evaluate the reliability and availability of energy access of pico-grids according to the multi-tier matrix method of World Bank's Energy Sector Management Assistance Program (ESMAP) [19].

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Smart low-voltage solar pico-grids

This study concerns seven solar pico-grids, which were installed in seven hamlets (small villages) in rural India near in the Unnao district in Uttar Pradesh. The installations were set up by Boond Engineering and Development, an Indian energy service company. The systems resemble a typical low voltage direct current (DC) distribution pico-grid, offering basic electricity services, mainly lighting and mobile phone charging, for households in villages without a grid electricity connection [20]. In 2017, some 1900 privately-run micro-grids could be found in Uttar Pradesh, most of which were of DC and pico-scale type [21]. Also NGOs and government institutions have installed DC pico-grids in Uttar Pradesh [13]. These systems served still only 0.1% of the people of this densely-populated state in 2017 [21]. Though the unit price of pico-grid electricity is several times higher than that of main grid electricity, the users save in their total monthly energy costs as they do not need to purchase kerosene for lanterns [20,22].

The seven rural hamlets selected in this study are small, inhabited by around 400–800 people each. Each grid connects 5–7 households, each with 7 persons on average. The hamlets are located in Safipur block, and 1–5 km from Chakal Wanshi village (26°41′16″ North, 80°24′12″ East, village code 141578) a distance long enough from other hamlets to make interaction between the people less probable (Fig. 1). Most hamlet villagers derive their main income from agriculture. Typical monthly earnings per household are 3000 INR per (46 dollars) [23]. The villagers have not had access to electricity in their homes before, but they have mainly used kerosene lamps for lighting and portable batteries or local service providers for their most urgent electricity needs, e.g. charging their mobile phones. The national power distribution lines have been extended to some of the hamlets in our study, but has not yet been available to the villagers.

The households connected to the pico-grids are provided with three LED light bulbs à 3 W, a fan, and a socket for connecting small electronic appliances (see Appendix A for the technical details and Fig. 2 for the grid configuration). In a typical pico-grid, the power would be available for 5–7 h in the evening [20], but in the pico-grids of this study, electricity is available 24/7, but limited to 30 Watts, which is controlled by an energy meter installed in each household (Fig. 3). The energy meters function in a pre-paid mode and the customers can buy energy credits from the operator, who puts the credits on the customer's 'energy stick', or dongle. The customer attaches the dongle to his/her meter and the credit is registered. The customers can monitor their instantaneous energy consumption and their remaining energy credits on the meter display. Lights on the meter indicate the currently valid electricity price, which varies dynamically according to the availability of the power in the battery bank. The electricity price is the same throughout the hamlet at all times and the price is sent to the households with a serial data cable. Further details of this dynamic pricing experiment and the effect of the changing prices on household energy consumption in presented in another publication [23].

The central charging station consists of PV panels with a capacity of 200 W and a battery bank of 120 Ah, which is centrally located in the house of the designated operator of the hamlet, who typically is a shopkeeper or another key person in the community. The operator is advised to clean the PV panels weekly. The general technical maintenance is handled by the system provider.

In order to ensure constant data recording, the energy meters were reconfigured to prevent the customers from turning them off. This reconfiguration was performed during a trial period of six months, and before the start of the actual experiments, as some customers were found to shut off the meters for the night because they thought the glowing light on the energy meter screen was consuming their energy credits.

Methods

To test the power reliability in pico-grids, electricity production and consumption were measured in 7 hamlets with a total of 43 households. In addition, the customers were interviewed weekly for their satisfaction. Two field trips were made to observe the installations.

In the central charging station, the data logger recorded the following values over 5-minute intervals: date, time, solar panel voltage (in volts, V), battery bank voltage (V), charging current (in amperes, A), discharging current (A) to and from the battery bank and load current to the grid (A). In all 43 households, the energy meters measured and stored the date, time, power consumption (in watts, W), meter output voltage (V) and energy price range over 10-minute intervals. The values were measured both at the supply and the demand side in parallel.

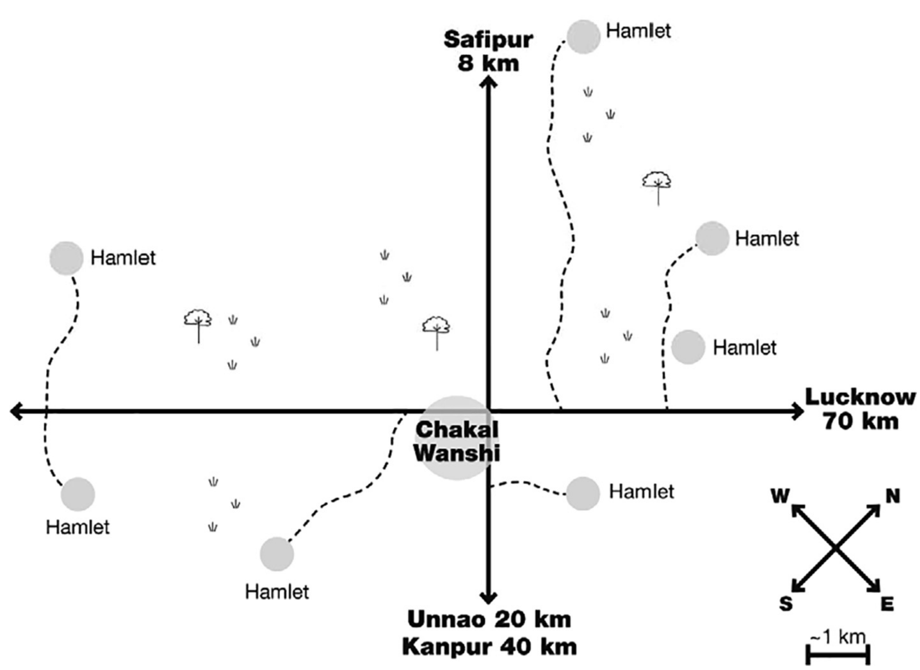

Fig. 1. Graphic showing the locations of the seven hamlets around Chakal Wanshi town in Uttar Pradesh.

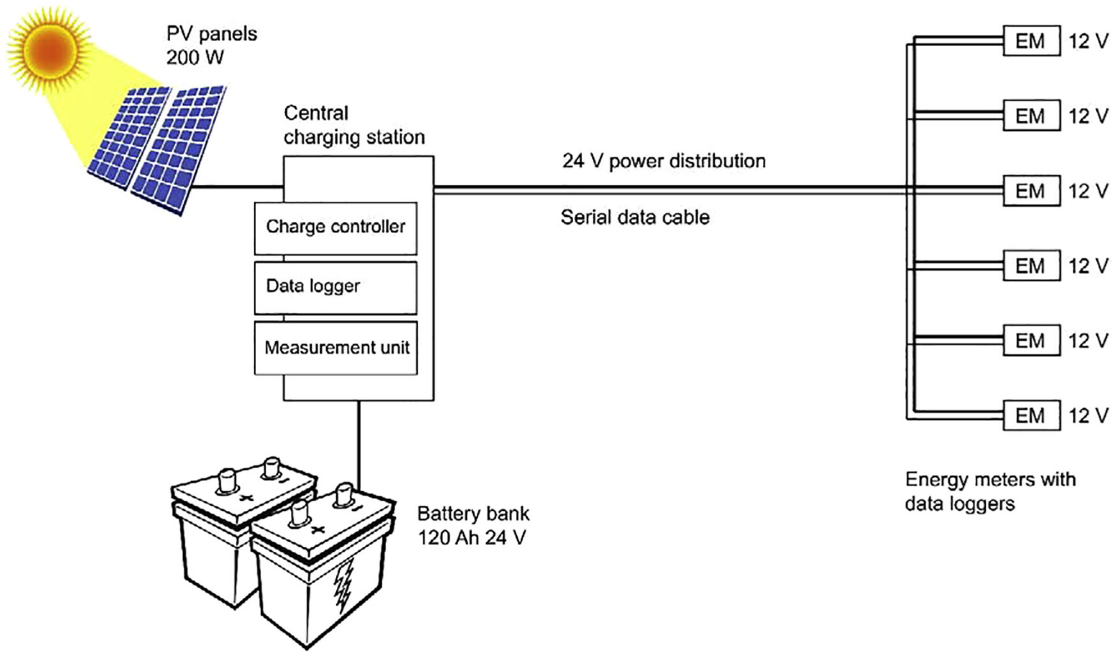

Fig. 2. Block chart of the supply, distribution and measurement system.

An enumerator of MORSEL India, an Indian research company, interviewed all customers on a weekly basis for their satisfaction with the energy service [23]. The interviews and all interaction with the customers were conducted in the local language (Hindi). In addition, the enumerator reported all key technical problems in the villages to the authors by email. The main author also made two field trips to the test sites, conducting two systematic analyses of the quality of the technical installations.

All technical performance data was downloaded manually from the energy meters by the enumerators on a weekly basis. They uploaded the data to a data cloud as .txt format files. The resulting measurement points totalled nearly 3 million (including over 8000 measurement points per day in all the hamlets combined), which necessitated a comprehensive software-assisted data analysis e.g. to double-check the data in the household energy meters as the data loggers were sometimes affected by noise from the communication equipment.

A systematic analysis was performed on the data between January 11, 2016 and December 31, 2016 (356 measurement days). An occurrence of a power outage could be singled out by a lack of measurement values in the household energy meter as the meters could not record the values at all if there was no available electricity in the grid for one reason or another. All energy meters in a hamlet are automatically shut off and all household data will be lost during a grid-wide power outage. The outage may be caused by a shortage of energy in the battery bank when the central charging stations stop the power injection to the grid, as they are designed to do when the cut-off voltage falls below 21.6 V. The station reconnects the battery to the grid once its voltage has risen above 25.6 V. A power outage can also be produced manually by a human being using the main switch in the central charging station. A technical problem in the central charging station equipment could also

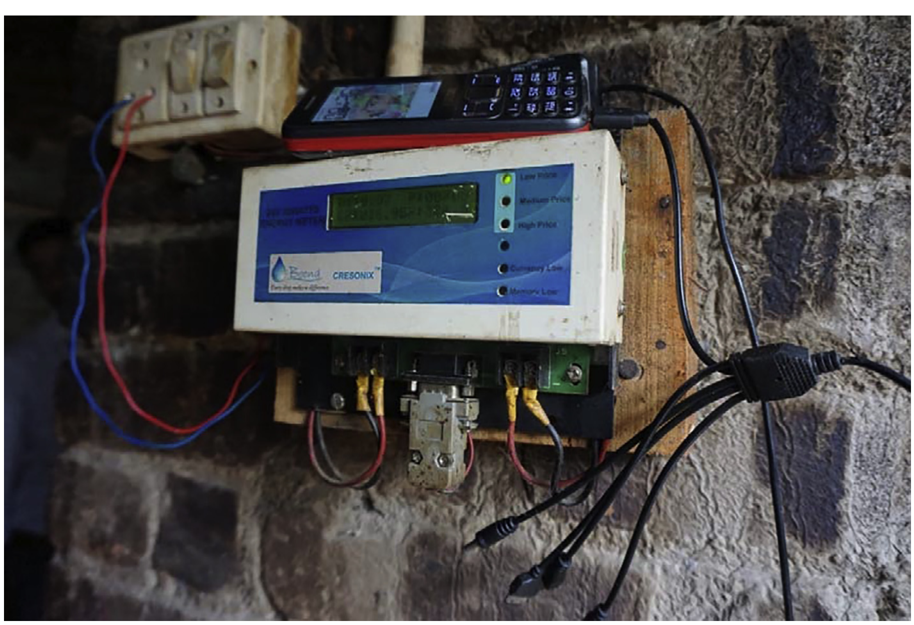

Fig. 3. Smart energy meter in the household.

be the reason.

A single meter stops recording if there is an overload (i.e. maximum instantaneous demand is exceeded by a user), or if there is a technical problem in the meter or in the equipment connecting the meter to the distribution grid. In this paper, 'power outage' refers to both a loss of power in an individual household as well as to broader hamlet-wide outages.

Our data analysis software compared the times of successive measurement points and listed all delays greater than 2 min to the nominal 10-minute frequency of the recordings. Initially, delays shorter than one minute were considered to reflect measurement latency. An interruption could have started during any minute after the last available data point, but it was assumed that all interruptions had started exactly 5 min after the last point and ended exactly 5 min before the next one. The lengths of the recording delays varied from a couple of minutes to several weeks. The delays were listed chronologically and categorised in groups comparable with the available data on the quality of the national distribution grid in the state [9].

In the search for the reasons for identified delays (power outages or other interruptions), the central charging station information on the battery status at the moment of the start of an interruption (normal, OFF, recovering, nodata) was also systematically analysed. Battery voltage was the most obvious indicator of a centrally-induced power cut, as the battery voltage was the control parameter of the output. Also, the energy meter output voltages at the starts of interruptions were followed in order to identify faults in single energy meters.

Unfortunately, the customer interview data could not be used systematically in this study as the customers were asked only to roughly recall the quality of the power supply of the last weeks (e.g. 'I observed one power cut during last week'). The data is, however, systematically analysed in a parallel paper in which the energy consumption patterns were studied [23]. However, the enumerators' notes were important supportive information when identifying anomalies in measurement data and major village-wide technical problems. Technicians' logs were unfortunately not available due to contracting and a language barrier.

The two field trips were made by the main author in June 2016, and December 2016, to visually inspect the technical installations. All households were visited, paying attention to the energy meters. The key technical problems were discussed with the technicians, including his observations on the physical grid installations from his weekly inspection visits. Interviews and field observations were used as supportive information to verify the technical findings especially when concluding reasons for the disruptions in service.

Error reduction and usable data

Shorter interruptions were concentrated in weeks when the energy price was sent to the households, in a manner that had statistical relevance. The dynamic pricing procedure of the experimental setup is explained in [23]. This confirmed that the shortest interruptions were due to the communications technology (e.g. in the cables, or in the communications-related electronic components of the energy meters), which produced noise and delayed the normal measurement functioning of the meters. In addition, a minute-wise analysis of the duration of the interruptions plotted against the total number for the year demonstrates a steady decrease in the number of interruptions as their duration increased. The peak of 10 min (see Table C.1. in Appendix C) reflects only a missed measurement point, or for example, the technician booting the devices during a check-up. For these reasons, only gaps longer than 15 min were considered.

Problems in the communication technology caused errors in the results in another manner, too. At irregular times, an error message on the meter, and a power cut was reported by some households. During these errors, the meters were not fully off, but recorded zero consumption. Customers solved the problem by rebooting the devices. The extent of the resulting error in the results could not be estimated. One household's (in Hamlet 4) data was left out of the analysis of the power outages due to a year-long occurrence.

Also, central charging stations caused some errors, affecting especially the analysis of the status of the battery. A laboratory test of a central charging station and analysis of the data demonstrated a variation 0.5 V in the cut-off and reconnection voltages; hence, the identification of the battery status at the start of the power outage was not 100% reliable. Data losses were most frequent in Hamlet 5, where 31% of all data was lost [23]. The lack of synchronisation between the energy meter clocks in a hamlet caused uncertainty in pinpointing village-wide power outages.

The analysed data was delimited to five of the seven hamlets, due to extensive technical problems. In Hamlet 6 the central charging station malfunctioned over the entire second half of the year and was finally removed. Communication problems in Hamlet 6 were frequent as well. In Hamlet 7, the central charging station had been malfunctioning since the spring, due to suspected misuse by the grid operator. Power theft attempts by tampering with grid components, were most common in this hamlet. Consequently, corruption of the measurement data was substantial.

Results

In the next, we present the key results basing on the data analysis. The frequencies, the lengths and the key causes of power outages were analysed basing on the available data.

Number of power outages

During the measurement period of 356 days, there were 200 days completely without power outages and 156 days with them. One household experienced in average 97 power outages, which equals to 8.3 outages per month (or 1.9 per week), as shown in Fig. 4. The corresponding total sums in hamlets are in Table C.2 in Appendix C. Household-specific data in Tables C.4–C.8 shows that a great majority of the outages were village-wide and only a small minority comprises individual households. All outages summed together, an average household experienced almost 45 days of power unavailability, or three hours daily, resulting to an average 87% power availability. Hamlet-specific details are in Table C.3.

The household energy consumption levels were low, and it was further decreased by power cuts, as shown in Table 1. On average, a household consumed 17 Wh a day, which equals only to one light bulb kept on for six hours per day. This demand level was rather invariable across hamlets. At the same time, energy meters would have allowed over 40 times higher consumptions, a 720 Wh daily per household.

Key causes of power outages

A lack of energy in the battery bank was the reason for 52% of power outages, as shown in Table 2, Table C.9 and Fig. 5. Low battery was a problem especially in December because the amount of sun irradiation was so low [24] and the weather extremely foggy. As such outages have a natural reason, they are separated from other automatic grid shutdowns due to a low battery voltage. The monthly distributions of power cuts can be seen in Tables C.10 and C.11 in Appendix C.

Low battery voltages in other months cannot really be explained. Namely, from a system sizing perspective, the battery bank capacity was big enough, as villagers' energy demand levels were so low. A fully charged battery bank of 120 Ah with a maximum allowed depth of discharge of 80% would cover the highest observed average daily consumption of 42 Wh per households (Hamlet 5) for almost five days without battery charging.

The mysterious outages from January through November represent the reason for 33% of outages in different hamlets, being the highest in Hamlet 3 (50%) and in Hamlet 4 (51%). Interviews show that some grid

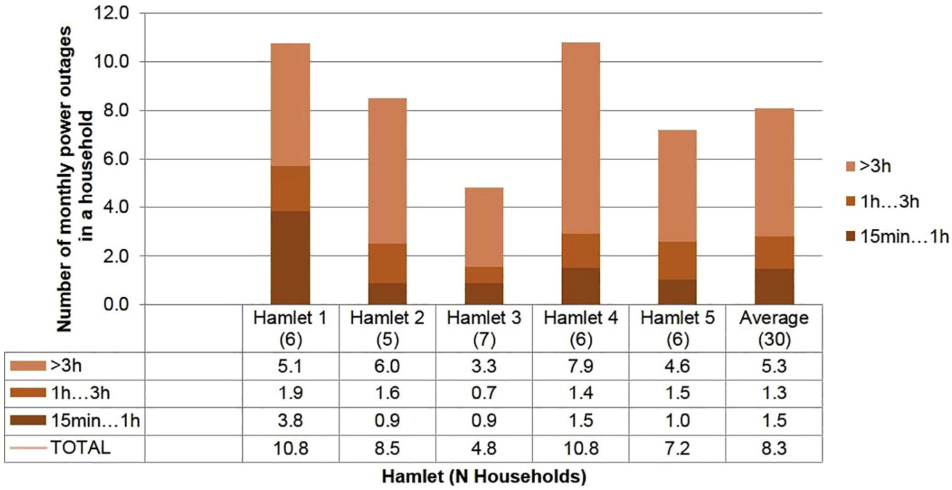

Fig. 4. Number of monthly power cuts per household in different length categories. In parentheses, the number of analysed households in the hamlet.

operators (especially the grid operators of Hamlet 4 and Hamlet 2) were mistrusted by some villagers and the system provider and criticized for taking private advantage of the batteries and loading the battery poles directly with private loads such as mobile phone chargers.

Such illegal behaviour is speculated and which we do not have full evidence of. But the energy balance (Table 1) shows that there indeed was an average unexplained daily energy loss of 31 Wh, after subtracting the battery losses 15% of the load [25], resistive distribution losses 5% and temperature losses 5% of the load, as reported by the system provider, and thermal losses of energy meters. The energy meters were measured to have substantial internal thermal losses in the laboratory (see Appendix B), around 30% of the load. Thus, total Transmission and Distribution (T&D) losses were as high as 37%.

Technical reasons for a share of outages (23%) lay mainly in breakups of central station components, especially in metering equipment resulting in data losses. On the other hand, technical faults in household energy meters did not cause interruptions in the whole grid. Single customers had tried to bypass their energy meters, resulting only to a breakup of their own energy meter. In total in all seven hamlets, an energy meter needed to be repaired 13 times. In six cases, the reason is suspected intentional; once accidental; once due to a small animal having entered the energy meter casing and five times due to a fault in the MAX485 module in the meter. Consumption overloads were highly unlikely, as people were not observed to possess high-consuming devices. As an extra device, only one radio of 4 W was observed.

In 17% of the cases, the supply was manually closed down by the grid operators in some hamlets for overnight, despite being told not to do so. In Hamlet 3 and Hamlet 5 this happened only during the fog season as they wanted to ensure energy sufficiency for all the hamlet. There is evidence that scheduled closedowns were sometimes requested by the villagers, as then they can better plan their activities than if a power cut happens randomly. The grid operator in Hamlet 2, instead, shutdown the grid for nearly every night since July, sometimes also for daytime. An unexplained energy loss (59 Wh/day) may be connected with the behaviour.

Discussion

As unscheduled power outages clearly diminish the usability of electricity among the consumers, we found it important to conduct power availability and reliability measurements and tests also for smaller power systems. Table 3 shows the check-up for some power systems in northern India according to the Multi-Tier Matrix of the World Bank [19]. From this perspective, the pico-grids were performing rather well. However, not all qualities (power reliability, among others) are even defined for the smallest power systems in the matrix.

To improve this pico-grid, the relatively high T&D losses should be reduced. Other DC pico-grids T&D losses in Uttar Pradesh are only in

Table 1
Energy balance based on a 5-minute data set from the central charging stations (columns A, B, F) and on a 10-minute data set from the energy meters (column C). First 11 months data was used to focus on the months with reasonable solar energy production. In parentheses, the energy values divided by the number of households in a hamlet.

Hamlet (N households connected)	A Daily PV production average, in Wh	B Daily energy delivered to load* in Wh	Median	C Average of daily loads, sum of energy meters values, in Wh	Median	D Unidentified energy loss (Wh)	E T&D loss**	F Daily energy delivered to load, days with no outages	G N days without outages > 1 h	H Unmet demand due to outages***
1 (6)	527	191 (32)	180	104 (17)	101	29	45%	202 (34)	110	5.6%
2 (5)	469	196 (39)	194	88 (18)	85	59	55%	196 (39)	249	0.1%
3 (7)	513	126 (18)	112	124 (18)	115	NaN	2%	128 (18)	270	1.3%
4 (7)****	449	172 (25)	157	104 (15)	101	11	40%	164 (23)	198	-4.7%
5 (6)	376	162 (27)	229	91 (15)	90	21	44%	254 (42)	172	57%
Average	467	169 (27)	174	102 (17)	98	30	37%	189 (30)	200	12%

* Average daily values per hamlet, and in brackets this number divided by the number of households. These values contain grid losses and energy meter efficiency losses.

** Includes distribution losses, battery losses, energy meter thermal losses and any unidentified losses. E = 1 − C/B.

*** Counted as the difference between the average daily value overall in the load delivered to the hamlet and the average value for only those days when there were no power outages limiting the electricity demand, respectively. H = F/B − 1.

**** Number of households using energy in Hamlet 4 was seven.

Table 2
Key causes of power outages (> 3 h) in different hamlets in a household.*

Cause of power outage (> 3 h)	1	2	3	4	5	SUM
Technical (all)	13 (22%)	14 (20%)	4 (11%)	16 (17%)	26 (47%)	14 (23%)
Maintenance and repair	*0*	*0*	*2*	*1*	*0*	*1*
No central station data	*4*	*13*	*1*	*6*	*23*	*9*
Unknown	*9*	*0*	*1*	*9*	*2*	*4*
Manual shutdown (all)	1 (1%)	35 (50%)	5 (13%)	9 (9%)	7 (13%)	10 (17%)
January-November	*1*	*21*	*0*	*8*	*3*	*6*
December	*0*	*14*	*5*	*1*	*26*	*5*
Low battery (all)	24 (41%)	21 (30%)	29 (76%)	65 (70%)	21 (40%)	32 (52%)
Low battery (December)	*14 (23%)*	*4 (5%)*	*10 (26%)*	*18 (19%)*	*13 (23%)*	*12 (19%)*
Low battery (unknown)	*11 (18%)*	*17 (24%)*	*19 (50%)*	*47 (51%)*	*9 (16%)*	*20 (33%)*
Household-specific line cuts	21** (35%)	0 (0%)	0 (0%)	3 (3%)	0 (0%)	5 (8%)
TOTAL (all year per household)	59	70	38	92	54	62
TOTAL (per month per household)	5.1	6.0	3.3	7.9	4.6	5.3

* Total sum measured by all energy meters divided by the number of households in a hamlet.
** Household 103 in Hamlet 1 experienced a power cut nearly every night after the end of March, possibly due to the customer's behaviour.

the range 4–20% [13]. In comparison, losses in the Indian main grid were 19% in 2014 [26], power theft forming a substantial share of that [27]. First, pico-grid components should be better protected from unnecessary users' interaction. For example the batteries were sometimes standing in a space or a room where anybody passing by could interfere with it. Locking batteries in cases was opted by the system provider after this pico-grid experience. Additionally, they have tested higher transmission voltages that could reduce an attraction of consumers in experimenting with the distribution system. In addition, the energy meter design has been updated so that the connecting screws are no longer as exposed for users (see Fig. 3).

An automatic upload of measurement data would be highly recommended as the amount of manual work needed for the data upload and data analysis in this experiment has a higher tendency to errors. An alternative for the series data cable in signalling the energy price would also be recommended, to avoid electrical interference issues between components.

To cover the energy insufficiency in December month, adding more PV panel capacity would not make a difference if the solar irradiation level is very low. One way to overcome the power deficit, could be to add more battery capacity which could be charged with solar energy during the period of excess solar insolation. In addition, the power consumption may need to be reduced to minimal in December to secure power adequacy. Another option could be to charge such an extra battery bank with grid power in a nearby village. The additional capital cost needed could be in the range of 10–15% of the system cost [23], which is actually not fully an extra cost, as this kind of secondary battery bank could replace the primary bank after its end of life in 4–5 years. In the current situation, manually scheduled power outages in low-power periods by local grid-operators were actually a rather innovative and frugal way to serve the customers. A more sophisticated alternative could be to add a secondary power source, e.g. a wind power generator, if the local wind conditions were favourable. Moving to such hybrid systems would in addition require an AC/DC converter and a more advanced control unit, which would considerably increase the investment cost and may need a much larger demand base to become economically justified. Also, just adding a secondary power source may not be optimal, but the system sizing of and integration of the hybrid system would need to be done as a whole considering the local conditions and limitations, which was beyond the scope of this study.

We were able to demonstrate some differences in the operational cultures among the hamlets. However, further studies are needed, for example, on how such semi-independent power systems in Tier 1 power

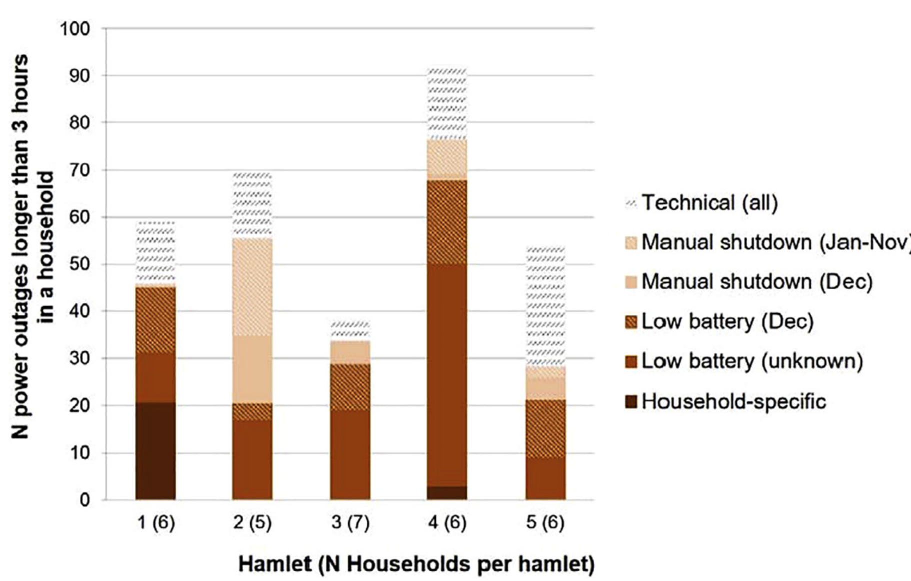

Fig. 5. Total number and the main causes of power outages greater than 3 h, summed over all households and over the whole measurement period, and divided by the number of households per hamlet. The share of outages taking place in December (Dec) is separated as automatic power cuts were nearly daily in all hamlets.

Table 3
Comparison of some energy access metrics of different small power systems in Tier 1.

	Power availability	Power reliability	Ref
Tier 1 (3 W…50 W)	At least 4 h, with a minimum of 1 h per evening	Not Defined	[19]
Pico-grid (measured)	21 h	2 disruptions per week (1.8…2.7)	This study
Pico-grid (theoretical)	24 h	Not known	This study
Husk Power System, (theoretical)	6 – hours 7 in the evening	Not known	[29]
Mera Gao Power (theoretical)	6 in evening, 1 in the morning	Not known	[30]
For comparison			[19]
Tier 2 (50 W…200 W)	4 h per day, 2 h per evening	Not Defined	
Tier 3 (200 W…800 W)	8 h per day, 3 h per evening	Not Defined	
Tier 4 (800 W…2 kW)	16 h per day, 4 h per evening	Max 14 disruptions per week	
Tier 5 (min 2 kW)	23 h per day, 4 h per evening	Max 3 disruptions per week	

level are actually appreciated, what mechanisms contribute to it, it what could be suitable ways for the prevention of possible misuses. Some reports on customer misuses in off-grid systems in India are from Bihar [28], however, probably most of the cases are left unfound or unreported.

Conclusions

The technical reliability of seven identical solar pico-grids was analysed using an extensive data set in rural northern India. On average, a household experienced close to 2 power outages a week over the one-year measurement period. We found that the power outages were predominantly due to a lack of produced energy (unfavourable weather), to technical breakups of system components, and unexpected user behaviour. The power cuts decreased the already low demand levels.

Though the yearly amount of solar insolation in northern India is substantial and is favourable for solar energy utilization, seasonal variations may be considerable and vary locally [31]. This may require more detailed site-specific design of the solar PV systems. The power supply of low-radiation periods need special attention and may need consideration of both a secondary power supply and better power demand management, which may, however, increase the system costs and complexity of the system design. Adding extra battery capacity and power demand control may be the simplest solution in such cases. Hybrid power systems which combine solar e.g. with wind power or bioenergy could in theory provide a solution for weather-dependent power outages, but these would be costlier, technically complex, and require more maintenance than the simple solar pico-grids.

Solar pico-grids though simple in technical design and robust in layout need to be properly protected and sheltered against unnecessary external or user interventions. For example, the batteries should not be positioned in spaces where they are exposed to any unauthorised private use. Also, the hardware e.g. control units or energy meters should be designed in a way not allowing the users to break in to these. All in all, the 'electronics' part of the solar pico-grid is subject to harsh conditions in villages and may also have high power self-consumption, which need close considerations in future systems. We also find that more comprehensive user education may be useful to properly deal with the solar systems and to maximize the use of the solar energy, e.g. by incorporating demand flexibility [23] to shift demand to high solar periods of the day or week from low solar periods (though this may also depend on cultural and behavioural patterns). System monitoring is useful to track the performance and status of the solar pico-grids and to better understand the underlying factors affecting operation. However, a more automatic data recording and export system is recommended, to decrease the number of measurement errors and ease data analysis.

The detailed performance analyses of the solar pico-grids presented here are unique and in the extent presented here not previously available. Independent studies on the reliability of installed energy systems will be increasingly important in the coming years, especially now when the PV market in the emerging economies, and in particular in India, is booming with new market actors and system providers.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.seta.2018.08.005.

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