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Analysis of standalone solar streetlights for improved energy access in displaced settlements

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A B S T R A C T

This paper examines the gap between the design and in-situ performance of solar streetlight interventions in two humanitarian settings. Displaced settlements often lack street lighting and electricity. Given that off-grid solar streetlights produce surplus energy, we hypothesized that this energy could be made available for daily usage, to improve system performance and provide further energy access to displaced populations. We recognize, however, that solar streetlight performance and longevity have typically been poor in remote and refugee settings. Eleven solar streetlights were fitted with ground-level sockets and their performance monitored, in two displaced settlements: a refugee camp in Rwanda and an internally displaced population settlement in Nepal. Considerable performance gaps were found across all eleven systems. Inefficient lights and mismatching system components were major issues at both sites, reducing targeted designed performance ratios by 33% and 53% on average in Rwanda and Nepal, respectively. The challenges of deploying these types of systems in temporary settlements are outlined and a number of suggestions are made to guide future developments in the design and implementation of sustainable solar streetlight interventions.

1. Introduction

Solar streetlights can provide affordable lighting in remote locations where a grid connection is not feasible [1]. Lighting is particularly important in informal settlements to improve safety, security and mobility [2] and solar streetlights can offer environmental benefits in comparison to grid-connected lights [3]. Nevertheless, numerous solar PV interventions in refugee camps and displaced settlements have failed, meaning that these benefits are not actually being realised in practice: vandalism, theft and poor performance are often cited as main problems [4]. Fuentes et al. [5] claimed that there were no clear success stories of solar programs in refugee camps. To investigate why, they examined twelve PV installations in Saharawi refugee camps after more than 10 years of operation. They suggested that frequent changes in ownership and a lack of training on operation had led to informal system modifications (e.g. system rewiring, additional connections, bypassing of safety features and replacement of mismatching components) damaging components and reducing battery life. Poor maintenance and cleaning of PV panels had further affected PV panel longevity and performance. However, evidence also suggests that technical problems occur soon after installation and that communities do not typically have an understanding of expected PV system functionality, access to replacement parts, a sense of responsibility for looking after systems, funds for basic repairs or local skills for maintenance [4].

Reliability is an even greater problem for off-grid PV systems in locations with highly variable seasons (e.g. a monsoon season) and that are further from the equator [6]. Moreover, in standalone solar systems, surplus solar energy is lost when there is no demand or it cannot be stored, which reduces the system's utilisation and viability [7]. The majority of studies in the literature have focused on assessing the performance of grid-connected PV systems, rather than standalone PV-battery systems [8]. To the authors' knowledge, research has not monitored and evaluated standalone solar systems in displaced settlements, to understand the design and deployment challenges that reduce performance.

This paper aims to present new knowledge in the area of design, procurement and provision of energy products and services in constrained contexts where there is minimal data or experiences to inform the design. By analysing design assumptions, component choices, implementation practices and consumer behaviour of a

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Nomenclature

A	Surface area of the PV array (m^2)
B_{cap}	Battery capacity (kWh)
B_{cp}	Battery charge power (kWh)
B_{dp}	Battery discharge power (kWh)
C_S	Capacity shortage (kWh)
E_A	Net energy from PV array (kWh/d)
E_D	Total load demand (kWh/d)
E_{Light}	Total light load output (kWh)
E_{Load}	Total load (lights and socket) output (kWh/d)
E_P	Potential PV power output (kWh/d)
E_{Socket}	Total socket load output (kWh)
Gpoa	In-plane irradiance on PV array (kWh/m^2/d)
L_{BoS}	Balance of system losses (h/d)
L_C	Capture losses (h/d)
PF	Production factor (%)
P_o	Peak power rating of the PV array (kW)
PR	Performance ratio (%)
SoC	State of Charge (%)
SoC_{max}	Maximum State of Charge (%)
SoC_{min}	Minimum State of Charge (%)
Y_A	Actual array yield (h/d)
Y_F	Final yield (h/d)
Y_R	Reference yield (h/d)
$\eta_{A,mean}$	Mean array efficiency (%)
η_{bat}	Round trip battery efficiency (%)
η_{BoS}	Balance of system efficiency (%)
η_{STC}	Efficiency of the PV array at standard test conditions (%)
η_{total}	Total system efficiency (%)

solar streetlight intervention, we provide an evidence base to answer the following specific research question:

What is the performance gap between designed and in-situ solar streetlight systems, what are the main causes for this and how can it be reduced in future solar streetlight interventions?

Research on the performance of solar streetlights in remote settings is limited; however, several authors have identified that there are significant challenges that require further investigation. At the African University of Science and Technology, Nigeria, 35 solar streetlights were installed in 2012 to improve security during blackouts [9]. Within the first year, 11 of the lights were not working properly due to faulty batteries, damaged charge controllers, poor cabling and LED light issues. In 2012, over 2000 solar streetlights, which were installed in 2008/2009, were assessed across 5 states in Nigeria; more than 50% were not working [10]. Other frequent issues included rain damage and PV panel misalignment. In 2016, 42 out of 62 assessed solar streetlights in Himachal Pradesh, India, were not working, including 14 out of 25 at Bhimakali Temple, 12 out of 21 at Mandi's slums and nearby villages and all 16 lights at Parashar Lake; the majority of these lights suffered from frequent power cuts and failed within 1–2 years [11]. The communities in these locations reported that the lights were never officially maintained by the relevant municipal authorities. As dust on PV panels in the Sahel region can reduce maximum PV power output by up to 78% within just a year [12], Kama et al. [13] suggested a remote monitoring system for solar streetlights in Senegal to notify municipalities of maintenance and cleaning requirements.

Due to diurnal and seasonal irradiance variations, decentralised solar streetlights are underutilised with daily capture losses (see section 2.6) typically ranging from 5% to 30% [14]. The surplus energy available is relatively low and limited by the PV-battery system (e.g. the battery's capacity and discharge rates) to a few hundred-Watt hours, which is unlikely to be enough to meet alternative local energy needs and justify connection. However, several authors highlight the potential benefit of even small quantities of electrical power in remote locations – e.g. to power radios, phones and televisions to connect these locations to the outside world [15,16]. The energy requirements in refugee camps are often low with the majority of refugees owning few electronic devices. Forsen et al. [17] found that in Kakuma Refugee Camp, Kenya, 77% of households had a mobile phone and spent 7% of their non-food item budget on phone charging. In 2010, Digicel deployed solar streetlights fitted with sockets for phone and battery charging in Haiti [18]. The motivation for the intervention was to increase customer usage of phones and service packages. The charging stations were initially free to use, but when the charging stations had no operator, clients preferred to pay to charge their phones somewhere else where they could be kept safe. Subsequent systems were installed by phone kiosks and run by entrepreneurs with profits of around 100–150 USD/month. Around 400 stations were established in total by Digicel in Haiti.

As standalone solar streetlights do not receive a reliable source of solar energy all year round, appropriate sizing and selection of components is needed to minimise potential capacity shortages (i.e. where load demand exceeds supply capacity). Oladeji et al. [19] demonstrated the process of designing a solar streetlight for Ilorin, Nigeria, supported by simulations using HOMERPro. A number of alternative designs have also been proposed by other authors to improve reliability and reduce storage requirements and costs. Nyemba et al. [20] presented a wind-PV solar streetlight design for Zimbabwe, suggesting battery capacity could be reduced by 40% and Lagorse et al. [6] optimised a hybrid fuel cell-PV design using genetic and simplex algorithms. However, these systems were not implemented and monitored to see if the simulated gains in performance could actually be realised in practice.

Research to date has primarily focused on the monitoring and analysis of grid-connected PV installations. Milosavljevic et al. [8] reviewed several studies on grid-connected PV systems ranging from 1 kW peak (kW_p) to 1 MW peak power rating of the PV array and reported annual performance ratios (PRs) to range from 65 to 87%. These in-situ performance ratios sometimes exceeded design phase simulations. Leloux et al. [21,22] reviewed 995 residential PV systems in Belgium and 6868 systems in France finding similar average annual PR values of 78% and 76%, respectively. Assessment of standalone PV systems has been more limited and there is a need to monitor and evaluate their performance for remote area power supply under real conditions [23]. Ma et al. [23] analysed a 19.8 kW_p standalone PV system on a remote island in Hong Kong. They found that the system losses were relatively low, highlighting that performance issues were mainly due to a generation-demand mismatch rather than technical problems, such as inefficiencies or reliability issues. Similar studies have also been carried out for a standalone 10 kW_p PV-battery system powering an isolated building in Thailand [24] and a 5.28 kW isolated system at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia [25]. These analyses were limited to periods where no missing data occurred due to interrupts or faults. However, data from PV systems is often incomplete owing to power outages, communication failures and component failures. Therefore, proper handling of missing data is crucial to mitigate information loss and avoid potential bias in analyses [26]. Previous research on handling missing data in PV systems has focused on imputation of irradiance and temperature data for grid-connected systems [27,28]. For standalone systems in isolated locations, data can be even more frequently lost due to outages (possibly caused by poor weather or high energy use), remote connection failures, inaccessibility for maintenance, limited local knowledge and a lack of local fault reporting [29].

Through the design, implementation, monitoring and evaluation of solar streetlights (deployed in displaced settlements to provide lighting and additional energy access), we investigate the gap between design and in-situ performance. Moreover, we analyse missing data gaps to identify capacity shortages due to power outages. Solar streetlight systems were designed and deployed in two different settings, Rwanda and Nepal, as outlined in Section 2. The data collection and processing techniques used to analyse the systems are detailed in Section 2.5. The performance analysis results are provided in Section 3 and a discussion in response to this paper's research question is provided in Section 4.

2. Method and materials

The research methods reported here were carried out for the Humanitarian Engineering and Energy for Displacement HEED research project (see Acknowledgements), in the period 01/09/2017–31/05/2020.

To build an evidence base on the value and benefits for humanitarian energy provisions, the HEED project worked with displaced communities in refugee camps in Rwanda and temporary settlements in Nepal. To determine the exact sites for deploying monitored energy interventions, we carried out a number of site assessments, baseline surveys of current energy practices and community co-design workshops. One of the outcomes from this community-facing work was the expressed community need for solar streetlights with additional energy access provided by ground-level AC sockets. Two sites were chosen for the streetlight intervention: Gihembe refugee camp, Rwanda and Uttargaya settlement, Nepal.

2.1. *Site 1: Gihembe refugee camp, Rwanda*

Gihembe Camp was established in 1997 in Gicumbi District in Northern Province, and in 2014 had a population of around 14,500 [30]. Gihembe camp has no main electric grid connection, with households dependent on candles and, increasingly, mobile phones for lighting. A survey of over 211 households, carried out by the HEED team in 2018 found that 88% of households had at least one mobile phone [31]. Although solar streetlights had been previously deployed in Gihembe, the venture had proved unsuccessful, partly due to poor performance, maintenance, theft and governance structures. There was also perceived issues around the location of the lights as the community considered the lights were situated to secure buildings, rather than improve night-time mobility.

2.2. *Site 2: Uttargaya IDP temporary settlement, Nepal*

The Rasuwa district in Nepal was one of the regions most affected by the April 2015 earthquake, with almost all of the households in the district damaged [32]. By June 2020, the formal process of permanent resettlement for the internally displaced people (IDP) had not started, with the largest settlement at Uttargaya (257 households). Unlike Gihembe camp, 86% of households in Uttargaya had access to electricity from a grid connection, but a significant minority still regularly used mobile phones for lighting in the home. As the site at Uttargaya is located on the bank of the Trishuli River, making mobility at night particularly dangerous, street lighting was perceived to be the most important energy need to be addressed [31].

2.3. *System design*

HOMERPro® [33], which is a widely used software package for PV-battery system optimisation, was used to arrive at a concept design for the streetlights in Rwanda and Nepal. Based on solar resource availability, energy demands, system constraints and component specifications and costs, HOMERPro recommends ideal component sizes to minimise the levelised cost of electricity. PV panel size is evaluated as a continuous variable whereas battery size is a discrete variable at 1 kWh intervals.

The design objective was to arrive at a cost-efficient solar streetlight design with an annual capacity shortage of less than 2.5%. A capacity shortage occurs when the hourly load demand exceeds the available power. Allowing a small capacity shortage when designing off-grid solar systems can significantly reduce system size and costs [34]. The assumption made was that the system needed to provide at least 0.78 kW h per day (kWh/d) with a peak load of 150 W. This was based on an LED light load of 60 W (full brightness) from 6 p.m.–12 a.m., local time, and 30 W (half

Table 1
Model assumptions for designing the solar streetlights interventions in HOMERPro.

Parameter assumption	Rwanda	Nepal
Daily average global horizontal irradiance[a]	4.74 kWh/m^2/d	5.11 kWh/m^2/d
Annual average clearness index	0.47	0.59
Generic flat plate PV panel location	North orientation, 15 tilt	South orientation, 28 tilt
PV panel derating	90%	90%
MPPT Solar Charger efficiency	95%	95%
Socket inverter size	0.2 kW	0.2 kW
Inverter efficiency	95%	95%
Li-ion battery roundtrip efficiency	90%	90%
Lead-acid battery efficiency	80%	80%
Li-ion battery minimum SoC	20%	20%
Lead acid battery minimum SoC	40%	40%
Socket load	0.3 kWh/d	0.3 kWh/d
Light load	0.7 kWh/d	0.7 kWh/d
Converter capacity	0.2 kW	0.2 kW
PV panel cost	1500 $/kW	760 $/kW
Li-ion battery cost	550 $/kWh	550 $/kWh
Lead-acid battery cost	180 $/kWh	190 $/kWh
Converter cost	500 $/kW	500 $/kW
Maximum annual capacity shortage	2.5%	2.5%

[a] Based on the National Renewable Energy Lab database.

Table 2
HomePro simulation outputs for alternative panel and battery configurations.

System	Rwanda				Nepal			
	Optimised		Fixed panel size		Optimised		Fixed panel size	
Battery type	Lead-acid	Li-ion	Lead-acid	Li-ion	Lead-acid	Li-ion	Lead-acid	Li-ion
PV array (kW_p)	0.438	0.412	0.32	0.32	0.448	0.307	0.3	0.3
Battery capacity (kWh)	3	2	4	3	2	2	3	2
Annual capacity shortage (%)	2.3	2.58	4.01	2.01	2.59	2.53	3.62	2.76

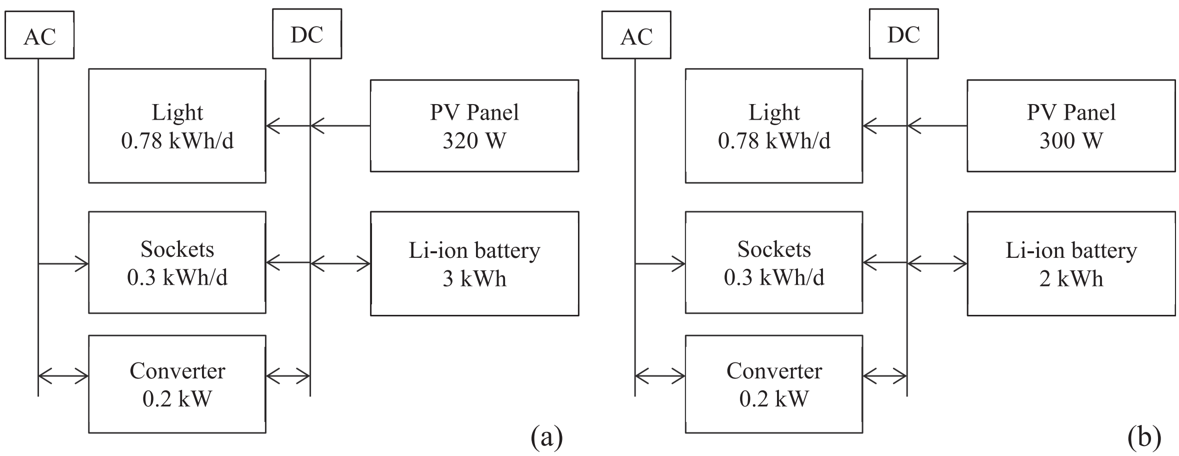

Fig. 1. Concept schematic for the solar streetlights in Rwanda (a) and Nepal (b).

brightness) from 12 a.m. to 6 a.m., and an auxiliary load of 10 W throughout the day (e.g. for monitoring equipment). For the ground-level socket demand, 0.3 kWh/d with a peak load of 0.14 kW was assumed with a peak demand occurring at midday, which is enough to charge approximately 40 phones with a charging requirement of 7 Wh [35]. A derating factor of 90% was used to take into account soiling, shading, wiring and other temperature-related losses. Two alterative storage solutions were also compared: lead-acid and li-ion. The HOMEPro model assumptions are outlined in Table 1.

The outputs from the HOMERPro simulations are summarised in Table 2. To avoid an excessively large panel and battery, in Rwanda, a 0.32 kW peak panel with a 3 kWh li-ion battery was chosen, achieving a capacity shortage of 2%; for Nepal, a 300 W_p panel with a 2 kWh li-ion battery resulted in a capacity shortage of 2.76%. Schematics of the concept designs are shown in Fig. 1.

A call was sent out to local suppliers to submit proposals for developing and installing the systems. The suppliers were evaluated based on their understanding of the requirements, ability to undertake the work within provided timescales and pricing. The HEED team selected suppliers and worked collaboratively with the communities to refine the design to meet their perceived needs. Community mobilisers were trained and appointed to provide weekly reports on system usage and performance issues.

Fig. 2. Map of Gihembe, showing the locations of the four advanced streetlights (denoted SL1 to SL4, Red) and the eight regular streetlights (Blue).

2.4. Systems description

2.4.1. The solar streetlights at Gihembe, Rwanda

A combination of regular and advanced (comprising ground-level AC sockets, programmable lights, data loggers and remote communications) solar streetlights were deployed in Gihembe (1 35′51.0″S 30 04′33.5″E), with the locations being chosen with support from UNHCR, camp governance, and the community (see Fig. 2).

The 8 regular solar streetlights had a 60 W LED light, 24 V/200Ah lead acid battery storage and a 0.25 kW_p PV panel. These streetlights were not equipped with monitoring equipment and are not reported on further in this paper. The 4 advanced streetlights had a 0.320 kW_p solar panel (Eagle 72P 320 Watt Poly Crystalline Module – JKM320PP-72) [36], two 12.8 V/120Ah li-ion phosphate batteries (Okaya – model OPLP128120LF) [37], 100/20 Victron solar charge controller, programmable 60 W light with ELG-75-C350D2 MEAN Well AC/DC LED Driver, Phoenix VE.Direct 12/250 (for the ground-level sockets), Victron Venus GX with GSM router for datalogging, Victron BMV 700 series battery monitor, Victron BatteryProtect 12/24 V|65A, and ground-level double sockets with four additional USB ports. Due to the availability of parts and a system-component voltage mismatch, an additional Victron 24/180 Inverter was required for the LED driver. The main components and connections inside the streetlight are outlined in Fig. 3.

The specifications of the PV panels and batteries used for the four advanced streetlights are given in Table 3.

To encourage utilisation of the sockets, an interface board was installed on site – located near the entrance to the camp – to show the community in real-time when surplus energy was available at each streetlight (see Fig. 4). The impact of this interface board is not assessed or discussed further in this paper.

Installation work was carried out from May to June 2019 (see Fig. 5) and a launch event took place in July 2019.

Table 3
PV panel and battery specifications for the advanced solar streetlights in Rwanda.

PV panel	Module efficiency under STC[a]	16.49%
	Peak power rating	0.32 kW
	Solar cell type	Multicrystalline
	Solar cell size	156 156 mm
	Module Dimensions	1956 992 mm
	Cell number	72
	Total array area (1 panel)	1.94 m^2
	PV panel tilt angle	18
	Orientation	North
Battery	LiFePO4 battery capacity	120 Ah
	Rated voltage	12.8 V
	Voltage range	10–14.2 V
	Rated battery charge/discharge current	10 A
	Max battery charge/discharge current	25 A

[a] Standard Test Condition (STC): 1000 W/m^2, 1.5AM and 25 C cell temperature.

2.4.2. The solar streetlights at Uttargaya, Nepal

Seven advanced streetlights were deployed at Uttargaya, at locations chosen by the community (see Fig. 6). The streetlights had two 0.15 W_p PV panels (Sunworth Solar – SW150P) [38], two 11.1 V/88Ah li-ion batteries (Indo-China International), a Victron 100/20 solar charge controller, a programmable 60 W LED light, a Victron Venus GX for datalogging, a Victron BMV 700 series battery monitor and ground-level sockets/USB ports powered by a 500 W Suoer DC-AC converter. An overview of the system and the battery box components are shown in Fig. 7. Fig. 8 shows the energy availability interface board.

The specifications of the PV panels and batteries for each streetlight are given in Table 4.

Installation work was carried out from March to June 2019 (see Fig. 9), and commissioning and community opening events took place in July 2019. The purpose of the community event was to introduce the community to the systems, showcase their functionality, and inform them of how the interface board would notify them when surplus energy was available at the sockets.

2.5. Data collection and analysis

Data from the PV systems was stored locally in the Venus GX as well as communicated to a remote Victron VRM portal via GSM in Rwanda and WiFi in Nepal. Performance analysis of the PV systems was carried out for data collected between July 1, 2019 (post commissioning) and March 31, 2020, using R. For the analysis, data was obtained for Solar Charger PV Power, Solar Charger Battery Power, System Battery Power, Battery State of Charge and System AC Consumption (for Rwanda streetlights only). The frequency of data acquisition was initially set to once every 15 min, i.e., ideally 4

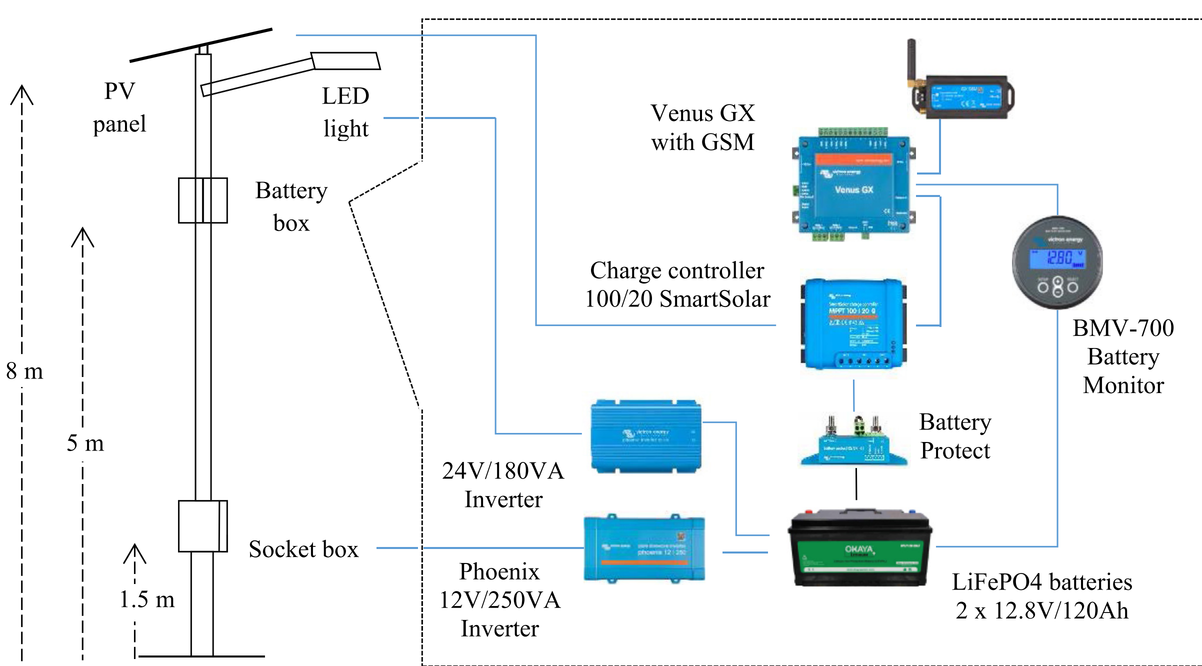

Fig. 3. Advanced solar streetlight system design in Rwanda: battery box components and connections diagram.

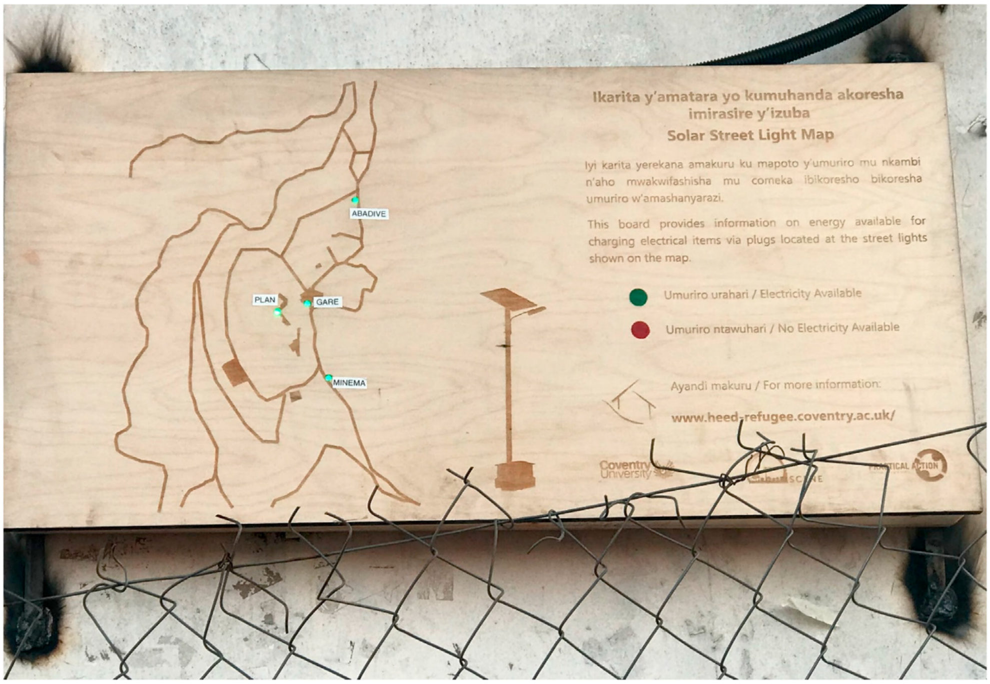

Fig. 4. Advanced streetlights socket energy availability interface board, Gihembe, Rwanda: displayed in a public space in the camp, with high traffic and visibility.

Fig. 5. An advanced solar streetlight with sockets installed at the entrance to Gihembe refugee camp, Rwanda.

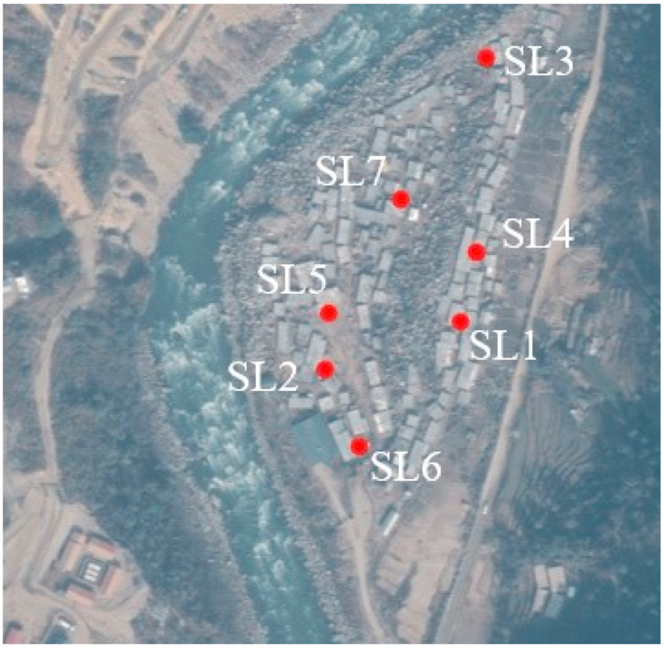

Fig. 6. Map of Uttargaya showing the 7 advanced streetlight locations (SL), labelled SL1 to SL7.

data points recorded per hour for each of the above variables. To improve the resolution of the monitored data, the frequency of data acquisition was increased to once every minute on August 5, 2019, for the Rwanda streetlights and October 15, 2019, for the Nepal streetlights. For analysis, the data was then summarised to obtain hourly measures by calculating mean values per hour.

Figs. 10 and 11 illustrate the data availability of Solar Charger PV Power data for Rwanda and Nepal streetlights, respectively. Figs. 10a and 11a show the daily data availability, which is calculated as the percentage of hours in a day for which data is available. Various instances of missing data can be observed that can be attributed to communication failures, component failures and power outages. To further understand the occurrence of missing data, the hourly data availability is shown for all days in a month (see Figs. 10b and 11b). Fig. 10b, highlights that the hourly data availability from the Rwandan streetlights was often low from around 12 a.m.–6 a.m. This was attributed to power outages, which was confirmed by field reports. The data availability was the same for all monitored variables apart from System AC Consumption (obtained from the VE.inverter for the streetlight sockets in Rwanda), which was around 10–20% lower for SL1, 3 and 4. Compared to the Rwanda streetlights, the nature of missing data was more variable at the Nepal streetlights, including periods of prolonged missing days, as shown in Fig. 11a and b. Missing data in Nepal occurred due to WiFi communication issues, mishandled SD cards and a faulty Venus GX for SL5. Due to component failures causing missing or erroneous data, Nepal SL5 (all months) and SL7 (between July and Sep) were not analysed further. Whilst SL3 and SL6 also had large periods of missing data, these systems were generally more reliable.

To mitigate the effect of data discrepancies on the performance analysis of the PV systems, the data was pre-processed to handle missing data. For large datasets, tuples with missing attribute values can often be ignored or only full data days can be analysed. However, for PV systems where missing data is time-sensitive and may represent a significant event, such as a power outage, these approaches generate a bias. Data imputation is, therefore, necessary.

A measure of central tendency, such as mean or median for an

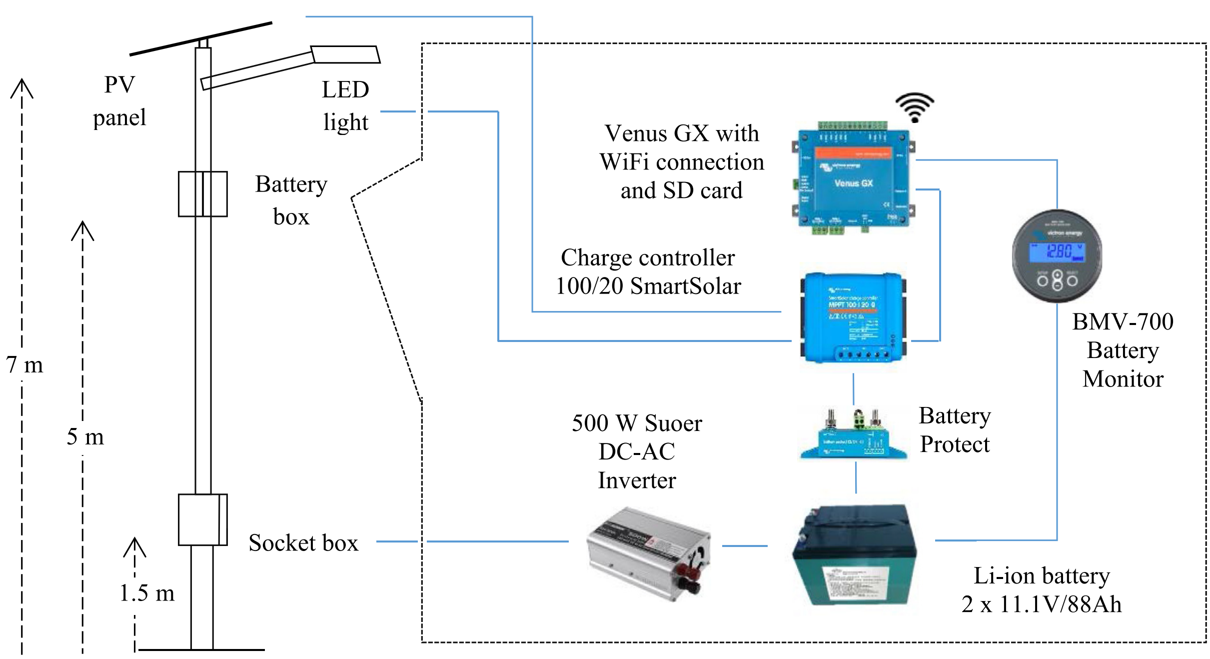

Fig. 7. Advanced solar streetlight system design in Nepal: battery box components and connections diagram.

Fig. 8. Advanced streetlights socket energy availability interface board, Uttargaya, Nepal: displayed outside the camp's grocery store.

Table 4
PV panel and battery specifications for the advanced solar streetlights in Nepal.

PV Panel	Module efficiency under STC[a]	15.2%
	Peak power rating	0.15 kW
	Solar cell type	Multicrystalline
	Solar cell size	156 156 mm
	Module dimensions	1480 665 30 mm
	Cell number	36
	Total array area (2 panels)	1.968 m^2
	PV panel tilt angle	27
	Orientation SL1-7	174 S; 143 SE; 143 SE; 170 S; 174 S; 176 S; 183 S
Battery	Li-ion battery rated capacity	88Ah
	Rated voltage	11.1 V
	Voltage range	8.4–12.6
	Rated charge/discharge current	5 A
	Max charge/discharge current	40A

[a] STC condition 1000 W/m^2, 1.5AM and 25 C cell temperature. Nominal operating cell temperature 46 ± 2 C at 800 W/m2, AM 1.5, wind speed 1 m/s, ambient temperature 20 C.

Fig. 9. A solar streetlight in Uttargaya, Nepal, being used to charge a phone and provide lighting at night.

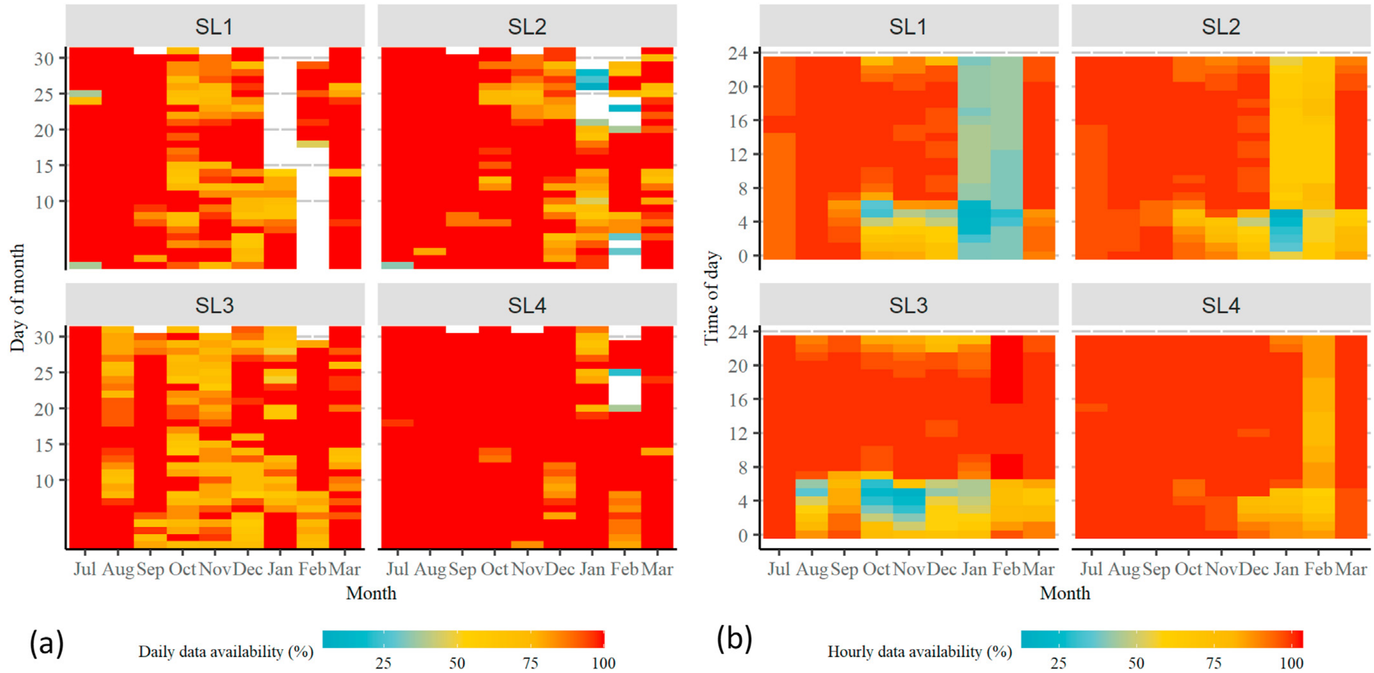

Fig. 10a–b. Daily data availability (a) and hourly data availability (b) for Rwanda streetlights SL1–4.

attribute, is often adopted for handling missing data. These methods also tend to create biases in the data as they do not consider association between neighbouring data points or correlation between different features. Thus, alternative methods have been proposed specifically for time-series based imputation, such as Seasonal Decomposition (Seas) [39]. Seas splits the seasonal component of a time-series, imputes missing values in the de-seasonalised series (using methods such as mean imputation, interpolation and Kalman smoothing), and reconstructs the original time series by addition or multiplication of the split components [40]. Seas has been shown to work well in comparison to other imputation techniques when handling missing PV data for estimating PV performance degradation [41]. As a PV system exhibits a daily pattern of change (e.g., as the battery charges and discharges), this behaviour can be leveraged using Seas with a frequency of a single day.

To assess the suitability of Seas imputation for the given dataset, a 20% subset of full data days were replaced with randomly chosen missing values. Seas imputation was then performed using a built-in function in R, na_seadec. RMSE values and summary statistics (mean, median standard deviation, skewness and kurtosis) were compared for a range of sub-Seas imputation techniques (interpolation, Kalman, moving average and mean) and other imputation methods (e.g., Generalized Additive Models). Seas-based interpolation was subsequently chosen as it performed well across all imputed variables.

After imputing missing data, several calculations and corrections were made due to the different system configurations and to remove outliers and erroneous data.

Small negative outliers (approaching zero to the order of 10^{10} to 10^{2}) for Solar Charger PV power and System AC consumption were set to zero

Battery State of Charge values for SL1-4 in Rwanda and SL7 in Nepal were replaced with estimated SoC values using the System Battery Power (see section 2.6, Eq. (9)); this was due to incorrectly configured BMV monitors providing erroneous SoC readings

A power outage was assumed to have occurred when data was missing and the battery was at the minimum SoC

Imputed values were used to estimate the expected load values during a power outage (i.e., the typical load demand on the system during these periods); the actual load delivered was taken to be zero

The difference between the demand and actual total load output during a power outage was used to approximate a capacity shortage (see section 2.6, Eq. (9)).

In Rwanda, the socket load output was provided by the System AC Consumption reading

In Nepal, the socket load was estimated from the solar charger and battery power readings

The light load for the systems in Rwanda was estimated from the System Battery Power, with the system losses and inverter efficiency measured at 77%; in Nepal, the light load output was provided from the Solar Charger Battery Power.

The raw data for each streetlight is available here [42].

2.6. Performance assessment of PV-battery systems

The solar photovoltaic systems were evaluated following the International Electrotechnical Commission Standard IEC 61724–1 [43], which includes details on how to monitor and assess several key performance indices for energy yield, loss and efficiency. IEC 61724–1 [43] provides further explanation of equation (1) through (7).

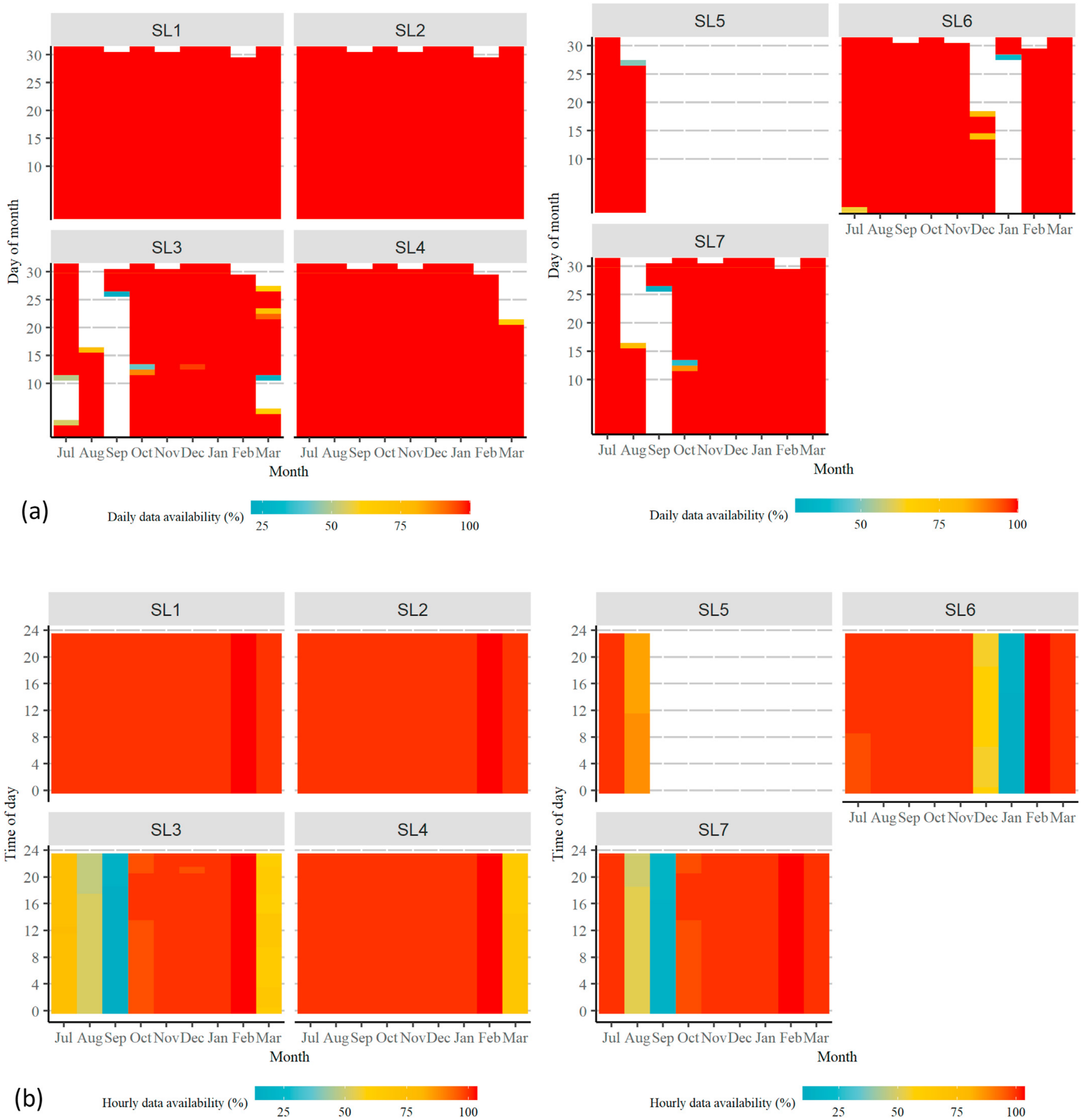

Fig. 11a–b. Daily data availability (a) and hourly data availability (b) for Nepal streetlights SL1–7.

A reference yield (Y_R), array yield (Y_A) and final yield (Y_F) are energy quantities normalised to the rated power of the PV array: Y_R is the potential energy output of the PV array operating at nominal efficiency under standard test conditions; Y_A is the actual output of the PV array, and Y_F represents the actual load served by an inverter. These yields can be obtained from:

$$Y_A = \frac{E_A}{P_o} \tag{1}$$

$$Y_F = \frac{E_{Load}}{P_o} \tag{2}$$

$$Y_R = \frac{A\ \eta_{STC} \sum Gpoa}{P_o} = \frac{E_P}{P_o} \tag{3}$$

where P_o is the peak power rating of the PV array, E_A is the net PV array energy output from the solar charger, E_{Load} is the total load output of the system, A is the surface area of the PV array, η_{STC} is the efficiency of the PV array at STC, $Gpoa$ is the in-plane solar irradiance incident on the PV array and E_P is the potential PV power output. Live irradiance data from SolCast was used to estimate potential PV power output, as satellite-obtained solar irradiance data is often used instead of a pyranometer to assess smaller PV systems (typically less than 5 kW_p) [44]. However, the use of satellite-measured irradiance data does introduce inaccuracies: root mean square errors for hourly global irradiance are low for clear conditions and can increase to over 25% for clouded skies [45].

The system capture losses, L_C, and Balance of System (BoS) losses, L_{BoS}, are derived from the yields:

$$L_C = Y_R \quad Y_A \tag{4}$$

$$L_{BoS} = Y_A \quad Y_F = Y_A(1 \quad \eta_{BoS}) \tag{5}$$

System capture losses result from generation-demand mismatching, system down-time, wiring losses, panel aging, dust and dirt, shading, solar charger inefficiencies and temperature and irradiance -dependant variations in performance. Generation-demand mismatching can result in power outages when demand exceeds supply and surplus solar energy goes to waste when demand is low (e.g. no user load and the batteries are fully charged). The BoS efficiency, η_{BoS}, can be calculated from $\eta_{BoS} = Y_F/Y_A$, and includes battery, inverter and wiring losses [43].

The performance ratio (PR), where $PR = Y_F/Y_R$, provides an indication of the overall losses in relation to the array's rated output [43]. As many of these losses are particularly influenced by temperature changes, weather-corrected PR models have been proposed to reduce the seasonal variability; however, temperature monitoring and modelling is not included in this research (see Ref. [46] for further information). The production factor (PF) is also considered in this research, where $PF = Y_A/Y_R$. The PF identifies the system's total utilisation of the potential array output; it does not require load output measurements and is, therefore, easier to monitor than PR [23].

The mean array efficiency, $\eta_{A,mean}$, is the ratio of the net PV array energy output to the incidence irradiance on the total array area:

$$\eta_{A,mean} = \frac{E_A}{A \sum Gpoa} \tag{6}$$

The overall total system efficiency, η_{total}, is given by:

$$\eta_{total} = \ \eta_{A,mean} \cdot \eta_{BoS} = \frac{E_{Load}}{A \sum Gpoa} \tag{7}$$

The total load output was calculated from the combined light, E_{Light}, and socket, E_{Socket}, consumption.

Capacity shortage, C_S, as a percentage, can be found by determining the theoretical load demand, E_D, and the actual delivered loud output, E_{Load} [47]:

$$C_S = \frac{E_D \quad E_{Load}}{E_D} \tag{8}$$

The battery State of Charge (SoC) at time t is the ratio of the battery energy level to the nominal battery capacity, and can be estimated from Ref. [48]:

$$SoC_t = SoC_{t \quad 1} + \frac{B_{cp_t}}{B_{cap}} \quad \frac{B_{dp_t}}{B_{cap}} \tag{9}$$

where B_{cp} is the battery charge power, B_{dp} is the battery discharge power and B_{Cap} is the battery capacity. The maximum state of charge, SoC_{max}, is subject to:

$$SoC_{max} \quad SoC_t \quad SoC_{min} \tag{10}$$

The minimum state of charge, SoC_{min}, was taken as 20%. The initial and maximum state of charge was assumed to be 100%, with the total energy capacity being 3.072 kWh in Rwanda and 1.954 kWh in Nepal. The battery efficiency, η_{bat}, can be found from $\eta_{bat} = B_{dp}/B_{cp}$. A battery charge efficiency and self-discharge rate was not considered.

3. Results

The in-situ performance of the two streetlight interventions in Rwanda and Nepal is compared with the anticipated design performance. The differences in system performance indices are evaluated and the main problems encountered are outlined. The cause and effect of these problems are explored, along with the possible solutions to reduce the design to in-situ performance gap. A number of remedial actions are suggested in addition to the pattern of socket usage that would then be required to maximise the solar streetlight systems' utilisation and performance. The two case studies are then summarised in response to this paper's research question.

3.1. Rwanda streetlight performance

The designed solar streetlight (SLD) and SL1 typical day performance from July 2019 to March 2020 in Rwanda is shown in Fig. 12a and b. Typical day plots for SL2–4 are provided as supplementary material in Appendix A. Fig. 12b shows that at SL1 the in-situ SoC was as low as 40% on average at 6 a.m., whereas the equivalent SoC was designed to be above 60%. The designed socket usage reduced the capture losses by around 40%; however, the actual socket usage was negligible. The battery discharge power typically reached 100 W at 7 p.m., which was well above the designed 70 W.

The monthly daily average socket and light output, capture losses, BoS losses and capacity shortages are shown in kWh/day for each streetlight in Fig. 13. Only a small increase in socket usage was observed over the analysis period (0.002–0.013 kWh/day per streetlight on average in July 2019 and March 2020 respectively). The designed socket usage was 0.3 kWh/day. Capacity shortages increased from October 2019 onwards as irradiance levels fell below 1.5 kWh/day.

The designed performance ratio ranged from 53 to 72% (see Fig. 14a). The monthly average in-situ performance ratio for SL1-4 was significantly lower ranging from 32% in September 2019 to 47% in January 2020, which was due to higher than designed capture losses. The in-situ capture losses ranged from 1.41 to 1.97 h/d, whereas the designed capture loss was 1.28 h/d. The increase in capture loss was a result of low socket loads, reduced array power output and slightly higher levels of irradiance on the PV panels. As the load output remained relatively constant over the analysis period, the monthly changes in PR and PF were due to the lower potential energy available between October 2019 and March 2020. The performance indices for the designed streetlight (SLD) and each installed solar streetlight are summarised in Table 5.

The in-situ production factors were in-line with the designed

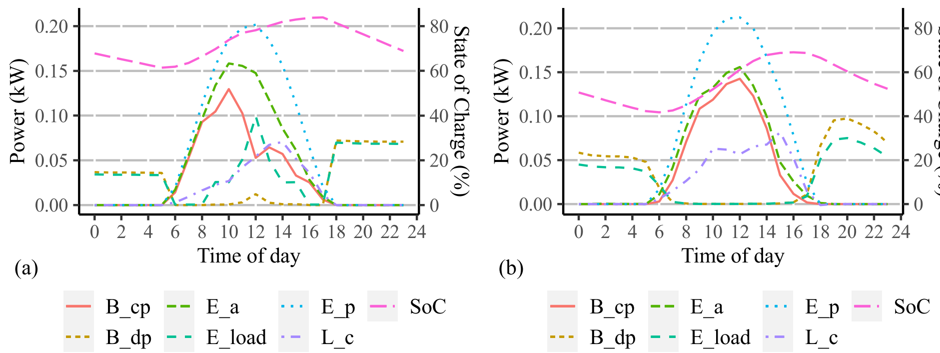

Fig. 12a–b. Design (a) and SL1 in-situ (b) typical day performance profiles for the solar streetlights in Rwanda, showing hourly averages for the battery charge power (B_cp), net energy from PV array (E_a), Potential PV power output (E_p), battery State of Charge (SoC), battery discharge power (B_dp), total load output (E_load) and capture losses (L_c).

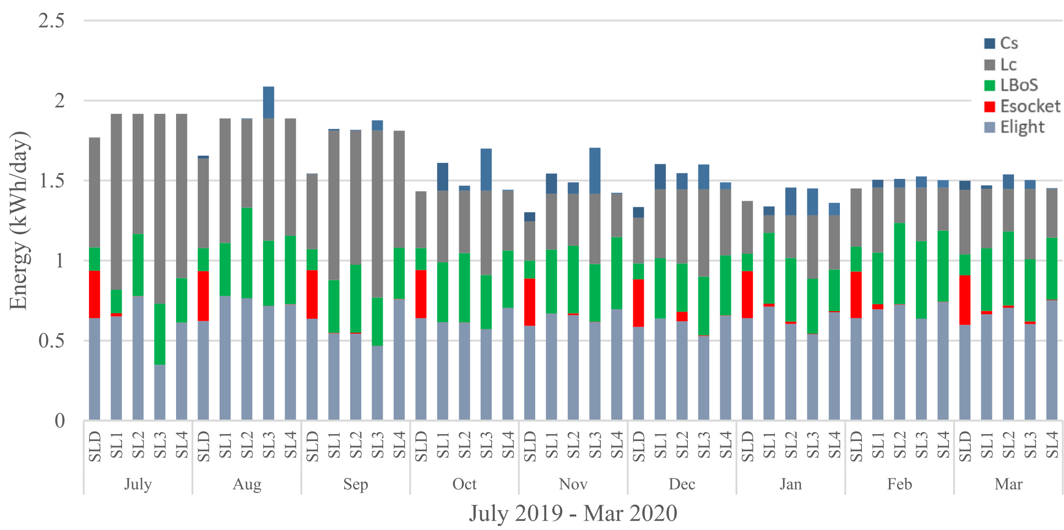

Fig. 13. Monthly daily average capacity shortage (Cs), capture loss (Lc), balance of system loss (LBoS), socket load (Esocket) and light load (Elight) in kWh/day for the designed solar streetlight (SLD) and SL1, 2, 3 and 4 in Rwanda.

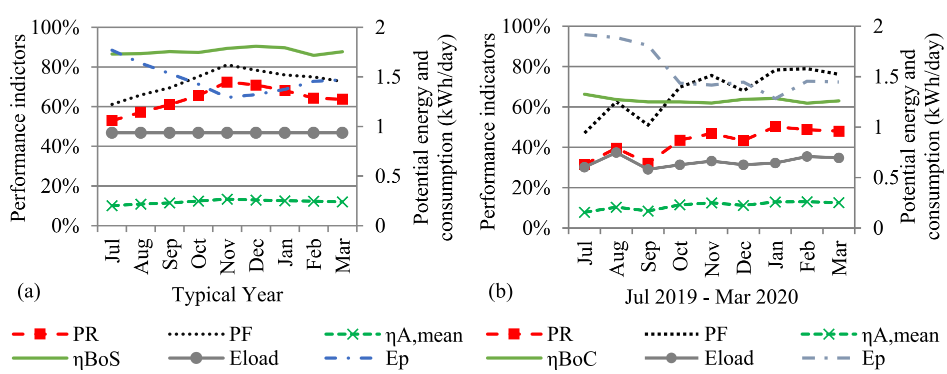

Fig. 14a–b. Monthly performance indicators (performance ratio, PR, production factor, PF, balance of system efficiency, ηBoS, and mean array efficiency, ηA,mean) for the designed solar streetlight (a) and monthly averages for the four installed solar streetlights in Rwanda (b). The potential PV power (Ep) and total load output (Ep) are shown on the secondary axis.

system at around 70%. However, PRs were significantly lower, due to high BoS losses. The BoS efficiency was around 63% for the four streetlights, whereas the designed BoS efficiency was 88%. This performance gap is attributed to a lower than designed inverter efficiency, additional converter losses, and unaccounted for electrical losses and LED driver inefficiencies. The higher than designed BoS losses resulted in an increase in capacity shortages, which resulted in frequent power outages. The capacity shortage at SL2 and SL4 was 9% and 3%, respectively. The average C_S was higher at SL1 (9%) and SL3 (20%) and peaked at 32% at SL3 in November

Table 5
Performance indices for the analysis period July 2019–March 2020 in Rwanda.

Parameter	Units	SLD	SL1	SL2	SL3	SL4
Irradiance on PV panels (Gpoa)	($kWh/m^2/d$)	4.61	4.90	4.90	4.90	4.90
Potential PV power output (E_p)	(kWh/d)	1.48	1.57	1.57	1.57	1.57
Net energy from PV array (E_A)	(kWh/d)	1.07	1.02	1.11	0.94	1.07
Total load output (E_{load})	(kWh/d)	0.94	0.67	0.68	0.56	0.70
Final yield (Y_f)	(h/d)	2.93	2.11	2.13	1.76	2.20
Reference yield (Y_r)	(h/d)	4.61	4.90	4.90	4.90	4.90
Array yield (Y_A)	(h/d)	3.33	3.19	3.48	2.93	3.35
BoS losses (L_{BoS})	(h/d)	0.40	1.08	1.36	1.17	1.15
Capture losses (L_C)	(h/d)	1.28	1.71	1.41	1.97	1.55
Performance ratio (PR)	(%)	64.02%	43.89%	44.07%	36.79%	45.86%
Production factor (PF)	(%)	72.75%	66.93%	72.12%	61.17%	69.75%
Capacity shortage (C_S)	(%)	2.37%	8.96%	8.00%	20.02%	2.84%
Solar charger efficiency (ηsc)	(%)	95.00%	95.77%	97.41%	96.00%	93.34%
Average SoC	(%)	72.53%	55.00%	51.93%	45.71%	63.48%
BoS efficiency (ηBoS)	(%)	87.93%	66.39%	61.16%	59.67%	66.00%
Mean array efficiency (ηA,mean)	(%)	12.00%	11.04%	11.89%	10.09%	11.50%

2019. The designed and in-situ PV array outputs were comparable; however, the in-situ potential PV was 0.11 kWh/day higher than expected based on Typical Meteorological Year (TMY) data. This was due to favourable weather conditions in July, August and September 2019. A high capture loss at SL3 resulted in the lowest mean array efficiency of 10.1%. The main problems that increased the design to in-situ performance gap at the solar streetlights in Rwanda are summarised in Table 6, along with potential solutions to reduce the gap.

With these solutions implemented, and based on the actual socket usage (see Fig. 15a) and updated component parameters (83.5% derating, 95% lithium iron phosphate battery, 87% inverter

Table 6
A cause and effect table of the main problems encountered at the solar streetlights in Rwanda.

Problem	Cause	Effect	Evidence	Solution
Higher than anticipated light load - sometimes in excess of 100 W (including additional inverter losses) for a 60 W light	LED driver efficiency of around 80%. Additional inverter for light with an efficiency of approx. 85%	Increase in capacity shortages (from 2.4% to 20%) resulting in frequent power outages.	Battery data	New non-dimmable LED and driver to avoid driver and inverter losses, reducing control of light.
System-component voltage mismatch	Lack of local supplier knowledge and familiarity with imported components. Limited local component availability and/or long lead times beyond project delivery schedule	Additional DC-DC converter required for socket inverter. LED driver DC voltage mismatch with load output on solar charger requiring additional DC-AC inverter. Frequent maintenance to restart systems due to voltage spikes.	Field observations, maintenance reports and system data	System rewiring and change to 24 V inverter for sockets. Change from AC to DC LED light.
Faulty SoC readings and over discharged batteries.	Battery monitors and charge controllers not configured correctly	Damaged batteries and delay in fault detection and miscommunication to community on health of system	Battery data	Replacement of batteries and system reconfiguration
Socket usage was 90% lower than designed	Community was concerned with leaving devices at socket boxes due to water ingress and potential theft, leading to 0.29 kWh/day less usage than predicted use on average over the 4 lights, during the analysis period	Increase in surplus energy available during sunny periods, which reduced the system's performance ratio.	Field reports and socket inverter data	Improve ingress protection of socket boxes. Connect with phone kiosks. Improve reliability of systems and community communication.

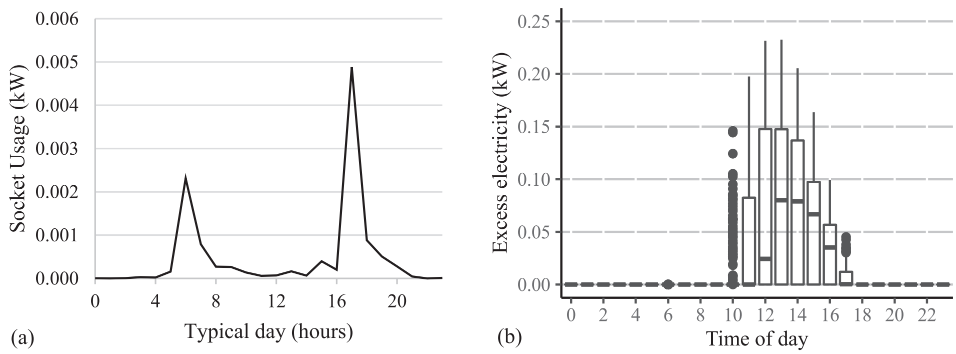

Fig. 15a–b. The average hourly streetlight socket usage in Rwanda (a) and the additional energy that could be utilised from the sockets, after remedial actions taken to improve system performance (b).

and 95.6% charge controller efficiency and a panel tilt angle of 18), Fig. 15b shows how much electricity could still be provided from the sockets for a typical meteorological year.

3.2. Nepal streetlight performance

The typical day plot for SL1 in Nepal shows that a high average SoC of 90% occurred due to lower than designed light and socket load outputs (see Fig. 16a and b). A similar trend was observed at all streetlights in Nepal (see Appendix A). Community engagement events to encourage socket usage had a negligible impact on changes in energy consumption at the sockets. There were significant issues with the lights at SL2 and SL7: SL2 was always dimmed and SL7 turned off at midnight. Despite numerous attempts to fix the LED lights, the load output was not increased over the analysis period. Furthermore, SL2 had an alignment error of around 37 , which was either due to installation error or movement during high winds. SL2 and SL7 are, therefore, not analysed further. The monthly daily averages for the designed and in-situ energy consumption and losses for SL1, 3, 4 and 6 in Nepal are shown in Fig. 17. The designed and in-situ average monthly performance ratios and production factors for the Nepal streetlights are shown in Fig. 18. The performance indices for each streetlight are summarised in Table 7.

Low load outputs were recorded at all the streetlights, which significantly increased the design-insitu performance gap. The total load was less than half of the design value at all the streetlights due to low socket usage and poor LED reliability: the LED light was designed to use around 0.6 kWh/day, whereas on average each streetlight LED was using only 0.24 kWh/day. The designed socket usage was 0.3 kWh/day and, on average, the actual socket usage was only 0.02 kWh/day. Subsequently, the average PR and PF over all streetlights was low ranging from 27.9 to 33% and 38.4–53.4%, respectively. The performance ratio could have been even lower, as the potential PV power output was not as high as expected (around 4.44 kWh m^{2}/day instead of 5.57 kWh m^{2}/day). This was due to low irradiance levels on the array (particularly in Sep 2019, Jan 2020 and Feb 2020) and panel azimuth south misalignments at SL3. Despite the reduced irradiance levels, no capacity shortages occurred because of the low load outputs. The designed capacity shortage for the monitoring period was 3.8% and the designed PR and PF were 55% and 65%; the monsoon season in Nepal makes it harder to have a better designed PF without further increases in capacity shortages. The main problems experienced in Nepal and the potential solutions are summarised in Table 8.

Assuming the proposed solutions were implemented, and based on the actual socket usage (see Fig. 19a) and updated component parameters (70% derating, 90% li-ion battery, 87% inverter and 97.5% charge controller efficiency and a panel orientation of 346 west of south with a tilt angle of 27), Fig. 19b highlights how much electricity could still be provided from the sockets during a typical

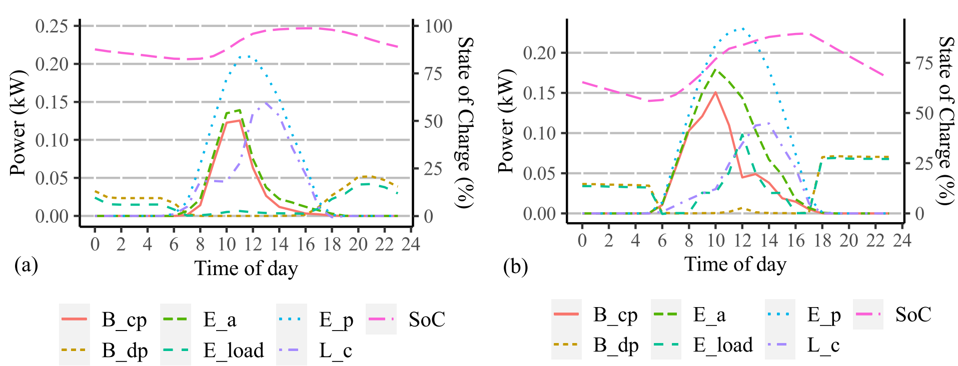

Fig. 16a–b. Design (a) and SL1 in-situ (b) typical day performance profiles for the solar streetlights in Nepal, showing hourly averages for the battery charge power (B_cp), net energy from PV array (E_a), Potential PV power output (E_p), battery State of Charge (SoC), battery discharge power (B_dp), total load output (E_load) and capture losses (L_c).

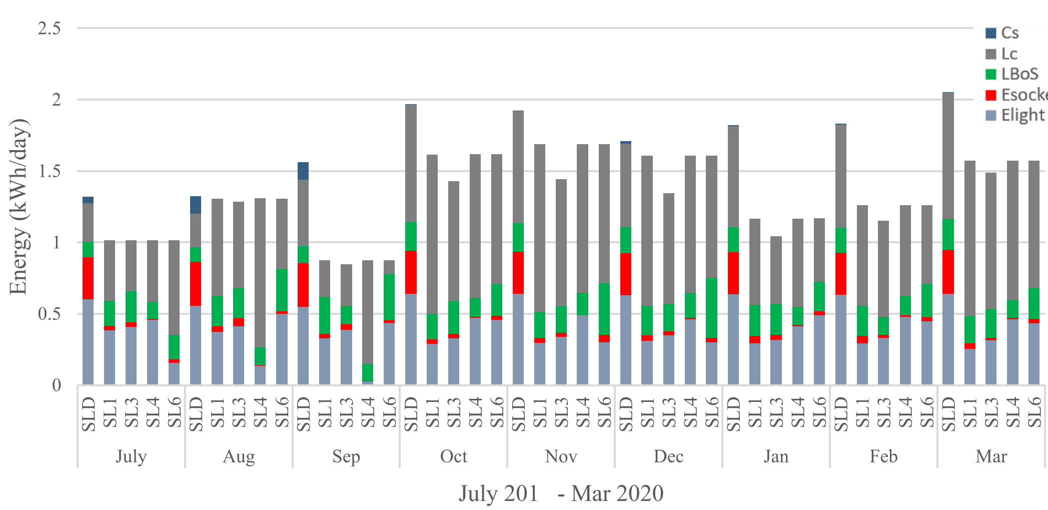

Fig. 17. Monthly daily average capacity shortage (Cs), capture loss (Lc), balance of system loss (LBoS), socket load (Esocket) and light load (Elight) in kWh/day for the designed solar streetlight (SLD) and SL1, 3, 4 and 6 in Nepal.

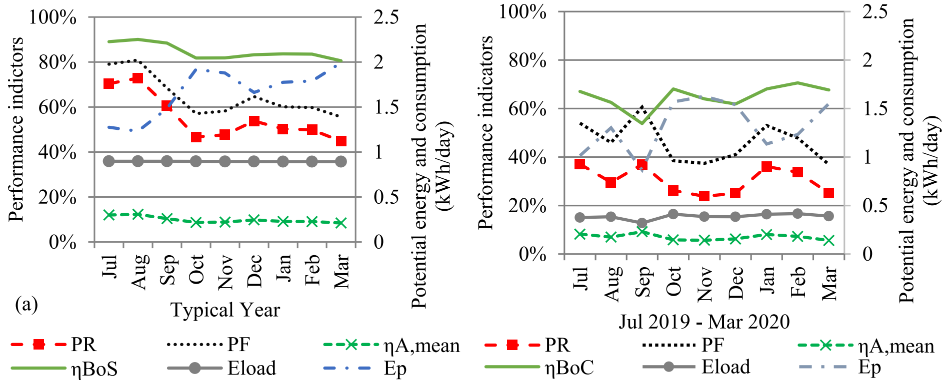

Fig. 18a–b. Monthly performance indicators (performance ratio, PR, production factor, PF, balance of system efficiency, ηBoS, and mean array efficiency, ηA,mean) for the designed solar streetlight (a) and monthly averages among SL1, 3, 4 and 6 (b). The potential PV power (Ep) and total load output (Ep) are shown on the secondary axis.

Table 7
Performance indices for the analysis period July 2019–March 2020 in Nepal.

Parameter	Units	SLD	SL1	SL3	SL4	SL6
Irradiance on PV panels (Gpoa)	($kWh/m^2/d$)	5.57	4.50	4.10	4.50	4.50
Potential PV power output (E_p)	(kWh/d)	1.67	1.35	1.23	1.35	1.345
Net energy from PV array (E_A)	(kWh/d)	1.06	0.56	0.58	0.52	0.69
Total load output (Eload)	(kWh/d)	0.89	0.35	0.39	0.38	0.42
Final yield (Y_f)	(h/d)	2.98	1.18	1.29	1.28	1.40
Reference yield (Y_r)	(h/d)	5.56	4.48	4.08	4.48	4.48
Array yield (Y_A)	(h/d)	3.53	1.86	1.92	1.73	2.31
BoS losses (L_{BoS})	(h/d)	0.55	0.68	0.63	0.45	0.90
Capture losses (L_C)	(h/d)	2.03	2.62	2.17	2.75	2.18
Performance ratio (PR)	(%)	55.2%	27.9%	33.0%	28.1%	32.6%
Production factor (PF)	(%)	64.9%	44.1%	48.6%	38.4%	53.4%
Capacity shortage (C_S)	(%)	3.8%	0.0%	0.0%	0.0%	0.0%
Solar charger efficiency (ηsc)	(%)	95.0%	97.9%	97.9%	97.0%	97.3%
Average SoC	(%)	73.2%	90.6%	91.9%	91.2%	89.5%
BoS efficiency (ηBoS)	(%)	84.7%	63.3%	67.5%	68.2%	60.4%
Mean array efficiency (ηA,mean)	(%)	9.86%	6.70%	7.39%	5.84%	8.11%

meteorological year.

Table 8
A cause and effect table of the main problems encountered at the solar streetlights in Nepal.

Problem	Cause	Effect	Evidence	Solution
LED lights too dim or not turning on/off when intended.	Unreliable custom LED light/driver	Low light load resulted in poor performance ratios and production factors (30–55%)	Solar charger data and field reports	Replace LED/driver
Poor reliability (increased capacity shortages) if LED solution was implemented	Panel misalignment, dirt and shade; mismatching battery	Low array and BoS efficiencies	System data	Replace battery, adjust panel mounting structure and schedule regular cleaning.
Components damaged during extreme weather	High winds, rain and lighting	Damaged WiFi amplifiers and flooded systems	Field reports	Improve resilience of system to heavy rain and lightning strikes.
In-situ socket usage was 10 times lower than designed. Community's desire for surplus energy access at sockets was not realised in practice.	Damaged socket connections. Low demand due to households having sub-metered grid access. Community fearful of using sockets and damaging system.	Usage limited to mobile phone charging (mostly teens/young adults) and nearby in-home lighting. Increase in surplus energy available during sunny periods, which reduces the system's performance ratio.	Field and maintenance reports	More robust socket connections. Additional on-site energy demand assessments prior to system design.
Faulty inverters	Unreliable component. Overloaded inverters. Lack of circuit protection.	Needed frequent restarts and replacement. Sockets not working.	Field and maintenance reports	Replace with higher quality inverters and add additional circuit breakers.
Water in battery and socket boxes	No Ingress Protection (IP) standard used for weather proofing.	Community wary of using sockets. Damaged components.	Field and maintenance reports	Improve ingress protection of battery and socket boxes.
Excessive installation time that took many months	Lack of knowledge and skill with using imported components.	Delay to project delivery.	Communication difficulties between project team, contractors and community.	Additional planning on-the-ground support
No mobile network coverage, and unreliable WiFi.	Remote location	Difficulties in remote control and monitoring for early identification of faults and maintenance requirements. Loss of data.	System data	Establishing local data collection and handling procedure before installation

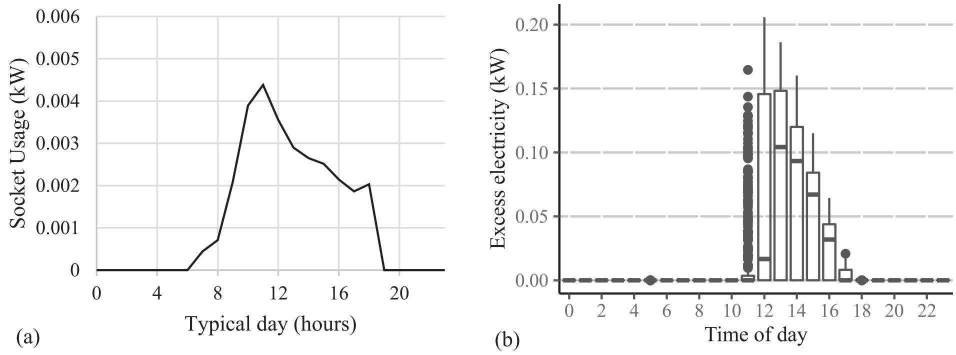

Fig. 19a–b. The average hourly streetlight socket usage in Nepal (a) and the additional energy that could be utilised from the sockets, after remedial actions taken to improve system performance (b).

4. Discussion

There was a significant gap between the designed and in-situ solar streetlight performance in both Nepal and Rwanda. The main causes for the gap were:

issues with LED driver and lights
low socket usage
lower than designed component efficiencies
limited availability of parts at local markets
mismatching and low-quality components
lack of supplier experience with non-standard systems and components
limited access for maintenance and cleaning

The installed LED light components were a major cause for the performance gap in both countries. Whilst both the Rwanda and Nepal streetlight systems suffered from lower than designed performance ratios, the reasons for a reduced PR were different. In Rwanda, the solar resource was overused due to component inefficiencies, which led to an increase in capacity shortages. In Nepal, the low PR was due to low utilisation of the solar resource. In both countries, the quality of the socket boxes was below the required standard with no appropriate ingress protection. This reduced communities' access and willingness to use the sockets.

Locally sourcing appropriate DC lights within the project timeframe, was difficult in both countries. In Rwanda, the poles had to be imported from Uganda, which caused significant delays in deployment. Importing parts and customs checks also caused delays in Nepal. An interesting observation was that the poor performance of the systems was not due to tampering, damage or component theft, which is often cited as a major problem for humanitarian PV system interventions. Significant on-the-ground effort went into community engagement events and the co-design process, which may have mitigated this risk. Designing a system that the suppliers were not experienced with led to problems in both countries and the design assumptions made did not take into account unreliable components or the installation of inappropriate parts, such as mismatching AC/DC drivers and inverter voltage ratings.

Lithium-ion batteries were chosen for the streetlights with the intent of reducing weight, maintenance and replacement requirements. The implementation reality was that importing li-ion batteries was significantly more expensive than anticipated and failure rates were high due to misuse within the first year of operation (2 out of 8 in Rwanda and 4 out of 14 in Nepal). Lead-acid battery types, such as AGM, GEL or EFB, could have been used instead. Lead-acid batteries would have been cheaper, more readily available and potentially more durable, as market established products could have been sourced. However, in Rwanda, to achieve the same reliability, in terms of capacity shortage, as the installed LiFePO4 batteries, a lead-acid battery of at least 4 kWh (see Table 2) would have been required, which would have resulted in an excessively large and heavy battery box for a streetlight pole. A cheap and reliable solution would be required (e.g. securing batteries below ground or within nearby buildings) before such a system could be more widely deployed.

Access to refugee camps and temporary settlements camps is carefully monitored by local government agencies. This caused a number of difficulties and delays during and post deployment. In Rwanda, camp access was limited to specific people and times, and access had to be reapplied for every month. Approval often took several days or weeks to be granted. In Nepal, road access was limited due to frequent landslides. Space in the vicinity of the solar streetlights was also limited at both sites. Cleaning of the solar streetlights was problematic at both sites, due to the height and location of the installations, and no cleaning was performed during the analysis period, which will have reduced the array efficiencies.

In Rwanda, the streetlights were spread over a wide area, so a centralized lighting system was impractical; however, this was a possibility for the settlement in Nepal. As demand never exceeded the socket's rated capacity, additional community support and improved access arrangements would have been needed if a centralized lighting system, with a single larger inverter, had been deployed to enable the community to use higher-power appliances. Before interventions of this type are made, a robust investigation is recommended to ascertain the real energy demands that would be placed on an open-access communal resource (e.g. by installing a simple battery-socket inverter device to monitor in-situ energy usage, prior to intervention design and deployment). Whilst socket usage was low, field reports indicated that the usage of sockets was particularly important to youths, as it enabled them to charge their phones, save money and stay socially connected.

Robust data handling and analysis is crucial to gain meaningful insights into the performance of PV systems. This is especially true for instances of power outages that cannot be represented in the dataset. The analysis performed in this paper assessed the behaviour of data as well as the nature of missing data to perform suitable imputation prior to analysis. Considering the lack of standard imputation techniques for PV data, a light-weight time series-based imputation technique was used. The data imputation and battery modelling allowed for the calculation of capacity shortages occurring when demand exceeded battery capacity, which needs be considered in the assessment of standalone PV-battery systems. However, other outages due to component failures and planned events, such as maintenance, were not considered. This would have required an independent power source for monitors and more detailed maintenance logs. Further research is required to develop a suite of imputation techniques suitable for PV data. In the future, we intend to compare performance of a Seasonal Decomposition approach with other imputation techniques such as Multiple Imputation Chained Equations, Kalman filtering, Random Forests, Neural Networks and Auto Regressive Moving Average (ARMA) based models.

Maintaining good performance is a challenge for all PV-battery systems, e.g. due to battery and PV degradation. This can be partially addressed through intelligent control of the solar charger and AC/DC loads (to maintain a healthy SoC) and better monitoring for early fault detection. However, this increases system complexity, the need for reliable remote communications, the risk of component failures, requirements for parts that might be difficult to locally source, and the difficulty of finding locally skilled and experienced technicians. In displaced settlements, reliability and good performance can be more important than cost-efficiency, and a balanced approach is needed for using advanced modern components and market-established products and systems within host communities.

5. Conclusion

This paper examined the design-insitu performance gap of solar streetlight interventions in two displaced settlements. The performance gaps were significance and the main causes for them were:

- Consumer demand of a co-conceived system was significantly lower than predicted
- Component efficiencies were lower than assumed at the design stage
- Mismatching system components were used by suppliers due to the availability of parts and limited experience with non-standard energy system requirements and design
- Community and maintenance logs were inadequate for fault diagnosis and missing data interpretation
- Restricted access and unreliable mobile network and local wireless communications delayed essential maintenance

In addition to standalone photovoltaic-battery systems, these findings are applicable for other off-grid energy systems built in similar contexts. The recommendations arising from this research, which will inform future research and humanitarian energy access interventions, are:

- Plan and mitigate for site access limitations, site population instability, limited availability of parts and skilled labourers, lengthy deployment times and unreliable components and remote communications.
- Ascertain real energy demands prior to system intervention and wider deployment
- Make appropriate trade-offs at the design stage, so desired functionality is balanced against the implementation challenges and opportunities
- Develop robust data monitoring, handling and analysis approaches to take into account scheduled and unscheduled downtimes, which are likely to be numerous and challenging to track over a long analysis period.

Data availability

Datasets related to this article can be found at http://doi.org/10.5281/zenodo.3947993, an open-source online data repository hosted at Zenodo [42].

CRediT authorship contribution statement

J.D. Nixon: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration, Supervision. **K. Bhargava:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. **A. Halford:** Writing – review & editing, Visualization, Project administration. **E. Gaura:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Project administration, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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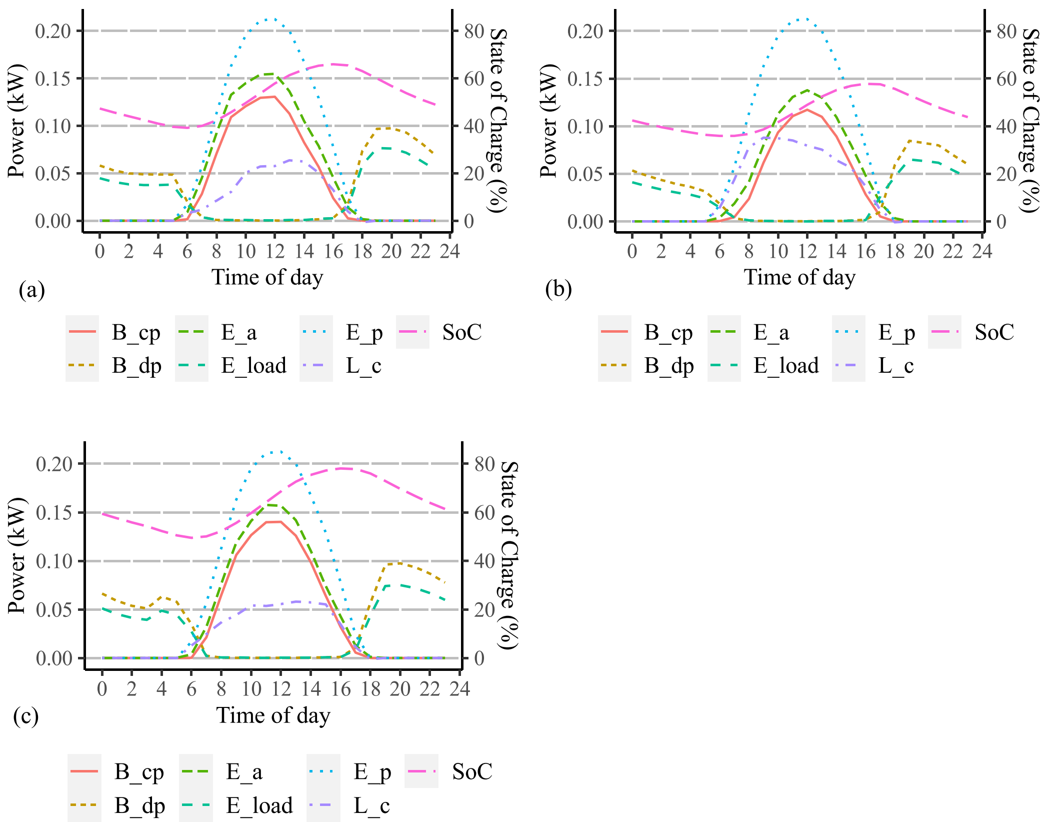
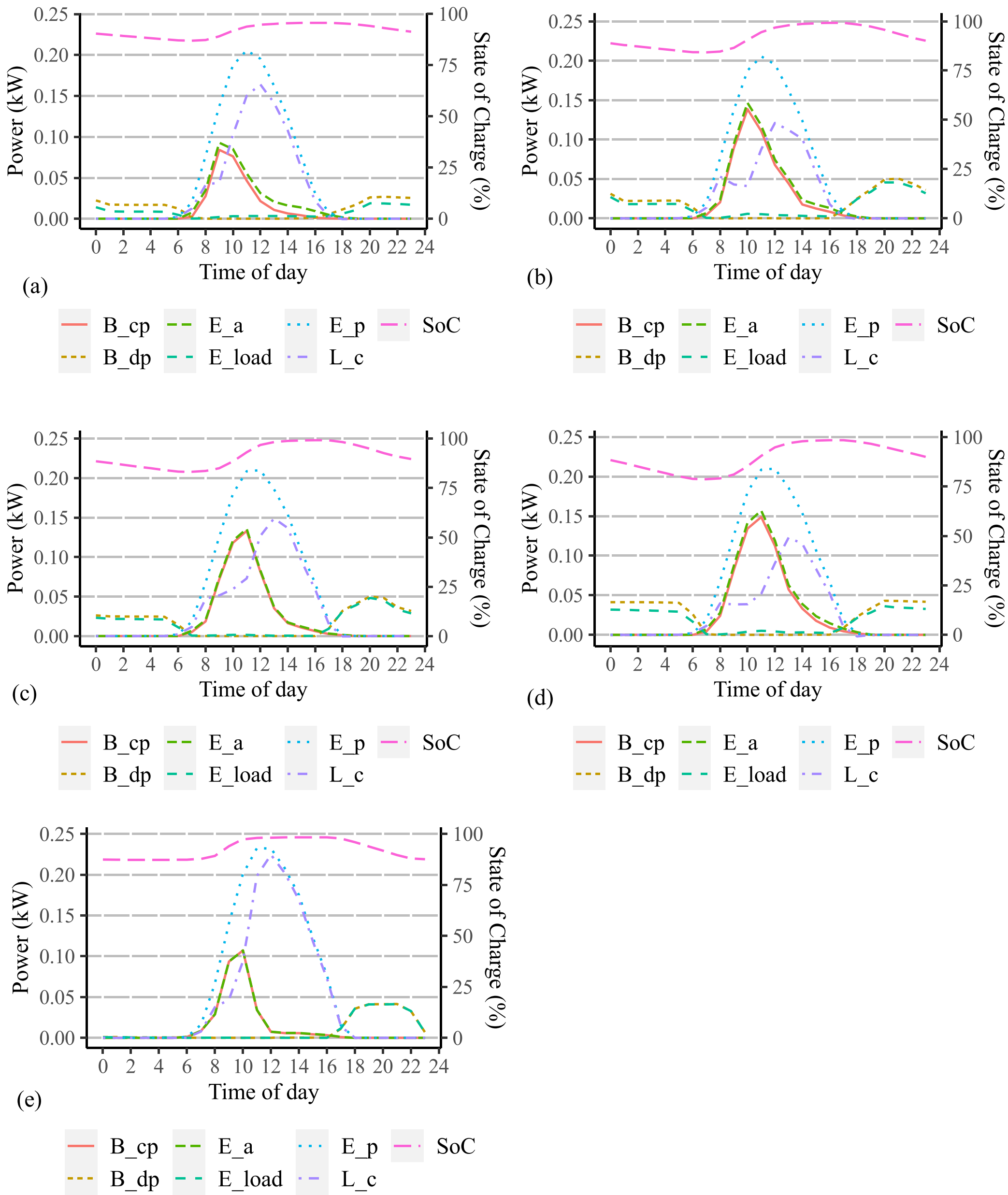
Appendix A

Typical day performance for SL2 (a) SL3 (b) and SL4 (c) in Rwanda from July 2019 to March 2020.


Power (kW)
State of Charge (%)
Time of day
(a)
(b)
(c)
B_cp
B_dp
E_a
E_load
E_p
L_c
SoC

Typical day performance for SL2 (a) SL3 (b) SL4 (c) SL6 (d) SL7 (e) in Nepal from July 2019 to March 2020.



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