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The challenges of community-based solar energy interventions: Lessons from two Rwandan Refugee Camps

J.D. Nixon *, K. Bhargava, A. Halford, E. Gaura

Coventry University, Faculty of Engineering, Environment and Computing, Coventry CV1 2JH, UK

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ABSTRACT

The paper presents evidence from the performance assessment of two solar energy interventions. Specifically, an evidence base was built around two community co-conceived standalone photovoltaic-battery systems, which were deployed in two refugee camps in Rwanda. We found that for both installations (a micro-grid and a community hall electrification system) energy consumption levels were low, showing that sizeable energy consumption gaps can still develop when co-conceived interventions are deployed. The consumption gap led to low performance ratios (33% and 25% respectively for the micro-grid and community hall system). To guide further work and improve the sustainability of community interventions, we draw a number of design principles for future energy interventions in similar contexts. To deliver sustainable energy transitions for refugees, there needs to be a move towards co-creating community interventions that promote self-governance to position communities as users, maintainers and suppliers of energy services, throughout an intervention's lifetime.

Introduction

An estimated 97% of displaced populations in camps had no access or limited access to electricity in 2019 (UNHCR, 2019). When refugee camps are formed in response to a crisis, the immediate issues to be addressed are food, sanitation and shelter; energy is not forethought by planners and, as a result, infrastructure is usually non-existent or poorly implemented. Even though many refugee camps end up operating for several decades – with the average camp age of approximately 18 years (Grafham & Lhan, 2018) – rather than introduce long-term infrastructures, short-term approaches to energy interventions have been the prevalent model in humanitarian energy planning (Tran, Seng To, & Bisaga, 2020). As more permanent energy systems are typically considered long-term investments, these infrastructures are considered unsuitable for humanitarian funding cycles that prioritise emergency aid needs and are hampered by inconsistent funding (Bellanca, 2014). In addition, in the absence of private-sector funding of clean energy infrastructures, displaced settings are framed as precarious, temporary settlements and are thus perceived as high-risk ventures (Alonso & Sandwell, 2020). Similarly, in planning and implementing energy, humanitarian agencies have not necessarily had the requisite expertise or knowledge to evaluate or negotiate complex technically and financially solutions (Shell & Economics, 2020). This, and other socio-political reasons, such as refugees' rights to work, have led to the widespread prevalence of energy poverty among displaced populations (Grafham, 2019).

Improving access to electricity in camps can enable the provision of critical services (food preservation, medical facilities, lighting for security and safety, water pumping and emergency communications) and other essentials, such as power for mobile phone charging, entertainment and educational equipment. However, refugee camps are often situated in rural areas (UNHCR, 2012) where a grid connection is not feasible due to high investment costs and transmission losses (Zia, Elbouchikhi, & Benbouzid, 2018). Even when camps are near national grids, host governments are often reluctant to provide refugees with services that could imply permanence or be negatively perceived by local host communities (Lahn, 2019). Where refugee camps do have electricity provision, it tends to come from costly and inefficiently operated diesel generators (Grafham & Lhan, 2018). The United Nations High Commissioner for Refugees (UNHCR) and humanitarian organisations are, therefore, encouraging the provision of clean and affordable energy to refugee camps, with a particular focus on micro-grids and other standalone solutions that use solar power (UNHCR, 2019).

As photovoltaic systems have become more affordable, decentralized renewable off-grids are viable and sustainable solutions to meeting displaced people's energy needs (Alonso & Sandwell, 2020). However, despite the potential of standalone PV systems to cost-effectively provide small-scale energy access solutions, solar energy interventions in refugee camps have often been unsuccessful (Fuentes, Vivar, Hosein, Aguilera, & Muñoz-Cerón, 2018; Grafham,

* Corresponding author.
E-mail address: jonathan.nixon@coventry.ac.uk (J.D. Nixon).

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2019). There is a lack of data on the energy access situation in displaced settings (UNHCR, 2019) and the majority of refugees do not have access to electricity. Refugees do not own many electrical appliances (although this may change if electrical services were more readily available) and energy needs could rapidly change (e.g. due to relocation schemes and forced migration). Generation-demand mismatches are a particular problem for standalone energy systems: storage is often limited and, unlike with grid-connected systems, surplus energy cannot be exported. The safety, maintenance and end-of-life management of solar facilities and PV micro-grid infrastructures are also not without contestation in the displaced setting. Energy interventions are vulnerable to disrepair and disuse due to non-optimal usage patterns, degradation, informal modifications, and systems not being fit for purpose (Nixon & Gaura, 2019). There are difficulties accessing sufficient locally available parts and funds for repairs, and technical expertise, skills and knowledge to maintain systems (Lahn & Grafham, 2015). Furthermore, issues around liability and governance impact the longevity of energy systems in the displaced setting, such as a duty of care for the systems, identifying stakeholders and feasibility of multi-tiered ownership, also needs to be resolved before deploying interventions (Demir, 2020).

Off-grid solar system performance

Due to the preponderance of grid-connected PV in developed countries, the majority of research on performance has focused on such systems; they typically achieve excellent performance ratios (PR) of around 80–90% (Milosavljević, Pavlović, & Piršl, 2015). The PR provides an indication of a system's utilisation (i.e. measured AC load output) in comparison to its rated potential output. Fewer works cover off-grid installations and, generally, when such research is reported, it shows lower in-use performance ratios. For example, PRs of 60–70% have been reported over a 2-year period at a 20 kW peak (kWp) PV system on an island in Hong Kong (Ma, Yang, & Lu, 2017) and ranged from 54 to 79% between June and November at a stand-alone 10 kWp PV-battery system powering an isolated building in Thailand (Sasitharanuwat, Rakwichian, Ketjoy, & Yammen, 2007). Low monthly performance ratios at both systems were attributed to the generation-demand mismatch rather than technical problems, such as inefficiencies or reliability issues. In refugee camps, large solar systems have only recently become available, including the first photovoltaic (PV) micro-grid supplying a refugee camp in 2017, a 5 MW system deployed in Jordan's Azraq camp. This PV micro-grid was soon followed by a larger 12.9 MW PV power plant located at Jordan's Za'atari refugee camp (Hashem, 2019); as of yet, to the authors' knowledge, there is no published performance or energy usage data for these systems.

Humanitarian energy system design

Humanitarian energy interventions have traditionally followed a top-down design model, as – during a displacement crisis – arguably there is little time to consult with communities. In addition, humanitarian agencies have adopted a ‘procure and provide’ model for energy equipment distribution with little or no conscious assessment of energy preferences and aspirations of displaced persons (Grafham & Lhan, 2018). In an effort to make energy access interventions more sustainable in protracted contexts, researchers have promoted bottom-up innovations with the participation of refugees, host communities, private sectors and aid agencies in planning and implementing energy interventions (Franceschi, Rothkop, & Miller, 2014). A community based approach to energy design, therefore, is increasingly seen by the UNHCR as a way of working towards UNHCR's Global Strategy for Sustainable Energy (2019–2024) and SDG7 to deliver clean and affordable energy to all (UNHCR, 2019).

Inclusive design approaches and community co-development activities can help to create self-reliance and income generation opportunities for refugees (Rosenberg-Jansen, Tunge, & Kayumba, 2019). de Groot, Mohlakoana, Knox, and Bressers (2017) suggest that community design approaches are needed to encourage marginalised and disempowered groups to engage with decision making about improved access to energy. They further assert that energy access interventions need to feature capacity building, education and finance to support growth, particularly among entrepreneurial women. Similarly, post-intervention evaluations are often missing to enable deeper learning on why some community interventions are successful whilst others fail.

Contributions to knowledge

Critical evaluations of energy access interventions – from system design to community impact – are now needed to enable valuable lessons to be learnt to inform future humanitarian energy access initiatives (Grafham & Sandwell, 2019). The lack of data on energy access in displaced settings is well documented and poses a challenge to having well designed, sustainable systems (Bisaga & Hamayun, 2019; Rosenberg-Jansen, 2019; Rosenberg-Jansen & Haselip, 2021). This research aimed to establish design principles for future community-based energy interventions by answering the following research questions:

i) What are the design, implementation and operational challenges that reduce the in-use performance of energy systems deployed in refugee camps?
ii) To what extent can community co-creation activities address these challenges?

We draw from the evidence base built around two community co-conceived standalone PV-battery systems deployed in refugee camps in Rwanda: (i) a micro-grid powering two nurseries and a playground, and (ii) a standalone solar system powering lights and sockets at a community hall. In evaluating the design and deployment of solar systems in the context of two African refugee camps, this paper provides insights into the challenges of co-creating a community-based energy intervention.

We start by describing the research methods and deployed solar systems, including the selection of community facilities through stakeholder engagement (as outlined in Method section). Then in Results section, we review the total energy demands and key system performance metrics. Following on from these findings, Discussion section discusses the challenges of conceptualising and deploying sustainable community-based energy interventions in displaced settlements to arrive at a set of design principles to guide future energy interventions in similar contexts.

Method

The methodology adopted in this research integrated well-established PV-battery system design methods (Salameh, 2014) with humanitarian energy access intervention good practice, which centres around capacity building, economic self -reliance and community engagement at all levels (Lahn & Grafham, 2015). Working with displaced communities and other local stakeholders, our approach involved three stages: i) select communal facilities for an energy intervention, ii) co-create system designs and implement, and iii) monitor and analyse system performance and utilisation.

Site and community facility selection

The research was carried out in Kigeme and Nyabiheke Rwandan refugee camps, which were selected following site visits and consultations with field experts, Ministry of Disaster Management and Refugee Affairs (MIDIMAR) camp authorities and the UNHCR.

Kigeme refugee camp is located in the Nyamagabe District, Southern Province, and is the second-largest refugee camp in

Rwanda with around 17,600 refugees (UNHCR, 2021). Nyabiheke refugee camp is located in the Gatsibo District and hosts around 15,000 refugees. Surveys carried out in 2018 from over 200 households in both Kigeme and Nyabiheke revealed that no households had a grid connection and the use of solar home systems was very limited, with the majority of households relying on mobile phones and candles for lighting (HEED, 2020a, 2020b). In response to deploying energy interventions in locations with limited robust governance structures and supporting long-term sustainability, community interest to participate in research was gauged first through field site visits. Building upon the relationships with camp leaders facilitated by delivery project partners, these visits were followed up with surveys, workshops and energy systems activities.

Whilst the surveys' comprehensive data was beneficial in understanding how, when and what kind of energy was being used in the camps, workshops were instrumental in engaging community committees in co-creating design principles of the energy interventions. The workshops offered a collaborative space that established whether there was sufficient community commitment to support the deployment and the selection of the facilities that they considered would benefit most from energy interventions. Bringing together groups that are often disempowered from the decision process around energy interventions, such as women and youths, as well as community committees, enabled discussions around how energy for different facilities could improve social cohesion and economic growth.

In Kigeme, despite the building being in a poor state of repair, with damaged equipment and smashed windows, there was a universal agreement between community leaders and residents that an energy system would be most beneficial for the camp's playground and two nursery buildings (see Fig. 1). For the community, their rationale was the lack of energy access limited their children's learning and social development opportunities. Situating a solar micro-grid for the two nurseries and playground would demonstrate the viability of common-pool resources in the displaced educational setting. Providing electricity to these buildings also offered an opportunity to establish rapprochement between participants, the project and other agencies, increasing the likelihood of greater community ownership and responsibility towards the proposed interventions.

In comparison, in Nyabiheke, Rwanda, we encountered competing agendas within the same community for ownership of research interventions as there was division over whether the site selection was to be a Church or a communal hall. The salience of faith for the community meant that the Church was regularly used, and the pastor was prepared to act as an energy gatekeeper, which could assist in maintaining communal interest. Similarly, the community hall (see Fig. 2) was managed by a committee that was actively involved in managing the space for activities.

Ultimately, the decision to select the community hall for the interventions was not reflective of a secular/religious divide but more due to the hall having a previous informal connection to a diesel generator, which they had used to power a television. Re-connecting energy to the hall re-introduced a communal space to watch programmes and host events, in a context where the provision of group leisure activities is often not at the forethought for energy interventions. In addition, the community hall committee was an elected body that enabled more democratic accountability to protect the interventions and encourage communal engagement.

Implementation

Site assessments were performed by an independent local energy supplier (e.g. to assess roof structure, roof area, shading, space for batteries, etc.) The workshops provided an opportunity for the communities to describe the type of appliances they envisaged using in the space and, based on the type of appliances that were anticipated to be used at both sites, the decision was made to fit the Micro-grid with a 2.55 kW PV array and 21.1 kWh battery bank and the Community Hall with a 2 kW PV Panel and 10.6 kWh battery bank.

Installation work was carried out at both sites from May to June 2019, with commissioning taking place in July 2019. Both systems used two strings of parallel-connected Trina PV panels, GEL batteries, a BMV-700 series battery monitor, a Victron solar charge controller and a Victron MultiPlus Inverter. The details of the PV-battery system, along with the downstream light and socket connections, are shown in Figs. 3 and 4. Each system had a Victron Venus GX, coupled with GSM antenna module, to enable system data (e.g. power generated and consumed, battery status, etc.) to be logged every minute and transmitted via a mobile network. Additionally, the supplier installed an in-house developed AC/DC Remote Monitoring Unit (RMU) along with AC socket meters and LED customer-premise equipment (CPE) to enable user loads at an individual light and appliance level to be recorded

Fig. 1. The sheltered playground and two nurseries at Kigeme Refugee Camp, Rwanda, were in the northern half of the campsite.

Fig. 2. The Community Hall at Nyabiheke refugee camp in Rwanda.

every minute. The metered loads are not reported on further in this paper (HEED, 2020a, 2020b).

In Kigeme, each nursery building had three classrooms (A, B and C) with separate entrances. Each classroom was fitted with an AC socket and five 10 W lights and an outdoor 10 W light. A spare socket was located in Classroom A. Light switches to manually control each LED light to be on/off and full/dimmed brightness were installed in each classroom. At the playground, two outdoor double sockets were installed, and fifteen 10 W

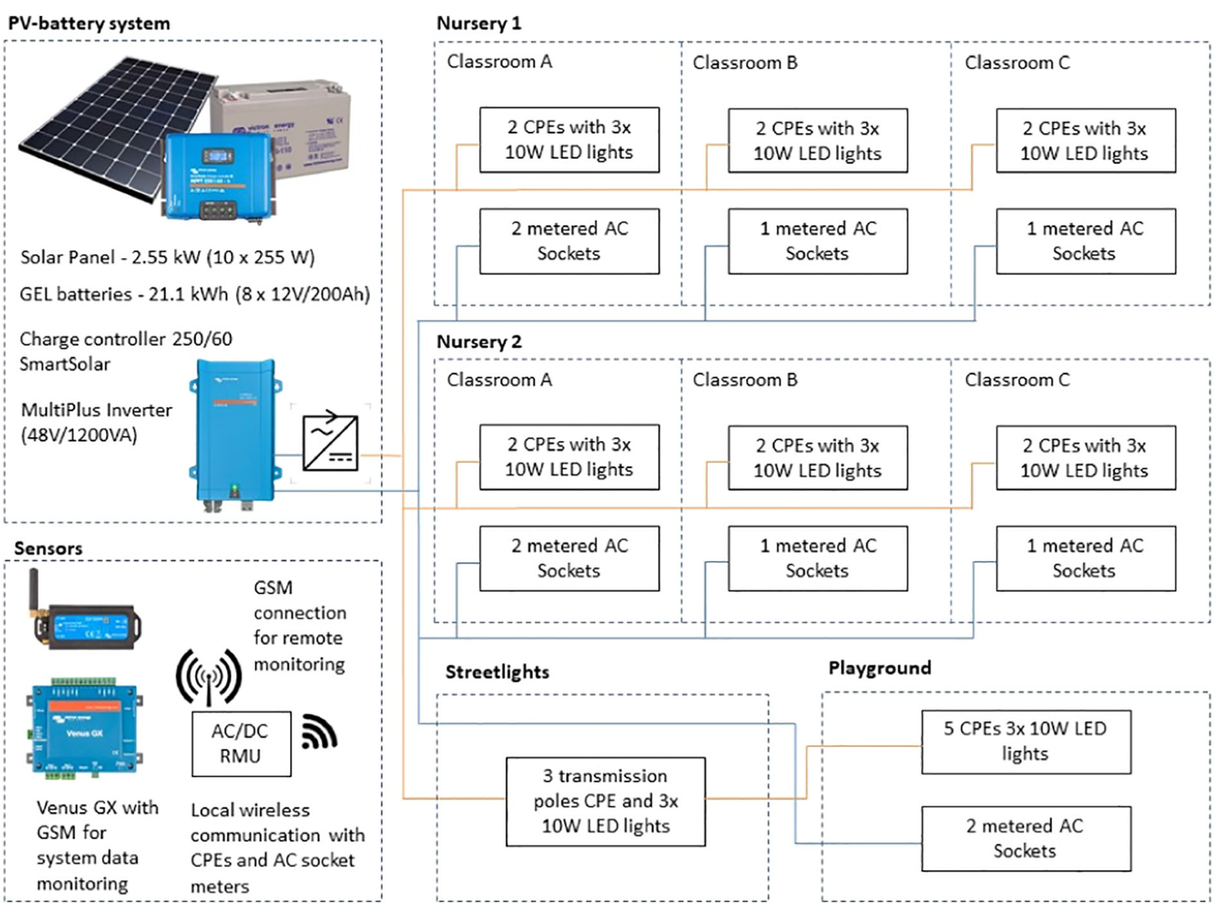

Fig. 3. Overview of the PV-battery system in Kigeme, Rwanda, powering lights and sockets for six classrooms, three streetlights and a playground.

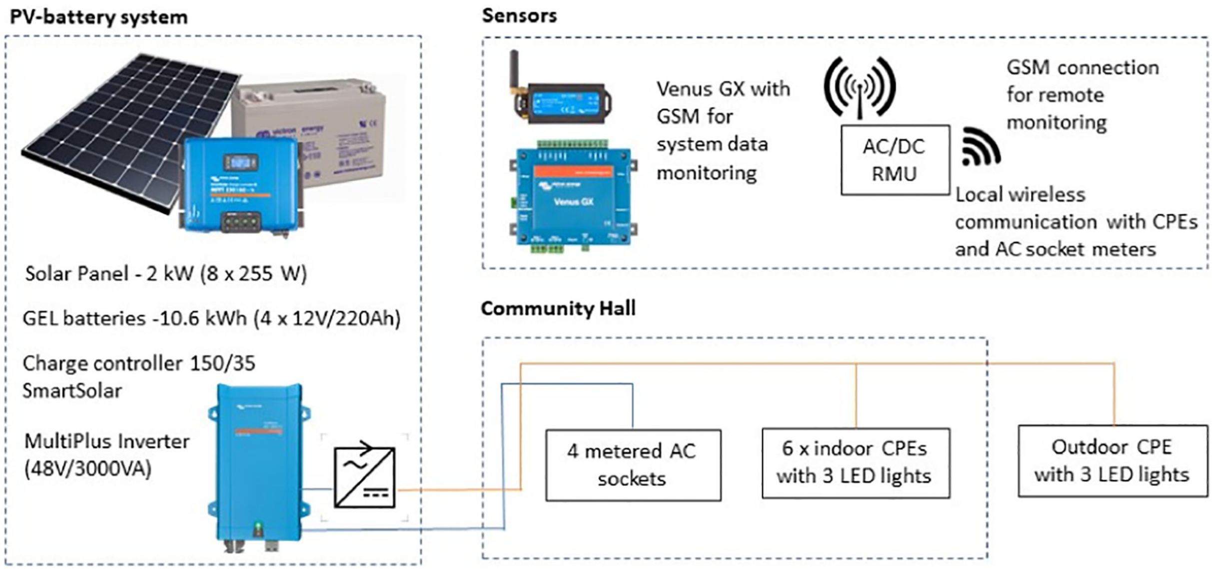

Fig. 4. Overview of the PV-battery system in Nyabiheke, Rwanda, powering lights and sockets at a community Hall.

lights were located in the roof structure. During installation, three transmission line poles were required between the nurseries and playground. Each transmission line was fitted with three 10 W lights for safety and security purposes, which also enabled them to act as streetlights (see Fig. 5). During commissioning, based on new information from the community, the nursery outdoor lights and streetlights were programmed to come on at full brightness at 18:00 and turn off at 06:00. The playground lights were set to come on at full brightness at 17:30, dim to half brightness at 00:00 and turn off at 05:00. At the Hall, the outdoor lights were set to come on at full brightness at 18:30 and turn off at 06:00 the next day. The indoor lights could be turned on and off as needed (see Fig. 6).

Monitoring and analysis

Community mobilisers and logbooks

At the end of the implementation phase, two community mobilisers were appointed at both the micro-grid and Community Hall to i) engage the community in using the systems, ii) maintain a logbook on system utilisation, and iii) perform rudimentary weekly checks. The community mobilisers were provided with information on the solar systems (e.g. design, components, functionality and limitations) in order to transfer this knowledge to the users and community more widely. The mobilisers managed a logbook for each building to record information regarding the activities that took place (e.g. type of activities, timings and groups involved) and note any additional comments by the users. A separate system check sheet was used by the mobilisers to record any technical problems (such as damage, theft or component faults), which informed the maintenance requirements.

Data collection

To assess the performance of the PV systems, data was collected from 2nd July 2019 – 31st March 2020 for the micro-grid and 20th July 2019 – 31st March 2020 for the Hall. Data from the PV systems was stored locally in the Venus GX and remotely communicated to Victron's online VRM portal. The data sets and data processing methods applied are available on Zenodo (Nixon, Bhargava, & Gaura, 2020). In-plane solar irradiance on the PV array was estimated from using live irradiance data provided from SolCast, which is a common approach for small PV systems (<5 kWp) (Copper et al., 2013).

Performance metrics

The solar photovoltaic power systems were evaluated following the International Electrotechnical Commission Standard IEC 61724-1 (2017), which defines several key system performance indices (yields, losses and efficiencies). The IEC (2017) provides further discussion on Eqs. (1) to (5).

A reference yield (Y_R), array yield (Y_A) and final yield (Y_F) was obtained from:

$$Y_R = \frac{A\,\eta_{STC} \int Gi}{P_o} = \frac{E_P}{P_o} \quad (1)$$

$$Y_A = \frac{E_A}{P_o} \quad (2)$$

$$Y_F = \frac{E_{Load}}{P_o} \quad (3)$$

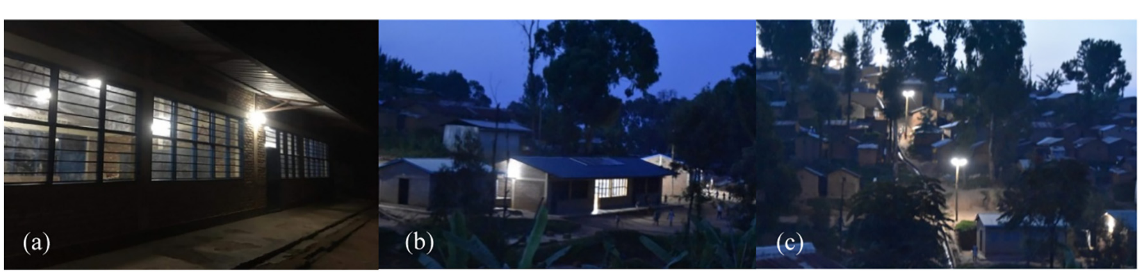

Fig. 5. The micro-grid installation at Kigeme powering two nurseries (a and b) and a transmission line ran up from the nurseries alongside a sewer canal to provide lighting to a playground located on a hilltop (c).

Fig. 6. The Nyabiheke solar system powering lights inside (a) and outside (b) the Community Hall.

Y_R is the potential energy output of the PV array (E_p) operating at nominal efficiency, $\eta_{STC,}$ under standard test conditions (STC) and is calculated from the surface area of the PV array, A, and the in-plane solar irradiance incident on the PV array, Gi. Y_A is based on net output from the PV array, E_A, and the peak power rating of the PV array, P_o. Y_F represents the actual load served by an inverter and is calculated from AC load output, E_{Load}.

The system capture losses, L_C, and Balance of System (BoS) losses, L_{BoS}, were calculated from:

$$L_C = Y_R - Y_A \quad (4)$$

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

System capture losses, L_c, result from generation-demand mismatching, wiring losses, shadowing and dirt on the array, maximum power point tracking (MPPT) errors and temperature and irradiance dependant variations in performance. The balance of system losses occurs from various system component inefficiencies (e.g. converter, battery and wiring losses).

A performance ratio (PR), where $PR = Y_F/Y_R$, provides an indication of the overall performance in relation to the PV array's potential power output.

Results

Standalone solar system performance metrics

The key solar system performance metrics (performance ratio, BoS efficiency) for the Hall and micro-grid systems are shown in Fig. 7.

At the Nyabiheke Community Hall, the performance ratio was:

- As low as 9% in July 2019 and peaked at 39% in December 2019
- Significantly reduced by lower than expected user loads and high system losses

At the Kigeme micro-grid, the performance ratio was:

- As low as 20% in September 2019, due to a power outage, and peaked at 43% in October 2019 due to peak consumption and low irradiance
- Reduced by low user loads

The average performance ratios of 25% at the Nyabiheke Community Hall solar system and 33% at the Kigeme micro-grid were significantly lower than those typically reported at other on and off -grid PV solar systems. The main cause for reduced PRs at both sites were low user loads, which resulted in high capture losses. The Victron batteries were more efficient than expected at both systems (around 85%) due to a high average state of charge. The micro-grid's 1.2 kVA inverter was well matched to the load demands and achieved an overall efficiency of 95%, which was as designed. In comparison, the Hall's 3 kVA inverter, which was upgraded during commissioning due to the availability of parts, was oversized resulting in a reduced efficiency of 85%. This resulted in a reduced BoS efficiency of 76.5% at Hall, whereas the inverter efficiency at its rated load is over 90%.

Capture losses were high at both systems. The power outage at the micro-grid in September resulted in the highest monthly capture loss of around 10 kWh/day. At the Hall, monthly daily average capture losses reduced by more than 4 kWh/day between July 2019 and January 2020; in January the AC load was around 2 kWh/day higher than in July, and

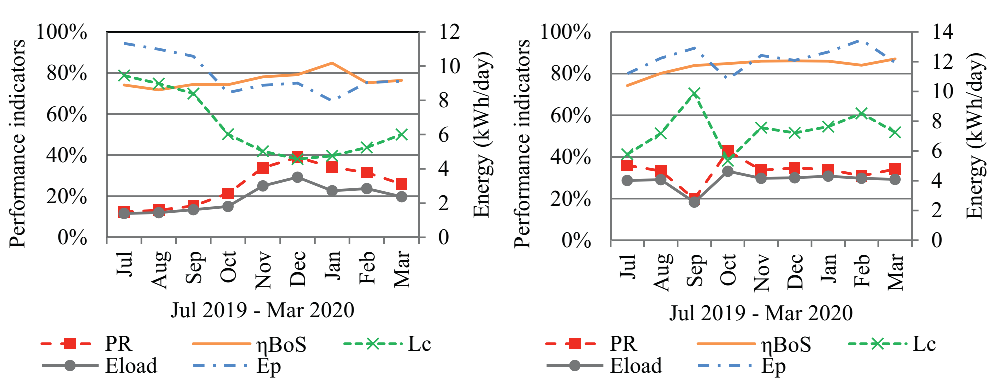

Fig. 7. The performance ratio (PR) and BoS efficiency at the Hall (a) and Micro-grid (b) since commissioning. The capture losses, Lc, potential PV array output, Ep, and the total load output, Eload, are shown on the secondary axis in kWh/day.

the rest was attributed to lower in-plane irradiance levels on the PV array. Table 1 summarises the performance parameters for the designed and in-use standalone solar systems.

User energy demands and change over time

The energy consumption trends at the Hall and micro-grid systems were significantly different. At the Hall, energy consumption was very low for the first 100 days (around 1.5 kWh/day) and then increased to as high as 5 kWh/day on several occasions, 130 days after commissioning. The daily total AC consumption at the micro-grid was approximately 4.5 kWh/day, and this remained relatively constant over the entire analysis period, except for the 2-week power outage in September (see Fig. 8a-b). It is important to note that each light and socket meters was estimated to consume 50–75 Wh/day, and therefore the actual user loads were around half of the AC load at both the Hall and micro-grid.

Fig. 9a-b shows how the typical daily load changed each month. At the Hall, the AC load peaked in the early and evening hours (10 a.m. and 7 p.m.). For the micro-grid, the AC loads were largely driven by the programmed night-lights, and loads remained low throughout the daylight hours across the monitoring period.

Discussion

Reflecting on the experience of co-creating with at-risk communities in environmentally and economically vulnerable settings, the authors suggest that there are three areas of practice that benefit from greater consideration when deploying energy interventions: 1) responding to implementation and operational constraints, especially around introducing new technologies in infrastructure-less settings, 2) designing systems that respect and reflect the socio-political-economic dynamics of refugee communities, and 3) introducing co-creation processes for sustainable community-based energy interventions in displaced settlements. By being transparent about some of the project challenges when implementing, monitoring and evaluating energy interventions in a more inclusive and collaborative approach with refugee communities, we aim to support improved outcomes for future energy interventions in similar contexts.

Responding to implementation and operational challenges

As previously noted, the hall and the nursery had a very strong community governance group at the onset of the research, which informed how the systems were sized based on expected demand profiles established by working with these committees and workshop participants. Whilst there were a few high energy consumption events at the Community Hall (e.g. wedding parties), aspirations for ownership and use of certain appliances and entrepreneurship activities did not appear to materialise. Therefore, the user loads were low, both at the outset of their installation and after nine months of operation. As the solar systems were significantly oversized this led to high capture losses and a low PR. To understand some of the reasons for low uptake, it became apparent that perceptions around system reliability had contributed to why the uptake of the hall and nurseries was limited.

Table 1
Average performance parameters from July 2019 to March 2020 for the designed and in-use Kigeme micro-grid and Nyabiheke Community Hall solar systems.

Parameter	Units	Micro-grid	Hall
Irradiance on PV panels (Gi)	(kWh m^{-2}/day)	4.76	4.64
Potential PV power output (E_p)	(kWh/day)	12.19	9.48
Net energy from PV array (E_A)	(kWh/day)	4.82	2.99
Total load output (E_{load})	(kWh/day)	4.02	2.30
Final yield (Y_f)	(kWh d^{-1}/kWp)	1.58	1.15
Reference yield (Y_r)	(kWh d^{-1}/kWp)	4.78	4.74
Array yield (Y_A)	(kWh d^{-1}/kWp)	1.89	1.49
BoS losses (L_{BoS})	(kWh d^{-1}/kWp)	0.31	0.34
Capture losses (L_c)	(kWh d^{-1}/kWp)	2.89	3.25
Performance ratio (PR)	(%)	33.2%	25.2%
Solar charger efficiency (η_{sc})	(%)	97.4%	96.9%
Battery efficiency (η_{bat})	(%)	85.1%	85.3%
Average SoC	(%)	96.2%	93.5%
BoS efficiency (η_{BoS})	(%)	83.6%	76.5%

Power outages (e.g. due to circuit breakers, low battery state charge or component faults) are not unexpected when deploying a system in a setting where resources are limited. To mitigate risks of outages due to component failings and limited access to the site by external contractors, fault finding procedures were put into place by employing refugees as ‘energy apprentices’ and ‘community mobilisers’. These employers, who resided in the camp, could rapidly report on faults and do simple repairs. Therefore, although we encountered more component faults at the micro-grid, the reliability of the Hall solar system was good, and no significant issues were documented. Yet, despite these measures and the small number of outages having a negligible impact on the overall performance of the systems, community mobilisers reported that the community feared using the systems and causing the lights to go out.

Reviewing the hall data, we noted a correlation between the power outages and the noticeable decline in usage. This suggested that community perception of outages led to diminished system usage, which potentially had a much more significant impact on the PR and contributed to communities feeling somewhat ambivalent towards new technologies. In focusing training of the community mobilisers and energy apprentices on resolving technical challenges, we had prioritised technology without considering how to build trust in the system. More time spent in the workshops explaining the causes of outages and measures introduced to address these failings could have instilled greater confidence in using and exploiting the systems.

In the early stage of the project, when interviewing participants to understand appliance usage patterns to size the systems, we missed the opportunity to explore more critically what current equipment was in use and accessible to refugees. Greater reflexivity would have given space to question the utilitarian of deploying systems that could provide energy for computers and irons that had been requested, despite not being owned, by the participants. Instead, an alternative solution to realise energy aspirations would have been to install smaller systems and invest savings in purchasing electrical appliances.

Designing systems that respect and reflect the socio-political-economic dynamics of refugee communities

Energy system infrastructures in camps are particularly challenging in camps as frequent, unpredictable and rapid expansion creates informal roads and paths located among households. Despite pre-deployment site assessments being conducted, there were still a number of unexpected challenges relating to having space for vehicles and new building structures. For example, in Kigeme camp, the terrain was very steep and unstable in places, which meant new drainage channels had to be built around the powerhouse following heavy rainfall. What was less recognised and planned for was how permissions to enter the camps could take several weeks to be agreed on every occasion and could be subject to restrictions. The acknowledgement of the additional complexity of camp governance structures, as well as physical limitations and obstacles, develops a more nuanced understanding about situating other micro-grid installations in refugee camps and informal settlements.

In addition to time delays arising from insufficient planning for site access permissions, there were challenges regarding community access to the systems. Whilst the Nyabiheke Community Hall had established governance (a legacy from the previous system installation) the micro-grid in Kigeme had multiple stakeholders that would oversee a building that had never had power before. Navigating structures that allowed access for the community was, at times, contested territory as the Nursery buildings were operated by an external NGO and, therefore,

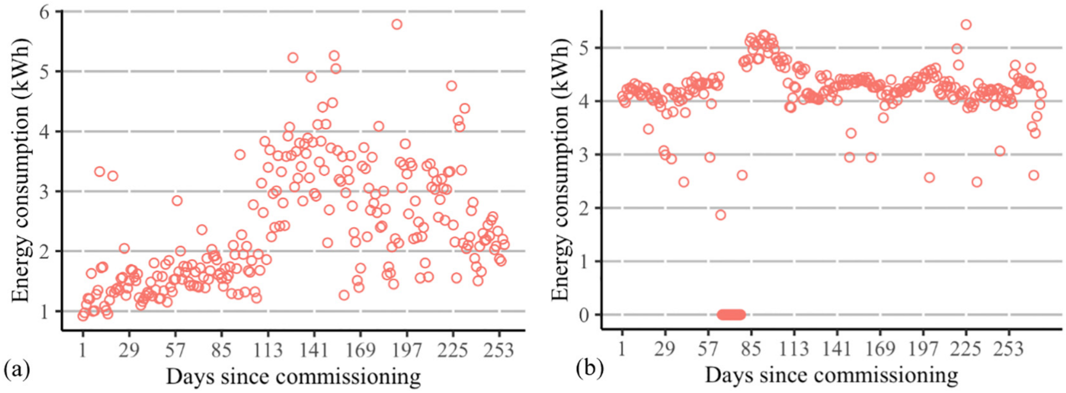

Fig. 8. Daily AC load consumption at the Hall (a) and micro-grid (b).

negotiating community access for anyone other than students and staff during weekdays resulted in fewer than expected activities taking place outside of the nursery's working hours as an educational building. Interestingly, an unexpected consequence of the COVID-19 lockdown (post-March 2020) was that the usage of the micro-grid increased significantly due to University students using the nurseries to study remotely.

The communities' ability and capacity to leverage on the available energy and mobilise around its use for entrepreneurship needed more time than afforded between the embedding of the intervention and the outbreak of the COVID-19 pandemic in March 2020. We had anecdotal reports from communities that a few enterprises were indeed discussed in community groups; however, the process of obtaining co-funding, permissions and approvals is a lengthy and arduous one for refugee communities; these activities have had limited success at the Nyabiheke Community Hall and no success at the Kigeme micro-grid. Whilst performance evaluations of solar systems for less than a year does introduce some seasonal bias (Dierauf et al., 2013), research on energy system usage and performance during and after COVID 19 needs to be considered separately and carefully to ensure the validity of findings (Fell et al., 2020). However, COVID 19 presents an opportunity to generate new insights on displaced communities' use of energy both before and during a pandemic, which will be explored in further research.

Lastly, the siloing of energy projects in camps can result in little communication or collaboration between other interventions occurring in the camps. At the time of installation for the solar interventions, a medium-scale programme of concerted, subsidised penetration of solar home systems took place in the camps in the vicinity of the installations. Therefore, having designed the system to have the capacity to charge devices, the introduction of electricity to many households saw a decline in the demand for free communal energy. Instigating dialogue between different energy interventions at the planning stage would have interrogated more critically what energy use is best situated in communal rather than private spaces.

Principals and processes for co-creation for sustainable community-based energy intervention in displaced settlements

Co-developed and community-based solar energy interventions are going to play an increasingly important role in improving energy access in displaced settlements. This paper provides insights on two community-based systems showing that despite involving all stakeholders and the community in the decision-making processes from system concept to deployment, anticipated performance was not realised in practice within the first nine months. The following design principles are recommended to improve the performance and sustainability of future solar energy interventions in refugee camps, reduce the risk of intervention failure and increase investment benefits.

Plan for longer projects to deliver sustainable energy transitions that establish, manage, and meet community energy needs in new ways. Significant time and support needs to be given to embed interventions so that refugee communities can leverage newly available energy resources and mobilise around its use for entrepreneurship. Although enterprises were indeed discussed in community groups; the process of obtaining co-funding, permissions and approvals is a lengthy and arduous one for refugee communities. Longer funding cycles will give more time to work alongside and support communities in developing an infrastructure that provides opportunities for community capacity building, skills development and self-determination, and this will increase the benefits and impacts of energy interventions.

Implement co-design methods that work towards co-creating energy interventions. Co-design as a participatory method brings together

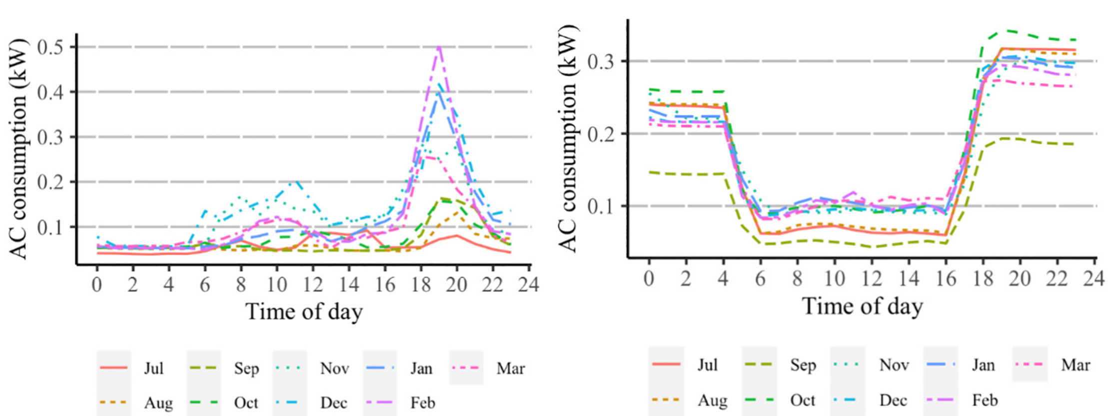

Fig. 9. Typical monthly daily AC load at the Hall (a) and micro-grid (b) for July 2019 to March 2020.

communities and energy actors in the design development stage to work towards energy systems that respond to and reflect community needs and aspirations. However, the aim should be for communities to be embedded in every level of the project, not just during the design process. The shift towards co-creating requires continuing group discussions that positions refugees, including marginalised groups (e.g. women, young and people with disabilities), as energy service users, maintainers, and supplies of energy services throughout the project timeframe. The feedback and feedforward of information and sharing of energy data, throughout the project, will help to establish understanding of new ways to address the long-term sustainability of energy interventions.

Introduce 'energy gatekeepers' and 'energy apprentices' to future proof interventions. Recruit refugees as community mobilisers to act as 'energy gatekeepers' to work with the community to encourage engagement with new technologies and promote fair sharing of access to community resources. Partner with local energy suppliers to build-in training mechanisms to investment in skills development to support community self-reliance. In our experience, this developed new skills for both refugees and local suppliers and built trust and strengthened relationships between all stakeholders. Furthermore, training of refugees as 'energy apprentices' proved to be invaluable during the COVID-19 camp lockdowns when suppliers could not enter the camp.

Before installing energy interventions implement exit strategies that promote ownership and self-governance to ensure survivability and effective system utilisation. Prior to wider deployment, where possible ascertaining how communities can support governance will situate refugees as integral energy actors to the sustainability of future systems. Devising and developing a handover process with the community at the start of the project will afford opportunities for sustainable exit strategies that engage with national structures, ownership laws and energy regulations and looks to empower communities by becoming project stakeholders.

Conclusion

This paper draws on the lessons learnt from the two systems to provide a set of design principles to guide future solar energy interventions in refugee camps, which will improve performance, reduce the risk of intervention failure and increase investment benefits. Further research is now needed on how to support, engage and accelerate refugees' use of flexible community energy systems, thus improving the sustainability and financial viability of future community-based energy interventions deployed in displaced contexts.

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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