Ahsan, Isna, Halford, Alison, Nixon, Jonathan, Bhargava, Kriti and Gaura, Elena
(2026) *Are solar mobile lanterns really mobile? What sensor data reveals about women's lantern use in refugee camps.* Energy Policy, 212 . ISSN 0301-4215.

Energy Policy 212 (2026) 115162

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Are Solar Mobile Lanterns Really Mobile? What sensor data reveals about women's lantern use in refugee camps

Isna Ahsan [a], Alison Halford [a,*], J.D. Nixon [a,c], Kriti Bhargava [b], Elena Gaura [a]

[a] Coventry University, United Kingdom
[b] University of Californa, Santa Cruz, USA
[c] University of Kent, United Kingdom

A B S T R A C T

Solar mobile lanterns are among the most widely deployed energy interventions by humanitarian organisations in refugee camps. Recent UNHCR guidelines advocate multipurpose lanterns that provide both lighting and phone charging, reflecting ongoing design efforts by humanitarian actors and manufacturers to enhance night time mobility and safety. This study examines how solar lanterns are used for night-time mobility in a protracted refugee camp, using embedded sensor monitoring, alongside household survey data analysed through a gender lens. Distributed in Rwanda's Nyabiheke refugee camp, we find that lanterns are predominantly used as stationary household lights, with the median lantern journey involving only 17 steps and lasting 1.72 min. These findings show that night-time mobility in refugee camps is shaped less by individual movement than by household-level energy practices and constraints. This disconnect between how solar lanterns are justified in humanitarian energy policy and how they function in practice, highlights the value of sensor-based monitoring for policy design, procurement, and evaluation.

1. Introduction

Solar mobile lanterns are among the most widely distributed energy products in refugee camps, providing a renewable, affordable, and accessible energy source in complex humanitarian settings with minimal infrastructure (Rosenberg-Jansen, 2018). In 2022 alone, the United Nations High Commissioner for Refugees (UNHCR) distributed over 900,000 lanterns across 51 different countries (UNHCR, 2022a). In 2025, UNHCR updated technical specifications, framing solar lanterns as advancing 'the environmental, technical, social, and economic sustainability of core relief items' (UNHCR, 2025), highlighting their continued importance. Despite widespread deployment, little is known about how these lanterns are used in protracted humanitarian contexts and how they shape the lived experiences of camp-based refugees. This knowledge gap is particularly relevant to women, for whom enhanced freedom of night time movement is often cited as a key benefit (UNHCR, 2022b), yet robust evidence remains limited.

Existing research on mobile lanterns largely relies on interviews and surveys that emphasize visible benefits, such as improved safety through communal lighting (Dynes et al., 2014; Hasan et al., 2023; Rosenberg-Jansen, 2018). Far less attention is given to institutional dimensions of energy delivery or to energy as a relational infrastructure that shapes social life. This reflects a broader institutional tendency to prioritise technical solutions to energy provision, sometimes at the expense of recognising energy access as a complex social infrastructure embedded in daily life, particularly within the operational constraints of refugee settings (Rosenberg-Jansen, 2022).

Complex humanitarian settings require equally complex approaches to data collection (Smith and Blanchet, 2019). Energy programs in camps frequently lack reliable data on fuel use, household energy practices, and costs, leading to poor planning and misaligned interventions (Lehne et al., 2016). Without detailed information on appliance usage, expenditures, and energy sources, interventions risk inefficiency and ineffectiveness, undermining both short-term impact and long-term sustainability.

Qualitative methods such as interviews and focus groups tend to dominate humanitarian energy research (Bisaga and Hamayun, 2020). While valuable, these methods often reinforce institutional blind spots and overlook critical dimensions of lived experience. Addressing data gaps requires not only more data, but also different forms of data collection that actively challenge epistemic and structural power asymmetries (Halford et al., 2022; Robinson et al., 2022). Such approaches are particularly important for exposing gender biases that reproduce discriminatory social constructs and for strengthening advocacy for women's inclusion in decision-making (D'Ignazio and Klein, 2020).

Energy provision is largely framed as an object-centered task, focused on distributing physical resources, reducing energy to a one-

* Corresponding author. Coventry University, United Kingdom.
E-mail address: ad4480@coventry.ac.uk (A. Halford).

https://doi.org/10.1016/j.enpol.2026.115162
Received 21 October 2025; Received in revised form 29 January 2026; Accepted 6 February 2026
Available online 20 February 2026

time provision and obscuring the ongoing challenges of access for protracted refugee settings (Rosenberg-Jansen, 2022). This approach assumes that improved access to energy benefits all users equally, and energy inventions that are most frequently used by women, such as cook stoves, will automatically empower them (Halford, 2020). Such assumptions overlook the socio-cultural structures, including gendered norms, that continue to constrain women's agency and shape how technologies are used (Listo, 2018a; Halford, 2024). In this paper, we understand gender not simply as a demographic category, but as a set of socially constructed norms, roles, and expectations that shape how women, men and other gendered groups experience, access, and negotiate energy technologies. When we refer to women as a category, we do so with the recognition that this is not a homogeneous group, but one defined through intersecting structures of power and norms.

In refugee camps, inadequate public lighting and the gendered burden of firewood collection exacerbate safety risks, reducing privacy and security and forcing women and girls into unprotected areas outside camp boundaries, where exposure to gender-based violence (GBV) is well documented (Corbyn and Vianello, 2018; Aubone and Hernandez, 2013; Global Alliance for Clean Cookstoves, 2016). In contexts of trauma, poverty, and disrupted social structures, such violence is often normalized, constraining both physical mobility and psychological well-being (Jensen, 2019). Efforts to improve safety in these settings often focus on communal lighting, fuel-efficient stoves, and portable solar technologies, aiming to reduce exposure to risk during daily tasks such as cooking, collecting firewood, or moving at night (Listo, 2018a, 2018b). Reducing GBV is frequently framed as a primary objective behind distributing solar mobile lanterns, which are intended to enhance women's safety by enabling safer movement at night (Dynes et al., 2014, 2016; UNHCR, 2011, 2022b; UNFPA, 2017). However, scholars caution that framing energy interventions as primary tools against GBV oversimplifies complex crises (Abdelnour, 2015) and solar lanterns are often 'fetishized' as tools of empowerment and protection for women (Rosenberg-Jansen, 2022),

A similar critique applies to lighting, where improved illumination is often assumed to automatically reduce GBV, a claim contested by Perkins (2015). Our own previous research has highlighted the reliability and operational challenges of solar-powered streetlights and other lighting facilities in camp-based settings (Nixon et al., 2021a, 2021b). Claims that energy interventions reduce risks for women must therefore acknowledge both the need for broader social-norm change and the limitations of technical solutions, such as solar lanterns (Bradley and Liakos, 2019).

1.1. From assumptions to evidence

Despite their widespread distribution, little is known about how solar mobile lanterns are actually used in protracted camp settings or how they influence women's movement patterns and nighttime behaviours. In contexts where fixed lighting is limited, it is not surprising that lanterns may be used primarily as stationary lights; what matters for policy decision makers is whether framing them as 'mobile' reflects how women actually use them in everyday life, and whether this framing supports or obscures their mobility and safety needs. Without comprehensive, user-centered data on patterns of lantern use and mobility, even widely adopted designs risk misalignment with the lived realities of refugees, particularly women and girls. Existing studies are often qualitative and rely on self-reported accounts, leaving assumptions about lantern usage and women's mobility largely untested. This lack of empirical evidence creates a critical gap between design intentions and everyday practice.

This paper takes those claims from assumption to evidence, presenting the first study to combine sensor-based monitoring with qualitative insights to systematically examine the mobility, usage patterns, and gendered implications of solar mobile lanterns in a protracted refugee camp setting. By critically examining whether and under what conditions lanterns enhance women's night time mobility, particularly in contexts where stationary lighting needs are only partially met, we aim to make visible the gendered constraints and trade-offs shaping everyday energy practices in refugee camps. Specifically, the research has three objectives:

1. **To analyse the actual mobility and usage patterns of solar mobile lanterns** using embedded sensor monitoring data collected in Nyabiheke refugee camp, Rwanda.
2. **To examine how women, as primary users, engage with and adapt lanterns** within the social and material constraints of camp life.
3. **To assess the extent to which solar lantern design and deployment align with the lived realities of refugees**, and to reflect on implications for humanitarian energy policy and intervention design.

We do this by, first outlining our data-driven approach to the design and deployment of mobile lantern sensor devices in a refugee camp setting. The results section then evidences that, despite being widely promoted as mobile technologies across off-grid energy access contexts (GOGLA, 2019), solar lanterns are frequently used in static ways within refugee camps. Finally, we present recommendations on how mobile lantern design and deployment could position women and girls as central actors in the decision-making process to improve the gendered dimensions of safety, autonomy, and mobility in protracted camp settings.

2. Methods and materials

Funded by the UK Engineering and Physical Science Research Council (EPSRC), the Humanitarian Engineering and Energy for Displacement (HEED) project aimed to improve energy access for displaced people, piloting seven solar interventions in Rwanda and Nepal, with open access data available via the HEED Data Portal (HEED, 2019). One of the key energy interventions as part of the HEED project was the distribution of mobile solar lanterns in the Nyabiheke Refugee Camp in Rwanda.

The Nyabiheke camp in Rwanda was established in 2005 to provide refuge for people escaping violence in the Democratic Republic of Congo and Burundi. The camp's ongoing existence shows that most refugee camps are rarely temporary settlements but tend to exist for prolonged periods (Grafham and Lahn, 2018). More recent data from UNHCR (2024) shows 66% of refugees under UNHCR's mandate had been displaced for more than five years. For this project, when participants were asked how long they had been in the camp, the median reported was 12 years, and the average was just slightly less than 12, aligning with wider

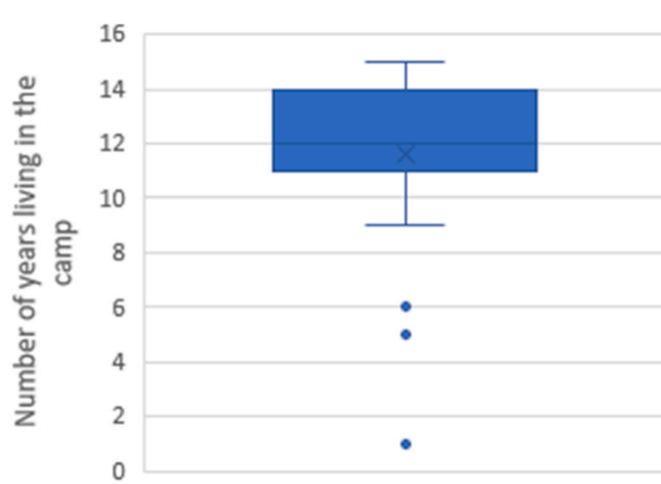

Fig. 1. Most participants reported that they had been living in the camp for over a decade.

evidence of protracted displacement (Fig. 1). Read together, these figures suggest humanitarian energy planning benefits from addressing the tension arising from prolonged residence without presumptions of permanence.

2.1. Case study camp

In 2019, the Nyabiheke Camp had a population of 14,479, comprising of 3490 households (Practical Action, 2020). As part of the HEED project, baseline surveys were conducted from 210 households of Nyabiheke camp to understand the energy access situation before the deployment of instrumented solar mobile lanterns in the Nyabiheke camp (HEED, 2019). A significant portion of households (58%) either lacked lighting at night or used only basic options like candles and torches to navigate the camps. A smaller proportion primarily relied on solar lanterns (21%) or solar home systems (16%) for their lighting needs. Nyabiheke sustains an active evening and night-time economy, including community events, religious gatherings, small-scale trade, providing important context for interpreting observed patterns of lantern use (Practical Action, 2020).

2.2. Sensor system design for mobile lanterns

The d. light S30 solar lantern is a portable lighting solution that charges through an integrated solar panel (d.light, 2025a). It is manufactured by d. light, a company committed to providing energy solutions to people without reliable access to electricity (d.light, 2025b). Since its founding in 2004, d. light has sold over 20 million solar lanterns, appliances, and home systems, improving the lives of more than 100 million people in 70 countries (GoodMarket, 2025). Given its proven impact and wide adoption, the S30 lantern was selected for the deployment of solar mobile lanterns in this case study.

The sensor system was designed to monitor user step count as the lantern was moved, and to track lantern battery voltage to detect both discharging due to use and charging through solar energy harvesting. The core of the system was a sensor node built around an Arduino MKR GSM 1400 microcontroller, which executed a custom program (Brusey, 2025) to sense, process, store, and transmit sensor data.

This sensor node supported the integration of external components, including an ADXL345 inertial motion unit (IMU) and an in-house-designed voltage monitor. It also enabled GSM communication to transmit data to a remote server for logging and analysis, and included local data storage via an SD card to serve as backup in case of transmission failures. A low-power sleep mode was implemented to minimise energy consumption during idle periods, which represented the majority of the device's operational time.

Given the deployment in off-grid households, the system was powered by a rechargeable 3.7V Li-Ion battery with a capacity of 7.59Wh. The microcontroller continuously monitored battery voltage to evaluate discharge behaviour based on use. Using step count change detection, data were stored and transmitted only when a significant change in activity was observed, leveraging the IMU's ability to trigger interrupts during motion or freefall. Table 1 lists all key components used in the monitoring system. The complete mobile lantern monitors consisted of d. light S30 solar lanterns fitted with the Arduino-based monitoring device, as shown in Fig. 2.

Table 1
Technical specifications of the system device.

Component	Description
Arduino MKR GSM 1400	Microprocessor
Sparkfun ADXL345	3-axis accelerometer to estimate step count
SD breakout board	To integrate the memory card
Voltage monitor	To measure solar battery level
Global System for Mobile Communications (GSM) Antenna	To allow GSM communication
3.7V Battery	To power the device

The ADXL345 IMU generated activity and freefall interrupts from acceleration readings, which were processed to estimate user step count. Step count was estimated from inertial sensor data using a rule-based algorithm. During development, the algorithm was calibrated through laboratory testing, in which a researcher walked with a lantern-mounted device while manually counting steps to provide a ground-truth reference. Estimated step counts were compared against these counts to verify consistent detection under typical walking conditions. While minor inaccuracies are possible, the metric is used to indicate relative movement patterns rather than precise step totals. Battery voltage data was simultaneously collected to assess energy usage and solar charging patterns. When significant activity was detected, updated values including step count, rate of change in steps, and battery voltage of both the device and lantern were stored locally and sent to the HEED-data server via GSM. GSM communication was selected despite its higher energy consumption due to the unavailability of Wi-Fi connectivity in the camp environments. Additionally, a heartbeat mechanism was in place to ensure that the device transmits at least one packet every 6 h to detect inactive nodes, even if no activity was recorded. Table 2 details the data collected by this system.

The entire monitoring system was housed within the lantern casing. The battery was mounted on the internal PCB cover using double-sided Velcro tape and positioned to avoid blocking the lantern's LED light output. The Arduino device was fixed securely inside the casing with the X-axis oriented vertically when the lantern was held upright. Insulation was added between all components to prevent short-circuiting, and custom cut-outs were made in the internal cover to allow access to the SD card breakout board and battery connector.

2.3. Deployment

54 Households were recruited through an open invitation in a district chosen in consultation with camp district leaders, UNHCR management, and Practical Action. No incentives were offered, although households were permitted to keep the lanterns once the monitoring device had been removed. Due to over-subscription, selection was overseen by representatives of the Refugee Committee and camp management on a first-come, first-served base. A higher proportion of women participants volunteered to take part. This likely reflects both the camp's demographic profile, where women constitute a larger share of the population than men, and women's greater involvement in day-to-day household energy management. The solar lantern with monitors were distributed to these households in July 2019, and data collection ended in December 2019. Participants were free to use the lanterns as they liked, but they were informed how the lanterns worked, that they can provide light when moving through public spaces at night and that they need regularly charging by placing them outdoors in sunlight. A

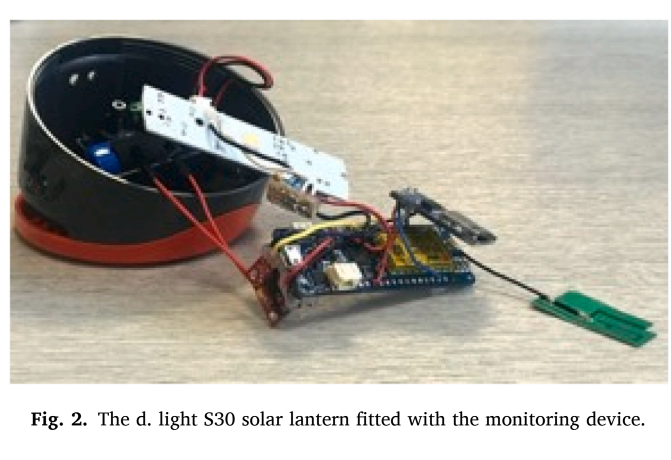

Fig. 2. The d. light S30 solar lantern fitted with the monitoring device.

Table 2
Data collected by the system monitoring device.

Data field	Description
Unix Timestamp	Real time when data is collected
Raw Step Count	Cumulative step count measured since device reset
Smooth Step Count	Cumulative step count measured and smoothed over past readings since device reset
Smoothed Step Rate	Rate of change of smoothed step count
Device Battery Level	Voltage level of the battery for Arduino MKR board. A raw integer value of 1023 corresponds to 4.2V
Solar Battery Level	Voltage level of the battery for the solar lantern. A raw integer value of 1023 corresponds to 6.6V
Error Code	Error code indicating specific failure in device functionality. An error code of 0 implies the functionality was successful without any errors.
Sequence Number	Sequence number of the packet

participant charging the lantern outside their home is shown in Fig. 3.

2.4. Participants baseline and endline surveys

The household participants took part in a survey conducted at the end of the study in December 2019. The endline survey collected information on how the participants used the solar lanterns, including the purpose and duration of use, as well as personal details such as age, gender, and occupation. 85% of the participants who took ownership of the solar lanterns were women. This suggests that women are seen as the primary caretakers of household lighting technologies in the camp. Participants were also asked to indicate their reasons for using the lanterns (The survey is available in Appendix A). In addition to the lantern deployment study, the analysis draws on findings of a survey of 210 households in Nyabiheke camp, part of a wider household energy assessment undertaken by Practical Action between March and April 2018 across refugee camps in Rwanda (https://doi.org/10.5281/zenodo.4454580).

Fig. 3. A solar lantern placed outdoors for charging in Nyabiheke Camp ©HEED/Edoardo Santangelo

2.5. Challenges and limitations

Several practical and analytical challenges emerged following the deployment of the lantern-mounted monitors. First, connectivity and hardware issues led to intermittent data gaps. Over time, wire cuts were observed, requiring repairs by local electricians. Hardware failures caused irregular interruptions in data collection, often necessitating manual device resets. While some SD cards were either reformatted or stolen, resulting in data loss. Instances of theft also occurred, particularly when lanterns were left outside for charging. Despite those issues, sensor data was successfully retrieved from 51 out of the 54 devices.

Data yield was calculated daily as the percentage of hours during which each device recorded data. For most days, the yield was relatively low, indicating data loss due to the above listed issues. To avoid partial-day artefacts, analysis was restricted to days with complete data (100% yield). In total, 161 days of full data were collected across 30 of the 51 functioning lantern monitors. It is possible that missing data could coincide with periods of higher lantern use, and this was considered in the analysis. However, movement does not prevent the sensors from recording, and data loss was mainly due to connectivity, power, or device issues. Missing periods were therefore treated as missing rather than as low activity.

Another potential concern was whether measurement quality varies under higher movement. Inertial sensing accuracy can be affected by speed and attachment (Park et al., 2014). As the sensors were mounted directly to lanterns, increased mobility is unlikely to suppress signal but may instead increase acceleration variance. The primary risk is therefore intermittent data loss due to physical shocks or loosening during transport. To address this, we screened time series for discontinuities, treated missing periods explicitly as missing data rather than inferring low mobility, and interpret all mobility findings conservatively.

Given intermittent data gaps and uneven sensor yield across households, we did not attempt a one-to-one linkage between an individual lantern trace and an individual survey response, as it would have introduced selection and attribution bias by restricting analysis to households with complete sensor data. Data stability is not neutral in this setting. Households with continuous sensor records could also be more likely to maintain charged lanterns and experience fewer interruptions to energy access. Restricting analysis to these households would weight results towards more stable conditions, obscuring the scarcity-driven dynamics under investigation. A further source of bias relates to attribution. Although the endline survey showed 85% of participants were women, the lanterns were distributed to households. Assigning lantern-level behaviour to a single individual would therefore misattribute collective or mixed-use patterns to one person, distorting individual and gender-level interpretation.

While future studies could enable gender-disaggregated quantitative analysis through individual-level monitoring approaches such as wearable sensors or participatory use logs, we instead combine lantern-level usage patterns with gender-disaggregated survey responses to examine the gendered implications of shared ownership, access, and use. This approach allowed us to identify thematic patterns across the data, regardless of sensor functionality, offering valuable contextual depth to the sensor data, and to ground the conceptual implications for humanitarian design and policy.

2.6. Data analysis assumptions

For the selected full data yield days of each lantern, mobile states were examined to determine whether mobility pertains to a single activity instance or multiple consecutive instances. This involved assessing the time gap between two successive packets having mobile states. If the time difference between two consecutive packets was under 2 min, continuous movement by the user was assumed. Otherwise, the mobility state is regarded as part of two distinct activity instances. Table 3 shows the number of full days of data collection and the number of mobility instances for every mobile lantern. Each mobility instance was then analysed to determine a step count and duration. The voltage values were also evaluated; a positive step rate and negative voltage, meant the light was on during the mobility instance.

3. Results

The number of steps per mobility instance is plotted for each lantern ID (Fig. 4), with the exception of IDs 33 and 34, as they had not registered any mobility instances. These results are aggregated across all lanterns in Fig. 5, showing that most lanterns never record a journey of more than 50 steps. The median step count is 17 steps and while distance calculated from step count does vary due to gender, age, health, load, weight, and height, this can be approximated to be a distance of 13 m, based on an average walking pace of 1935 steps per mile (Welk et al., 2000). Therefore, the distance covered using lanterns while moving appears to be largely limited to the confines of a refugee household, which typically consists of single storey, one room structures, or short trips to nearby toilets. The outliers are generally below 100 steps (~82 m), and even the lantern with the highest recorded steps only reaches about 340 steps (~278 m), indicating a very short journey, considering that the Nyabiheke camp covers 350,000 m^2 of land (UNHCR, 2023).

To help distinguish meaningful lantern mobility, e.g. through a public space rather than minimal, incidental use within or around the home, we assess the duration of each mobility instance. Fig. 6 presents the duration of each mobility instance for individual mobile lanterns, and Fig. 7 shows the aggregated distribution across all devices. Most mobility instances are under 4 min and the median duration is 1.72 min, further highlighting that lantern movement was brief and limited, rather than sustained or extensive. Even when a mobility instance time appears to be more significant, the distance travelled can be short. For example, Lantern ID 24 has a mobility instance lasting approximately 10 min, but the maximum number of steps recorded for this lantern is below 25. This highlights that the movement was frequent, with steps recorded at intervals of less than 2 min, but not one continuous long journey.

The limited movement observed in the sensor data could be interpreted as reflecting low demand for night-time mobility in this setting. While the sensors capture when and how lanterns are moved, they cannot record journeys that do not take place, nor can they distinguish between mobility that is avoided, postponed, or substituted due to lighting constraints. By looking at survey responses on routine short trips after dark, suggest that night-time movement does occur but often supported by mobile phone torches. Fully assessing the extent of unmet mobility demand would have required complementary methods, such as time-use diaries, mobility recall surveys, or participatory reporting of foregone or avoided trips. In the absence of such measures and in-line with the survey data, the results are best interpreted as evidence of constrained and partial mobility rather than an absence of night-time mobility needs.

To examine the potential disconnect between distance and duration, Fig. 8 plots step count against duration for each mobility instance. This figure is particularly significant, as it confirms the broader pattern identified in this research: that lantern mobility involves mostly short, time-limited, and spatially constrained movements. This emergent pattern calls into question humanitarian design and procurement assumptions that solar lanterns function as individual, mobility-enabling devices in all refugee camps, without interrogating how it may differ across camp types, such as long established camps, like Nyabiheke, or more transient internally displaced settlements.

To understand when the lanterns were actually being used, we looked at the hourly probabilities of lanterns being switched on (i.e. the battery powering the light would discharge at some point in the hour) and step counts being recorded. For each hour of the day, these probabilities were calculated as the proportion of lantern–hour observations, across all devices and all days with complete data, in which battery discharge or a positive step rate was detected. As expected, both movement and discharge probabilities are highest at night-time, with peak usage occurring at 8 p.m. (see Fig. 9). Daytime usage is also substantial, and the probability of lantern discharge consistently exceeds that of movement. This pattern indicates solar mobile lanterns are frequently being used as static light sources in the home during the day, suggesting that many mobility needs are met in daylight, while night-time movement is largely limited to short, routine tasks rather than extended journeys. Daytime use may also reduce available charge for longer night-time trips, further constraining lantern-supported mobility after dark.

The endline survey aligns with the sensor findings that camp-based refugees prefer to use lanterns as a static light source. 48 out of 54 respondents selected domestic work as the main activity when using the lantern (see Fig. 10). This was followed by visiting the toilet (45 out of 54) and eating (38 out of 54). While both domestic work and sanitation involve short-duration activities close to the home, night-time trips to toilets are frequently highlighted in the literature as a key justification for distributing mobile solar lanterns in humanitarian settings, particularly in relation to women's safety and mobility. Humanitarian camp design guidance recommends that shared sanitation facilities be located within a short walking distance of shelters, typically within approximately 50 m, to minimise safety risks, particularly for women and girls (Wardeh and Marques, 2023). Although exact distances between shelters and toilets were not measured for individual households, the very short distances and durations recorded by the lantern-mounted sensors are consistent with movement over this scale.

While the lantern-specific survey did not directly ask why devices were used in fixed rather than mobile ways, ownership patterns and findings from the wider household energy assessment were used to

Table 3
Number of full days of data collection and number of mobility instances for every mobile lantern.

Mobile Lantern ID	Number of Full Days Data Collection	Number of Mobility Instances
ML01	3	19
ML02	7	27
ML03	9	74
ML04	1	13
ML05	8	70
ML06	4	11
ML07	5	49
ML08	9	14
ML09	1	12
ML10	4	17
ML12	3	10
ML13	24	94
ML14	4	35
ML18	2	16
ML22	5	33
ML24	3	22
ML26	6	106
ML29	11	115
ML31	7	64
ML33	1	0
ML34	5	0
ML36	6	111
ML37	2	28
ML40	8	115
ML44	7	55
ML48	5	13
ML54	2	35
ML60	3	9
ML61	5	7
ML62	1	4

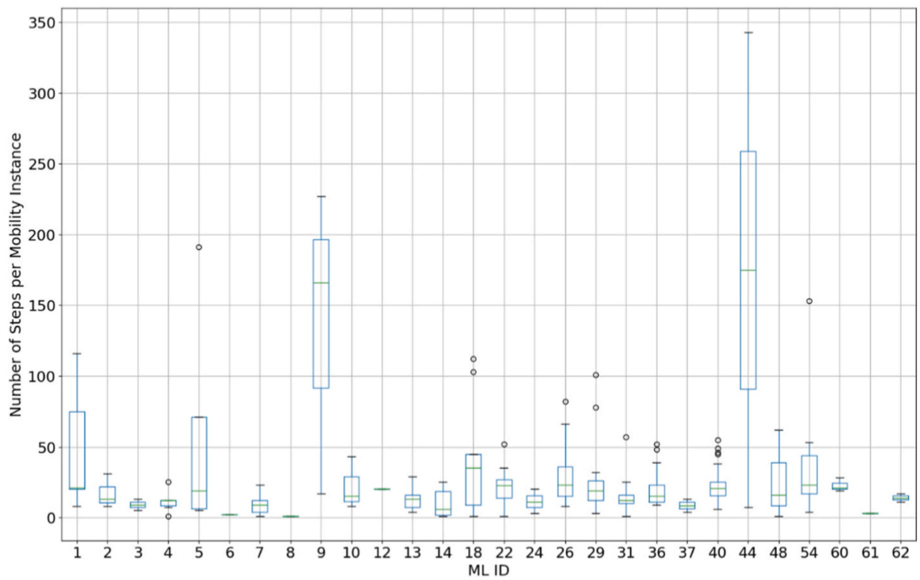

Fig. 4. Box-and-Whisker plot for number of steps per mobility instance for individual mobile lanterns.

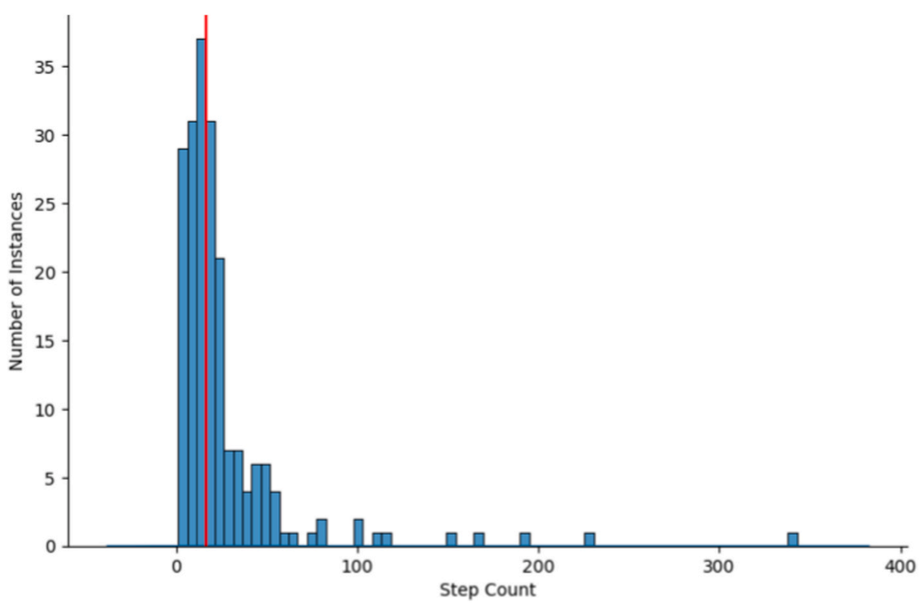

Fig. 5. Distribution of step count per mobility instance across all devices.

contextualise observed usage behaviour (n = 209). Mobile phone ownership was near-universal, with 199 households reporting ownership of at least one phone. In contrast, only 79 households reported owning a solar lantern. Ownership overlapped only partially, 77 households owned both a mobile phone and a solar lantern, while 122 households owned a mobile phone but no lantern. Only two households reported owning a solar lantern without a mobile phone. This imbalance indicates that solar lanterns were substantially scarcer than mobile phones, which may help explain the observed reliance by women on phones for short-duration lighting needs. It also aligns with wider literature on a widespread use of mobile phone torches for night-time mobility (HEED, 2019; Practical Action, 2020).

4. Discussion

The findings suggest that solar mobile lanterns are not consistently functioning as mobility tools for women in the ways implied by their design and distribution narratives. Instead, their use appears shaped by household-level sharing, competing demands for indoor lighting, and the ready availability of mobile phones for short, task-based illumination. This pattern raises questions about whether current lantern designs and distribution approaches sufficiently reflect women's everyday routines, constraints, and priorities in camp environments.

4.1. *Constrained by design*

Across the study, solar lanterns became part of routine household lighting, supporting near-home activities more than extended night-time mobility. The median journey comprised of just 17 steps and lasted only 1.72 min. The limited use of solar lanterns for longer-distance mobility, alongside the high reliance on mobile phone torches for short night-time movement, is not inherently problematic, but it does have implications for women's everyday energy practices in camps. By repurposing lanterns as static lighting sources in the home, women could be responding

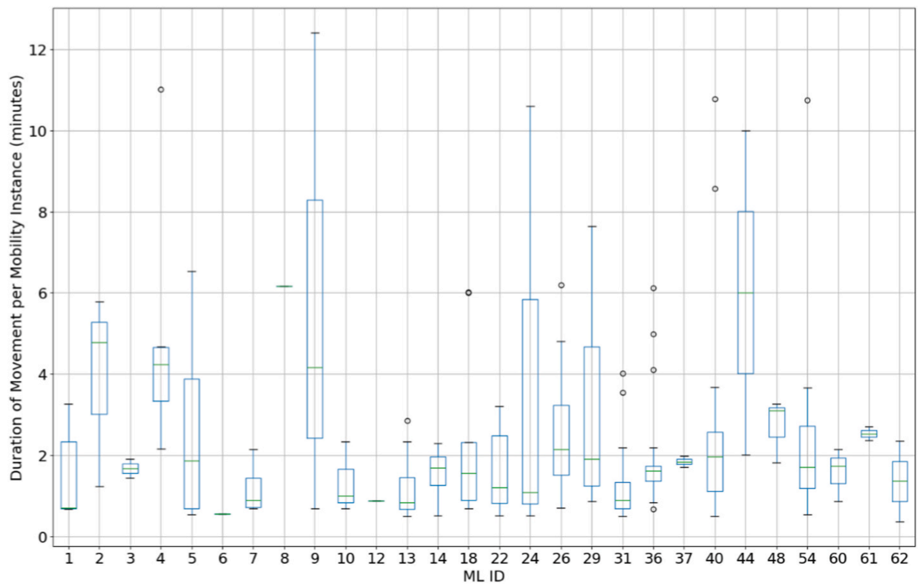

Fig. 6. Duration of each Mobility Instance (minutes) for Individual Mobile Lanterns.

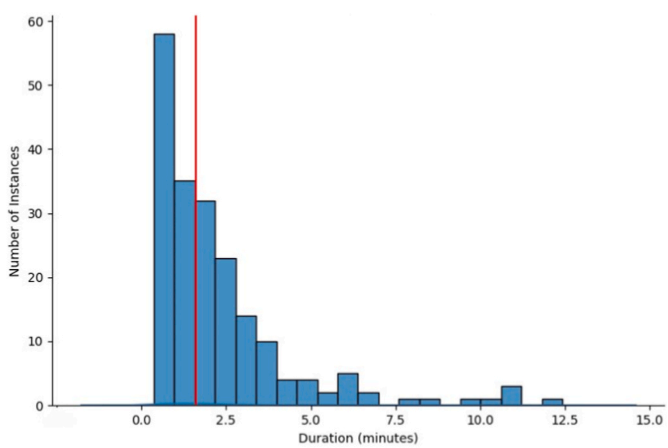

Fig. 7. Distribution of duration (minutes) per mobility instance across all devices.

to how technology devices are accessed and managed within the camp. Mobile phones tend to operate as personal or semi-personal items, whereas solar lanterns are typically distributed at the household level and shared, rather than allocated to women individually. By default, including in our project, women often become custodians of a shared resource and took responsibility for managing access and preserving its use. This framing of the mobile lantern as a collective resource may explain why they prioritise collective domestic needs over personal mobility and reinforcing how energy negotiations are shaped by scarcity rather than choice. By energy negotiations, we refer to the everyday decisions and trade-offs women make that become less a matter of individual preference and more a reflection of constrained agency.

These gendered patterns of resource prioritisation point to the need for humanitarian energy policy to consider not only gendered differences in use and design, but also how energy technologies are distributed, governed, and owned across the supply chain. Research in gender and energy has long shown that women and men experience, value, and use energy technologies differently, shaping how the benefits of energy access are realised within households (Clancy et al., 2019). Insights from our Design for Energy workshops in Nepal and Rwanda reinforce this contention, when discussing how savings from solar energy would be used, men more often described investing in additional appliances, while women prioritised children's education, small-scale livelihood activities, and essential domestic expenditure such as food (Halford, 2024). These same logics help explain lantern use and without attention to ownership and control, humanitarian energy interventions risk reinforcing gendered custodial roles, limiting women's mobility even when technologies intended to support it are present.

4.2. Rethinking the impact of solar lanterns

In energy planning, the concept of lighting ‘utility’ is not fixed, but shaped by need, environment, and risk. In refugee camps, lighting utility is still too often approached through a narrow basic-needs logic, something to be delivered either on an individual or communal level, rather than understood as part of a lived system of movement, care, work, and risk (Rosenberg-Jansen et al., 2022). This framing matters because it shapes how technologies are designed, procured, and justified, and what kinds of impact are assumed to follow from their distribution.

The mismatch between the assumptions around solar mobile lanterns and their actual use exemplifies a broader issue of techno-chauvinism, the overreliance on technology as as a stand-alone solution to complex social problems (Cobbe, 2022). Our findings show that solar lanterns are used predominantly as stationary household lighting, with only brief and localised movement. This does not reflect user failure, nor does it suggest that mobility is unimportant. Rather, it reveals how households actively govern scarce energy within existing infrastructural constraints. For policymakers, this distinction is critical. When mobile lanterns are treated as substitutes for fixed lighting or as stand-alone safety interventions, their impact is easily overstated. When they are understood as one element within a broader lighting ecology, their value, limits, and trade-offs become visible.

It is important to recognise that the shortcomings highlighted by this study are not unique to solar lanterns. Improved lighting, whether in the form of solar lanterns, streetlights, or other devices perceived as outdoor lighting, cannot, on its own, address the deeper social and structural conditions that shape women's safety (Listo, 2018a, 2018b). Such approaches risk overlooking the social relations, power dynamics, and patterns of access that shape how lighting (and access to energy more broadly) is used and who benefits or who bears the associated risks. Rethinking the impact of solar lanterns therefore requires a shift away from device-led claims towards system-level thinking. Sound policy should ask not only what technologies are distributed, but how they interact with existing infrastructure, social norms, and women's

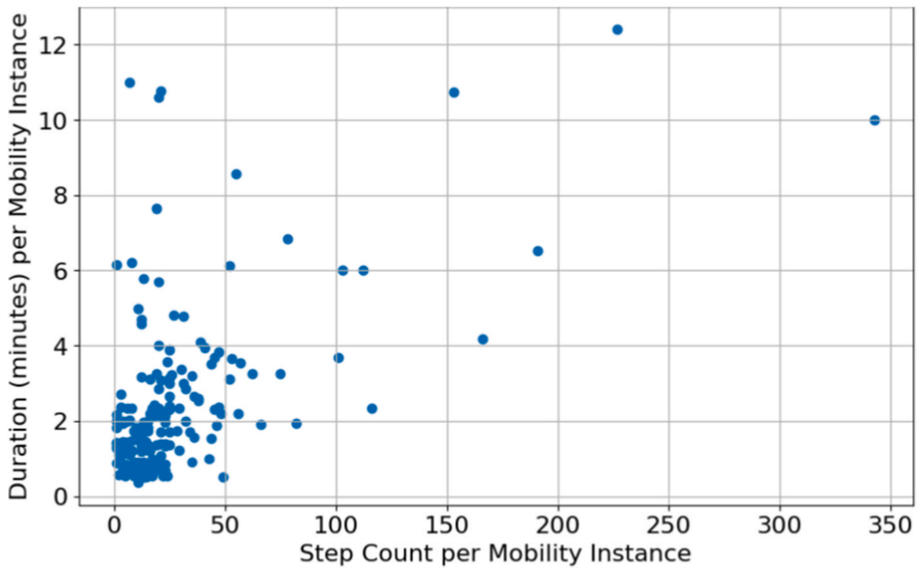

Fig. 8. Step Count Vs Duration (minutes) per Mobility Instance using Solar Lanterns.

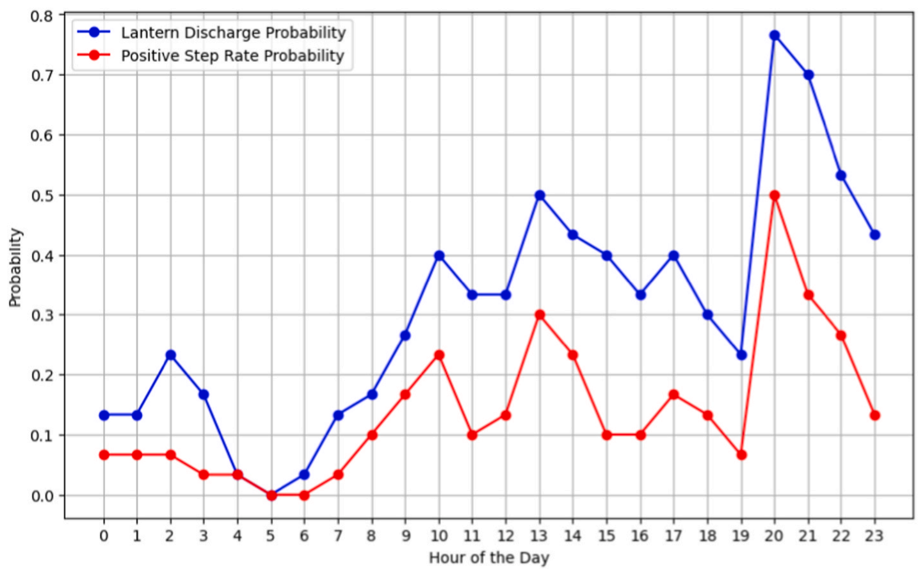

Fig. 9. Probabilities of lantern discharge and positive step rate across hours of the day.

everyday decision-making. Without this shift, lighting interventions will continue to offer symbolic reassurance rather than the substantive support needed to improve safety, autonomy, and life after dark.

4.3. *Going beyond surveys*

Policy and practice must be rooted in the realities of women's energy use. This means engaging directly with women to understand what forms, timings, and placements of lighting work best in their daily lives if interventions are to deliver meaningful and lasting utility. The UNHCR (2020, 2022c) is increasingly moving towards participatory approaches to design and implementation and has a key objective of improving quantitative data from displaced populations. This study highlights the importance of using sensors, rather just carrying out yet more surveys on a survey-fatigued community group. The sensor data offered objective, computable information about lantern usage, tracking movement frequency, journey duration, and battery discharge patterns throughout the day. This combined with qualitative data added explanatory depth to reveal the reasoning and essential context behind usage.

While the sensor data revealed information around the low journey duration and distance, a survey helped explain this usage pattern by highlighting the specific needs and preferences of the users, such as the tendency to use lanterns mainly for domestic chores or to use the latrine. It revealed not just how lanterns were used but also why, allowing for more user-oriented interpretations. This triangulation, where objective patterns in sensor data are corroborated and explained by participant-reported experiences, enhances the credibility and complexity of the findings.

5. Policy implications

This paper focuses primarily on women's experiences of managing and using shared household lighting technologies in Nyabiheke camp, but the patterns identified highlight policy-relevant gaps between design assumptions and everyday use across protracted refugee settings.

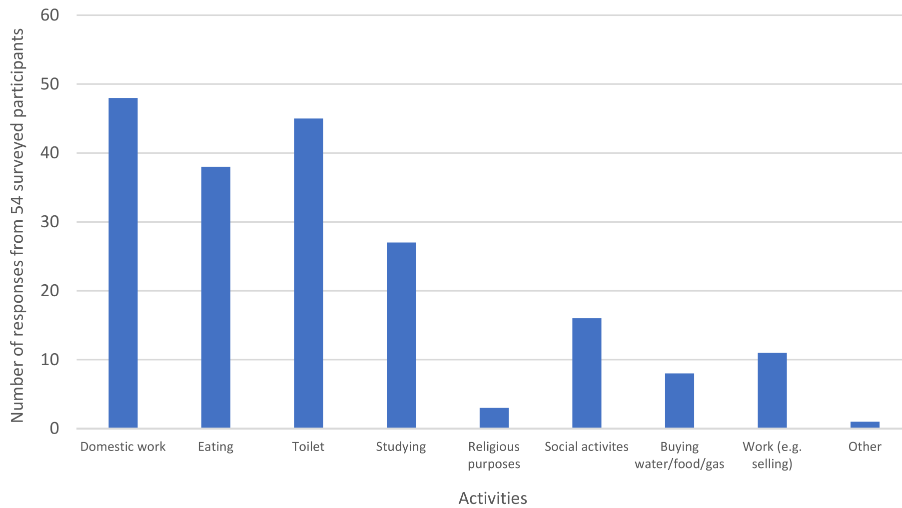

Fig. 10. Primary activities of refugees when using a mobile solar lantern in December 2019.

5.1. Use solar lanterns as part of a phased energy access plan

Solar lanterns are a practical and essential solution in the early phases of displacement, their utility must be evaluated within the broader evolution of the camp setting. Sensor monitoring provides clear evidence that lantern use is predominantly static, with few sustained night-time journeys, while mobile phones are more commonly relied upon for short movements after dark. This distinction is difficult to capture through self-report alone and highlights how lighting technologies are actually used in practice.

As camps transition from temporary to semi-permanent or even long-term settlements, the limitations of solar lanterns become more apparent. If mobile phones have become the primary tool for night-time mobility, and lanterns are largely used as static lights, this raises a critical question for future planning: should efforts focus on producing more adaptable solar lanterns capable of charging phones, or should investment shift towards making mobile phone charging stations more widely available and freely accessible? Either approach requires humanitarian energy planning to position solar lanterns as part of a phased plan, alongside solar home systems, access to mobile phone chargers or communal solar street lighting that better reflect lived patterns of useage.

5.2. Integrate circular economy principles into solar lantern design and deployment

Although solar lanterns are renewable and off-grid, sustainability is not defined by the energy source alone. Our findings show that lanterns are used frequently and for extended periods as static household lighting, rather than intermittently for short-term mobility. This sustained, everyday use places different demands on durability, reliability, and maintenance than those assumed in short-term or emergency deployment models.

Regulatory standards, such as those introduced by the Ministry of Infrastructure in Rwanda (Ministry of Infrastructure, 2022) and recent technical guidelines set by UNHCR for solar lanterns (UNHCR, 2025), aim to improve product performance. Yet, there is less attention given to the end-of-life management of solar mobile lanterns within a broader circular economy framework. For many households, these lanterns become embedded in daily living, rather than used for short-term or occasional mobility needs. This necessitates a policy response that not only plans for product durability and maintenance but also considers sustainable pathways for repair, reuse, and disposal. Integrating circular economy principles into humanitarian energy planning around solar mobile lanterns could therefore, not only increase long-term utility, but also actively contribute to advancing a greener agenda within the humanitarian sector.

5.3. Recognise and respond to the differentiated energy negotiations of camp-based displaced populations through participatory co-creation of solutions

This study provides evidence of how women in refugee camps navigate constrained energy options in practice, making observable trade-offs in how solar lanterns are used within the household. The use of sensors makes these negotiations visible, revealing how lanterns are prioritised, repurposed, and rationed in everyday practice. Despite this active role, these women remain largely excluded from decisions about the design and deployment of energy interventions, resulting in solutions that poorly reflect lived realities.

Cost-effective tools like sensor monitoring offer one promising avenue for systematically integrating user behaviour into energy planning, providing continuous data that reflects real-world use. Recognising solar lanterns as gateway technologies, rather than end-point solutions, positions community engagement, particularly with women, as critical to shaping pathways towards more permanent systems, such as solar home kits. Through co-creation, these pathways can better align energy interventions with how energy is negotiated and valued in camp life.

6. Conclusion

This research shows that in long-term refugee camps, solar mobile lanterns are used primarily as household lights, with very limited evidence of sustained night-time mobility. Most recorded lantern movement is brief and spatially constrained, aligning with survey responses that prioritise domestic tasks and short trips, such as visits to nearby latrines. While these findings do not allow safety outcomes to be measured directly, they do challenge policy and design narratives that assume solar lantern distribution straightforwardly translates into safer night-time mobility for women.

By providing sensor-based evidence of patterns of use, this study moves beyond intention-driven evaluations and shows how lanterns function in practice in protracted displacement settings. For policymakers, sensor-based monitoring provides a practical way to incorporate women's patterns of use into policy decisions, supporting more realistic choices about design, procurement, and complementary infrastructure as camps transition from emergency response to long-term settlement. By reframing solar lanterns as one element within a broader lighting system shaped by women's roles in managing shared household energy under conditions of scarcity, this study has implications for gender-responsive humanitarian energy policy. Solar lanterns can play a meaningful role in supporting everyday domestic tasks and short-distance movement, but their wider impact depends on how they are integrated within complementary lighting infrastructure and women's lived routines. Framed in this way, the insights from Nyabiheke are transferable to other protracted refugee settings and to humanitarian contexts where energy interventions must evolve beyond emergency provision toward longer-term, system-based solutions.

CRediT authorship contribution statement

Isna Ahsan: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alison Halford:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **J.D. Nixon:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Kriti Bhargava:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Elena Gaura:** Supervision, Funding acquisition, Conceptualization.

Ethics statement

This study was conducted in accordance with ethical standards for research involving human participants. Ethical approval was obtained from Coventry University Research Ethics Committee (reference number Ref: P166588). All participants provided informed consent prior to involvement in the study, and participation was voluntary. Care was taken to ensure confidentiality and anonymity, and particular attention was paid to safeguarding considerations given the study's focus on refugee populations.

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.

Acknowledgements

The first author gratefully acknowledges the support of the British Council through the MRes Women in STEM Scholarship 2023/2024, which provided funding for this research.

The authors would like to acknowledge the financial support of the Engineering and Physical Science Research Council (EPSRC) for funding the Humanitarian Engineering and Energy for Displacement (HEED) project as part of the Global Challenges Research Fund (EP/P029531/1). The authors would like to acknowledge and thank project delivery partners Practical Action and Scene Connect for their significant role in coordinating in-camp activities and providing technical inputs and tools. We would also like to recognise the support of MIDIMAR (Ministry of Disaster Management and Refugees) and UNHCR (United Nations High Commissioner for Refugees) and the contributions of the Global Plan of Action, Chatham House, and the RE4R (Renewable Energy for Refugees) Project (a partnership between Practical Action and UNHCR, supported by the IKEA Foundation).

Appendix A. Interview survey on the use of solar lanterns (Rwanda)

Background of participants

1. Age
2. Gender
3. Occupation
4. Education attainment of respondent (No education; 2 years' or less; 3 to 4 years; 5 to 6 years; 7 to 8 years; 9 to 10 years; Over 10 years' schooling; other)
5. Marital status of respondent
6. Number of children (if any)
7. Total number of household members
8. Year respondent arrived in the camp

Uses of the solar lanterns

9. How many solar lanterns do your household own and use in this house?
   a) 1
   b) 2
   c) More than 2
   d) Broken and not replaced
   e) Stolen and not replaced
10. Thinking of the lantern with the monitor attached, how long on average did it take to charge the lantern over the last 30 days
    a) 1-3 h
    b) 3-6 h
    c) More than 6 h
11. In the last 30 days, how many hours were you able to use the lantern after it was charged?
    a) Less than 3 h
    b) Between 3 and 6 h
    c) More than 6 h
12. In the last month, what has the lantern been used for? (select all that apply)
    a) Undertaking domestic work during dark hours (e.g. cooking, washing dishes, change the baby)
    b) Eating, including breastfeeding
    c) Visiting the toilet
    d) Studying
    e) Religious purposes (e.g. attending church)
    f) Social activities (e.g. visiting friends, or attending outdoor/cultural activity)
    g) Buying water/food/gas or other household items
    h) Work (e.g. selling)
    i) Other(s) specify
13. Of all the uses mentioned above, which have been the most important activities for which the lamp has been used over the last month?
14. Have you had any difficulties with the lamp in the last month?
15. If yes, what difficulties have you had
16. Is there anything else you would like to share with us concerning the use of the lantern over the last month?

Data availability

openly available in the Zenodo repository at https://doi.org/10.5281/zenodo.4269809.

References

Abdelnour, S., 2015. The cookstove–rape prevention myth and the limits of techno-saviorism. In: A, Hostettler Silvia, H.E., Gadgil (Eds.), Sustainable Access to Energy in the Global South. Springer International Publishing, pp. 205–215.

Aubone, A., Hernandez, J., 2013. Assessing refugee camp characteristics and the occurrence of sexual violence: a preliminary analysis of the dadaab complex. Refug. Surv. Q. 32, 22–40.

Bisaga, I., Hamayun, M., 2020. Overcoming the data wall: harnessing big data to understand the energy needs of off-grid communities and the displaced. In: Grafham, O. (Ed.), Energy Access and Forced Migration. Routledge. ISBN 9781032082134.

Bradley, T., Liakos, K., 2019. Vulnerability of women and girls in refugee settings: considerations for energy programming. In: Grafham, O. (Ed.), Energy Access and Forced Migration, first ed. Routledge, pp. 122–140. ISBN 9781032082134.

Brusey, J., 2025. HEED monitoring. https://github.com/jbrusey/HEED-Monitoring/tree/master/Lantern/Lantern.
Clancy, J., Barnett, A., Cecelski, E., Pachauri, S., Dutta, S., Oparaocha, S., Kooijman, A., 2019. Gender in the Transition to Sustainable Energy for All: from Evidence to Inclusive Policies.
Cobbe, J., 2022. What is technochauvinism?. In: Technochauvinism. SciencesPo https://www.sciencespo.fr/public/chaire-numerique/en/2022/05/20/policy-brief-technochauvinism/.
Corbyn, D., Vianello, M., 2018. Prices, Products and Priorities Meeting Refugees' Energy Needs in Burkina Faso and Kenya. Chatham House, the Royal Institute of International Affairs.
d.light, 2025a. https://www.dlight.com/products/s30.
d.light, 2025b. https://www.dlight.com/about.
Dynes, M., Tomczyk, B., Rosenthal, M., Hardy, C., Holly, W., Torre, L., Hulland, E., Blanton, C., Rivelli, F., Miquel, J., Shivshanker, A., Ward, L., Metzner, T., Sami, S., Williams, H., 2014. Evaluation of Handheld Solar Lights Among Displaced Populations in Haiti. Centers for Disease Control and Prevention and USAID Office of Foreign Disaster, USA. Assistance (USAID/OFDA).
Dynes, M., Rosenthal, M., Hulland, E., Hardy, C., Torre, L., Tomczyk, B., 2016. Handheld solar light use, durability, and retention among women and girls in internally displaced persons camps in Haiti - 2013-2014. Int. J. Disaster Risk Reduct. 18, 160–162.
D'Ignazio, C., Klein, L., 2020. The numbers don't speak for themselves. In: Data Feminism. The MIT Press. https://data-feminism.mitpress.mit.edu/pub/czq9dfs5.
Global Alliance for Clean Cookstoves, 2016. Gender-based violence in humanitarian settings: cookstoves and fuels. https://cleancooking.org/reports-and-tools/gender-based-violence-inhumanitarian-settings-cookstoves-and-fuels/.
GOGLA, 2019. H1 2019 global off-grid solar market report. https://www.lightingglobal.org/resource/h1-2019-global-off-grid-solar-market-report/.
GoodMarket, 2025. https://www.goodmarket.global/dlight.
Grafham, O., Lahn, G., 2018. Improving how we use and account for energy in humanitarian operations. https://www.chathamhouse.org/sites/default/files/publications/research/2018-1210-MEItoolkit.pdf.
Halford, A., 2020. Working towards modern, affordable & sustainable energy systems in the context of displacement: recommendations for researchers and practitioners. Humanitarian Engineering and Energy for Displacement (HEED) Project. Coventry University.
Halford, A., 2024. Participants or recipients? Negotiating gender and energy as empowerment in the displaced setting. In: Women and the Energy Sector: Gender Inequality and Sustainability in Production and Consumption. Springer International Publishing, Cham, pp. 297–314.
Halford, A., Gaura, E., Bhargava, K., Verba, N., Brusey, J., Nixon, J., 2022. Off the boil? The challenges of monitoring cooking behaviour in refugee settlements. Energy Res. Social Sci. 90, 102603.
Hasan, M.M., Al Baker, A., Khan, I., 2023. Is solar power an emergency solution to electricity access? Findings from the largest Rohingya refugee camps. Energy Res. Social Sci. 103, 103071. https://doi.org/10.1016/j.erss.2023.103071.
HEED, 2019. HEED project data portal. https://www.unhcr.org/sites/default/files/2023-07/2305336E_UNHCR-AR-2022_web_V3.pdf.
Jensen, M.A., 2019. Gender-Based Violence in Refugee Camps: Understanding and Addressing the Role of Gender in the Experiences of Refugees, vol. 11, 02. http://www.inquiriesjournal.com/a?id=1757.
Lehne, J., Blyth, W., Lahn, G., Bazilian, M., Grafham, O., 2016. Energy services for refugees and displaced people. Energy Strategy Rev. 13–14, 134–146.
Listo, R., 2018a. Gender myths in energy poverty literature: a critical discourse analysis. Energy Res. Social Sci. 38, 9–18.
Listo, R., 2018b. Preventing violence against women and girls in refugee and displaced person camps: is energy access the solution? Energy Res. Social Sci. 44, 172–177.
Ministry of Infrastructure, 2022. Ministerial guidelines on minimum standard requirements for solar home systems by ministry of infrastructure, Republic of Rwanda. https://www.reg.rw/fileadmin/user_upload/Ministerial_Guidelines_on_Minimum_standards_Requirements_for_Solar_Home_Systems_2022.pdf.
Nixon, J.D., Bhargava, K., Halford, A., Gaura, E., 2021a. Challenges of community-based solar energy interventions: lessons from two Rwandan refugee camps. Energy Sustain. Dev. 175–184.
Nixon, J.D., Bhargava, K., Halford, A., Gaura, E., 2021b. Analysis of standalone solar streetlights for improved energy access in displaced settlements. Renew. Energy 895–914.
Park, W., Lee, V.J., Ku, B., Tanaka, H., 2014. Effect of walking speed and placement position interactions in determining the accuracy of various newer pedometers. Journal of Exercise Science & Fitness 12 (1), 31–37.
Perkins, 2015. Light impacts SGBV, but not in the way you think. UNHCR Innovation. https://www.unhcr.org/innovation/light-impacts-sgbv-but-not-in-the-way-you-think/.
Practical Action, 2020. Ensuring Refugee Camps in Rwanda Have Access to Sustainable Energy. Practical Action Publishing, Rugby, UK. https://beamexchange.org/resources/1582/.
Robinson, B.L., Halford, A., Gaura, E., 2022. From theory to practice: a review of co-design methods for humanitarian energy ecosystems. Energy Res. Social Sci. 89, 102545.
Rosenberg-Jansen, S., 2018. Research in brief: refugee energy. Refugee Studies Centre. University of Oxford. https://www.rsc.ox.ac.uk/publications/research-in-brief-refugee-energy.
Rosenberg-Jansen, S., 2022. The secret life of energy in refugee camps: invisible objects, technologies, and energy systems in humanitarianism. J. Refug. Stud. 35 (3), 1270–1291.
Rosenberg-Jansen, S., Al-Kaddo, H., Hangi, J., Fohgrub, T., Demir, E., Owen, E.D., et al., 2022. The state of the humanitarian energy sector: challenges, progress and issues in 2022. Global Platform for Action on Sustainable Energy in Displacement Settings.
Smith, J., Blanchet, K., 2019. Research methodologies in humanitarian crises. https://www.elrha.org/docs/document/r2hc-research-methodologies-in-humanitarian-crises-new.pdf?file_url=document/jatnlhf6614gjcoor0atuumr0d/imnodsqei5jhb5q-kjiriowoeo0/original?content-type=application%2Fpdf&name=r2hc-research-methodologies-in-humanitarian-crises-new.pdf.
UNFPA, 2017. Solar lanterns light perilous path to shared toilets in Myanmar refugee camps. United Nations Population Fund. https://www.unfpa.org/news/solar-lanterns-light-perilous-path-shared-toilets-myanmar-refugee-camps#:~:text=Solar%20lanterns%20reduce%20the%20risks,are%20not%20made%20safely%20accessible.
UNHCR, 2011. Action against sexual and gender-based violence: an updated strategy. https://www.unhcr.org/uk/media/unhcr-action-against-sexual-and-gender-based-violence-updated-strategy.
UNHCR, 2020. UNHCR data transformation strategy 2020 – 2025. https://www.unhcr.org/uk/media/data-transformation-strategy-2020-2025.
UNHCR, 2022a. Global report 2022. https://www.unhcr.org/sites/default/files/2024-10/multipurpose-solar-lantern-eco-design-with-unhcr-logo.pdf.
UNHCR, 2022b. Protection-sensitive access to lighting. https://www.unhcr.org/sites/default/files/legacy-pdf/63fcd2fe4.pdf.
UNHCR, 2022c. UNHCR 2022-2026 strategy. file:///C:/Users/ac2569/Downloads/UNHCR%20Strategic%20Directions%202022–2026.pdf.
UNHCR, 2023. Nyabiheke refugee camp. Rwanda - UNHCR Data Portal. https://data.unhcr.org/en/documents/details/106325.
UNHCR, 2024. Mid-year trends, 9 October 2024: key displacement and solutions trends in the first half of 2024. https://www.unhcr.org/us/mid-year-trends?utm.
UNHCR, 2025. UNHCR environmentally friendly procurement. https://www.unhcr.org/sites/default/files/2024-10/multipurpose-solar-lantern-eco-design-with-unhcr-logo.pdf.
Wardeh, M., Marques, R.C., 2023. Progress on sustainable development goal 6 in refugee camps in the Middle East: a comparative study. Util. Policy 82, 101575.
Welk, G.J., Differding, J.A., Thompson, Raymond W., Blair, S.N., Dziura, J., Hart, P., 2000. The utility of the Digi-Walker step counter to assess daily physical activity patterns. Med. Sci. Sports Exerc. 32 (Suppl. ment), S481–S488.