Energy Research & Social Science 90 (2022) 102603

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Off the boil? The challenges of monitoring cooking behaviour in refugee settlements

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ARTICLE INFO

Keywords:
Cookstoves
Humanitarian energy
Data and evidence
Sensors
Socio-technical systems
Internet of Things
Monitoring

ABSTRACT

To address the need for improved access to energy and meet the United Nations Clean Energy Challenge (2019), humanitarian agencies require robust, valid, and meaningful data that documents the everyday energy practices of displaced people. Collecting data through sensor monitoring is one way of providing quality energy data that will aid humanitarian actors in designing and delivering sustainable affordable energy solutions. Using the case of the design and deployment of 20 stove use monitors (SUM) in Kigeme refugee camp in Rwanda, this paper discusses the benefits and limitations of collecting data on cookstove usage using wireless sensors in refugee settlements., Central to the discussion is the value of reflexivity or critical reflection to uncover significant knowledge gaps that can apply more generally to the problem of designing and deploying sensor systems for the displaced setting. If sensor monitoring systems are to collect data that aid appropriate energy planning and support technology development in the humanitarian sector, we contend improvements in sensor design and deployment protocols are needed to accommodate the displaced setting's cultural, economic, and political complexity. These improvements include the uptake of sensor monitoring design that embeds ethical, progressive, and inclusive protocols when working in the displaced setting.

1. Introduction

To address the scale of inequality in access to energy between camp-based refugees and host communities, the United Nation's Clean Energy Challenge [1] is working towards all refugee settlements having access to modern, safe, and reliable energy by 2030. Around 79.5 million people are forcibly displaced globally, with over a quarter residing in refugee camps [2]. An estimated seven million displaced people in camps have access to electricity for less than 4 h a day and heavily depend on traditional biomass and kerosene for household cooking [3]. The continuing use of traditional cookstoves has resulted in environmental overexploitation, with corresponding tension between hosted and hosting communities [4]. Health implications arising from inefficient cookstoves and poor ventilation means women and young people, especially, are disproportionately affected by the continuing use of fossil-fuelled and wood-burning indoor fires and cookstoves [5–7]. There are increased risks involved for refugee women and young girls when collecting wood for traditional cookstoves, as they have been subject to or fearful of acts of sexual violence impacting their psychological and physical well-being [8]. While approaches to gender-based violence and cookstove interventions should seek more complex narratives [9], alternative stove usage that reduces or replaces the need for wood is one action amongst many that combat violence against women in displaced camps.

Humanitarian agencies have aimed to combat the negative health and environmental impacts of using open fires and traditional stoves by distributing free improved cookstoves to camp-based refugees [10]. Energy stakeholders see improved cookstoves (ICS) as the preferred alternative to traditional cookstoves in the displaced setting [11]. ICS are more energy-efficient, produce less harmful emissions and are safer than traditional cookstoves [12] [13]. Policymakers and energy researchers have prioritised cookstove design requirements around improved fuel-efficient and reduced cooking time in the belief that these factors alone will transition stove usage towards cleaner fuel [14,15]. Still, 80% of displaced people living in rural camp locations collect firewood or charcoal to cook with, and stove stacking (where more than

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https://doi.org/10.1016/j.erss.2022.102603
Received 15 September 2021; Received in revised form 31 January 2022; Accepted 28 March 2022
Available online 22 April 2022

one type of cookstove is used) is common [16]. Resistance to the uptake of improved cookstoves as the sole means of cooking is not unique to the displaced setting. Lambe et al. found similar patterns of reliance on wood for fuel when looking at rural communities in Kenya [17]. In Sub-Saharan Africa, only 14% of households have access to clean fuels, with low-income rural households impacted the most by energy poverty [7]. Despite the large volume of research on ICS in the humanitarian sector, there is still much to be done to understand stove usage and cooking patterns in the displaced setting if the clean energy challenge is to be achieved [4].

There are overlaps between the lived experience of camp-based refugees and host communities in accessing clean cooking energy. But adoption of improved cookstoves on a larger scale in the displaced setting is hindered by (camp specific) unreliable supply chains, short term humanitarian funding cycles, and issues around refugees rights (including the rights to work) [13,18]. The literature agrees that to increase up-take of cookstoves, design protocols for ICS should centre around local cooking behaviour, the in-situ performance of cookstoves, availability of fuel and the economic negotiations around the cooking processes [19,20]. Debate continues, however, around whether engineers designing ICS have sufficiently responded to the social and cultural context of food preparation [21]. Abdelnour et al. contend that to design and deploy sustainable clean cooking interventions, projects should aim for incremental changes, be more circumspect when defining the problem or the solution, avoid making assumptions about the end-user and ensure the design process includes users, donors, manufacturers and implementing agencies [22]. Furthermore, critical in the ICS design process is understanding how women and girls use cookstoves without essentialising women to support product sustainability [6]. Insights on cookstove usage index-linked to gender, cultural norms and the political context are necessary to address the gap in humanitarian data on cooking patterns and stove usage.

In the humanitarian sector the use of Wireless Sensor Networks (WSN) to collect cookstove usage data is less customary, with a corresponding gap in the literature. Yet, advances in the Internet of Things technologies [18] and the widespread availability of temperature sensors means that sensing systems can be devised that are low cost and less intrusive than other traditional data methods [23]. Within the limited body of work on sensor monitoring in the complex infrastructure settings, a study in Darfur refugee camp, Ethiopia, shows how WSN systems can productively monitor everyday encounters with ICS's [10]. Likewise, research in rural Uganda demonstrated that a sensor-based system that monitored household fuel supply and cookstove temperature improved the quality of quantified understanding of fuel stacking, technical performance of cookstoves, and cooking habits [24]. Ruiz-Mercado et al. work on temperature dataloggers as stove use monitors (SUMs) in households in rural Guatemala was able to collect data with a high-level resolution accuracy when recording daily use and meal frequency [25].

Thus, if collecting data through sensor monitoring on cookstoves is feasible, relatively affordable, and can produce objectifiable, observable and detailed knowledge, a more critical examination is needed on the barriers in implementing cookstove monitoring more widely in the displaced setting. There is also further scope to explore how sensor data collection can improve the delivery of energy services for refugees and displaced people, and greater enquire on how stove use monitoring 'translates SUMs data into actual benefits for the user' [26]. Nevertheless, the latter requires further research given the requirement for long-term monitoring to underpin future interventions [27] and the influence of short-term monitoring on cooking behaviours [28].

The value of deploying unattended sensor systems in refugee households is the ability for the sensors to produce robust evidence base on the cookstove temperature and time spent cooking in real-time that can improve design principles to future proof sustainable cookstoves solutions and aid the uptake of cookstoves. In addition, collecting sensor monitoring data on cookstove energy usage and camp-based refugees will address a lacuna of in-depth scientific research on current energy usage amongst communities living in the humanitarian contexts [29,30]. Although, recent studies, such as those by Haselip et al. [31], Rafa et al. [32], and van Hove and Johnson [33], have contributed much to debate around how refugees use and consume energy. Still, more research and data, both quantitative and qualitative, is needed to ensure that energy systems reflect the displaced context [3,34,35].

1.1. Socio-technical frameworks

Emerging from post-World War II organisational studies [36], a socio-technical systems approach understands that technologies, over time, become embedded into societal structures [37]. Conceptualising social and technical systems as symbiotic, socio-technical approaches to engineering design with new technology acknowledges how technical advances inform and are informed by social norms in a particular time, context, and culture [38]. A key benefit of socio-technical approaches is the way end users are acknowledged in how technology is applied, integrated or adapted [39]. Similarly, the 'social embeddedness' of technology, when technology coalesces with everyday practices, policies, and values, can inform to what extent these technologies are likely to be viable or sustainable long term[40].

For this research, our theoretical approach to socio-technical approach to designing and deploying sensor monitoring interventions in the displaced setting was shaped by Ulsrud et al.'s (p. 295) [41] idea of 'technological change as a social learning process'. In the context of this paper, we define social learning as the way people and communities (including researchers) experiment, learn, implement, and utilise technologies to embed them into everyday practices [42]. We feel that integrating social learning into a socio-technical framework then shifts the standpoint away from technologies that 'teach the learner' [43](p. 199) and towards empowering communities to connect with the appropriate technologies that reflect their socio-economic-political context [44]. There is also the possibility that approaching socio-technical design as a form of social learning acknowledges how learning will also come through failure or ambivalence in outcomes.

The existing body of evidence of the value of socio-technical approaches in complex settings, such as refugee camps, shows how to optimise delivery and critically inform policy and practices that aid long-term viability and replicability of energy systems and the potential for scaling up interventions [45–47,4].

This paper, however, disrupts established convention to offer new insights and protocols on sensor monitoring design within socio-technical frameworks by exploring the research findings through reflexivity. When working in a context where there is a considerable distance in terms of contextual knowledge and cultural norms between researcher and researched, reflexivity as a method is a way to interrogate visible and hidden cultural and gendered hierarchies [48]. A reflexive researcher can better understand and improve the research process by questioning social relationships with research subjects, seek ethical decision-making, and are accountable for the way knowledge has been produced [49,50]. Reflexivity differs from individual reflections as it is a collective account of how research is constrained and contested through limitations arising from researcher positionality. There has been criticism of this process as self-indulgent, but this fails to recognise that a reflexive stance goes beyond an individual or group introspective examination of the study [51]. Instead, reflexivity holds the wider research discipline to account for how research design includes or excludes certain voices, theories, and practices, which in turn can perpetuate researcher privilege.

Taking a reflexive standpoint towards our study on the deployment of twenty stove use monitors (SUM) in a Rwandan refugee camp from June to October 2019, we asked the following research questions, i) what are the challenges and usefulness for researchers and communities when collecting sensor data in complex settings? ii) how can sensor data collection benefit from design protocols shaped by spatiotemporal, cultural and local socio-economic contexts? and iii) how can sensor data aid the development of socio-technical frameworks to sufficiently meet camp-based refugees' energy needs and aspirations?

By examining our work reflexivity, we hope this paper contributes a more complex, nuanced stance in line with our feminist sensibilities that seek more ethical, inclusive methods when designing and using wireless monitoring systems to improve energy access in the displaced setting.

2. Research design, methodology, and methods

No research design is conceived in a silo; as researchers, we approach the process informed by our respective field of study, as well as our social, intellectual, and political standpoints [50]. As an interdisciplinary research team of social scientists and engineers, the research design was informed by a socio-technical framework, with a particular focus on social learning. Simply put, we wanted a research design that allowed us to understand how to engage people (as well as ourselves) in a learning process about collecting sensor monitoring data in the displaced setting. The intent was to produce research outcomes that generated new avenues of inquiry and alternative discourse around energy policies, products and systems [5] that could positively impact future energy system design, policies, and practices. The overarching research aim was to explore to what extent designing unattended sensor monitoring devices around socio-technical frameworks is a robust systematic method or tool in the displaced setting. A secondary aim was to address the gap in knowledge around energy data and refugees by providing cookstove monitoring data informed by transparent, ethical, and progressive design protocols.

Constructing a research design that could accommodate epistemic differences between disciplines, such as positivist and interpretivist paradigms, is not without tension. One solution is to adopt methodological triangulation, a practice that employs multiple methods that can mitigate data bias by the inclusion of more than one method of data collection [52]. The benefit of triangulation is that sensor data on stove usage could be compared with the qualitative survey responses to identify discrepancies between self-reporting and material reality. Likewise, this approach allowed us to include reflexivity in the research process. In addressing the research questions, this paper critically reflects on how we chose to implement socio-technical approaches in design when collecting sensor data in complex settings. In seeking verity about some of the challenges we encountered in the field, there is an implicit admission that the spatiotemporal, cultural and socio-economic contexts that shape the design process also inform how we conceptualise the research design. This paper, therefore, also queries the researcher as an authority in knowledge production and holds to account their role in the ethical and methodological implications for design in the humanitarian setting.

The data was collected using qualitative and quantitative methods: an energy assessment survey, interviews, and sensor data collection on stove use for a number of households. The survey was conducted in two stages; the first phase was a quantitative questionnaire-based survey conducted with households living in three refugee camps in Rwanda and four displaced sites in Nepal. The survey, amongst other questions about household energy use, asked a series of cooking-based questions, such as the location of cooking, resources shared with other households, ventilation, primary stove type and fuel type, secondary stove and fuel, hours of usage per day on the primary and secondary stove, firewood quantity, and what are some of the important features of stove. The second stage was a series of interviews, and focus group discussions were held with various stakeholders in Nepal and Rwanda.

The sensor data was from twenty stove use monitors (SUM), designed, constructed, and deployed on traditional clay stoves in 20 refugee households in Kigeme refugee camp, Rwanda. In line with Ruiz-Mercado et al. (p. 459) [25] definition of SUMs, these devices could provide objective stove-use data through measurement of ‘physical or chemical parameters’, in this case, temperature, of stoves. SUMs are an unobtrusive method of collecting data that addresses observational bias that ‘people act differently when they know they are being observed’ [53]. The SUMs were designed to measure temperature within and outside the stove to understand the stove usage (time of day, duration and frequency) in refugee households. Before designing and deploying the sensors, 202 households were surveyed to establish a baseline of cookstove activity and appliances [54]. The sensor data was collected in two phases over four months (July–October 2019). The project delivery partner was Practical Action, a development agency that supports and develops innovative solutions for agriculture, water and waste management, climate resilience, and clean energy in partnership with communities. Permission to conduct the research was obtained from MINEMA and UNHCR representatives in the camp, and ethical approval was sought and granted by Coventry University (Ref: P61091).

The SUMS were designed for clay stoves with briquettes, three stone stoves, and advanced clay stoves, with an understanding the fuel used would be briquettes. Although policy initiatives in Rwanda are working to move away from clay stoves that use fossil or wood as fuel, the rationale for attaching the sensors to traditional clay stoves was in a setting where fuel, energy and financial resources are scarce, clay stoves were still the most commonly used stove. Similarly, in response to a ban on the supply of firewood to refugee camps as part of a strategy to reduce Rwanda's reliance on wood fuel [2], the data collected was evidence of how clay cookstoves were used during a time of transition towards less environmentally damaging fuel, like briquettes.

2.1. Case study: Kigeme Camp, Rwanda

Kigeme refugee camp (Fig. 1) is in the Nyamagabe District in Rwanda's Southern Province. The camp was established in 2012 and is home to around 18,000 refugees escaping conflicts between government forces and militias in the Democratic Republic of Congo [2]. Kigeme refugee camp has a limited connection to the main electricity grid [55]. Camp residents live in metal-roofed mudbrick dwellings with no main electricity and where traditional mud (clay) cookstoves or three-stone stoves are still the primary methods for heating and cooking [56]. UNHCR provide access to cooking energy through cash assistance programs [57]. Most cooking occurs either inside the homes or a separate building with no ventilation and most households ‘fuel stack’ [58]. For the past four years, and until it ceased operating, the cookstove company Inyenyeri in partnership with the UNHCR, provided free fuel-efficient stoves, which used sustainable biomass fuel pellets purchased from the suppliers [59].

2.2. Sample and recruitment

Prior to deployment, permission to recruit participants in the research programme was approved by MINEMA and UNHCR representatives in the camp. Recruitment for the SUM study began in March 2019 and was organised through Practical Action. Prospective participants were selected if they used a clay stove primarily for cooking and were not expecting to be resettled for six months from the beginning of the study. The sampling was purposive, with a random draw of 20 households being made from those who expressed an interest in joining the study. This was done in the presence of representatives of the refugee committee, camp management and UNHCR, with care taken to ensure fair participation. As we were simultaneously conducting another energy intervention in the same location (building a standalone PV-battery microgrid for two nurseries and a playground) and given another larger-scale energy project operating in the same Rwandan refugee camp, the Renewable Energy for Refugees project (RE4R) [60], we were mindful to avoid over-research with participants. Research fatigue amongst refugees is well documented, which can result in distrust or hesitance to participate in research [61]. In addition, drawing upon ethnographic research design principles that the volume of interviews are less relevant than a deep understanding [62], the number of cases allowed us to reach

Fig. 1. A view over Kigeme Camp, Rwanda, July 2019.

saturation and gain new insights into cookstove usage in refugee camp-based settings.

2.3. Stove use monitor (SUM) sensor design

The SUMS were designed for clay stoves with briquettes, three stone stoves, and advanced clay stoves, with an understanding the fuel used would be briquettes. Accordingly, custom SUMs were designed to measure both the inside stove and outside shell temperature using a thermocouple and Si7021 temperature and humidity sensor, respectively (see Table 1). As we would be monitoring the use of briquettes in clay stoves, the thermocouple, the main component to monitor stove use, was designed to withstand temperatures of up to 1000 °C. The sensors were connected to an Arduino MKR GSM 1400 board, which processed data collected by the two sensors to detect instances of stove-use using an event-based algorithm called Edge Mining [63]. Whereas the SUM was programmed to sense data every minute, the temperature values, along with the timestamp, were recorded only if a significant change in either of the temperature values was detected compared to the last stored values or the time since the last value was recorded exceeded a given threshold. The data was stored locally in an SD card fitted in an Arduino MKR mem shield, connected to the Arduino board, and sent to a remote server hosted at Coventry University via GSM-MQTT communication.

Table 1
SUM components and description of purpose.

SUM component	Description
OMEGA K-type thermocouple	Sensor to measure temperature within-the-stove
Sparkfun Si7021 sensor	Sensor to measure surface temperature outside-the-stove
Arduino MKR GSM 1400	Micro-processor board
Adafruit MAX31850 board	Amplifier to connect the thermocouple to MKR GSM board
GSM antenna	External antenna for GSM communication
Arduino MKR mem shield	Memory card shield
3.7 V battery	Rechargeable battery to power a SUM
IP65 casing	Casing to package the device
Silicon sheets	Insulation

The SUM was powered by a rechargeable Li-Ion battery of 3.7 V and a rating of 7.59 Wh and enclosed in an IP65-rated casing for mounting on the stove. The event-based data collection significantly reduced the number of packets transmitted via GSM and increased the expected battery lifetime of the SUM from 1 day to 1 week (considering 2–3 instances of stove use per day), after which the battery had to be replaced and recharged. The monitors were secured using metallic horseshoe clamps that went around the inside cavity of the clay stove to hold the devices in a fixed position. An additional layer of silicon padding was placed between the device and stove to prevent damage through heat dissipation. Due to variation in the design of clay stoves, the thermocouples were placed inside the stove either through the stovetop or a cavity on the bottom, as shown in Fig. 2.

2.4. Deployment

As will be discussed later, the deployments presented the team with some logistical challenges. For example, most stoves were located in a small corner inside the house with no light or ventilation, thus making it difficult to assess the fixings and given the poor network reception in the camp, situating SUMs in these locations would impact the GSM functionality of the monitors. There were also difficulties in testing before the team left the camp. Often, devices could not be tested at deployment due to a lack of briquettes or households had just finished or were in the process of cooking, meaning the stoves were hot and the rooms crowded.

The number of stove use instances per day for each SUM averaged between 0 and 3, with the exception of one SUM, all stoves recorded seven or fewer instances of stove use. The duration of average use varied considerably, with certain instances lasting for more than 10 h (for more detailed data on stoves, see [64]). Some of the varieties we encountered in the data can be attributed to installation, such as the position of SUM in the pit/cavity and thermocouple, the way the stove retained heat, and the physical environment of the stove caused the SUM to misfunction. A case in point, looking at the data collected on the thermocouple temperature for SUM 17 on a random day of study (4th Oct 2019), two distinct instances of activity or stove-use can be observed – one during the day and another at night. While the change in temperature is rapid at

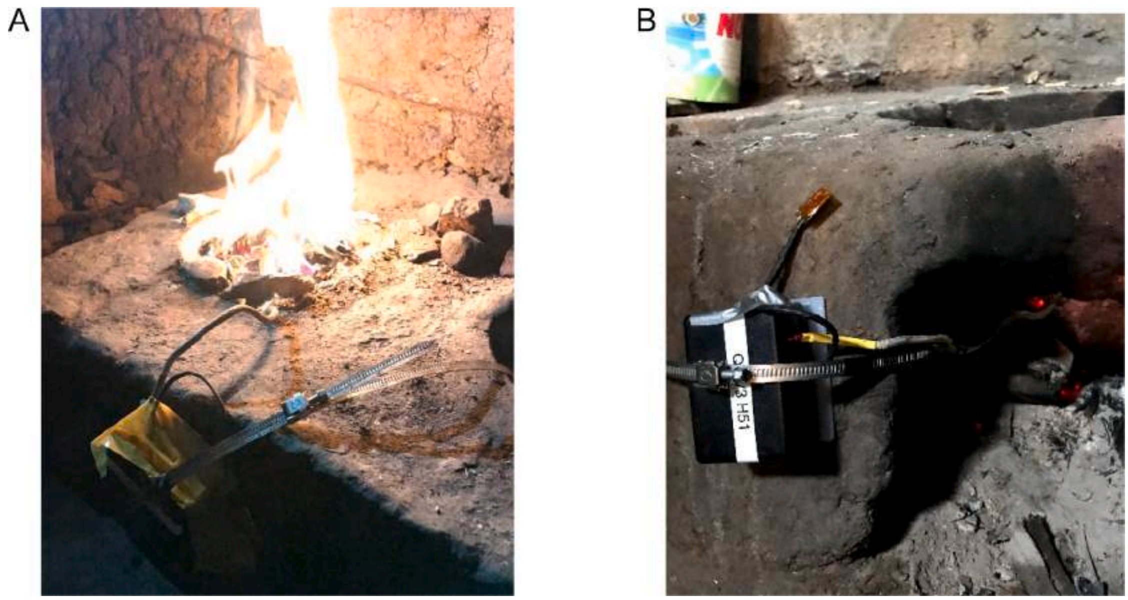

Fig. 2. SUM deployed on a clay stove showing a thermocouple placed through the stovetop (a) and through the cavity at the bottom (b).

the start of an activity, the change is rather slow during the stove cool down. As a result, the temperature within the stove remains well above the ambient temperature even when the stove is cooling down or idle prior to the start of a subsequent activity instance (Fig. 3).

However, taking the density distribution of duration of use per instance for all SUMs along with the mean value suggests that most cooking activity lasts for 2 h.

Similarly, we have defined active cooking as subsequent active cooking periods that are individually larger than 10 min, where the thermocouple temperature is higher than 100 °C and the time difference between these instances is less than an hour. This high threshold ensures that a fire is going on in the stove and that fluctuations in temperature across long term cooking do not result in separate instances being identified. The resulting layered cooking instances can be seen in this random selection of SUMs data (Fig. 4), where there are expected peaks around mealtimes preparation the cooking instances at 12 pm and 7 pm, suggesting preparation of two meals per day on average.

2.4.1. Phase 1

Deployment of the SUM was conducted in two phases. The first phase was from July 2019 to September 2019, when SUM was deployed on 15

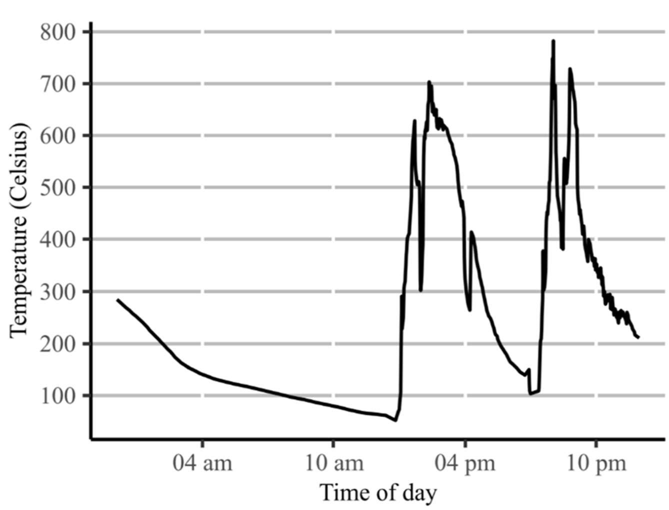

Fig. 3. Thermocouple temperature for a SUM on 4th October 2019.

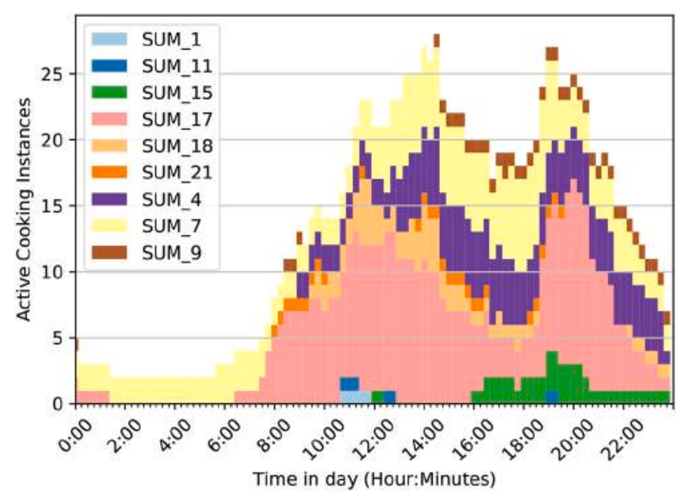

Fig. 4. Phase 2 stove usage daily cooking instance distribution stacked per SUM, October 2019.

clay stoves. Post-deployment, we experienced two long-lived challenges. Firstly, poor network connectivity led to GSM and MQTT connections failures throughout the first three months of the study. Due to these missing timestamp values that were to be collected using the get-GSMTime functionality, this caused considerable gaps in data collected by SUM.

Consequently, these connectivities failings led to poor yield for all SUM, as shown in Table 2, where yield is calculated as the number of observations recorded with valid timestamps (and sent successfully to the server) as a percentage of a total number of observations recorded. For example, SUM_1 delivered the lowest yield for all devices with 0.01%, the highest by SUM_3 with 13.7%, and the mean yield for all devices was 6.45%. Moreover, the packet retransmission attempts caused rapid battery loss for the SUM, resulting in shorter battery lifetimes.

Secondly, it emerged that some participants resorted to using alternative fuels such as charcoal and firewood instead of briquettes (for reasons explained in the next section). These fuels evidently burn at temperatures above the upper threshold of the thermocouple used and cause damage to the thermocouple and other components of the SUM.

Table 2
Yield of data collection for the nine undamaged SUMs in study phase 1 between 1st July 2019 and 30th September 2019.

SUM ID	Yield (%)
SUM_1	0.01
SUM_3	13.7
SUM_6	6.2
SUM_7	13.3
SUM_11	5.7
SUM_12	6.9
SUM_15	3.2
SUM_16	6.5
SUM_18	6.6
SUM_19	2.1

As a result, by the end of phase 1 of the study, 9 out of 15 SUMs were damaged. In response to the damage to SUM and poor quality of data gathered, phase 1 of the study was terminated, and a new SUM was designed and deployed.

2.4.2. Phase 2

Phase two of the study saw re-designed SUM deployed for a period of two weeks in October, with data last collected on 17th October 2019. The adjustments made to the SUM design included adding an external Real-Time Clock (RTC) module to the SUM to gather accurate timestamps. The use of GSM functionality was discontinued, and the data was only stored locally on the SD card. The uneven supply of briquettes was resolved by pre-purchasing 53Kg of briquettes for each household participating in the study. These changes resulted in 100% data yield for all SUM as all temperature values were recorded along with valid timestamps measured by the RTC module and prevented accidental damage to the SUM owing to the use of briquettes as the only fuel.

The SUMs were intended as unattended recordings of cooking patterns, and once the SUMs were deployed, there was minimal field involvement for researchers, which offset the cost of the sensors. However, during both monitoring phases, refugees were employed and trained as community mobilisers to conduct basic checks on the SUM in-situ. Their main responsibilities were to (weekly) ensure the thermocouple was in the pit/cavity of the stoves, that the devices have not been damaged or removed from the stoves, check on the availability and use of briquettes, and monitor the battery and replace if necessary.

3. Results and discussion

The objective of the research was to explore to what degree wireless systems aid data collection to inform and improve socio-technical energy design frameworks for cookstoves in the displaced setting. The study did achieve its aim, in so much as it demonstrated that it is possible to collect sensor data unattended to measure cookstove usage and cooking practices. However, in line with Sovacool et al. [65] as 'research that draws attention to the critical analysis of powerful social institutions that shape the design of technological systems and the agendas of research fields', this paper's contribution goes beyond addressing questions around the efficacy of sensor monitoring unattended systems and the benefits of using sensor monitoring data to understand energy needs and usage of displaced people. In suggesting a shift towards a more inclusive, ethical, and progressive approach to scientific enquiry around sensor monitoring design, these findings address questions around the challenges of collecting sensor data in infrastructure-less environments. There is also an exploration of best practices when designing and deploying WSN to collect data to understand energy behaviours and attitudes.

3.1. The challenges and usefulness of collecting sensor energy data in the displaced setting

In an environment where resources are scarce, any study implementing untested data collection methods introduces an additional element of risk and uncertainty on whether the tool designed can provide adequate responses to address the studies objectives. One of the challenges we encountered when collecting sensor monitoring data was the complex negotiation around energy poverty in refugee households. Project myopia around the lived experience of energy poverty is not limited to the displaced setting [21]. Notwithstanding, the dominant policy and political milieu around displaced settings often see refugees are framed or conceived as communities in transit rather than potential settled residents [66]. This is one reason why, along with humanitarian short-term funding cycles, result in immediate temporary energy solutions rather than long-term infrastructures [67].

Sustainable, affordable, and appropriate supply chains are critical in producing clean cooking solutions in the displaced setting. In this research, we found that the lack of a robust supply chain for fuel forced refugees to revert back to fossil or wood, which impacted the quality of data and the function of the SUM. Survey responses indicated wood was still the primary fuel type used, and charcoal was secondary, with households buying up to an additional 60 kg of both over a month [54]. Nevertheless, the governmental ban on the supply of firewood to refugee camps informed our decision to design SUMs using briquettes for fuel, with the assumption there would be in place a reliable chain supply during the study. Collecting sensor monitoring data on how cookstoves were used during a period of transiting from wood to briquettes could help plan future changes towards a less environmentally damaging fuel in the humanitarian setting.

During phase 1 of deployment, before the SUMs were installed, households were aware they should only use briquettes or otherwise the SUMs could malfunction. The means to purchase briquettes was transferred via the mobile app to refugees, but despite assurances by camp staff, the supply of briquettes in Kigeme camp proved unreliable and intermittent. As households struggled to access a reliable and affordable source of briquettes to light their stoves, with no other choice they used charcoal and firewood for fuel. As wood burns at temperatures above 1000 °C, this caused damage to 9 of the 15 thermocouples and other components of the SUMs through heat dissipation. In contrast, in phase 2, we pre-purchased sufficent briquettes for the length of the study , which resulted in the correct fuel being used with the SUMs.

If we had considered more carefully how to resolve supply chain issues before deployment and been more transparent with participants around the impact of using fuel other than briquettes on the performance of SUM thermocouple, we might have collected higher quality data. For example, we knew from the surveys that wood was still the main fuel, but we anticipated refugees would automatically shift to briquettes in response to policy change. More thought also should have been given to how households fuel stack [68,69]. Through reflexivity, we acknowledge that not collecting data on how households fuel stack when resources are scarce is a limitation of this study. Moreover, our framing of refugees as passive participants in energy decision making failed to recognise that they would and could choose to decide what fuel they would use, including what was readily available and affordable, irrespective of camp policy change.

Equipped with greater insights around the politics of energy supply chains and supplies in the displaced setting, we would have sought design considerations that acknowledge how households may not always have access to supply of briquettes or used a thermocouple that withstood a range of fuels that can possibly be used for cooking in a clay stove. Retrospectively, we should have created protocols to address if/when participants struggled to access or lacked the financial means of acquiring briquettes for their cookstove for the study's duration.

3.2. Principal protocols: designing cookstove sensor monitoring for the displaced setting

Sensor data can deliver fine-grained automated measurements. In conjunction with qualitative findings, it can articulate complex scenarios, making it a critical tool in developing design energy frameworks that respond to immediate and future community energy needs [70]. Other studies have shown that deploying wireless sensing systems in the displaced setting can offer granular insights into cookstove usage in refugee households [10]. Therefore, it could be assumed that existing sensor design protocols need little adaption to gather objective replicable data on stove usage in precarious environmental and political landscapes, like the displaced setting.

We suggest otherwise: that sensor design frameworks adopt what we have termed '*principal protocols*' to anticipate some less predictable deployment challenges around wireless systems in the displaced setting and identify best practice for sensor monitoring in the humanitarian contexts. We define principal protocols as *inclusive, ethical, and progressive sensor design principles that prioritise socio-technical frameworks*.

To conceptualise principal protocols, we critically interrogated what it means to design energy systems in an inclusive, ethical, and progressive framework. Choosing SUMs as the case study for reflexivity was a deliberate act to recognise the discourse around gendered roles and cookstoves, including socio-cultural cooking practices that reinforce inequality and how gender informs decisions around cooking and cookstoves [15]. For instance, in the Kigeme survey, data collected reinforced the extent women are central to household cooking systems, as they are involved in the collection, production, and bartering of fuel and cooking [54]. In comparison, there are relatively few discussions on how wireless monitoring can define and measure comprehensively the impact of interventions on household gender dynamics in the displaced setting [28]. The lack of access to clean energy is gendered but so too are the design processes. Approaching the study with a commitment to greater ethical and inclusive design protocols, collecting sensor data on stove usage, and with the insights gained through qualitative research, we hoped to address androcentric cookstove system design.

Principal protocols recognise and aim to address concerns around inequality, inclusion, and informed consent when sensor monitoring. Concerns about transparency and informed consent are not unique to the displaced setting, but when working in a context where people have been exposed and subject to violence and exploitation, energy sensor design protocols should prioritise an ethics of care.

Without interrogation about how we can address inequality in shaping design protocols for new technologies, like WSN systems, there will continue to be imposed narratives that are essentialising women and are not necessarily reflective of best practice on how refugees are using stoves in their houses. Likewise, greater reflexivity around inclusion, ethics, and progressive protocols when designing sensor monitoring systems will strengthen the evidence base and support critical approaches to sustainable policies for cooking in refugee settings (Table 3).

Table 3
An example of inclusive, ethical, and progressive sensor design principles that prioritise socio-technical frameworks using gender as a case study.

Sensor design principles	Barriers/concerns	Protocol	Example
Inclusive	SUMs that look at patterns and trends in stove usage without including users, who are mainly women, in the design stage or reporting back the findings.	Ask women what they feel is important to know about their cooking patterns and incorporate them into the design framework. Report back findings with them to address gaps in knowledge and to reciprocity.	Sharing data with the women will establish why and what behaviours resulted in high stove usage outside of anticipated peak times. I.e. why in some cases, the SUM showed the use of the stoves was longer and even at night (see Fig. 4).
Ethical	ICS's equipped with SUMs without explicit consent from the women for the SUM on the cookstoves or explain the function of the SUM to participants [72].	Adopt robust ethical frameworks emphasising consent to monitoring and/or engage with the SUMs systems. Seek to uncover gender-partiality that homogenous the female experience.	Engage women in understanding the purpose of the SUMs and why use sensors for the study. Allow them to reflect and respond to how participation in the research with SUMs could inform stove usage or cooking practices, deployment, design improvements or cooking practices.
Progressive	Traditional positivist approaches to sensor monitoring and ICS design largely overlook the structures of power that silence marginalised communities, who have less access to economic power and political influence, such as displaced people and particularly women.	Interrogate how the research design of SUMs can collect data on the gendered dynamics in cookstoves' design, production, and deployment. Question unconscious bias, which is reproducing androcentric/ Eurocentric knowledge and/or authority	Ask marginalised groups, women, young people, older people and those with disabilities, what knowledge/ skills they need to shift towards a broader inclusion as part of the design process. To avoid essentialising stove use or cooking practices as exclusively female domains, include men (separately or together) in the discussion but ensure decision making is shared between groups.

3.3. Socio-technical frameworks: complex problems need complex solutions

In this research, we looked at how WSN, when collecting sensor data for stove usage in the displaced setting, can aid decision making that centres around a socio-technical framework in energy planning, technology development, and adaptation. Research-grade wireless sensors need both structure and infrastructures to achieve both high yield and reduce damage. But there is also a need for research structures that connects communities with research findings to build resilience and capacity through engaging with new technologies and promoting energy literacy. How can displaced communities make informed choices about energy systems without the relevant knowledge on how these solutions adapt to different phases of humanitarian crisis and respond to the cultural significance of cooking rituals, meaning, and performances? Arguably, therefore, what is needed is not necessarily more cookstove monitoring data that focuses on how the stove performs but sensor data that monitors cookstoves as cooking activities to explore multiple realities.

Comprehensive and systematic sharing of energy sensor and survey collected data appears to remain between energy stakeholders, policymakers, or academics. To produce socio-technical frameworks, reciprocity, where research data is shared with participants, is critical in generating a collective understanding of best practices in addressing energy provision for domestic consumption in the displaced setting. To illustrate, the SUM data permitted triangulation with the survey responses, which identified the connections and disconnections between self-recorded and real-time stove usage. So, survey responses found the majority of participants (75%) reported that their primary stove (clay stove) was used on average between 2 and 5 h a day, and usage was never less than 2 h or more than 7 h [58]. Notwithstanding, sensor data indicated the stove use per instance was far more varied between devices and across days for the same device (see Fig. 5).

Reporting back findings to participants allows them to identify why cookstoves were in use for longer than stated (e.g., was it to heat water, batch cooking, or cooking for more people), which in turn allows refugees to become more informed about their use of cookstoves and energy needs and trends.

4. Conclusion

The usefulness of sensor stove use monitoring lies with the ability to produce meaningful, robust data unattended with relatively simple data processing techniques from sparse data sets in refugee households with limited and irregular cooking fuel supply. Moreover, data in the hands of participants could be a useful tool in dismantling barriers to the uptake and adoption of ICS. Significantly, engaging participants in conversations around perceived and actual lived practices and behaviours around stove usage could generate broader discussions on the role of improved energy in the safety, well-being, and protection of refugees. This could also avoid researchers assuming they have sufficient or appropriate knowledge about the end-users and encourage a gradual but embedded uptake of clean energy cooking solutions [22]. To support the transition to an inclusive, safe and sustainable low-carbon society, refugee communities will need to engage with new technologies and understand renewable energy benefits. In acknowledging that there was insufficient consideration of how to improve digital literacy when communicating technical concepts to participants, we hope to address the reluctance of researchers to disclose project shortcomings that inevitably occur when researching challenging settings.

There are continuing unfulfilled data needs around sustainability and engagement when designing cookstoves for displaced communities. If located in a broader understanding of camp-based displacement, sensor data has the potential to inform policy, improve the design of energy systems and encourage the provision of affordable and appropriate energy infrastructures to develop livelihoods, build community capabilities, improve health, and achieve life potential. This research shows how sensors can be used in unattended deployments and embedded in difficult and complex environments and how reflexivity engaged before, during, and after the design stage can benefit technical considerations and solutions and promote shared decision making between the research team, participants and humanitarian stakeholders.

Similarly, ethical considerations around the way data is collected, stored, and disseminated should be transparent to participants in the study. Including traditionally excluded or marginalised groups in a meaningful way before starting the design stage could address ethical implications sooner and anticipate the potential difficulties for field-deployed sensor systems when delivering them in political and economic sensitive environments.

In discussing what we have learnt from the study outcomes, we hope to disrupt narratives around notions of what is meant by successful research milestones or outputs. We show that the limitations or difficulties encountered in the research process are equally profound impactful contributions to knowledge by presenting opportunities for improved project resilience and build researcher capacity. Moving forward, we suggest that when utilised within a socio-technical framework underpinned by principle protocols, sensors to collect energy data could offer a more granular explanation of how camp-based refugees and displaced people use energy daily. In turn, researchers will become better prepared to delivery and design culturally appropriate energy systems that reflect and respond to the humanitarian setting.

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.

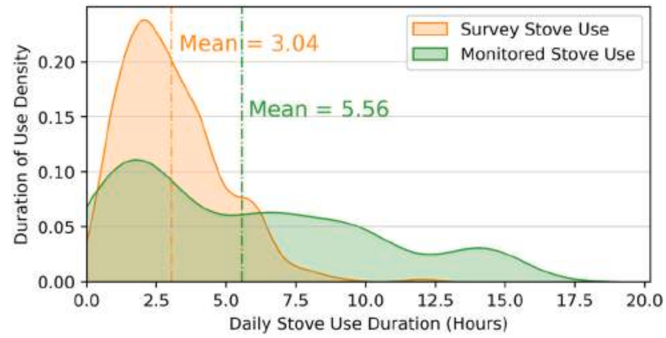

Fig. 5. Survey stove use data compared to sensor monitored stove use data.

Acknowledgements

The HEED team would like to acknowledge the financial support of the Engineering and Physical Sciences 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 HEED team would like to 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).

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