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Research article

Management of environmental impacts of fossil fuel use in refugee camps through transition to renewable energy infrastructure: Case studies in Uganda and Bangladesh

AbuBakr S. Bahaj [*,1], Majbaul Alam [1], Luke S. Blunden [1]

Energy and Climate Change Division, Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, SO16 7QF, UK

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ABSTRACT

Many refugee camps exist for decades but associated infrastructure needs are only planned for the very short term, including provision of power. This study advocates a shift in approach to sustainable electrification of essential services in refugee camps for lighting, refrigeration, health, water, education, alongside camp operations. Qualitative and quantitative surveys were conducted in refugee camps in Uganda and Bangladesh which assessed the electrical supply needs across such categories. A range of solar photovoltaic (PV) power systems (Solar Home Systems, AC/DC mini grids) and their emission mitigation potential were modelled based on survey data. Proposed designs were compared with presently-used diesel systems in terms of applicability, environmental impact and economics. Results indicate significant cost savings are achievable through the PV systems deployment for different areas in two major refugee camps. Estimated savings range from USD31,000–140,000 and USD166,000–653,000 for five-year and twenty-year project lifetimes respectively. These savings apply to sub-areas of much larger camps, with potential savings increasing substantially if scaled to the whole camp. Results indicate that PV-battery systems were more cost-effective than diesel, even for five-year projects, with investments recoverable in second year of operation. Furthermore, replacing the existing 50 kW diesel generator in Bidi-bidi camp with a 40kWp PV-battery system would result in a reduction of 2.4 $MtCO_2e$ over a 20-year project lifetime. Adopting presented approaches will enhance humanitarian service provisions, reducing both cost and emissions. These findings are applicable to many refugee camps in Africa and Asia that have similar solar resource and lack of grid access.

1. Introduction

Geopolitical instabilities create human and environmental impacts that need to be addressed through research and development, and international action (Nguyen et al., 2023). Currently, there are around 120 million forcibly displaced people worldwide and 43.4 million of these are refugees (UNHCR, 2024). Around 40% of such population are children who immediately need access to core services such as education, health and clean water that will require energy. Many low and middle-income nations which are persistently struggling with their own welfare are hosting 75% of global refugees (UNHCR, 2023). Uganda reported 514,000 new refugees mainly from South Sudan in the second half of 2016 (UNHCR, 2016) and Bangladesh had 700,000 Rohingya refugees from Myanmar in August 2017 (UN Women, 2018) bringing the total to 1.4 and 1.1 million refugees respectively in these two countries. Provision of electricity for such forcibly displaced people is imperative as it will open up opportunities to provide needed support services. For example, in Bangladesh, refugee camps need indoor lighting for more than 180,000 families, over 16 million litres of safe water every day, lighting for 50,000 toilets, 5000 equipped classrooms, 43 primary health centres, 144 health posts and 100 nutrition centres (Global Focus, 2018). All these services are dependent on the supply of electricity. Moreover, camp operation activities, street and premises lighting, security lighting, onsite relief storage, refrigeration for medicines, etc. need uninterrupted electricity supply.

Forcibly displaced people, many of whom become refugees, are understandably subjected to policies with the immediate aim to provide critical needs such as shelter, water, food and medical support. The

* Corresponding author.
E-mail address: a.s.bahaj@soton.ac.uk (A.S. Bahaj).
[1] (https://energy.soton.ac.uk/).

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actions are inherently centred around such urgent provisions in the hope that many of the refugees will not stay for long in the provided facilities. However, this is invariably not the case, with many refugee camps existing for decades; on average refugees live 17 years in the allocated camps (Jeffries, 2017). Aung et al. (2021) found that in the case of Rohingya refugees, regardless of several initiatives of negotiation between the governments of Bangladesh and Myanmar, and UNHCR, the majority of the families were not willing to return to their home country. This is generally the case globally in other countries hosting refugees (Zetter, 2020). Although energy services underpin many needs of such forcibly displaced people in emergency situations, from cooking and lighting to medical treatment; humanitarian agencies designated to care for the refugees do not have the wherewithal to address providing such services from the beginning. This is mainly due to their concentration on other essential services, prioritisation of typically insufficient funding and inadequate long term policy planning for energy services including electricity supply. Energy infrastructure, especially electrification, is seen as a long-term investment, and thus difficult to justify or foresee in the context of immediate emergency relief. As such, access to electricity is seen as a core concern from a long-term development perspective but frequently falls outside the remit of instantaneous humanitarian responses (Bellanca, 2014).

In terms of energy provisions, humanitarian organisations, governments and local authorities traditionally respond to refugee situations by deploying diesel generators (DG) for immediate camp setup and operations. Diesel generators are compact and easy to install, providing immediate solutions, but with high environmental impact and running cost. Renewable energy sources, such as solar photovoltaic (PV) systems although modular, require more time to deploy but do not need regular use of expensive fuel when compared to diesel generators. At the family level, various sizes of Solar Home Systems (SHS), solar torches and solar lanterns were distributed among refugees in recent years (Hove and Johnson, 2021). However, more than 80% of the refugees living in camps still do not have access to reliable electricity (Lahn and Grafham, 2015). In addition, environmental concerns relating to using DGs for refugee camp electrification are highlighted by several studies (Alonso et al., 2021; Neves et al., 2021; IRENA, 2019). Furthermore, the impact of deforestation caused by refugee influx in East Africa studied by Tafere (2018) recommended provision of alternative renewable fuels for long term environmental sustainability.

Innovation and reliability of renewable energy technologies coupled with appreciable cost reductions, especially modular PV systems and battery storage, have opened up opportunities for the provision of sustainable and reliable electricity supply whilst reducing the cost burden for aid agencies. However, existing policies and strategies of aid agencies in initial procurement processes will need new approaches to place energy provision as part of their primary considerations for refugee support. The main barrier to replacing DG solutions is the initial higher capital cost (CAPEX) of such PV systems. Implementing a holistic planning approach that takes into account renewable energy systems and regional characteristics is needed, rather than use of fossil fuel as the first and the preferred option for electrification of refugee camps. Such an approach is also likely to enhance the local economy by developing appropriate supply chains and creating growth for communities around the settlement areas.

To address the above challenges, this work explores the potential of leveraging renewable energy resources and systems to support different service provisions in refugee camps and mitigating the environmental impacts of currently deployed diesel power systems. The research addresses and evaluates solar PV-based electrification solutions to widen electricity access in the camps, and emphasises the needed strategic approach to be embedded in policy from the start of the refugee settlement process. Different PV-based electrification options were assessed and compared with normal practice of diesel power provision and alleviating emissions of pollutants. The presented research is organised as follows: Section 2 outlines the current electrification provisions in refugee camps followed by authors' proposed framework for transitioning electrification of refugee camps from fossil fuel to renewable resources in Section 3, and methodology in Section 4. Section 5 presents the results and discussion. Section 6 covers conclusions and Section 7 summarises the research recommendations.

2. Electrification provision in refugee camps

A significant proportion of the world refugee population is hosted in developing countries, who in the main are energy poor (UNHCR, 2016). The United Nations High Commissioner for Refugees (UNHCR) reported that 86% of the global refugees reside in these countries, and 27% of these are in the least developed countries (UNHCR, 2020). For example, Uganda is currently hosting the second largest refugee population globally, followed by Pakistan, ranked the third, and Sudan, Bangladesh, and Ethiopia, positioned as fifth, sixth and ninth respectively (UNHCR 2021). Data from the World Bank (2020) revealed the low electrification rates in these host countries. For instance, the Ugandan electrification rate is at 42%, Pakistan, 75%, Sudan, 55%, Bangladesh, 96%, and Ethiopia is 51%. Refugee camps in remote areas often exhibit much lower electrification rates than the national averages. This is evidenced by the refugee influx in Uganda (UNHCR, 2016), and Bangladesh (UN Women, 2018), where camps in both countries were set in remote areas far away from the national grid infrastructures. Similar situations prevail in other less economically developed countries (LEDC) which are currently hosting 24 million refugees (UNHCR, 2021). Such refugee settlements will therefore be better served by independent power supply systems.

Despite the sophistication of humanitarian agencies in urgent crisis response, their interventions and approaches are heavily dependent on local political power structure and socio-political dynamics (Motard et al., 2018; Maria and Motard, 2019) as well as available funding. Moreover, the persisting operational mismatch between traditional business logistics and its effectiveness in humanitarian context (Mays et al., 2012) also characterise the initial procurement and deployment of electricity generation and the delivery models used by the aid agencies as a matter of immediate crisis response. Humanitarian logistics prioritise moral obligations over financial gain, focusing on delivery in unpredictable environments, unlike traditional business models aimed at profit maximisation and market stability. Consequently, energy delivery approaches for refugee camps rely on established diesel generator systems for operational needs.

Nevertheless, there is now a recognition of the need to integrate low carbon technologies in refugee energy solutions, as seen in pilots of solar PV projects in Jordan, Kenya and Burkina Faso (UNHCR, 2014). These interventions range from distributing pico-solar systems (IKEA Foundation, 2016) to megawatt scale grid connected installations, such as 2MWp Azraq and 13MWp Mafraq Za'atari solar parks in Jordan (Pyper, 2015; Hashem, 2017). Other PV applications, such as powering streetlights (UNHCR, 2017) and water pumping (Llario, 2017) have been deployed but remain insufficient to meet the actual demand (Rosenberg-Jansen, 2018). Other initiatives by aid agencies, governments and NGOs, have initiated PV based electrification projects in refugee camps. In Uganda, such efforts align with its current rural electrification goals to serve 1.5 million refugees (IRENA, 2018), with initiatives such as the US African Development Foundation's (USADF) USD 0.4 million funding to initiate clean electricity supply in refugee settlements in northern Uganda (New Vision, 2019). Similarly, the Asian Development Bank (ADB) financed 50, 5kWp PV mini grid projects in Bangladesh for street lighting and limited refugee household lighting (ADB, 2018). Additionally, the International Organisation for Migration (IOM) deployed solar power systems for their health clinics in Bangladesh (IOM, 2017).

Recent efforts have emphasised participation of private sector and innovative financing for the development of sustainable business models to enhance electricity access in refugee settings. Key initiatives include direct grant financing to companies like Fenix International, SolarNow and Bright Life (Wanyahoro et al., 2021). These organisations promoted Pay-As-You-Go SHS in Kiryandongo and Rwamwanja refugee settlements in Uganda and sold over 4000 SHS products (USAID, 2020). Such intervention was designed to de-risk private sector investment while avoiding market distortions by free SHS distribution. Similarly, SNV Kenya supported market-based energy access in Kakuma refugee settlements, and facilitated sales of 7000 solar PV products for basic electricity access using both PAYG methods (GIZ, 2020). Mercy Corps in Bidi-bidi refugee settlement, Uganda deployed demand side interventions partnering with d.light and Village Power through result-based financing mechanism (Mercy Corps, 2019). Lessons learned from the aforementioned interventions highlights the affordability issue as the key challenge for refugee electricity access. Nonetheless, in many established refugee camps both formal and informal solar PV markets have emerged naturally to meet electrification needs by refugee households. Besides the affordability issue identified earlier, such markets face imminent growth challenge due to poor product quality, inefficient design and lack of aftercare services (Fuentes et al., 2018). However, the effectiveness and scalability of such solutions remain under-researched, highlighting the need for evidence to guide policy adaptations and wider applicability in different regions in the world.

Furthermore, the ongoing cost of existing fossil fuel-based electricity generation in refugee camps is difficult to estimate due to poorly documented energy utilisation and expenditure. Without comprehensive data, attempts to provide robust cost assumptions in such settings will be subject to a large error. According to an estimate by Shell (2020), humanitarian agencies spend around USD 1.6 billion annually on electricity and cooking, with only one fifth of this expenditure allocated to refugee households. The remaining expenditure supports aid agencies' operations including health centres, schools and host community services, predominantly relying on fossil fuel driven generators. For example, during 2015 and 2016, humanitarian organisations in Kenya spent around USD 570,000 annually on petrol and diesel for generators (Grafham and Lahn, 2018). Such large expenditure for relatively small consumption footprint – primarily administration facilities – highlights inefficiencies. Transitioning to renewable energy systems offers a pathway to reduce fossil fuel dependency, enhance environmental sustainability, and achieve cost savings. This critique underscores the urgent need for data-driven approaches and strategic interventions to replace diesel generators with well-designed renewable energy solutions, aligning with broader sustainability goals.

There is now a growing recognition that renewable energy resources should play a greater role in refugee electrification provisions. This should be the part of a systematic policy approach which should sit at the centre of electrification needs for both refugees and camp operations. This research is aimed at providing evidence to such policy needs. It addresses and promotes the utilisation of renewable energy resources and technologies in refugee camps coupled with the phasing out of current fossil fuel dependency. This study combines qualitative and quantitative field data with energy system modelling to provide robust evidence to support the transitioning of fossil fuel based energy provisions in refugee camps to low carbon technologies. It explores unique techno-economic propositions for the replacement of diesel generators with clean, cost-effective PV solutions, extending benefits beyond refugee camp operations to include household electricity access and support for productive activities. It is underpinned by thorough analyses of field data and valuable insights gathered from key stakeholders operating across refugee camps in two different countries, Uganda and Bangladesh.

3. Framework for transitioning electrification of refugee camps to renewable resources

As highlighted in the preceding section there is a critical need for a paradigm shift in electrification strategies for refugee camps, transitioning them from costly fossil fuel dependency to sustainable renewable energy solutions. However, achieving such a transition will necessitate significant changes of existing processes and operational frameworks of aid agencies. A potential strategy is to make governmental and institutional aid contingent upon meeting low carbon emission targets and reducing environmental impacts within refugee camps. Such a transition is complex and extend beyond just moving one source of fuel to other (Fattouh et al., 2018). In essence, the transition process or processes will need to explore gaps between the present electrification approaches and the target renewable environmentally sensitive provisions, linked through robust business models informed by field data. This will undoubtedly require multilateral stakeholder cooperation on policy, funding and field applications.

Literature indicates that there are three major interrelated dimensions that are likely to be involved in this energy transition (Sovacool and Geels, 2016). These are: (a) actors and their conducts (i.e., existing/new strategies, investment pattern, policy and capability), (b) tangible elements of the energy resources and their system (i.e., technology, energy generating system, electrical demand, infrastructure, market and supply chain) and (c) socio-technical elements (i.e., policies and regulations, institutional mindset, in-country supply chain and social practice). Linking these facets together will necessitate the development of a framework designed to connect the actors, dimensions and practices, and systematically identify the aforementioned gaps.

To address these requirements, a simplified conceptual framework is proposed here, as depicted in Fig. 1, highlighting steps that can be exploded further to underpin the scope and provide the building blocks for each step and the connectivity to others in the framework. Fig. 1 summarises the needed approach, starting with reviewing currently deployed electrification processes, the current policy framework, the technology platform in both current practice and those for the future based on renewable energy resources, policy transformation and adaptation, geographical dependency for systems, culminating in the needed business models and financing, arriving at an energy transition based on evidence.

4. Methodology

Addressing some of the components of the transitioning framework presented in Fig. 1, and building on the discussions outlined in Sections 2 and 3, a methodology was developed which is summarised in Fig. 2. This transitioning research is underpinned by modelling and analysis of

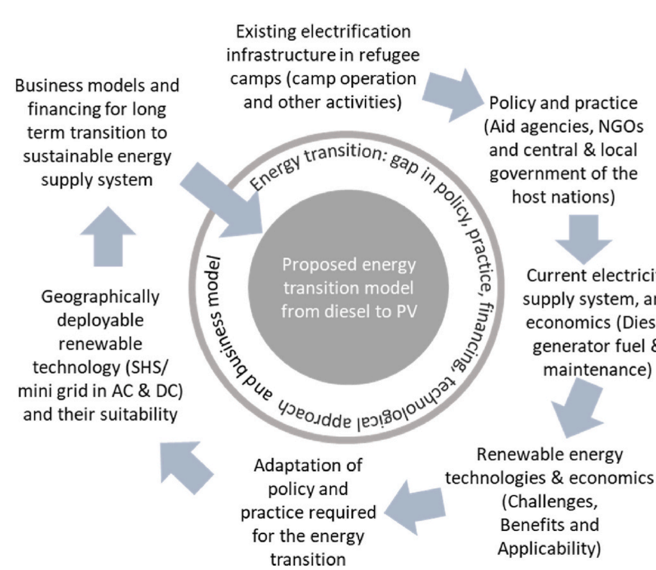

Fig. 1. Transitioning framework for migrating electrification from fossil fuels to renewable energy resources for refugee households and camp operations.

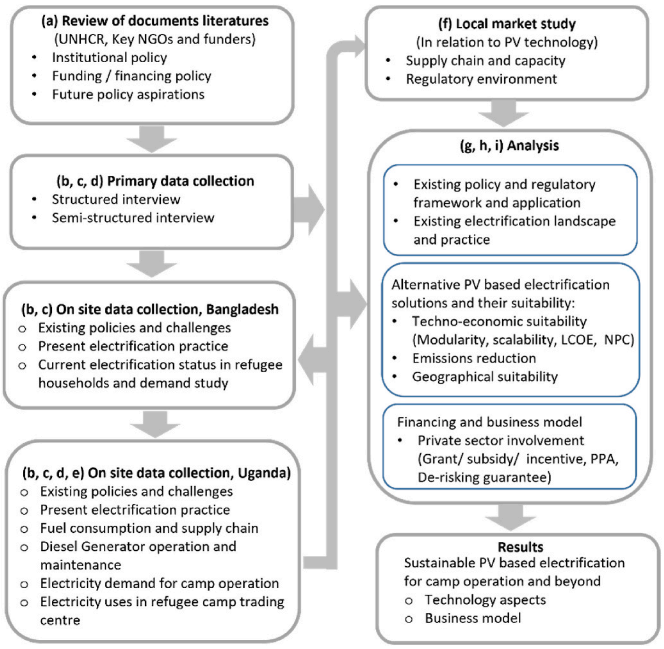

Fig. 2. Methodology undertaken to support the study taking into account the descriptions given in items (a) to (i) in the text.

different energy generating systems informed by the stakeholder surveys and data collection of electricity demand for Bidi-bidi base camp and the trading centre in Imvepi refugee settlement in Uganda, as well as the refugee households in Kutupalong camp, Bangladesh. The survey tools, procedure and description containing anonymized survey data, results tables and modelling parameters needed to reproduce the techno-economic assessment will be available on publication at https://eprints.soton.ac.uk/491894/with Digital Object Identifier https://doi.org/10.5258/SOTON/P1175. The surveys were subject to ethical approval by the University of Southampton Ethics and Research Governance committee (ERGO ref: 3659).

With reference to Fig. 2, the following text provides a summary description of the various steps undertaken to support the study as well as the framework described in Section 3 and in Fig. 1.

(a) Relevant literature were reviewed to gather secondary data related to current institutional policy and field operation of UNHCR and other key stakeholders, and their future aspirations towards renewables.
(b) For primary data collection, both structured surveys (of refugee households and assessment of fuel consumption by diesel generators), and semi-structured interviews (of stakeholders who support refugee camp operations) were conducted in Uganda (Yumbe, Northern Uganda) and Bangladesh (Cox's Bazar, Southern Bangladesh). In 2019, data was collected from different stakeholders associated with supporting refugees and camp operations. In Uganda, representatives from UNHCR, Mercy Corps (MC)-West Nile and African Initiatives for Relief and Development (AIRD) were interviewed covering wider areas of existing electrification approach and practice in this region. Similar questions were used in Bangladesh for UNHCR, International Organisation for Migration (IOM) and Refugee Relief and Repatriation Commissioner (RRRC) Officials.
(c) 60 representative refugee households were surveyed from a small section of a sub-camp of Kutupalong refugee camp (Cox's Bazar, Bangladesh) to assess their current electricity access status and anticipated basic electricity demand. This small section is the part of the sub-camp where approximately 300 newly arrived Rohingya families of different sizes live. During the time of the survey, the selected section of the sub-camp accommodated these newly arrived 300 refugee families, which represents the real picture of needed electricity access among refugee households and their aspirations to be considered in this research. Data collected from the Kutupalong sub-camp was scaled up to a cluster of 400 households for energy system modelling including required numbers of communal streetlights, toilet lights and some other basic energy uses as indicated by the respondents during the survey. Communal streetlights and toilet lights are considered as integral part of the electrification here based on the UNHCR (2017) report outlining the importance of such lighting for safety and security, especially for women and children. The scaled data was used to develop electrical load profile scenarios for PV system design and analysis. The number of streetlights and communal toilet lights was based on the density of the settlement in the Kutupalong camp, especially the surveyed section of the camp.
(d) Questionnaires were used to capture detailed capital expenditures (CAPEX) and operational costs (OPEX) for diesel generators used by UNHCR for camp operations. This included repair, maintenance, recorded and unrecorded fuel costs, and fuel loss etc. The procurement, installation, running cost and operational data of a 50 kW diesel generator at the Ugandan Bidi-bidi base camp was collected during site visits in 2018/19. While UNHCR provided procurement, installation and running costs, AIRD's maintenance department supplied the operational data. The 50 kW generator was deployed to supply power to AIRD offices and for four UNHCR storage sheds all housed in a large compound. However, UNHCR had planned to relocate other five partner NGOs in this compound. Based on the electrical demand data collected from all these organisations an estimated daily load profile for this base camp was developed.
(e) Electricity consumption data and future demand in a trading centre in Imvepi refugee settlement in Uganda were also collected. Considering the availability of DC appliances in Yumbe, the research considered load profiles both in AC and DC for this trading centre. When considering DC appliances as alternative to AC items for load profiling, like for like performance capacities were matched.
(f) Local PV market status in relation to cost, supply chain and technical skill levels was also studied in both Bangladesh and Uganda. The limited availability of secondary data in this regard was supplemented through the information collected from the procurement teams of related organisations during site visits at these two camps.
(g) The collected data and the supporting analyses informed the modelling, which considered different PV systems (AC mini grid, DC mini grid and SHS) and compared their techno-economic suitability with diesel generators including potential environmental impact such as CO_2 and NO_x emission avoidance. All the proposed PV-battery power plants and SHSs were restricted to a maximum flexibility of 5% capacity shortage. This range of capacity shortage may result in only few incidents of power outages while offering great savings on CAPEX. Only the cost of power generating plants were considered while modelling different PV-battery electrification solutions to compare with diesel generators. It is assumed that the distribution network cost will be similar for all PV systems and diesel cases.

The approach of Buller et al. (2022) to estimate CO_2 and NO_x emission avoidance through replacing diesel generators using HOMER® software tool (homerenergy.com) were used in the research. Fuel consumption and corresponding emission reductions were calculated based on a 16 h of daily runtime by each generator. Although HOMER calculates the emission of six pollutants (CO_2, CO, UHC, PM, SO_2 and NO_x) while modelling diesel generator-based electricity generation, only CO_2 and NO_x

emission avoidance have been presented here as these represent the highest volumes of pollutants. This is similar to the approach applied by Baldi et al. (2022) to indicate greenhouse gas emissions of diesel generators in refugee camps in Kenya.

(h) Different power generation systems (diesel generators and PV-battery systems) were considered. HOMER® Pro (homerenergy.com) microgrid simulation tool was used for optimisation and economic analyses using a range of sensitivity variables (i.e., different project life spans, extent of capacity shortage). Location specific metrological datasets were used from the open source library of the US National Renewable Energy Laboratory, which are integrated with in the simulation tool. Three key economic matrices were used: (i) Levelised Cost of Electricity (LCOE), (ii) Net Present Cost (NPC) and (iii) Lifespan Cost (LS Costs) derived through the simulations. These were compared to establish the suitability of different technological solutions (Alam and Bhattacharyya, 2016; Asuamah et al., 2021).

The NPC focuses on comparing the investment recovery of PV-battery systems, which feature high upfront capital expenditure (CAPEX) but low operational costs, against diesel generators that have lower initial CAPEX but significantly higher running costs. Hence the NPC of a power generating system refers to the present value of all the costs of installation and operation of the system over a considered project lifetime, minus the present value of all the revenues that it earns during the considered period (i.e., 5, 10 and 20 year). The simulation tool used calculates the net present cost of each component in the system, and of the system as a whole. It defines the LCOE as the average cost of a kWh of useful electrical energy produced by system. A standard nominal discount rate of 8% was applied to incorporate the real discount rate and inflation rate for all economic case scenarios. This value of discount rate was adopted from the study by Szabó et al. (2021), which considered small scale PV system design and analysis in sub-Saharan Africa and south Asia context. It is notable that the simulation tool HOMER computes the annual real discount rate, which is also referred to as the real rate of interest based on the selected nominal discount rate and the expected rate of inflation. Besides the NPC and LCOE, year on year accumulated cost of the different power generating systems were also used to compare the costs for different project lifespan scenarios. Year on year accumulated cost of an energy generating system at a specific year is the total value of the CAPEX and the accumulated annualised cost up to that year – defined as Lifespan Cost (LS Cost) here. The accumulated annualised cost represents the annual running cost of the project. Such presented values give a comparative pictures of investment recovery of PV-battery systems, having high CAPEX and low running costs compared to the low CAPEX and high running costs of diesel generators.

(i) The current state of aid agencies' refugee electricity access initiatives aimed at strengthening this market with the involvement of the private sector (Chatham House, 2016; Rouse, 2019) was studied to support recommending pathways to transform diesel-powered energy ecosystem to sustainable renewable energy such as solar photovoltaics (PV).

5. Results and discussion

This section provides the results of the study covering, outcomes of interviews and surveys conducted in the field, an appraisal of the current diesel electricity consumption profiles in the studied camps. It also presents the outcomes of the modelling of appropriate solar photovoltaic (PV) systems designed to support expected consumption profiles and beyond. Solar PV systems were selected as the solar radiation resources were found to be the best suited for the geographical locations under consideration.

5.1. Stakeholders and refugee household studies

In the camps studied in this present work, the UNHCR was the lead stakeholder alongside many other NGOs, national and international aid agencies, and country specific refugee-related government organisations engaged in support work in Uganda and Bangladesh. Despite the number of refugees in both countries being almost the same, the camps in Bangladesh are more densely populated when compared to Uganda.

5.1.1. Stakeholder engagement in Uganda and Bangladesh

Using the qualitative data collected through interviewing stakeholders (see Section 4, item (b) and (c)) in both Uganda and Bangladesh, insights were gained related to present electrification practices, initiatives and challenges faced when aid agencies respond to refugee crises. Below some of the key findings are summarised that are likely to be encountered when planning the transition from diesel generators to renewable energy resources and systems.

5.1.1.1 Aid agencies mainly prioritise electrification of camp operations (e.g., admin offices, warehouses, and communications). Providing electricity to refugee households is considered as secondary in priority.

5.1.1.2 Electricity generation in humanitarian response is invariably planned around the availability of funding which mostly results in the use of diesel generators requiring low capital investment (CAPEX) in almost every geographical location where UNHCR and its other partners operate. Aid organisations deploy oversized diesel generators as a standard practise to accommodate future growth in electrical demand. In addition, fuel loss, theft, and contamination are the regular challenges. For example, although the UNHCR has a set guideline for fuel loss limit at 0.1% for diesel generators in Ugandan sites, actual loss is estimated to be around 5%. This figure was cross checked and justified with AIRD's field office which maintains diesel generators for UNHCR.

5.1.1.3 Aid agencies associated with the refugee response, especially UNHCR, do not as yet have a clear policy that outlines the deployment of renewable energy systems such as PV for electrification. This is partly due to short term funding cycles (from donors etc.) and budget constraints which make it difficult for the UNHCR to plan for the high initial capital cost of renewable energy systems, defaulting to the cheaper capital cost inherent in the deployment of diesel generators.

5.1.1.4 Refugee hosting governments do not encourage building permanent infrastructure including electricity generation systems as these give the impression of permanency which will make voluntary repatriation difficult in the future.

5.1.1.5 Although many of the aid agencies and donors are convinced by the appropriateness of renewables such as solar PV for electrification in refugee camp settings, there are still no clear pathways/guidelines yet identified.

5.1.1.6 For electrification beyond camp operations using, say, PV technologies, aid agencies will undoubtedly need clear sustainable guidelines and business models with some ethical private sector participation.

It is clear from the findings summarised above that more appropriate life cycle analyses are needed to provide appropriate guidelines and compare the fuel-less renewables with diesel generators which for the latter, in addition to environmental impacts open up a plethora of challenges including fuel supply chain and maintenance requirements in remote settings.

5.1.2. Refugee household survey - Bangladesh

Kutupalong refugee settlement in Bangladesh is one of the most densely populated refugee camps in the world (NRC, 2018). However, it

Table 1
Demographic and income data of the surveyed Rohingya refugee households in Kutupalong refugee camp, Bangladesh, (sample population 308, surveyed households n = 60).

Variable	Value
Family size	Up to 4 people: 20%; 5–6 people: 52%; 6+ people: 28%
Age group	0–6 years: 31%; 7–17 years: 38%; 18+ years: 31%
Gender	Male: 44%; Female: 56%
Access to income	Yes: 53%; No: 47%
Source of income	Cash for work: 40%; Illegal labourer: 10%; Small trading: 3%
Average work frequency	2 days/week.
Average income	USD 3.6/day
Main source of income	Selling allocated food for other essentials: 12%.

is difficult to obtain real data on the demographics of the camp. Nevertheless, a survey of 60 households was conducted in the camp. Data shows that the majority of respondents identified as female (56%), with 80% of households consisting of more than 5 members in a family and the majority (69%) of the sample population are below the age of 18 years (Table 1). It is recognised that this sample may not be representative of the whole camp population but can provide some insights into the demographics. Furthermore, a recent report by the UNHCR indicated that refugee demographics and family sizes are almost homogeneously distributed among all the camps, sub-camps and sections in Cox's Bazar (UNHCR, 2019). Although the provision of formal employment is prohibited, survey findings indicate that about half of the respondents (53%) have access to informal income streams. Income arose from 'cash for work' for 40% of the refugees, 10% work as illegal labourers and 3% run small trades inside the camp (Table 1). Average income of the people who get opportunity to work was around USD 7 per week. About 12% of respondent households sell part of their allocated food to buy other essentials, such as kerosene, firewood, LPG and medicine.

Other survey results in Table 2, also show that prior to taking refuge in Bangladesh, around half (48%) of the surveyed households had electricity through their own solar home systems (SHS) and shared diesel generators in Myanmar (Table 2). At present in the Kutupalong refugee camp only 27% of the refugees have access to lighting through solar home systems which were either bought by themselves or donated by different NGOs (Table 2). The SHSs used in the refugee camp have capacity in the range of 3Wp-10Wp and account for 81% of the sample, the rest have capacities around 30Wp. However, 80% of the households expressed dissatisfaction with their existing SHS. Families who do not have SHS or any other means of power, use kerosene and paraffin for lighting. The results from the survey indicated that the monthly spending on lighting is on average USD 1.40 for the majority of the respondents (68%), with 17% spending USD 0.95, and 15% spending USD 2.15, (Table 2). It is important to note that, estimation of kerosene consumption by the households who also have SHS was not included in the data collection and analysis.

All surveyed households (100%) wanted to have electricity for lighting, with the majority (62%) willing to have two LED bulbs and 34% wanted only one LED (Table 2). Estimated monthly electricity consumption for lighting ranged between 1.1kWh and 1.8kWh for the one and two light bulb users respectively. This estimate is based on respondents' intended hours of usages. Despite being financially constrained, 68% of households expressed their willingness to pay (WTP) for electricity as most of the households (72%) assume that LEDs to be a cheaper option than kerosene for lighting. The survey indicated that only 67% of the respondents had mobile phones, and 42% had portable radios.

The majority of the household members of the surveyed sample were women and children (under the age of 18) (Table 1). According to UNHCR's standard of operation, street and communal toilet lighting for

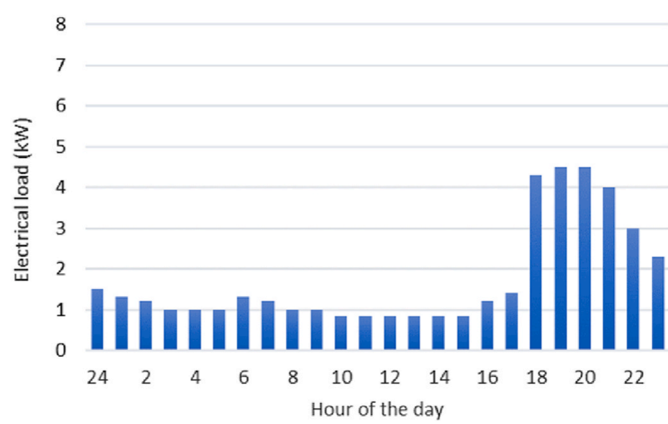

Fig. 3. Estimated hourly electrical load profile for the cluster of 400 refugee houses, Bangladesh.

Table 2
Electricity access, cost and electricity demand by the surveyed Rohingya refugee households in Kutupalong refugee camp (surveyed households n = 60), Bangladesh.

Category	Variable	Value
Electricity access	Access to electricity prior to fleeing home	Yes: 48%; No: 52%
Electricity access	Source of electricity	Own/sharing SHS: 30%; Diesel Generator: 18%
Electricity access	Size of SHS	3W–10W: 81%; <30W: 19%; ≥30W: 0%
Electricity access	Satisfaction with existing SHS	Yes: 20% No: 80% (issues with panel, battery and LED)
Lighting	Current lighting source	SHS: 27%; Kerosene: 57%; Paraffin: 16%
Lighting	Monthly cost of lighting (USD)	0.95: 17%; 1.45: 68%; 2.25: 15%
Electricity needs	Willingness to have electricity	Yes: 100%; No: 0%; Not sure: 0%
Electricity needs	Intended number of lights per family	1 LED (5W): 34%; 2 LED (5W): 62%; LED & other appliances[a]: 4%
Electricity needs	Estimated consumption per family	1 LED (5W): 1.1 kWh/month; 2 LED (5W): 1.8 kWh/month
Willingness to pay	WTP for electricity	Yes: 68%; No: 24%; Not sure: 8%
Willingness to pay	Reason for WTP for electricity	Cheaper: 72%; Better light:11%; Security: 17%
Electrical appliances	Mobile phone ownership	Yes: 67%; No: 33%
Electrical appliances	Radio ownership	Yes: 42%; No: 58%

[a] Note: data related to other appliances include cooling fans and television were not collected.

security reasons and access are important considerations for such these groups (UNHCR, 2017a). Hence, these essential requirements were considered in PV system modelling.

In order to properly estimate and model the required PV systems to supply a population of the camp, and as indicated in the methodology consideration (c), the collected survey data was scaled up to a cluster consisting of 400 households to estimate the overall electricity demand. This demand consists of indoor lighting, electrical demand for 50 streetlights, 30 communal toilet lights, 240 mobile phones and 160 radios. Based on these requirements, the resultant estimated load profile is shown in Fig. 3, which gives an overall estimated load of 42.2kWh/day.

5.2. Diesel fuel use in camp electricity generation

UNHCR is responsible for procurement of diesel generators, fuel supply and their operations at most of their refugee camps including those in Yumbe district, Northern Uganda. At the Yumbe Bidi-bidi camp, electricity is only supplied to the aid agency offices and non-refugee compounds through ten diesel generators of capacities ranging from 25 kW to 60 kW, housed at different locations. Diesel fuel for these generators is purchased in 200 L metal drums and supplied to different sites in 20 L jerry cans on a daily basis. On many occasions, fuel allocations for generator and vehicle fleet get mixed-up as they are very difficult to segregate. To overcome this, UNHCR has planned to install an underground diesel storage tank of 20,000 L at an estimated cost of USD 35,000 at their new compound in Yumbe, Uganda to create a secured and efficient fuel supply chain for all its generators.

It must be noted that during the site visit to the Kutupalong camp in Bangladesh, there was no data available for diesel power generation in the camp. Therefore, for modelling of PV systems, the extensive data sets provided during the site visits to Uganda were used.

5.2.1. Diesel fuel use in Bidi-bidi base camp, Uganda

According to the African Initiatives for Relief and Development (AIRD) operational data, most of the UNHCR diesel generators in Bidi-bidi camp operate between 15 and 20 h a day at various electrical loads. Although recommended life of generators varies between 20,000 and 25,000 h based on their operating conditions, UNHCR carry out major overhauls around every 10,000 h of operation rather than replacing the generators. Despite having regular service contacts with third party contractors (i.e., Africa Action Help (AAH)) for all the camps in Yumbe district, UNHCR spends around USD 800 to USD 1200 for every major overhaul per generator, depending on the size and age of the generators. In the case of smaller generators of approx. 10 kW size, UNHCR normally replaces these after 25,000 h of service.

During the survey, the 50 kW generator operated and maintained by AIRD at the Bidi-bidi base camp was serving an electrical load which was less than half of its nameplate capacity, at a reported daily average diesel fuel consumption of 90 L. Electrical load requirement for this base camp was estimated to be 96.2 kWh/d based on the demand data provided by AIRD officials (Fig. 4). However, this load will only be achieved when electricity will be supplied to all planned offices for NGOs to be moved into the same compound, storage sheds and staff accommodation (see Section 4, (d)). Fig. 4 provides the hourly load profile for this base camp plotted from data obtained from the camp operator AIRD and is used for modelling PV systems.

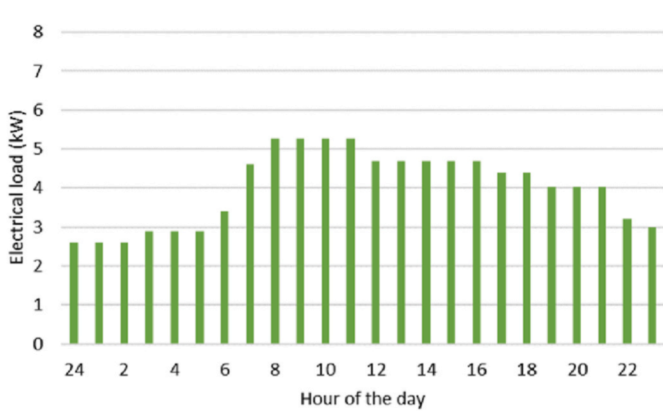

Fig. 4. Estimated hourly electrical load profile for the Bidi-bidi base camp, Uganda.

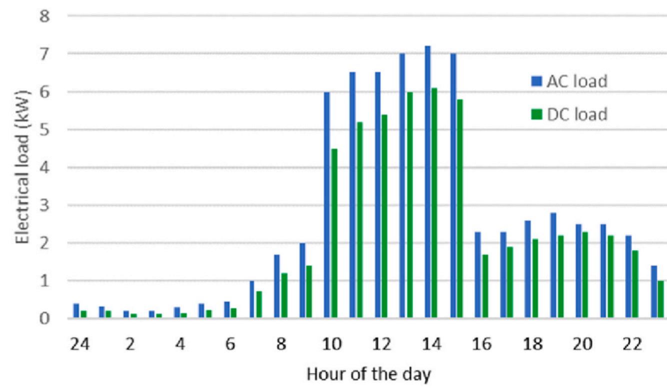

Fig. 5. Estimated hourly electrical load profile for the Imvepi trading centre, Uganda.

5.2.2. Diesel fuel use in the trading centre at Imvepi refugee settlement, Uganda

The trading centre at Imvepi refugee settlement uses three privately owned small diesel generators, supplying power through a local distribution grid. Consumers pay a fixed amount every day based on their pre-assessed electricity consumption which was indicated to be in the range USD 2.15/kWh and USD 2.50/kWh. However, survey respondents also indicated that supply was very unreliable, and the power quality was poor with regular voltage fluctuations. The trading centre has 43 businesses including one small posho mill, a bike mechanic shop and a small clinic. The collected electricity demand data that allowed the estimation of the daily load profiles for both AC and DC supply cases (see Section 4, (e)) are shown in Fig. 5. As can be seen from the figure, the estimated daily AC electrical load was 66kWh while the estimated DC load was 53kWh, which are used in the modelling.

5.3. Diesel based power supply cost analysis

Following UNHCR's diesel generator deployment trend and using the collected electrical load requirement data for different case scenarios, costs of electrification through 50 kW, 25 kW and 10 kW diesel generators were analysed. As the 50 kW generator was oversized for the demand (see Section 4.d and 5.2.1), the analyses considered the lower capacities of 25 kW and 10 kW to understand their modelled contribution to the required demand. Proportionate cost of fuel storage tank and other costs were also added for this analysis. All cost components are summarised in Table 3. Operational data acquired from AIRD show that the 50 kW diesel generator consumes 90 L of fuel per day. For other two diesel generators (25 kW and 10 kW) modelled here, fuel consumptions were optimised based on the loads served by the generators for specific cases. Costs of such diesel generator-based electrification were further analysed and compared with the PV options in the following sections.

5.4. Modelled solutions of PV based electrification

As indicated earlier, humanitarian organisations traditionally see the refugee related electricity access as a long-term investment provision and tend to justify the financial cases accordingly (Grafham and Lahn, 2018). This work provides analyses that can be used to justify

Table 3
Cost components (USD) of 50 kW, 25 kW and 10 kW diesel generators used in the modelling.

Type[a]	Item	50 kW	25 kW	10 kW
C	Generator (delivered to site and installed)	30,000	22,000	10,000
C	Diesel storage tank installed (proportionate cost)	5000	3500	2000
C	Generator housing and fuel supply facility	4000	3500	3000
C	Admin and other costs	3000	3000	3000
O	Operator wages (direct and indirect)	90	80	80
O	Fuel cost (@USD 1.05/l)	2835	Optimised	Optimised
O	Maintenance cost (Parts & servicing)	65	50	40
O	Periodic major overhaul (10,000 h)	65	45	30
O	Fuel loss or unaccounted usages (@ 5%)	140	Optimised	Optimised

[a] C = Capital; O = Operating cost.

Table 4
PV-battery power plant[a] and SHS component cost.

System type	System component	Size	Cost (USD)
PV–battery power plant	PV modules (with accessories)	1 kWp	800/kWp
PV–battery power plant	Battery (SLA)	2V, 500 Ah	225/kWh
PV–battery power plant	Charge controllers	80A	500/Unit
PV–battery power plant	Inverter charger	5 kW	4000/Unit
Solar Home Systems	PV module (with accessories)	250 Wp	225/module
Solar Home Systems	Battery (SLA)	12V, 83.4 Ah	300/kWh
Solar Home Systems	Charge controllers	20A	60/Unit
Solar Home Systems	Inverter charger	–	–

[a] Note – mini grid network costs are not included in the analyses as these will be the same for either the PV or diesel power supply case.

investment in sustainable electricity supply and support the need for earlier thinking to deploy these in the field. The techno-economic analyses undertaken present the modelling of different solar PV systems spanning project life of 5, 10, 15 and 20 years. In the analyses, considerations were given, and comparisons were made when deploying diesel generator power supply systems and those based on solar PV systems.

The cost and availability of PV-battery power plant (supporting mini grid power delivery network) and solar home system (SHS) components were collected in Uganda and Bangladesh during the surveys. Both countries have moderately established PV markets with a growing trend of mini grid based rural electrification being established (Bahaj and James, 2019). The cost of the PV mini grid and SHS components used in the analysis are given Table 4.

The analyses presented here used the load profiles of Figs. 3–5 determined through the survey of base camp, trading centre and refugee households at different refugee settlements to simulate the optimum size of PV-battery power plants (no network design undertaken) and SHSs to serve the required loads under the different project life scenarios. The designs of the optimised PV-battery power plants and SHS have the following characteristics:

a) Battery bank backup are set at 36 h for refugee households and base camp, 24h for the trading centre, and 48h for households with SHSs.
b) To achieve long battery life and thus resilience of different PV-battery systems, maximum depth of discharge (DoD) of battery bank was set to 50% except for few days of the year when consecutive days of poor solar resources may affect performance of the PV system. However, discharge of the battery bank below 50% was only scheduled to serve only the critical or essential loads (i.e., security lights etc.).

The results of the modelling are summarised in Table 5, where the proposed PV-battery power plants and SHSs covering size, types, autonomy, initial capital and yearly operation and maintenance costs are shown.

The results indicate that the optimally sized PV system has a capacity of 40kWp AC and will be able to support the electrical demand of Bidibidi base camp (96.2kWh/d), Uganda at an initial investment of USD112,500 (Table 5), as compared to the currently used 50 kW diesel generator's CAPEX of USD 42,000 (Table 3). The designed PV power plant will support all the loads of NGO offices, storage sheds and staff accommodation.

Due to the close proximity of refugee accommodation, the case in Bangladesh allows a comparison of operating PV power plants for the settlement in either AC or DC power supply mode for the same site. Modelling results show that the particular electrical demand of 42.2kWh/d (Fig. 3), can be supported by the optimised design of PV

Table 5
Proposed PV battery power plants and SHS capacities for the surveyed sites.

Type of proposed system	Surveyed sites in Bangladesh and Uganda	Required load (kWh/d)	PV system capacity (kWp)	Battery bank Capacity (kWh)	Battery autonomy (hours)	Initial capital (USD)	Cost of O&M (USD/y)
PV power plant	Bidi-bidi base camp, Uganda	96.20 (AC)	40	175	36	112,500	2200
PV power plant	Imvepi trading centre, Uganda	65.80 (AC)	28	119	24	82,000	2000
PV power plant	Imvepi trading centre, Uganda	52.8 (DC)	18	96	24	58,000	1800
PV power plant	400 household cluster, Bangladesh	42.20 (AC)	20	110	36	73,000	1800
PV power plant	400 household cluster, Bangladesh	42.20 (DC)	16	95	30	56,000	1800
SHS	6 household cluster, Uganda	0.60 (DC)	0.25	2	48	1175	60

power plant of capacities of 20kWp for AC power supply, and 16kWp for DC. The proposed solution favours the DC power supply mode where the initial cost is approximately 23% cheaper (Table 5). Either of the PV power plants will support the required demand arising from the indoor lighting for 400 refugee households (2 × 5W LED bulbs in each house), 240 mobile phones chargers (5W each charger), 160 radios (5W each with rechargeable battery), 50 security (20W LED each) and 30 outdoor communal toilet lighting (10W LED each).

Unlike all the refugee camps in Bangladesh, some refugee settlements in Uganda are not densely packed, hence it is feasible to cluster houses together which are within a perimeter of about 100 m. For a cluster of 6 houses, one shared SHS can provide power to household loads (2 LED lights, 1 mobile phone charger, 1 radio or other audio device) as well as outdoor security and communal toilet lighting (2 security and 2 toilet lights for each cluster). Estimated daily electrical demand for one of such clusters is 0.6kWh, and a SHS of 250Wp with 48 h of battery autonomy can serve the required loads (Table 5).

For the Imvepi trading centre in Uganda, while the AC power supply option needs a 28kWp PV system with 24 h of battery autonomy, the DC supply option only needs 18kWp PV, and the battery bank autonomy remains the same. Initial cost of DC power supply for this trading centre is USD 24,000 cheaper compared to the AC option (Table 5).

5.5. *Diesel and PV power supply cost comparison*

The following sub-sections present economic comparisons between the two solutions (diesel and PV). It must be noted that electricity distribution network costs are not included in the analyses as these will be the same for both the PV and diesel power supply cases. The sub-sections also discuss the technical suitability of the proposed PV systems when compared with power derived from diesel generators which were in use by UNHCR and other aid organisations at the sites considered.

5.5.1. *Power supply considerations for the Bidi-bidi base camp, Uganda*

The 50 kW diesel generator at Bidi-bidi base camp was deployed to serve an estimated future daily load of 96.2kWh (Fig. 4 and Table 3). As indicted earlier, this generator is oversized for such a load, therefore, to support the estimated and realistic future demand growth, an appropriately sized diesel generator of 25 kW capacity has been proposed here. This will also allow a like for like comparison to be made with the proposed 40kWp PV-battery power plant specified in Table 5, designed to serve the same electrical demand in this base camp.

Net present cost (NPC) and levelised cost of electricity (LCOE) for the two diesel generators (50 kW and 25 kW) and the 40kWp PV-battery power plant for various project lifetime scenarios are shown in Table 6. LCOE for the project life span ranging from 5 to 20 year varies between USD 1.37/kWh and USD 1.28/kWh for the 50 kW generator, as compared to USD 1.00/kWh to 0.92 USD/kWh for the appropriately sized 25 kW generator. Hence, for the Bidi-bidi base camp electrification, UNHCR would be spending around USD 0.36/kWh more if it does not downsize the currently used 50 kW generator to 25 kW regardless of the life-time of the project (Table 6). Over a period of 20 years, this translates into an additional expenditure of USD 252,700 (USD 0.36/kWh x 702MWh over 20 years). Hence, it is recommended aid organisations use appropriately sized generators for significant cost savings.

LCOE from the proposed 40kWp PV-battery power plant for Bidi-bidi base camp varies between USD/kWh of 0.57 for a 5-year project life and USD 0.35/kWh for 20-year project life (Table 6). For the 20-year project life scenario, the LCOE arising from PV-battery power plant is USD 0.93/kWh and USD 0.57/kWh cheaper than the cost of electricity provided by the 50 kW and 25 kW generators respectively (see Table 6). During this period the 40kWp PV-battery power plant will deliver cost savings of USD 653,000 (USD 0.93/kWh x 702MWh) and USD 400,000, (USD 0.57/kWh x 702MWh) when compared with the running cost of the 50 kW and 25 kW generators respectively as shown in Table 6. Similarly, substantial savings can be achieved even in the shorter project life (5-year to 15-year) scenarios (Table 6).

LCOE and NPC presented in Table 6 reflect the initial high capital cost (CAPEX) required for the 40kWp PV-battery power plant (USD 112,000) as compared to those of the 50 kW (USD 42,000) and 25 kW (USD 32,000) diesel generators. Such high CAPEX of the PV plant can be offset by its cheaper LCOE through replacing the diesel generators for any project lifespan between 5 and 20 years (Table 6). Further consideration of the economics shown in Fig. 6 (a) indicates that, the NPC and LCOE values of the 50 kW and 25 kW diesel generators surpass those of the proposed PV plant in the first and second year of operation respectively in a 20-year project life scenario for all the energy generating systems. While considering project life scenarios of 5-year, 15-year and 20-year, the life span cost (LS Cost) as described in Section 4(h) of two modelled diesel generators (50 kW and 25 kW) surpass the cost of proposed PV-battery power plant (40kWp) in the 2nd year and at the end of 3rd year respectively (Fig. 6(b) and (c) and (d)).

Cost comparisons for 5-year and 15-year project life scenarios presented here (Table 6; Fig. 6) for the proposed PV system with very high CAPEX against the cheaper diesel generators would enable UNHCR and other donor agencies or investors to justify investment in PV-battery plants even in short-term investment contexts. The results indicate that even in a 5-year business case scenario, the 40kWp PV-battery

Table 6
Net present cost (NPC) and levelised cost of electricity (LCOE) for 50 kW and 25 kW diesel generators (DG) and 40kWp PV-battery power plant along with total required loads served by the energy generating systems and savings potentials of the PV system against diesel generators over different project life scenarios for Bidi-bidi base camp, Uganda.

Variable	DG 50 kW	DG 25 kW	PV-battery 40kWp
Load (5 year, MWh)	176	176	176
Load (10 year, MWh)	351	351	351
Load (15 year, MWh)	527	527	527
Load (20 year, MWh)	702	702	702
CAPEX (USD)	42,000	32,000	112,000
NPC (USD, 5 year)	215,000	154,000	87,500
NPC (USD, 10 year)	374,000	269,500	118,000
NPC (USD, 15 year)	505,000	365,000	143,400
NPC (USD, 20 year)	613,500	443,000	162,800
LCOE (USD/kWh, 5 year)	1.37	1.00	0.57
LCOE (USD/kWh, 10 year)	1.31	0.95	0.42
LCOE (USD/kWh, 15 year)	1.29	0.93	0.38
LCOE (USD/kWh, 20 year)	1.28	0.92	0.35
PV saving vs. diesel (USD, 5 year)[a]	140,800	75,680	–
PV saving vs. diesel (USD, 10 year)[a]	312,400	186,000	–
PV saving vs. diesel (USD, 15 year)[a]	480,600	289,850	–
PV saving vs. diesel (USD, 20 year)[a]	653,000	400,000	–

[a] Saving = [($LCOE_{DG}$ − $LCOE_{PV}$) × Load served].

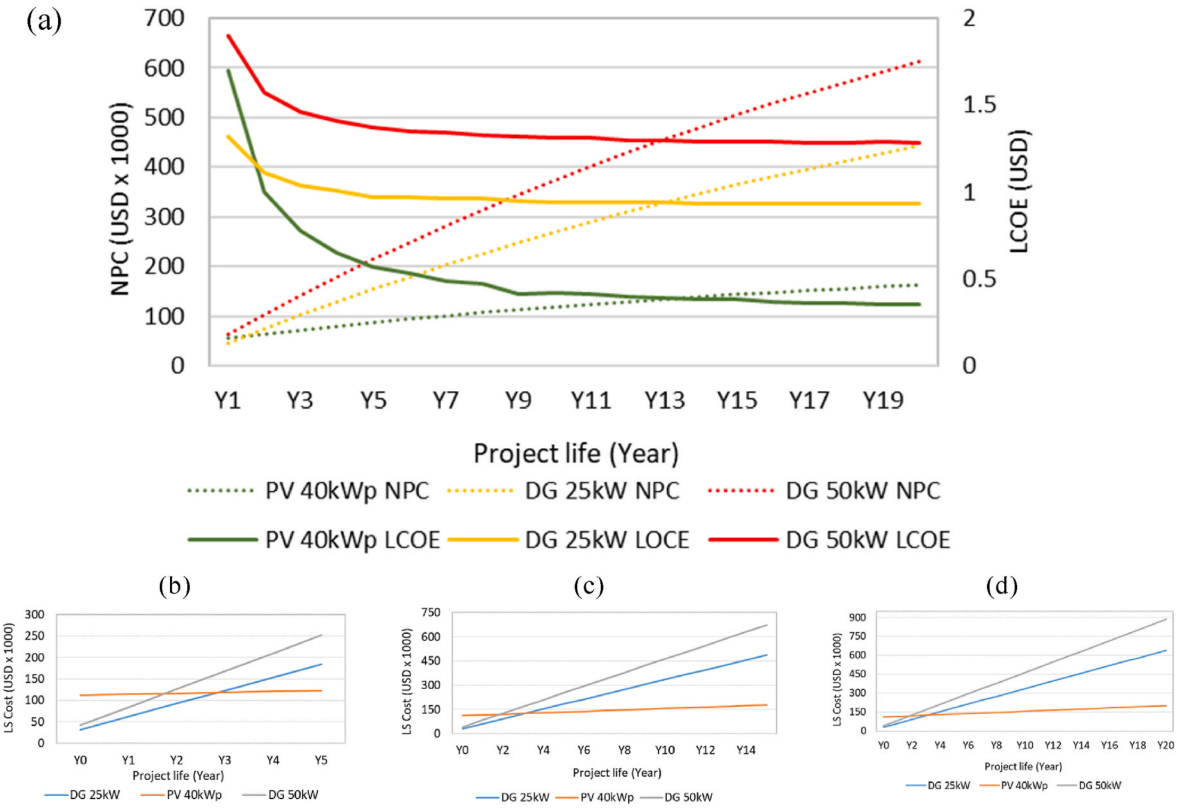

Fig. 6. (a) Net present cost (NPC) and levelised cost of electricity (LCOE) generated from 50 kW to 25 kW diesel generators (DG), and a 40kWp PV-battery power plant for Bidi-bidi base camp over 20 years. Life span cost (LS Cost) comparisons for the same case for (b) 5 year, (c) 15 year and (d) 20 year project life scenarios; (note y-axis magnitude is different to illustrate project life effects).

Table 7
Net present cost (NPC) and levelised cost of electricity (LCOE) for the 10 kW diesel generator and equivalent PV-battery AC and DC power plants along with total required loads served by the energy generating systems and savings potential of PV systems against the diesel generator over different project life options in Imvepi trading centre, Uganda.

Variable	DG 10 kW	PV-battery 18kWp (DC)	PV-battery 28kWp (AC)
Load system (5 year, MWh)	120	96.40	120
Load system (10 year, MWh)	240	193	240
Load system (15 year, MWh)	360	289	360
Load system (20 year, MWh)	480	385.60	480
CAPEX (USD)	19,000	58,000	82,000
NPC (USD, 5 year)	88,600	47,000	67,000
NPC (USD, 10 year)	150,000	61,000	88,000
NPC (USD, 15 year)	200,000	72,000	105,00
NPC (USD, 20 year)	243,000	81,000	119,000
LCOE (USD/kWh, 5 year)	0.83	0.55	0.64
LCOE (USD/kWh, 10 year)	0.77	0.40	0.46
LCOE (USD/kWh, 15 year)	0.75	0.34	0.40
LCOE (USD/kWh, 20 year)	0.74	0.31	0.37
PV saving vs. diesel (USD, 5 year)[a]	–	33,600	22,800
PV saving vs. diesel (USD, 10 year)[a]	–	67,200	45,600
PV saving vs. diesel (USD, 15 year)[a]	–	100,800	68,400
PV saving vs. diesel (USD, 20 year)[a]	–	134,400	91,200

[a] Saving = $[(LCOE_{DG} - LCOE_{PV}) \times \text{Load served}]$.

system offers substantial savings of USD141k over the 50 kW and USD76k over the 25 kW diesel generators (Table 6).

5.5.2. Power supply considerations for the Imvepi camp trading centre, Uganda

The trading centre in Imvepi refugee camp is an example of a refugee community with thriving economic activities. Most of the appliances (i.e., refrigerators, hair clippers, TVs) used in the trading centre were of DC origin, and users convert the AC electricity supplied from multiple small diesel generators to DC. Based on the survey the estimated electrical demand (Table 5) was modelled to arrive at an optimum size of a diesel generator which was found to be 10 kW, with an overall cost of USD 19k (Table 3). For this trading centre, two PV systems in AC and DC modes were modelled to supply the same loads as the diesel generator (Table 5). To supply the 65.8kWh/d AC load, a 28kWp PV-battery AC power plant. However, a DC solution, seems more appropriate for this small footprint representing a demand of 52.84 kWh/d DC. The analyses indicate that a 18kWp PV-battery DC system to be the optimum power plant to serve a smaller load compared to its AC counterpart (Fig. 5), and will have least conversion (AC-DC) losses.

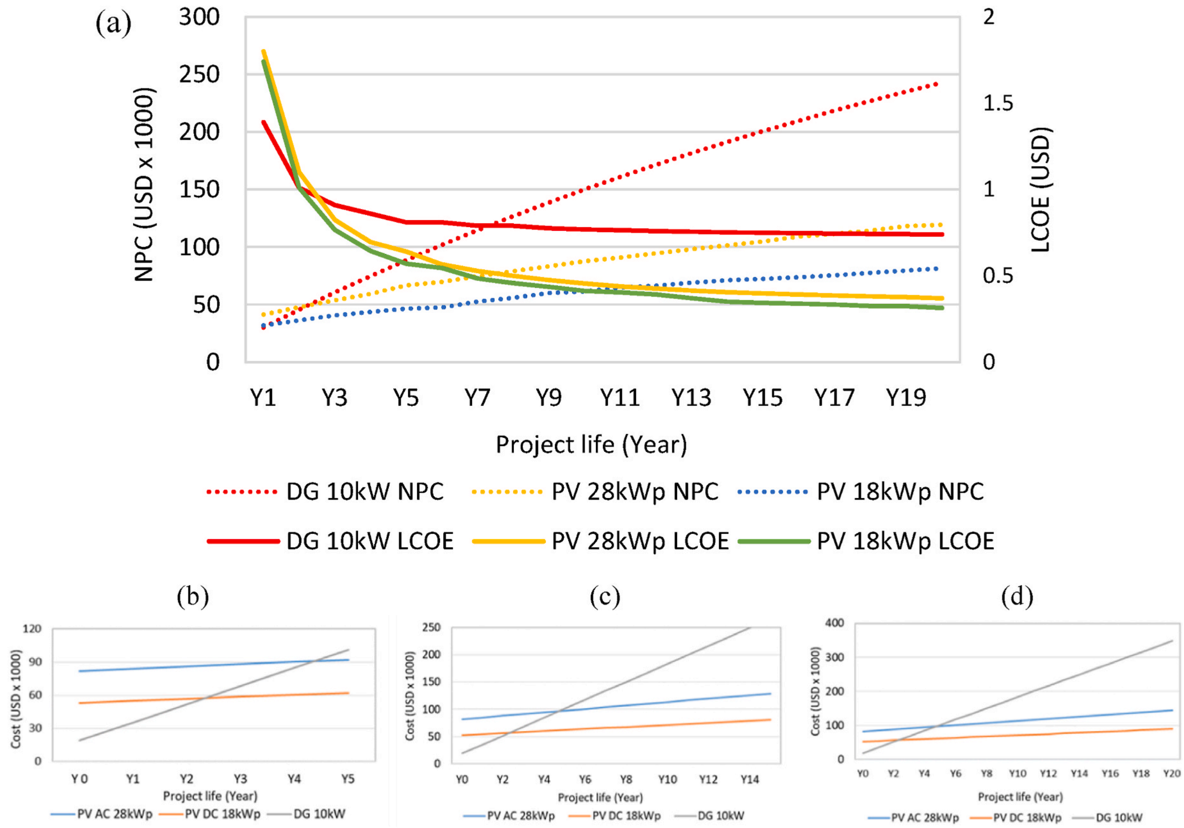

Fig. 7. (a) Net present cost (NPC) and levelised cost of electricity (LCOE) generated from a 10 kW diesel generator (DG), and 28kWp & 18kWp PV-battery power plant for the Imvepi trading centre over 20 years. Life span cost comparisons for the same case for (b) 5 year, (c) 15 year and (d) 20 year project life scenarios.

Table 8
Net present cost (NPC) and levelised cost of electricity (LCOE) for 10 kW diesel generator (DG) and PV-battery power plants in AC and DC over different project life options for refugee household indoor lighting, mobile phone charging, radio, security and outdoor communal toilet lighting in Kutupalong refugee camp, Bangladesh.

Variable	DG 10 kW	PV-battery 16kWp (DC)	PV-battery 20kWp (AC)
Load system (5 year, MWh)	77	77	77
Load system (10 year, MWh)	154	154	154
Load system (15 year, MWh)	231	231	231
Load system (20 year, MWh)	308	308	308
CAPEX (USD)	19,000	56,000	73,000
NPC (USD, 5 year)	80,000	50,000	64,000
NPC (USD, 10 year)	134,000	67,000	86,200
NPC (USD, 15 year)	179,000	81,000	105,000
NPC (USD, 20 year)	215,000	92,000	120,000
LCOE (USD/kWh, 5 year)	1.16	0.76	0.98
LCOE (USD/kWh, 10 year)	1.10	0.56	0.73
LCOE (USD/kWh, 15 year)	1.05	0.50	0.66
LCOE (USD/kWh, 20 year)	1.00	0.46	0.60
PV saving vs. diesel (USD, 5 year)[a]	–	30,800	13,900
PV saving vs. diesel (USD, 10 year)[a]	–	83,200	57000
PV saving vs. diesel (USD, 15 year)[a]	–	127,100	90,100
PV saving vs. diesel (USD, 20 year)[a]	–	166,300	123,200

[a] Saving = [($LCOE_{DG} - LCOE_{PV}$) × Load served].

Cost comparisons for the proposed PV AC and DC power plants with the 10 kW diesel generator are presented in Table 7. The results for the NPC and LCOE indicate that the 18 kWp PV-battery DC power plant is the least cost electrification option for this trading centre. Even the 28kWp PV-battery AC power plant also provides much cheaper electrification compared to the 10 kW diesel generator. The modelled LCOE for the diesel generator was in the range between USD 0.83/kWh and USD 0.74/kWh for different project life spans of 5, 10, 15 and 20 year (Table 7). The costs of electricity for both PV-battery AC and DC power plants drop substantially with the increased project life periods. For a 5-year project life, the LCOE are USD 0.64/kWh for AC and USD 0.55/kWh for DC, for a 20-year project life these values are USD 0.37/kWh for AC and USD 0.31/kWh for DC (Table 7). With the cheaper LCOE, both the PV-battery systems deliver considerable savings over the 10 kW diesel generator regardless of project lifespans. Potential savings through the 18kWp and 28kWp PV-battery systems range from USD 33,600 and USD 22,800 to USD 134,400 and USD 91,200 for the 5 year and 20 year project life respectively (Table 7). NPC and LCOE of the 10 kW diesel generator surpass those of the proposed 18kWp and 28kWp PV-battery plants between the first and second year of a 20 year project life

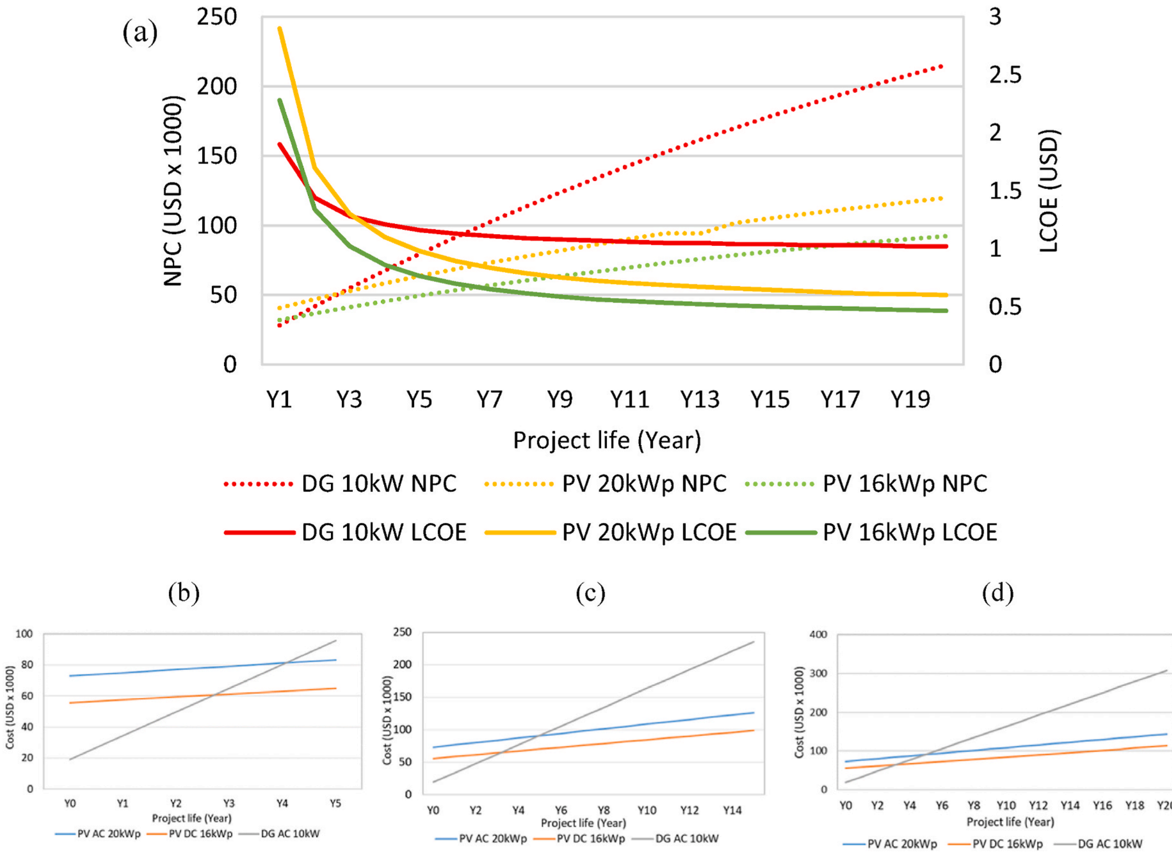

Fig. 8. (a) Net present cost (NPC) and levelised cost of electricity (LCOE) generated from a 10 kW diesel generator (DG), and 20kWp and 16kWp PV-battery power plant over 20 years. Life span cost comparisons of electrification of a cluster of 400 refugee household for lighting and basic accessories, 50 streetlights and 30 communal toilet lights in Kutupalong camp, Bangladesh using 20kWp AC or 16kWp DC PV-battery power plants, and 10 kW diesel generator for (b) 5 year, (c) 15 year and (d) 20 year project life scenarios.

Table 9
Net present cost (NPC) and levelised cost of electricity (LCOE) over different project life options for a 250Wp shared solar home system (SHS) serving a small cluster of 6 houses (2 LED lights, 1 mobile phone charger, 1 radio or other audio device for each house) as well as 2 outdoor security and 2 communal toilet lightings for each cluster in a refugee camp, Uganda.

Variable	250Wp shared SHS
CAPEX (USD)	1175
NPC (USD, 5 year)	1100
NPC (USD, 10 year)	1900
NPC (USD, 15 year)	2500
LCOE (USD/kWh, 5 year)	1.12
LCOE (USD/kWh, 10 year)	1.08
LCOE (USD/kWh, 15 year)	1.06

scenario. Lifespan cost comparisons presented in Fig. 7(b) and (c) & (d) indicates that diesel generator cost surpasses those of the PV-battery solutions between the 3rd year and 4th year. Hence even for a shorter project lifespan (i.e., 5 year), it is much more economic to invest in the low carbon PV systems instead of diesel generator for this trading centre.

5.6. Power supply considerations for the Kutupalong refugee camp, Cox's Bazar district, Bangladesh

Refugee settlements in Bangladesh are densely populated. For example, in Ukhia and Teknaf areas of Cox's Bazar district, Bangladesh around 600,000 Rohingya refugees are living in 13 square kilometre area (UNHCR, 2018). The survey findings presented in Table 2 revealed an electrical load of around 42.2 kWh/d (Fig. 3 and Table 5) for a cluster of 400 refugee households including security and toilet lighting in the

Table 10
Overall CAPEX recovery periods and estimated savings of PV-battery systems compared to currently used (and equivalent) diesel generators for different refugee electrification applications in Uganda and Bangladesh. Refer to Table 5 for details of load requirements for AC and DC configurations.

Location	Current system	Proposed system	CAPEX USD	CAPEX recovered in year[a]	Estimated savings by proposed PV systems at different project lifetime (USD x 1000)			
					5-year	10-year	15-year	20-year
Bidi-bidi base camp, Uganda	50 kW genset	40kWp PV system	112,000	2	140.80	312.40	480.60	653
Bidi-bidi base camp, Uganda	25 kW genset	40kWp PV system	112,000	3	75.70	186	290	400
Imvepi trading centre, Uganda	10 kW genset	28kWp PV (AC) system	82,000	4	22.80	45.60	68.40	91.20
Imvepi trading centre, Uganda	10 kW genset	18kWp PV (DC) system	58,000	3	33.60	67.20	100.80	134.40
Kutupalong refugee camp, Bangladesh	10 kW genset	20kWp PV (AC) system	73,000	3	14	57	90.10	123.20
Kutupalong refugee camp, Bangladesh	10 kW genset	16kWp PV (DC) system	56,000	4	30.80	83.20	127.10	166.30

[a] CAPEX Recovery period of PV compared to diesel generators (Year).

Kutupalong camp. All the light bulbs, mobile phones and radios in this cluster use DC power. Hence, both AC and DC cases have been modelled. Modelling outcomes presented in Table 8 indicate that generating and supplying electricity in DC requires a smaller PV-battery system (16kWp) compared to the AC option (20 kWp), with a cost saving of USD 17,000. This is mainly due to the cost of the DC-AC-DC conversion for the balance of system in the AC supply configuration.

Comparing the costs of the modelled PV-battery systems (16 kWp in DC and 20 kWp in AC) with the 10 kW diesel generator, the results show that for a 20 year project life, the PV-battery DC power plant offers the least LCOE (USD 0.46/kWh) followed by the PV-battery AC system (USD 0.60/kWh) (Table 8). NPC values for the PV systems (USD 120,000 for 20 kWp PV and USD 92,000 for 16 kWp PV) also remain much lower than the diesel generator (USD 215,000).

While the LCOE for the 10 kW diesel generator do not vary much over the different project lifetime of 5 year–20 year (USD 1.16/kWh to USD 1/kWh), the cost of electricity drops considerably in the case of both AC PV-battery (USD 0.98/kWh to USD 0.60/kWh) and the DC power plants (USD 0.76/kWh to USD 0.46/kWh) (Table 8). Nevertheless, the cheaper LCOE from both the PV-battery systems (AC and DC) delivers significant savings over the 10 kW diesel generator for different project lifespans. Potential savings through the 16 kWp and 20 kWp PV-battery systems range from USD 30,800 and USD 13,900 to USD 166,300 and USD 123,200 for the 5 year and 20 year project life respectively (Table 8). NPC and LCOE values presented in Fig. 8 (a) for a 20 year project life scenario indicate that NPC and LCOE values of the 10 kW diesel generator cost surpass those values of 16 kW and 20 kWp PV-battery plants on the 2nd year 3rd year. Life span costs presented in Fig. 8 (b), (c), and (d) depict that costs of running the diesel generator surpasses the costs of proposed PV-battery options between the 3rd year and 4th year. Therefore, it is evident that even for shorter project lifespan (i.e., 5 year), it is still worthwhile to invest in the low carbon PV systems compared to diesel generator.

It must be noted that the LCOE of the PV-battery solutions (20 kWp AC and 16 kWp DC) in Cox's Bazar (Table 8) are comparatively higher than those for the Bidi-bidi base camp and the Imvepi trading centre (Tables 6 and 7) in Uganda. This is because of the peak loads for refugee household in Cox's Bazar, Bangladesh, mostly occurring in the evening hours (Fig. 3), requiring large battery capacities. In comparison, most of the loads in the Bidi-bidi base camp and Imvepi trading centre, occur during daytime hours (Figs. 4 and 5).

5.7. *Power supply considerations for a small clusters of refugee households, Uganda*

The electrification of a small cluster of six refugee houses can be provided through appropriately sized shared solar home system (SHS) as shown in Table 5. The modelling considered 2 LED lights (5 W each), 1 mobile phone charger (5 W each), 1 radio or other audio device (5 W each with rechargeable battery) for each house in the cluster. The cluster also had 2 outdoor security (20 W each) and 2 communal toilet lighting (10W each). Such electrification seems suitable in terms of cost for dispersedly located clusters of refugee households (such as many refugee camps in Uganda) as it avoids expensive distribution network cost and transmission losses. Estimated total DC load for such a cluster is 0.6 kWh/d, which requires a 250 Wp PV system with 48 h battery bank autonomy (Table 5). LCOE from this proposed shared SHS vary between USD 1.12/kWh and USD 1.06/kWh for 5 year and 15 year project life (Table 9). Results also indicate that the scaled capital cost of such shared PV system for 400 houses (USD 78,000 = (400 × USD1175/6)) remains higher compared to the costs of proposed PV-battery systems in Cox's Bazar, Bangladesh (USD 73,000 for 20 kWp PV AC and USD 56,000 for 16 kWp PV DC) as presented in Table 8. Furthermore, the LCOE of such SHS solution is also higher than all PV systems presented earlier (Tables 6–8). This is due to the comparatively higher PV technology costs at a smaller scale. The procurement of multiple systems with higher accumulated power capacity will undoubtedly reduce the cost of electricity.

5.8. *Overall comparison of the CAPEX of the technologies and systems*

Table 10 provides an overall comparison of CAPEX and cost recovery periods of PV-battery systems including estimated savings compared to currently used (and equivalent) diesel generators for different refugee electrification cases considered. For example, this research clearly demonstrate that the high CAPEX of the proposed 40 kWp PV-battery system in a base camp in Uganda can be recovered in the 2nd and 3rd year of its operation as compared with the currently used 50 kW diesel generator and the modelled appropriately sized 25 kW diesel generator prospectively. Similarly, early cost recovery of different PV-battery systems compared to equivalent diesel generators are also evident in Imvepi trading centre, Uganda, and cluster of 400 refugee households in Bangladesh (Table 10). Estimated savings from PV systems presented here (Table 10) also indicate the benefits for the longer project life options (i.e., 15 year, 20 year) where the amount of savings increases tremendously (see also Tables 6–8; Figs. 6–8).

5.9. *Environmental impacts*

Environmental impacts associated with the use of diesel fuel were quantified in terms of CO_2 and NO_x emissions that can be displaced through replacing the fuel with the proposed PV battery systems (Table 5). The emissions arising from the operations of the (a) currently used, oversized 50 kW; (b) appropriately sized 25 kW diesel generators in the Bidi-bidi base camp; 10 kW diesel generators at (c) Imvepi trading centre in Uganda, and (d) the cluster of 400 refugee households in Bangladesh, are presented in Table 11.

As can be seen in Table 11, replacing the current diesel generator in Bidi-bidi base camp, Uganda with solar PV battery system would result in a reduction of 2.4 $MtCO_2e$ over a 20-year project lifetime. Similarly, for the case of the appropriately sized diesel generator, this saving equates to 1.2 $MtCO_2e$ over the same period. As highlighted in the table, the emissions savings, including for NO_x, and for the other cases are significant. Clearly, the environmental impact of diesel generation can be mitigated through renewable energy sources which also have significant cost saving advantages as presented in Table 10.

Table 11
Estimated CO_2 and NO_x avoidance by replacing specific diesel generators with suitable PV battery systems in refugee camps in Uganda and Bangladesh.

Application case	Location	Diesel generator	Diesel consumption (1000 l/year)	Estimated emission avoidance	
				$MtCO_{2e}$/20 year project life	tNO_x/20 year project life
(a) Oversized (current)	Bidi-bidi base camp, Uganda	50 kW	45	2.40	53
(b) Appropriately sized	Bidi-bidi base camp, Uganda	25 kW	23	1.20	26
(c) Appropriately sized	Imvepi trading centre, Uganda	10 kW	11	0.57	13
(d) Appropriately sized	Cluster of 400 households, Bangladesh	10 kW	10	0.50	11

5.10. PV systems performance and resilience

Performance and resilience of PV-battery electricity generating systems substantially depend on their load serving capabilities and the health of the battery bank. For the latter, system capabilities and performance of the battery banks are also analysed as a part of this study. Capacity analysis of the modelled optimum PV-battery systems including the small scale SHS indicate that such systems are capable of serving the required loads within the 5% (maximum) set capacity shortage limit. The detailed results of the resilience of the above systems are given in Appendix A. Furthermore, all the PV-battery power generating systems and Solar Home Systems (SHS) modelled and analysed for this research are modular and hence can be expanded with additional power capacities in the future. Such system flexibility allows options to support higher power energy access for the target communities such as refugees and remote and dispersed villages (Bahaj and James, 2019; Vernet et al., 2019; Bahaj et al., 2019, 2020).

6. Conclusions

The presented research focussed on sustainable electrification of refugee camps to support services, such as lighting, refrigeration, health, water, education as well as camp operations. The analyses were underpinned by surveys undertaken in selected refugee camp sites in Northern Uganda and Southern Bangladesh where the solar resource is highly available. Various solar photovoltaic (PV) electrification solutions with battery storage were modelled to support mini grid deployment in camps as well as Solar Home Systems (SHS) for housing clusters. System performance and resilience related to required loads were investigated with analyses providing comparison not only in relation to identified PV solutions but also to the currently used diesel power systems. The analyses presented were based on a relatively small sample of data but the results are clear and can be scaled up and applied to refugee camps in other geographical locations with similar characteristics.

This work clearly identified that there is a need to overhaul the current electrification delivery approaches for refugee camps. An indicative pathway for transitioning currently used fossil fuels to renewable energy resources is also presented as a framework (Fig. 1) to support electrification of both the refugee households and camp operations. The findings of the stakeholder surveys (Section 5.1.1) indicate that such transitioning is hindered by issues such as: (i) the short-term funding cycles, (ii) the lack of clear cost comparison data between diesel generators and renewable energy options, and (iii) the absence of appropriate policy guidelines.

Collected electrical demand data for different refugee camp operations and other services (i.e., base camp operation, refugee households, trading centre), were use to undertake a techno-economic analysis of representative diesel generators and their replacement with appropriately designed PV-battery systems are presented (Section 5.1.2 to Section 5.8). The results of modelled modular PV-battery AC and DC systems, and SHSs (informed by collected survey data) show the clear benefits of deploying such systems for the refugee households, camp operations and other services. For households, the research covered lighting and mobile phone charging, however, as refugee settlements mature, household electricity demand tends to grow, requiring large-scale multifaceted data sets for energy system modelling. In contrast, electrification for camp operations and trading centres covered higher-power energy provisions for uses, which can be replicated in other settings.

The research also demonstrated the economic and the environmental benefits, including significant emission avoidance, in transitioning to PV-battery plants and SHSs systems (Sections 5.8, 5.9 and Table 10). The high initial capital cost of proposed PV-battery solutions can be fully justified on the basis of the resultant long-term savings achieved as compared to diesel generators even in the case of a very short project life scenario (i.e., 5 year) (Tables 6–9). In terms of emissions, a 40kWp PV-battery system would result in an overall reduction of 2.4 Mt CO_2e over a 20-year project lifetime, for the current utilised system in Bidi-bidi base camp. Such rapid and significant economic savings and environmental benefits demonstrated can be invested in welfare activities focussed on health, education and inclusive rehabilitation of refugees.

The presented solutions are generalisable and contribute to the United Nations Sustainable Development Goal 7 (SDG 7: access to affordable, reliable and clean energy), and Goal 13 (SDG 13: climate action through reducing emissions). Based on the presented evidence, it is important that aid agencies and governments adopt holistic approaches to enhance support for electricity access in refugee camps and ensure that electrification is a strategic component to be embedded in infrastructure planning processes from the outset of responses to refugee crises. It is also recognised that this may be difficult to achieve in an emergency setting. However, this could be remedied by having an agreed framework, as presented here, so that all stakeholders can understand and act upon it quickly.

7. Recommendations

This study aimed at providing evidence to assist aid agencies, governments and other stakeholders to adopt holistic approaches to enhance sustainable electricity access in refugee camps. The following recommendations are made are based on the presented findings:

(a) Sustainable electrification in refugee settings should be seen as a strategic approach, and be embedded in the planning process from the outset of crises with energy infrastructure seen as fundamental to the wellbeing of refugees.
(b) The renewable energy-based electrification should be prioritised on the basis of cost effectiveness, reducing environmental impacts and their contribution United Nations Sustainable Development Goals, SDG 7 and SDG 13.
(c) Aid agencies, donors and governments need to adopt policies to move away from the traditional expensive fossil fuel-based electrification to renewable options for all refugee services. This will require longer-term investment to support essential services as on average, refugees reside 17 years in the allocated shelters.
(d) It is essential that electricity supply provisions for the refugees should be implemented beyond just supply for lighting and should include productive use of energy. The savings from deploying solar PV systems as shown here, can be reinvested in facilitating support for productive use of energy; important for creating employment and enhancing the livelihoods of refugees.
(e) Humanitarian organisations, could establish country specific databases for assessment of technology readiness for regions with ongoing sources of conflict. These databases could detail the availability of resources, such as PV technology and the dynamics of private sector involvement in the energy market. This would provide an overall reference to aid agencies and stakeholders on the ground, providing a clear pathway to engage with and understand the potential and challenges of different business models.
(f) Private sector participation in electrification of refugee camps is important. Such business models can be delivered through offering capital subsidies, fixed term power purchase agreements, performance-based financing and other forms of investment geared to de-risking electricity access in refugee camps.

CRediT authorship contribution statement

AbuBakr S. Bahaj: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Majbaul Alam:** Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Luke S. Blunden:** Writing – review &

editing, Validation.

Declaration of Competing Interest

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

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Appendix A. PV systems performance and resilience

In terms of satisfying the load, modelled 40 kWp PV-battery AC system for Bidi-bidi base camp serves the year-round load of 96.2 kWh/d with only 1.25% capacity shortage, which is clear from Figure A1 with only a few outliers that indicate where electrical demands might remain unmet by the system. Similarly, the 28 kWp system for Imvepi trading centre serves 65.8 kWh/d AC load with 2.8% capacity shortage (Figure A2), whilst the 18 kWp DC system for the same trading centre serves load of 52.8 kWh/d with 1.1% capacity shortage (Figure A3). The 20 kWp PV-battery DC system for the cluster of 400 refugee houses and other security lights in Kutupalong, Bangladesh serves 42.2kWh/d load with 3.2% capacity shortage (Figure A4), whilst the 16 kWp PV-battery DC system serves the same load with 3.6% capacity shortage (Figure A5). The 250 Wp shared Solar Home System serves required load with only 0.8% capacity shortage (Figure A6).

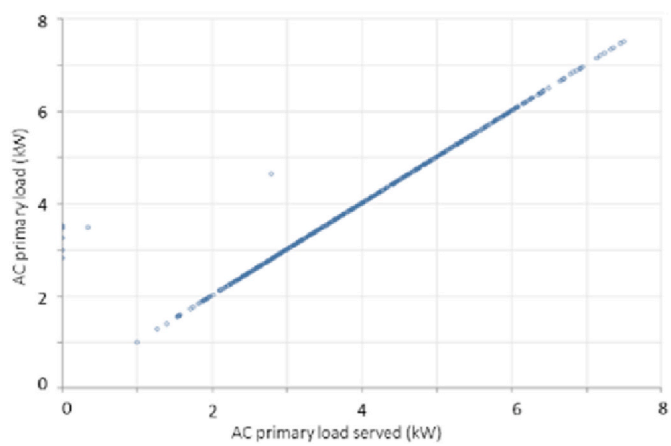

Fig. A1. Load serving capability of the proposed 40 kWp PV-battery AC plant in Bibi-bidi base camp, Uganda.

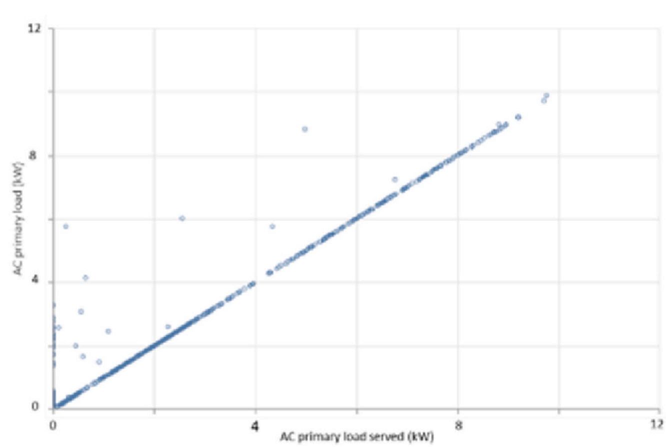

Fig. A2. Load serving capability of the proposed 28 kWp PV-battery AC plant in Imvepi trading centre, Uganda.

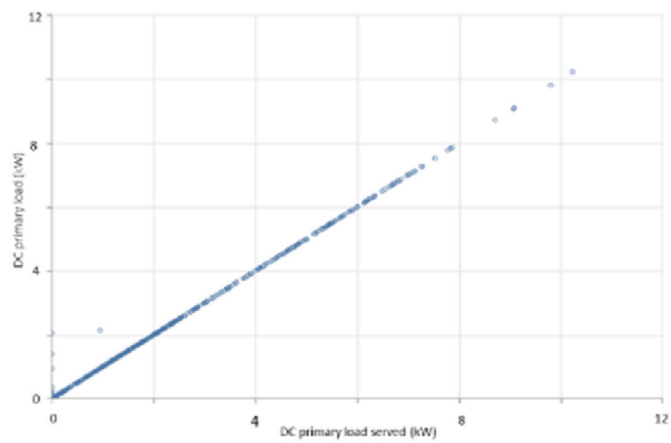

Fig. A3. Load serving capability of the proposed 18 kWp PV-battery DC mini grid in Imvepi trading centre, Uganda.

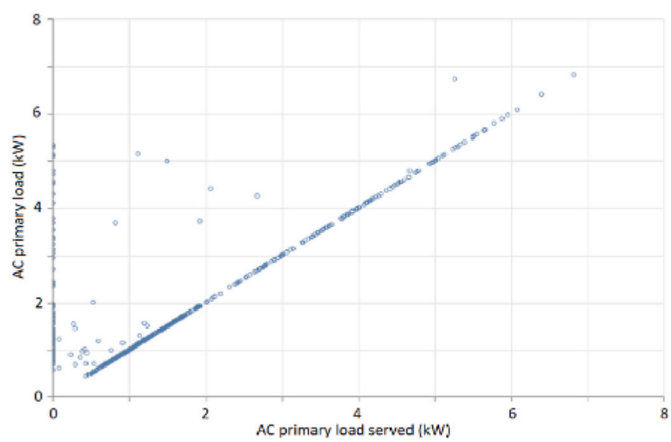

Fig. A4. Load serving capability of the proposed 20 kWp PV-battery AC power plant for refugee households in Bangladesh.

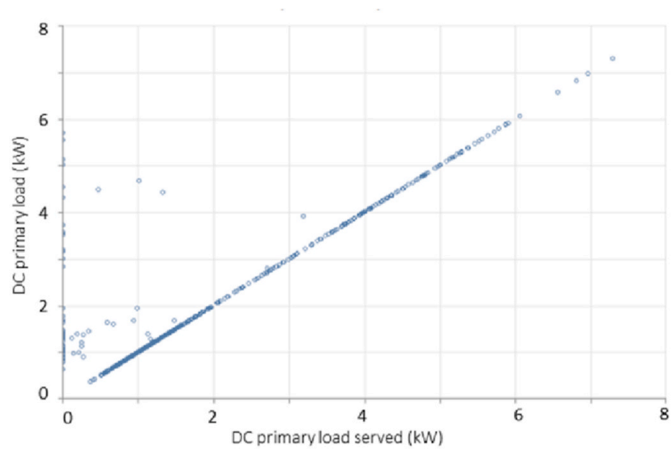

Fig. A5. Load serving capability of the proposed 16 kWp PV-battery DC power plant for refugee households in Bangladesh.

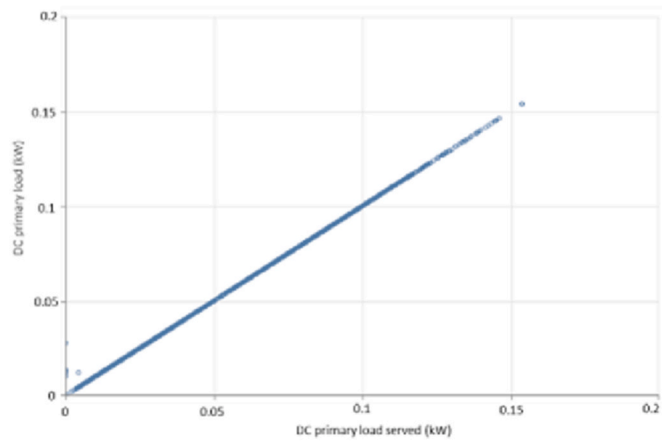

Fig. A6. Load serving capability of the proposed 250 Wp shared Solar Home System for small cluster of refugee households in Uganda.

Performance analysis of the different battery banks of the modelled PV systems indicates that most of the days in a year, the state of charge (SoC) remains around or over 70%, while only in few occasions battery SoC goes near or below 50% (Figure A7 – A12). Figure A7 presents few incidents over a year when SoC of the battery bank of the 40 kWp PV system in Bidi-bidi base camp reaches 40%. For the two PV-battery plant options for Imvepi trading centre in Uganda (28 kWp AC and 18 kWp DC system) none of these battery banks' SoC drops below 50% (Figure A8 & Figure A9). While battery bank SoC for the 20 kWp PV-battery AC system for the cluster of 400 refugee houses and other security lights does not fall below 50% (Figure A10), battery bank's SoC of the 16 kWp DC system serving the same load occasionally reaches 40% (Figure A11). Similarly, SoC for the battery bank of the 250 Wp PV-battery DC system for a small cluster of refugee houses and other security lights in Uganda drops to 40% on a few cases (Figure A12).

Requirements of serving critical loads in the evening and occurrence of poor local solar resources are directly related to the battery bank dropping to 40% SoC occasionally. Figure A13 shows an example of the battery bank's state of charge reaching to 40% on the days with poor solar irradiance for the 16 kWp PV-battery DC system for a cluster of 400 refugee houses and other security lights in Kutupalong refugee camp, Bangladesh. Such incidents can be minimised by increasing the size of the battery bank which in turn would substantially increase the CAPEX and LCOE. However, the analyses indicate that battery SoC occasionally reaching 40% for the modelled systems does not affect the longevity of the battery banks.

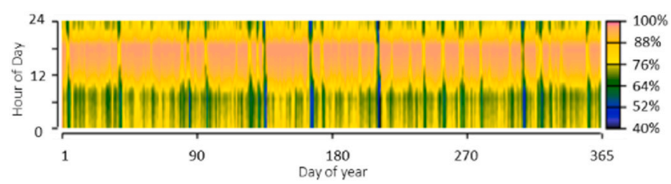

Fig. A7. Battery bank state of charge at different hours of the day over a year for the proposed 40 kWp PV-battery (AC) system in Bidi-bidi base camp.

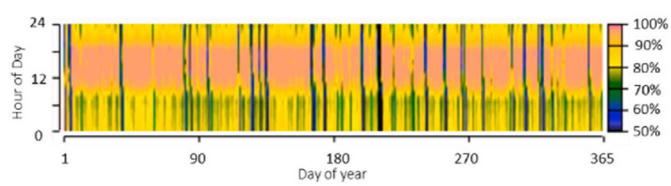

Fig. A8. Battery bank state of charge at different hours of the day over a year for the proposed 28 kWp PV-battery AC system in Imvepi trading centre.

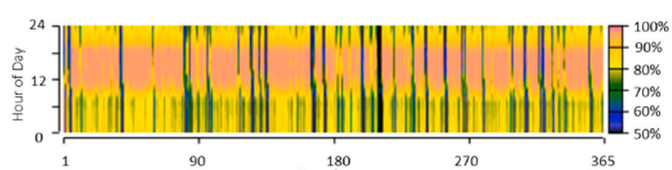

Fig. A9. Battery bank state of charge at different hours of the day over a year for the proposed 18 kWp PV-battery DC system in Imvepi trading centre.

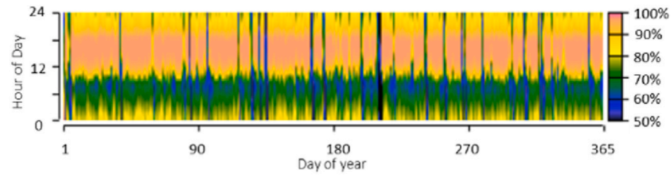

Fig. A10. Battery bank state of charge at different hours of the day over a year for the proposed 20 kWp PV-battery AC system for a cluster of 400 refugee houses and other services in Bangladesh.

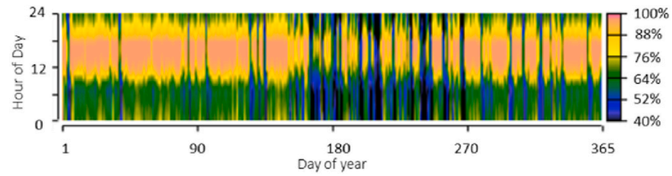

Fig. A11. Battery bank state of charge at different hours of the day over a year for the proposed 16 kWp PV-battery DC system for a cluster of 400 refugee houses and other services in Bangladesh.

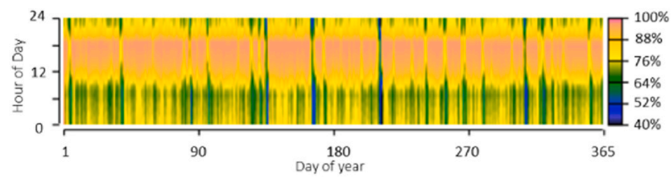

Fig. A12. Battery bank state of charge at different hours of the day over a year for the proposed 250 Wp PV-battery DC system for a small cluster of refugee houses and security lights in Uganda.

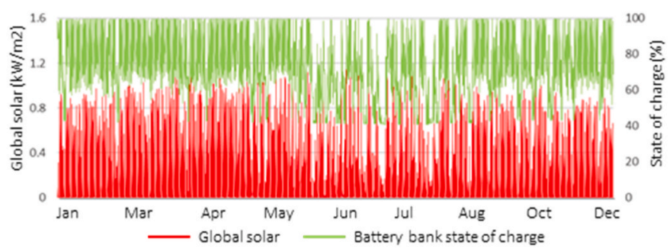

Fig. A13. Battery bank state of charge related to available solar irradiance for the 16kWp PV-battery DC system for a cluster of 400 refugee houses and other security lights in Bangladesh.

Data availability

A spreadsheet containing anonymized survey data, results tables and modelling parameters along with a survey procedure report needed to reproduce the techno-economic assessment will be available on publication at https://eprints.soton.ac.uk/491894/ with Digital Object Identifier https://dx.doi.org/10.5258/SOTON/P1175.

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