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Comprehensive approach for electricity and clean cooking access through solar photovoltaic mini grids: The Kobe refugee camp case study

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ABSTRACT

The literature on e-cooking lacks case studies on integrated energy and clean cooking approach for community-based infrastructures in displacement settlements. This case study from the Kobe refugee camp fills this gap by incorporating up-to-date and context-specific data. The study enhances e-cooking literature by specifically examining the integration of electric pressure cooker (EPC) demand into scalable photovoltaic mini-grids (PVMGs) designed under a comprehensive approach – to address electricity and cooking needs – and long-term sustainability. Using HOMER Pro, a recognized power system modelling software, to optimize the MG from the load profile, the study assesses the benefits, challenges and open issues, with a particular focus on access levels achieved, costs and environmental impact; demonstrating that integrating high efficiency e-cooking appliances as EPCs significantly increases initial investment but has minimal impact on the levelized cost of energy (LCOE) while creating a stable demand anchor. This research also demonstrates that when capital expenses are covered through donations, and the system is and properly maintained, this solution enables Multi-Tier Framework (MTF) Tier 4 energy access, equivalent to Modern Energy Cooking Services (MECS). Comparative analyses of metrics such as leveraged cost of cooking a meal, global warming potential and MTF level confirm that an e-cooking solution combining EPC with optimized PVMG is economically and environmentally beneficial in this context compared to the baseline situation of cooking with traditional three-stone firewood stoves, with high scalability potential to other refugee camps in the context. Additional advantages include reduced deforestation and resource conflicts between refugees and host communities.

Although findings may not be universally applicable, the decreasing costs of lithium-ion batteries and solar PV and the increasing reliability and quality of the solar PV technology, alongside rising biomass fuel prices, make electric cooking a cost-effective alternative, particularly in displacement settings. This study offers a valuable resource for energy practitioners and policymakers, supporting integrated e-cooking and electricity solutions. It addresses climate, energy, and development challenges in the humanitarian sector while contributing to SDG 7 and SDG 13.

Abbreviations: SA, Shire Alliance; CI, Communal Infrastructure; BLEENS, biogas, liquefied petroleum gas, electricity, ethanol, natural gas, and solar; EPC, Electric Pressure Cooker; ESMAP, Energy Sector Management Assistance Program; GHG, Greenhouse Gas; LCOE, Levelized Cost of Energy; LCCM, Levelized Cost of Cooking a Meal; CCM, Cost of Cooking a Meal; LPG, Liquified Petroleum Gas; MECS, Modern Energy Cooking Services; MG, Mini Grid; MTF, Multi-Tier Framework; NEP, National Electrification Program; PV, photovoltaic; PVMG, Photovoltaic Mini grid; RC, Refugee Camp; SDG, Sustainable Development Goal; TSF, three-stone fire-wood stoves; UNHCR, United Nations High Committee for Refugees.

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Introduction

"*At the end of 2023, 117.3 million individuals were forcibly displaced worldwide as a result of persecution, conflict, violence, human rights violations or events seriously disturbing public order* " (UNHCR, 2023) and "*if no action is taken, the number of climate migrants could reach 216 million by 2050 worldwide*" (Clement et al., 2021). This upward trend generates an increase in humanitarian needs worldwide. Forced displacement has varied causes – and combinations of these – such as poverty, food insecurity and the search for new economic opportunities; violence in its many facets (persecution, human rights violations, terrorism, abuse, ethnic conflict, repression, war) and climate change and natural disasters, among others. Paradoxically, most displaced individuals seek refuge in low-income countries, which typically have fewer economic resources than their countries of origin (Salas Ruiz et al., 2021). As a result, Least Developed Countries (LDC) host around seven million refugees, with Ethiopia—ranked ninth globally—accommodating over one million refugees as of October 2024 (UNHCR, 2024b). Consistent with this trend, the rising costs of the humanitarian model—reaching approximately $28.9 billion in 2018—continue to strain efforts to support refugees (Salas Ruiz et al., 2021).

In response, the New Declaration for Refugees and Migrants led to the Comprehensive Refugee Response Framework (CRRF) (UN General Assembly, 2016), which aligns with the 2030 Agenda to improve refugees' access to essential services within host communities. The CRRF underscores the vital role of modern energy, including clean cooking and electricity, in supporting households, businesses, community infrastructures (CIs), and humanitarian operations. Limited energy access restricts work, education, safety, and self-reliance, while reliable energy for facilities such as health and education are crucial for socioeconomic development (Bhatia & Angelou, 2015). The CRRF advocates for sustainable, affordable energy solutions that address both immediate and long-term needs, in line with SDG 7 (Al-Kaddo & Rosenberg-Jansen, 2021). However, while governments such as Ethiopia recognize the energy needs of displaced populations within the framework of the National Electrification Program (NEP), they do not set specific targets to improve their access to sustainable electricity. Improving access could also enhance the efficiency of humanitarian operations, which currently depend on low-efficiency diesel generators. Addressing this gap would align with the UN's 10-year Climate Action Plan and the UNHCR Strategy for Sustainable Energy 2020–2025 (UNHCR, 2019).

However, nowadays, 94 % of climate refugees globally do not have access to electricity and 81 % rely on firewood and charcoal for cooking (Ndahimana et al., 2023; Rosenberg-Jansen & Al-Kaddo, 2022; Sandwell et al., 2024). These figures are largely worse than worldwide trends, 9 % lack access to electricity and 26 % rely on firewood and charcoal for cooking, resulting in a significant challenge. Availability, affordability, and acceptability of sustainable energy technologies continue to be key barriers to their adoption across diverse humanitarian contexts (IEA et al., 2024). The consequences of inaction on clean cooking are extensive, with significant impacts on health, gender equality, environmental sustainability, and economic productivity. In developing countries, cooking energy constitutes a substantial share of national energy demand and is largely derived from biomass resources (Bhattacharya et al., 2002). This reliance on traditional biomass contributes to deforestation and exposes individuals to indoor air pollution, leading to severe respiratory illnesses and premature deaths. Moreover, the labour-intensive task of firewood collection, primarily undertaken by women and children, limits access to education and income-generating opportunities. For instance, women may have to travel long distances—sometimes up to 18 kms—to gather firewood, exposing them to risks such as harassment (Silva, 2020). The global economic cost of inaction is estimated at $2.4 trillion annually, including $1.4 trillion in health-related expenses, $0.8 trillion due to gender inequalities, and $0.2 trillion from environmental degradation (ESMAP, 2020b).

Although electricity and cooking provision are essential for facilitating basic assistance and service delivery in the humanitarian sector, they have historically not been prioritized (Tracy Tunge, 2020). In addition, there is a significant lack of standardized data and information on energy access levels in this context (Grafham & Sandwell, 2019; IRENA, 2019). Consequently, the humanitarian sector has developed a limited understanding and adopted a fragmented approach to energy provision, without inclusion of cooking needs. Many humanitarian organizations lack a coordinated strategy for managing energy use, resulting in common practices that often lead to undersized and inadequate energy supply systems (IRENA, 2019).

Research on energy access for displaced populations remains limited, often relying on literature or laboratory data while overlooking innovative solutions. Energy-efficient electric cooking powered by renewable energy supports SDG 7 and the Paris Agreement, offering health and resource management benefits. However, challenges such as affordability, grid stability, and socio-cultural acceptance persist. Existing studies frequently neglect key factors like energy demand forecasting and system optimization. The lack of real-world case studies on scalable e-cooking solutions in displacement settings is particularly concerning given the rising number of displaced people, underscoring the urgent need for targeted research and strategic planning with quality information and data availability.

This article aims to address gaps in the literature by: (i) analysing the impact of incorporating cooking needs into the life-cycle sizing of electricity systems using reliable context-specific data from Shire Alliance (SA) project, and (ii) evaluating the techno-economic feasibility and benefits of deploying Electric Pressure Cookers (EPCs) powered by optimized PVMGs for clean cooking in CIs in resource-limited environments like, in the selected case study for this paper, the Kobe displacement settlement (Ethiopia). The paper compares these solutions based on updated context data to alternative approaches and existing data from other contexts, bridging the gap between theoretical models and practical implementation. The paper structure includes in Cooking needs and solutions in humanitarian settings section a review of the state of the art on cooking solutions in humanitarian settings, the description of the case study in Description of the case study: the Kobe refugee camp section, method and materials in Materials and methods section, the results in Results section, the results analysis and discussion in Results analysis and discussions section, the conclusions in Conclusions and policy implications section, and the recommendations for future research in Limitations, recommendations and further research section.

Cooking needs and solutions in humanitarian settings

A review of cooking systems for humanitarian settings (Vianello, 2016) highlights that research on energy access in this context remains limited, often relying on estimates due to insufficient real-world data. Uneven attention to solutions and limited exploration of innovative approaches further hinder progress. While cooking challenges in stable and displaced communities share similarities, restrictions on movement, employment, resource use, and governance gaps complicate energy supply in refugee settings. Addressing these challenges requires innovative solutions, increased funding for clean cooking systems, and the active involvement of women in decision-making (Njenga et al., 2024).

Efforts to promote Improved Cooking Stoves (ICS) have raised concerns about their ability to meet the World Health Organization (WHO) household air pollution (HAP) standards and their long-term environmental sustainability (Aung et al., 2016; Council, 2016; Pope et al., 2017; Quansah et al., 2017). Firewood scarcity in displaced settlements exacerbates tensions with host communities (Njenga et al., 2024). Meanwhile, some governments prioritize Natural and Liquefied Petroleum Gas (LPG), these fuels face supply challenges in rural and displacement contexts which are vulnerable to economic and geopolitical factors, and conflict with long-term climate goals (Council, 2016; Nerini et al., 2017). Table 1 presents the Global Warming Potential (GWP) values for various energy resources, as reported by the

Table 1
GWP by energy resources.

Energy resource	Tn eq. CO2/MWh
Wood or Wood waste	4,397
Charcoal	4,257
Gas/Diesel oil	2,685
Other kerosene	2,606
LPG	2,278

Intergovernmental Panel on Climate Change (IPCC) (Buendia et al., 2006).

On the other hand, while electric cooking is widespread in high-income countries, it remains limited in low- and middle-income nations, where rural electrification strategies often overlook its potential (IEA et al., 2018). In light of this, mini-grids (MGs) are recognized as essential for expanding electricity access (Sayani et al., 2022a) and research increasingly supports electric cooking (e-cooking) as a sustainable option for clean cooking, especially in off-grid areas including displaced settlements (Batchelor et al., 2018; Yangka & Diesendorf, 2016). Indeed, the Levelized Cost of Energy (LCOE) for solar PVMGs has significantly decreased from 0.47 to 0.92 $/kWh in 2015 to approximately 0.20 and 0.55 $/kWh (Okunlola et al., 2018). Projections suggest a further decline between 0.19 and 0.35 $/kWh (Come Zebra et al., 2021), reflecting a reduction of about 28 %.

Highly efficient devices such as induction stoves and EPCs reduce energy consumption and could revolutionize the cooking sector, similar to how light-emitting Diodes (LEDs) transformed lighting, driven by declining costs and increasing affordability of MGs (Clements et al., 2024; Sánchez-Jacob et al., 2021). EPCs integrate an electric hotplate, a pressure cooker, an insulated casing and a fully automated control system, reducing energy consumption by up to 80 % compared to traditional hotplates. Insulation helps retain heat, allowing cooking to continue during brief power outages and keeping food warm, making EPCs ideal for under-resourced communities with unstable electricity (Batchelor et al., 2022). They also decrease meal preparation time, saving working hours and energy for cooking meal costs (Avila, 2016; Chreiber et al., 2020). Furthermore, EPCs are particularly relevant for community cooking in school feeding programs, which play a crucial role in refugee education and nutrition. A major challenge in MG design is accurately forecasting electricity demand in non-electrified communities, particularly for cooking, where regional practices significantly impact infrastructure size, reliability, and financial viability (Batchelor, 2015; Blodgett et al., 2017; Leary et al., 2019; Louie & Dauenhauer, 2016; Sayani et al., 2022b). Cultural identity also plays a role in technology adoption, requiring community engagement to overcome resistance and ensure successful implementation (Tamire et al., 2018).

However, gaps and limitations persist in the literature and real-world projects, which often rely on outdated literature or laboratory data, stand-alone PV systems lacking economies of scale, oversimplified economic models that fail to optimize systems based on load profiles (Ahmad et al., 2018; Jeuland & Pattanayak, 2012; Lombardi et al., 2019; Odoi-Yorke, 2024; Stritzke & Jain, 2021). Some studies find e-cooking competitive, while others disagree or remain inconclusive but emphasize energy costs as key to affordability (Jacobs & Couture, 2019; Keddar et al., 2021; Zubi et al., 2017). To date, only two case studies have examined e-cooking via MGs for CIs: a review of Tanzanian households and CIs (Lombardi et al., 2019) and a study on large electric pressure cookers (EPCs) in Lesotho schools (Nsengiyaremye & Khalifa, 2023). However, neither study focuses on displacement settings, with only the Tanzanian study exploring an off-grid context.

There are numerous cooking metrics that are commonly cited, yet none appear to be universally dominant. In household-focused studies, costs are often measured over specific time periods, such as days, months, or years. However, for institutional contexts (ICs), where both the number of people served and the daily meal count vary, assessing costs per single meal provides a more practical and standardized approach. The Levelized Cost of Cooking a Meal (LCCM) is a key metric for evaluating the economic viability of cooking solutions, analogous to the LCOE in the energy sector. LCCM offers a standardized metric for comparing various cooking technologies and fuels by accounting for both initial investment and recurring expenses over the equipment's lifespan (ESMAP, 2020a). In contrast, the Cost of Cooking a Meal (CCM) focuses solely on recurring costs. Despite its relevance, LCCM has been applied in relatively few studies, including analyses of fuel and technology choices in Kenyan households (Nerini et al., 2017) and the review of Tanzanian households and CIs, while CCM has been used in the case study of Lesotho schools. Therefore, Table 2 summarizes LCCM data from the literature, adjusting per single meal based on the number of "fully cooked" meals considered—three in the Lombardi case and four in the Nerini study.

In Lesotho case study, for those schools that serve super-cereal porridge, the energy EPC demand and CCM data for the whole school and per student meal -calculated from the whole school data- are shown in Table 3.

Poorly designed systems with limited quality data can result in unreliable electricity supply, affecting e-cooking adoption and limiting the benefits of clean cooking transitions. Furthermore, the lack of common cooking metrics makes comparisons and scaling difficult for appropriate energy planning in refugee contexts. In this context, the following section presents descriptive information of the case study referred in this research to provide substantial evidence in this area and advance cooking design strategies for refugee settlements.

Description of the case study: the Kobe refugee camp

Ethiopia, a country with one of the lowest Human Development Indexes, hosts refugees primarily from Sudan, Somalia, Eritrea, and South Sudan, mainly in the Gambela and Somali refugee camps, which face significant challenges for energy access. The Melkadida/Dollo Ado office, established in 2011 by the Ethiopian government and UNHCR, supports over 200,000 Somali refugees. In 2017, Ethiopia adopted Refugee Proclamation No. 1110/2019, one of Africa's most progressive refugee laws, granting refugees the right to live, work, and access social services (UNHCR, 2024a). In March 2023, the Kobe refugee camp (RC) alone housed 37,461 refugees. Ethiopia ranks third globally in the number of people without electricity access (56 million), with 94 % of the population still relying on polluting cooking fuels like firewood and three-stone stoves (Ethiopia Energy Outlook – Analysis, *2023*). In this context, the Ethiopian government has set ambitious targets to achieve SDG 7: reaching a 100 % energy access rate by 2025 through the Ethiopian National Electrification Program (NEP) (Ministry of Water, Irrigation, and Energy, 2019) and 100 % access to Modern Energy Cooking Services (MECS) by 2030. However, progress is hindered by a lack of prioritization for cooking sustainable fuels, insufficient data for effective learning, and limited funding. Only 0.5 % of Ethiopia's budget for high-

Table 2
LCCM literature data.

Cooking Solutions	LCCM ($/meal)		LCCM ($/single meal)	
	Lombardi[a]	Nerini[b]	Lombardi	Nerini
Gathered Firewood	0–0,5	0,06	0–0,16	0,015
Purchased Firewood	0–0,5	0,10	0–0,16	0,025
Charcoal	0,1-0,55	0,10	0,033–0,18	0,024
Kerosene	0,2-0,7	0,27	0,06-0,23	0,068
LPG	0,3-0,8	0,25	0,1-0,26	0,063
e-cooking	0,35-0,65	0,35	0,12–0,22	0,088

[a] Two extreme LCCM values are obtained for each technology-fuel combination by accounting for all possible sources of variability: a) fast firing, higher efficiency range and lower fuel price range; or b) slow firing, lower efficiency range and higher fuel price range.

[b] Cost of electricity in the county from approximately 0.25 $/kWh.

Table 3
Lesotho case study cooking energy and meal cost data.

		Hole school meal[a]		Student meal	
	N[a] Students	kWh/ meal	CCM ($/meal)[b]	kWh/ meal	CCM ($/single meal)
St Bernadette School	190	1,4	0,2	0,007	0,0011
Victor Nthethe	180	1,7	0,25	0,009	0,0014
Average				0,008	0,0012

[a] Meal and dish are considered the same for super cereal porridge on this case study.
[b] Overall end-user electricity price is around 0.13 $/kWh.

relevance programs is allocated to cooking provision (UNHCR, 2022). Furthermore, people in rural settings face barriers such as low incomes, cultural perceptions, safety concerns, and limited government commitment to transitioning from traditional to cleaner cooking methods. The Ethiopian NEP estimated that in 2018 only 37 % of refugees had electricity access for lighting and basic services, while more recent assessments revealed even lower access rates (Sandwell et al., 2024). Across all Ethiopian settings, over 90 % of refugee households relied on firewood as their primary fuel (Viola Merkl et al., 2023).

As of November 2022, the Kobe RC and its host community had various essential facilities, including eight health centres, eleven educational centres, ten NGO offices, and five government buildings. Fig. 1 depicts the distribution of these facilities:

Under this scenario, established in December 2013, SA, "the first experience of a multi-stakeholder alliance in the humanitarian field promoted by Spanish Cooperation" (Alianza Shire, 2024; Moreno-Serna et al., 2020, 2021) has been implementing a humanitarian intervention in Dollo Ado refugee camps (Hillaweyn and Kobe) (Project to promote access to energy, *2024*). The SA project "Access to energy for host and refugee communities" aimed to improve living conditions in refugee settlements and their host communities by creating livelihood opportunities, strengthening local capacity, and expanding energy services. One key objective was to improve essential services, such as healthcare, education and protection, by connecting CIs to a PVMG. Specifically, the SA aimed to enhance electricity and clean cooking access in these facilities through PVMGs for electricity and EPCs for cooking in schools. Given SA's budget constraints, the intervention prioritized specific CIs. As a result, this study primarily focuses on health and education CIs, as detailed in the following sections.

Materials and methods

This research employs a mixed-method approach, beginning with a comprehensive data collection process supported by extensive fieldwork based on SA's intervention in the Kobe RC during its design phase. This involves multiple rounds of surveys to gather primary data (from May 2021 to October 2024) supplemented by an in-depth review of relevant literature to provide additional context information to refine and preprocess the inputs, ensuring data accuracy and relevance before their application in a subsequent modelling phase. In the modelling phase, the study utilizes HOMER Pro, a widely used optimization software for energy system modelling. Various scenarios of electricity demand (with and without the inclusion of cooking needs) were explored within this framework by integrating different combinations of diesel generators and solar PV systems. These scenarios aimed to assess the feasibility, efficiency, and economic viability of MGs to power EPCs. Cooking Solutions Metrics are then defined and computed to assess: (i) the overall levels of energy and cooking access according to Multi-tier Framework (MTF), (ii) the economic viability, and (iii) the environmental impact, comparing it with a baseline scenario without EPC and MG. Finally, the findings are analysed, and conclusions are drawn regarding the techno-economic feasibility of this approach. The different steps of the methodology and the data used are summarized in Fig. 2 as described below:

Data collection process and treatment

Fig. 2 provides a comprehensive overview of the input data required for each stage of the methodology. Annex 1 details these data by outlining the objective of the data, type, and source of information. The data was collected from surveys of CIs managers, project reports, and relevant literature. Optimizing MG design in remote and refugee settings requires a clear understanding of electricity demand and consumption patterns influenced by factors such as appliance ownership, income, and location. Given the challenges of using costly logging devices that require specialized training and their limited effectiveness in low-energy access areas, this study estimated electricity consumption through surveys on device types, usage times, and power ratings, resulting in an "Ideal Hourly Load Profile. The detailed process of data acquisition, analysis, triangulation, and prioritization is referred to the Communal Services SA report (Pascual et al., 2024a).

CIs data

First, Table 4 presents the list of CIs identified by SA in the Kobe RC, highlighting autonomous solar systems and diesel generators as the primary electricity sources. The LCOE in the context of Ethiopian displacement is 0,23 $/kWh and the price of electricity in the country is 0,007 $/kWh for households and 0,22 $/kWh for business (UNHCR, 2022). Considering the diesel fuel price and a specific diesel consumption rate of 0.28 L/kWh, the cost of electricity (COE) for diesel generators in this context is estimated at 0.49 $/kWh.

Second, daily cooking energy consumption depends on the number of meals, dishes, cooking processes, and food quantities. To improve the MG system design and address previous studies limitations, survey data on local cooking practices were analysed and validated with bibliographic references. A 'Final Ideal Time Profile' was developed for each CI, with an example school load profile. Therefore, Fig. 3 shows morning and afternoon electricity peaks corresponding to school meal preparation times.

Each CI Aggregate Annual Load Profile is derived from the 'Final Ideal Hourly Load Profile,' incorporating weekly and seasonal variations validated by local stakeholders. This includes a consumption decrease of 5 % during weekends, except for CS-KR-24, which reduces to 15 % and accounts for closures during holiday periods.

Optimization information: resources, technologies and constraints

The Kobe RC, located at coordinates 4.478°N, 41.748°E, receives an annual solar radiation of 2260.23 (European Commission, 2024), making photovoltaic (PV) generation a highly attractive option due to declining costs of solar PV components (Feldman et al., 2021). In this research, the proposed generation system includes solar panels, batteries, MPPT charge controllers, and inverters, with a potential backup system (diesel generators), supported by low-voltage infrastructure and a remote monitoring network. Capital expenditure (CAPEX) data is based on actual acquisition price in the context, replacement costs based on failure distribution (Weibull distribution) (Walker, 2018), operation and maintenance costs (assumed to be 3 % of the CAPEX for any given module or component), and lifespan for each component are detailed in Table 5 based on the SA data. The system's modular design allows for future expansions to accommodate potential increases in electricity demand.

First, within Ethiopia's regulatory framework, two directives relevant to energy access for CIs in refugee camps are Directive No. 836/2021 on "Captive or Non-Commercial Uses" and Directive No. 268/2020, the "Mini-Grid Directive." In the context of the SA project, the system will be donated and owned by the Ethiopian Refugees and Returnees Service, therefore, the MG, for this case study, is designed under the framework of the "Captive or Non-Commercial Uses" directive,

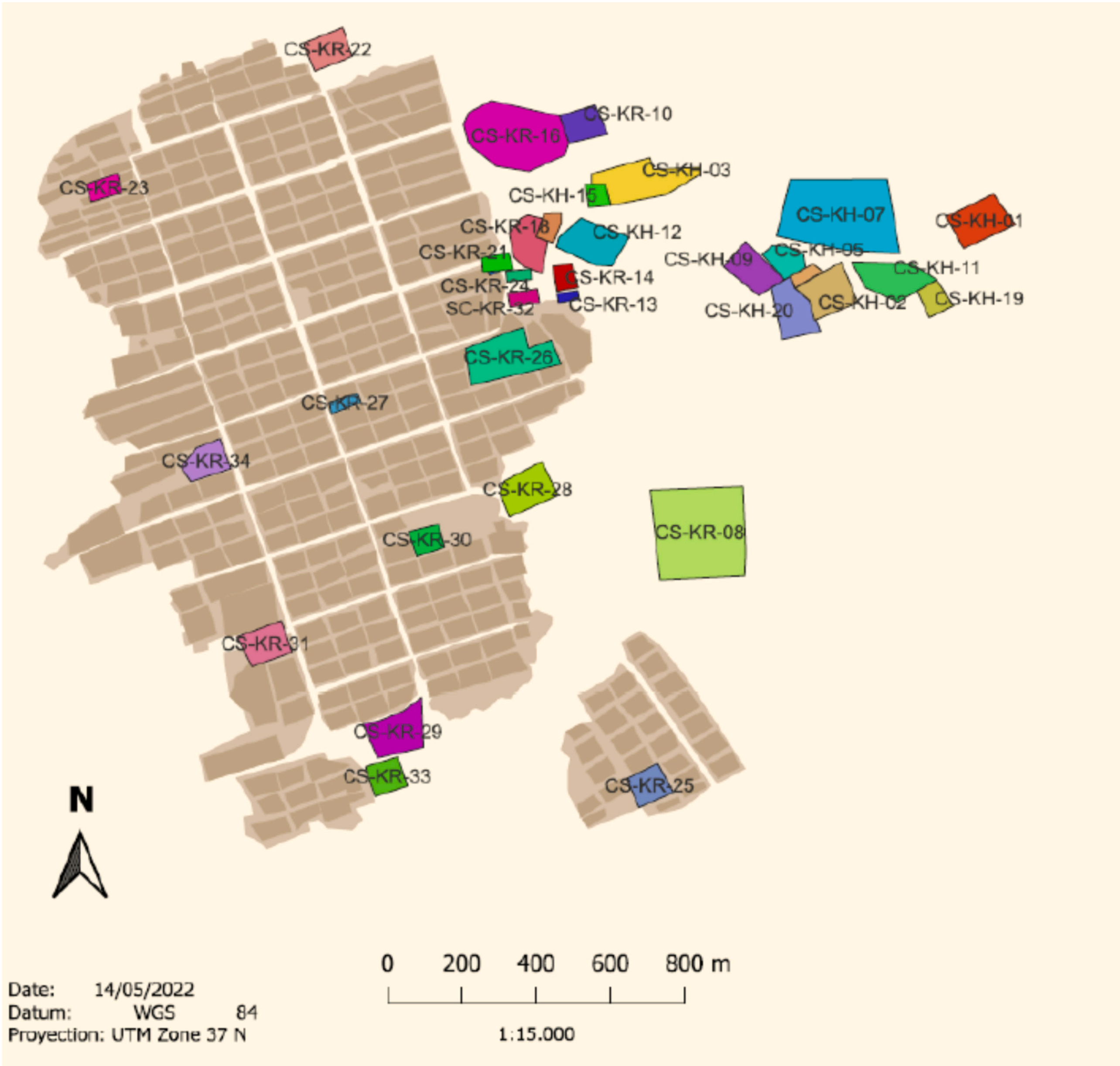

Fig. 1. Map of CIs in Kobe camp (Pascual et al., 2024a).

which limits the generator capacity to 200 kW. This legal constraint establishes a maximum capacity for the system.

Second, in electric grids operating reserves are crucial for maintaining electricity supply during disruptions. In this line, HOMER Pro identifies any shortfall as a *capacity shortage* and allows this parameter to be set according to the expected system reliability levels. Furthermore, the project's budget availability is €0.53 million allocated for engineering, procurement, and construction of the MG (CAPEX). Preliminary simulations indicate that designing a system to meet electricity demand without capacity shortages would exceed this budget, necessitating an increase in acceptable capacity shortages to align with budget limits and energy access expectations. According to the MTF for Measuring Access in CIs (Bhatia & Angelou, 2015), a 5 Tier on Availability attribute is defined as a system being operational almost all working hours (minimum 95 %), equating to a 5 % *capacity shortage*. Thus, this research sets the operational capacity shortage constraint at 5 % to achieve Availability MTF Tier 5 within budget availability for the system implementation.

Description of cooking metrics data from schools in the Kobe RC

In the Kobe RC schools, the School Feeding Program provides supercereal porridge cooked by incentivized workers using three-sones firewood (TSF) stoves and 25 L pots (Fig. 4). Cooks reported discomfort due to high temperatures and expressed interest in safer, modern cooking systems.

Prosopis Juliflora firewood, sourced from the surrounding area, is the most commonly sold firewood in the Kobe market, boasting a calorific value of 4952 kcal/kg (Oduor & Githiomi, 2013) and a cost of 0,25 $/kg, less than Lesotho case study (0,48$/kg) (Nsengiyaremye & Khalifa, 2023) and higher compared with other contexts (0,15 €/kg) (Jacobs & Couture, 2019). In Kobe schools, a daily firewood consumption of 135 kg/day is needed to cook 4634 porridge meals. The TSF stoves used in the schools of the Kobe RC are inefficient - exhibit thermal efficiencies ranging from 7 % to 12 % (Mwandosya & Luhanga, 1993; Wiskerke

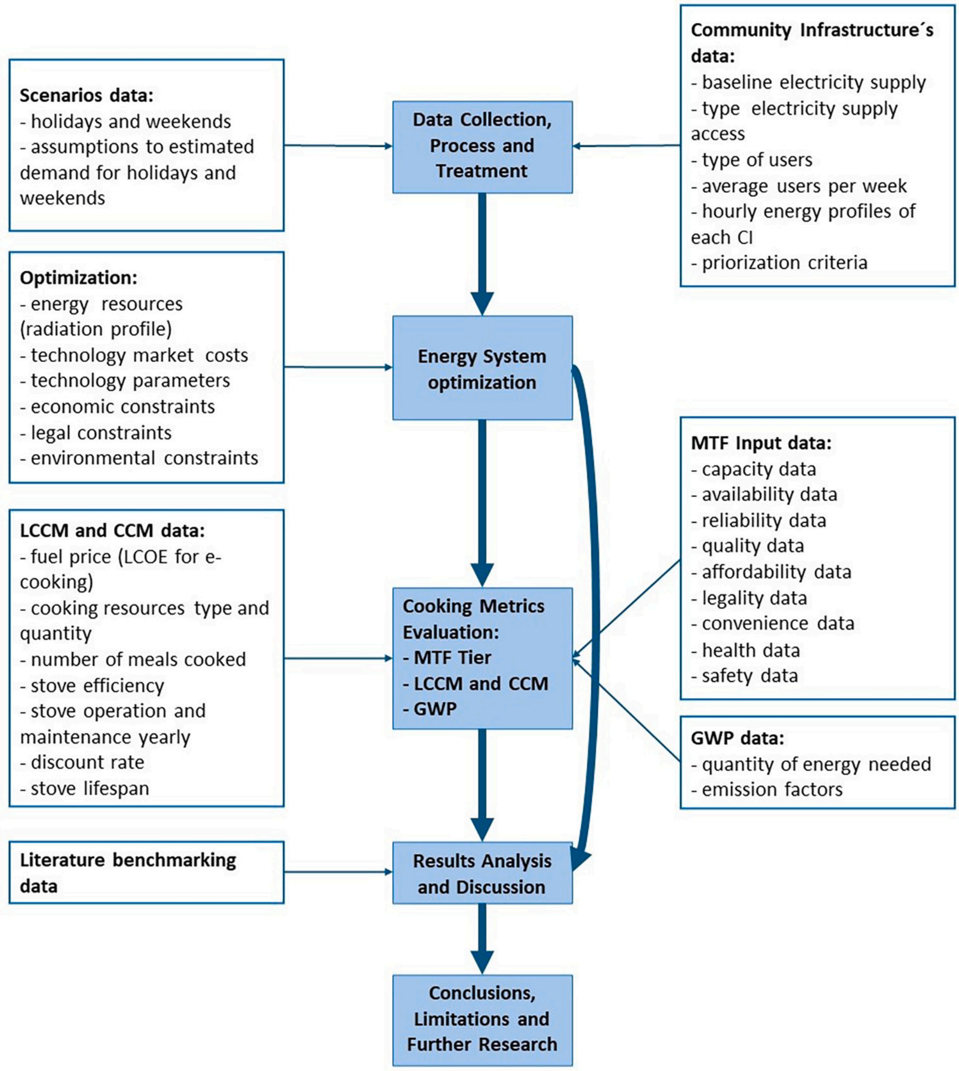

Fig. 2. Methods and materials.

et al., 2010), and unsafe, emitting substantial amounts of particles. The estimated primary firewood energy needed is 0,17 kWh/single meal. Each TSF stove costs 10,44 $[1] with a lifespan of 5 years, and it was estimated 3 % of the investment cost for operation and maintenance.

Energy system optimization

HOMER Pro modelling tool

HOMER (Hybrid Optimization of Multiple Electric Renewables) Pro 3.13.1 is a widely recognized tool for optimizing MG designs, extensively referenced in energy system modelling literature (Connolly et al., 2010; Ringkjøb et al., 2018; Sunanda Sinha, 2014) and widely applied in numerous case studies (Ahmad et al., 2018; Phurailatpam et al., 2018; Sen & Bhattacharyya, 2014). It is utilized for optimizing electrical designs and determining the ideal sizing of hybrid systems with storage, employing multiple inputs under constraints such as budget, capacity shortages, planning goals, funding limitations and environmental impacts (Eras-Almeida et al., 2020; Keddar et al., 2021; Qiblawey et al., 2022; Rajbongshi et al., 2017). The optimization process incorporates numerous inputs, such as technology parameters and costs, electricity demand (aggregated energy load profile), and GPS-based data like the area's radiation profile and a set of constraints. Outputs key metrics like LCOE, CAPEX, operating expenditure (OPEX) and GWP allow to assess the feasibility and economic and environmental impact of including cooking requirements into MG sizing across their life cycle.

The *LCOE* estimates the average net present cost of electricity generation over a power generator's lifespan, and it can be also calculated by Eq. (1).

$$LCOE = \frac{\textit{sum of costs over lifetive}}{\textit{sum of electrical energy produced over life}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Equation 1. Levelized cost of electricity (LCOE).

where:

- I_t: investment expenditures in the year t
- M_t: operations and maintenance expenditures in the year t
- F_t: fuel expenditures in the year t
- E_t: electrical energy generated in the year t
- r: discount rate
- n: expected lifetime of the power generation systems

LCOE is a key metric for assessing the economic feasibility of

[1] Change Ratio (ETB/$): 57.48 (Oanda (30-06-2024).

Table 4
Key info CS Kobe camp and Host community obtained from local surveys.

CI CODE	Elec. supply	Elect. supply	Users	Average users/week
CS-KH-01	No	–	Ref &Host[a]	533
CS-KH-02	Yes	PV direct	Host	14
CS-KH-03	No	–	Ref & Host	72
CS-KH-04	Yes	MG	Ref & Host	7
CS-KH-05	Yes	Generator	Host	42
CS-KH-06	No	–	Ref & Host	27
CS-KH-07	Yes	Generator	Ref & Host	2250
CS-KR-08	Yes	Generator	Ref & Host	894
CS-KH-09	Yes	Generator	Ref & Host	207
CS-KR-10	No	–	Ref	94
CS-KH-11	No	–	Ref & Host	101
CS-KH-12	Yes	PV direct	Ref	62
CS-KR-13	No	–	Ref & Host	110
CS-KR-14	No	–	Ref	–
CS-KH-15	No	–	Ref & Host	40
CS-KR-16	No	–	Ref & Host	170
CS-KR-17	No	–	Ref	36
CS-KR-18	Yes	PV direct	Ref & Host	80
CS-KH-19	No	–	Host	90
CS-KH-20	Yes	PV direct	Ref & Host	3450
CS-KR-21	No	–	Ref	119
CS-KR-22	Yes	PV direct	Ref	305
CS-KR-23	Yes	PV direct	Ref & Host	124
CS-KR-24	Yes	PV direct	Ref & Host	500
CS-KR-25	No	–	Ref	560
CS-KR-26	Yes	PV direct	Ref	117
CS-KR-27	Yes	PV direct	Ref & Host	270
CS-KR-28	No	–	Ref	249
CS-KR-29	Yes	PV direct	Ref	57
CS-KR-30	Yes	PV direct	Ref & Host	144
CS-KR-31	Yes	PV direct	Ref	179
CS-KR-32	Yes	PV direct	Ref	402

[a] Ref: refugees, Host: hosts.

renewable energy systems (IRENA, 2024; Lai & McCulloch, 2017). It allows for standardized comparisons across different energy sources, supporting investment decisions and showcasing the growing cost-competitiveness of renewables like solar and wind due to decreasing technology costs (IRENA, 2024). Despite its usefulness, LCOE has limitations, such as not accounting for unforeseen costs or future industry changes, yet it remains valuable for initial assessments of renewable projects.

Definition of MG optimization scenarios

To assess the viability of considering e-cooking needs in the design of a MG, several optimization scenarios were developed by aggregating load profiles from different numbers of CIs. By determining energy consumption based on device usage time and power ratings (daily load profile), post-processing was required to account for seasonal and calendar-specific variations so that the aggregated load profile reflects changes over the course of a year, including weekends and holidays.

SA intervention prioritized certain CIs based on several criteria agreed upon with local stakeholders, such as the type of CI, user demographics, and weekly user numbers. As a result, 19 CIs were selected and categorized by priority level: ten were designated as high priority (A), eight as medium priority (B), and one as low priority (C), while the remaining institutions were excluded from the intervention (Pascual et al., 2024a).

The optimization scenarios were defined based on two key criteria: (i) the number of CIs potentially connected to the generation system,

Fig. 4. TSF stove in Kobe RC.

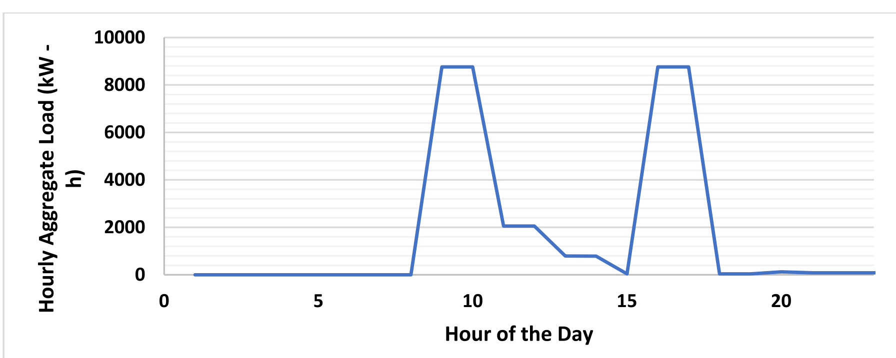

Fig. 3. CS-KH- 31 daily load profile.

Table 5
Costs for component.

Module	Component	Unit[a]	Cost	Replacement	O&M	Lifespan (years)
PV system	PV panel + structure	€/kWp	855	684	26	25
	Charge controller	€/kW	373	298	11	10
Inverters	PV Inverter	€/kW	189	151	6	10
	Battery Inverter	€/kW	603	482	18	10
Battery	Li-ion Battery	€/kWh	698	559	21	15
LV Grid	Distribution lines	€/m	16	13	0	25
Diesel Generator	Diesel Generator (Reber et al., 2018)	€/kW	400	400	25	25
	Fuel	€/L	1,73			

[a] Change Ratio (€/$): 0.93 (Oanda (30-06-2024).

considering their priority levels (A, B, or C), location, and annual load demand and (ii) the inclusion or not of cooking needs. Each optimization scenario is characterized by its *daily demand, annual demand, annual cooking demand, peak load, load factor* (a measure of the PVMG's utilization rate, defined as the average load divided by the peak load over a year), and *e-cooking factor* (annual cooking demand divided by total annual electricity). To name the different scenarios, the code elements (#, letter) presented in Table 6 are combined as it will be presented in the next sections:

Cooking metrics analytical process

A holistic approach is crucial for informed decision-making in the sustainable energy transition (Kost et al., 2024). To compare the suitability of the clean e-cooking solution - based on photovoltaic mini-grids (PVMGs) and electric pressure cookers (EPCs) -, with alternative cooking solutions from the baseline firewood stoves scenario and other contexts, the focus was placed on obtaining reliable, timely, and high-quality metrics (Stritzke & Jain, 2021). These metrics evaluate energy and cooking access level for CIs, as well as the environmental and economic impacts:

- Energy and Cooking Access MTF Tier. Survey data is used to determine the energy access level of each CI with cooking needs, based on the Multi-Tier Framework for Measuring Access (Bhatia & Angelou, 2015). Access is classified from Tier 0 to Tier 5, with capacity measured in power output for grid, MG, or diesel generator-based systems, and in daily supply for batteries and solar solutions. Fuel combustion health risks are rated from Tier 0 (non-BLEENS fuels used indoors without smoke extraction) to Tier 5 (BLEENS fuels or equivalent), where Biogas, LPG, Electricity, Ethanol, Natural gas, and Solar cookers are considered BLENS cooking solutions. Each attribute is assigned a tier level from 0 to 5, with the overall access level determined by the lowest tier across all attributes.
- The economic feasibility assessed using the LCCM, which measures the cost of preparing a standard meal with a specific fuel-technology combination accounting for both upfront and recurrent costs, calculated by Eq. (2) (Nerini et al., 2017).

$$LCCM = LCCM_{fuel} + LCCM_{stove} = \frac{C_{fuel} \times E_u}{\eta_{stove}} + \frac{\sum_{y=1}^{n} \frac{C_{stove}(y) + O\&M_{stove}(y)}{(1+r)^y}}{\sum_{y=1}^{n} \frac{Ml\ (y)}{(1+r)^y}}$$

Equation 2. LCCM.

where:

- C_{fuel} is the fuel price in $/kWh (for e-cooking, obtained as a result of the MG optimisation (LCOE))
- E_u is the final energy required for cooking a meal in kWh/meal
- $Ɒ_{stove}$ the stove efficiency [%],
- C_{stove} is the stove purchase cost, occurred in the y-th year, in $
- $O\&M_{stove}$ are the stove operation and maintenance yearly costs.
- Ml (y) are the number of meals cooked in the time y-th year
- r: discount rate
- n is the stove lifetime [years]

In addition, the CCM is analysed, focusing solely on recurrent costs. While alternative metrics like daily or monthly costs are used for household evaluations (ESMAP, 2020a; Hakizimana & Hyung-Taek, 2016; Saha et al., 2021), they are less suitable for CIs cooking access, where meal numbers vary. Therefore, cost per single meal is considered a more appropriate metric for comparison.

- The environmental impact is evaluated using the GWP metric, which quantifies greenhouse gas emissions in CO_2-equivalent terms, from energy production and use, directly affecting climate change (IAEA, 2005). GWP is calculated using emission factors from the GHG Protocol (Buendia et al., 2006) and for HOMER Pro output data.

Table 6
Optimization scenarios.

Criteria	Variable	Code element
N° of CI supplied	10 (CI with priority A)	0
	16 (CI with priority A, B and C, except three more distant and with low demand)	1
	19 (CI with priority A, B and C)	2
Cooking needs are considered	Yes	a
	No	b

Results

Proposal of e-cooking solution

A *40-L Ewant* EPC (Fig. 5) has been chosen, in consultation with local stakeholders, due to its efficiency and compatibility with East African culinary practices, where over 90 % of typical menus, including porridge, can be prepared using this technology (MECS Programme, 2021). With biomass resources becoming scarcer and more expensive—leading to the suspension of the WFP school feeding program in 2022—the EPC offers a sustainable alternative.

The selected EPC has thermal efficiencies of 87 % (Batchelor, 2021) and an estimated lifetime of 5 years (Rousseau et al., 2021). The estimated electricity required to cook a meal with EPC is 0.02 kWh/meal. Each EPC stove costs 551 $, with operation and maintenance expenses estimated at 3 % of the initial investment (Mondal et al., 2017).

Determined electricity and e-cooking needs

The SA prioritization process resulted in nineteen priority CIs with different levels of priority (Pascual et al., 2024a), shown in Fig. 6.

For each prioritized CIs, Table 7 shows the estimated daily load demand, the estimated yearly load demand, and the load rate (% of load demand on each CI in relation with the total load demand of the system).

Fig. 5. 40-L Ewant EPC (Ewant 15L 17L 30L 35L 40L high quality energy saving high efficiency commercial large electric pressure cooker, *2024*).

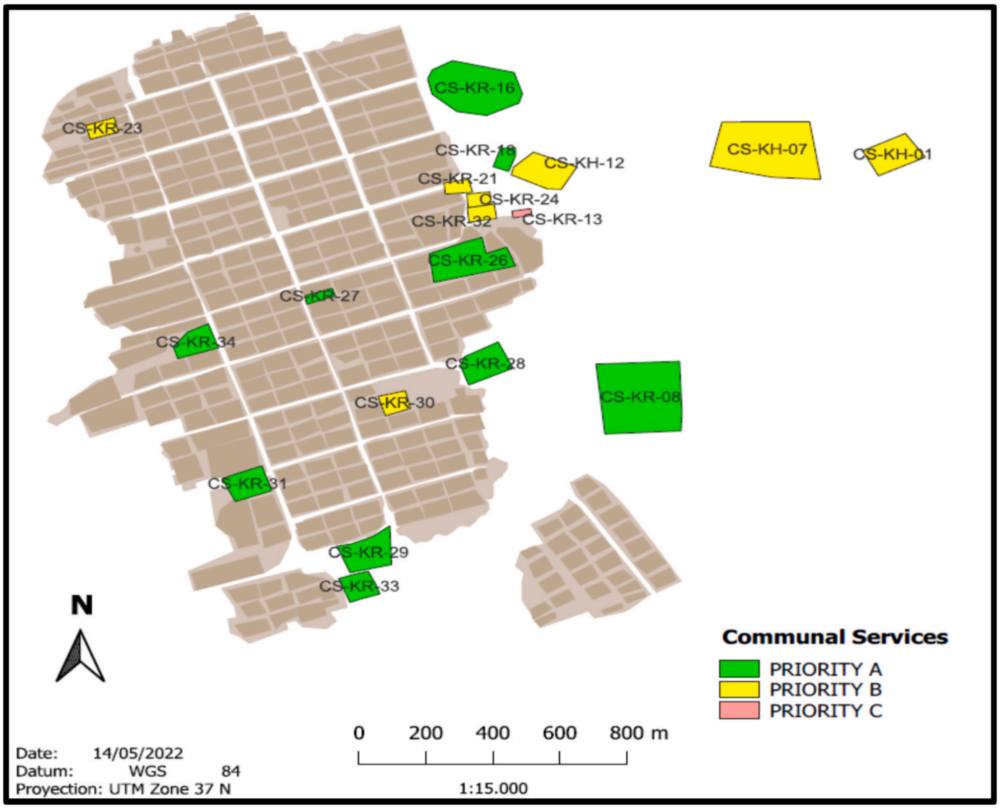

Fig. 6. Map of priority CIs.

Table 7
Daily load estimation.

CI	Priority	Type of Facility	Daily Load Demand (kWh/day)	Yearly load demand (kWh/year)	Load rate (%)
CS-KH-01	B	Education	6.01	2,193	1.3 %
CS-KR-07	B	NGO Office	22.14	8,081	5.0 %
CS-KH-08	A	Education	87.69	31,992	19.7 %
CS-KR-12	B	NGO Office	8.12	2,964	1.8 %
CS-KR-13	C	Health	3.14	1,146	0.7 %
CD-KR-16	A	Health	4.74	1,730	1.1 %
CS-KR-18	A	Health	12.72	4,643	2.9 %
CS-KR-21	B	Education	17.74	6,475	4.0 %
CS-KR-23	B	Health	1.09	398	0.2 %
CS-KR-24	B	Health	42.17	15,393	9.5 %
CS-KR-26	A	Education	13.72	5,010	3.1 %
CS-KR-27	A	Health	6.39	2,334	1.4 %
CS-KR-28	A	Education	58.35	21,297	13.1 %
CS-KR-29	A	Education	14.18	5,178	3.2 %
CS-KR-30	B	Health	8.33	3,041	1.9 %
CS-KR-31	A	Education	56.53	20,634	12.7 %
CS-KR-32	B	Health	13.62	4,971	3.1 %
CS-KR-33	A	Education	55.78	20,360	12.5 %
CS-KR-34	A	Education	13.24	4,833	3.0 %

Characterization of the electric load and optimization scenarios

The Aggregate Load Profile for all CIs in each scenario is constructed by concatenating the hourly load profiles for each day of the year, differentiating between weekdays, weekends, and holidays. Fig. 7 illustrates a daily aggregate load profile featuring two peaks corresponding to cooking practices in schools, happening at 8:00 and 16:00 h; and Fig. 8 depicts a yearly aggregate load profile, showing decreased consumption during November and December due to school holidays.

Table 8 shows the characteristic data of each scenario (refer to Table 6 to understand the definition of each scenario).

MGs optimization outputs

The optimization approach in this research uses HOMER Pro software to minimize LCOE under various demand scenarios, incorporating inputs such as energy resources, technological parameters, and costs, while maintaining a capacity shortage constraint of 5 %. The lowest LCOE for each scenario was achieved through the combination of PV generation and battery storage, excluding diesel generation, due to the high diesel price in the Kobe RC context (50 % more than the global average price (Diesel prices around the world, *2025*)), consistent with what generally happens in rural regions due to increased transportation costs and lower competition among fuel suppliers.

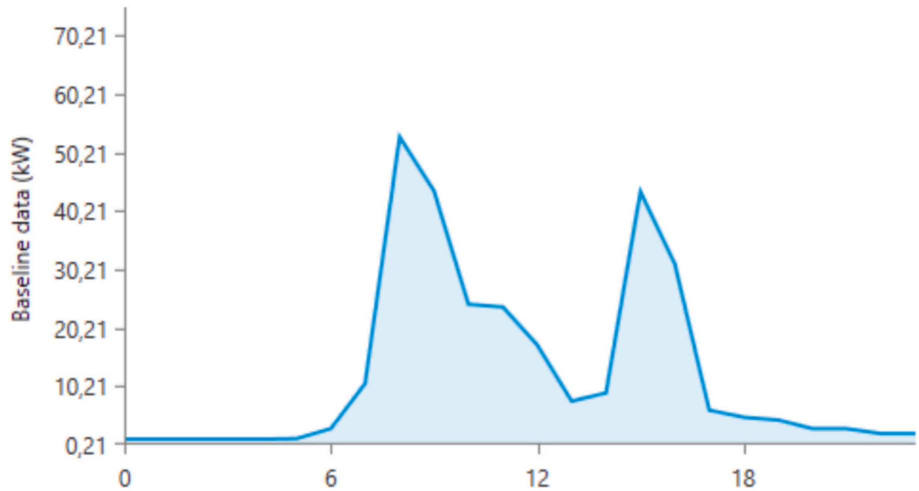

Fig. 7. Typical aggregated daily load profile for the scenario 1.a in May.

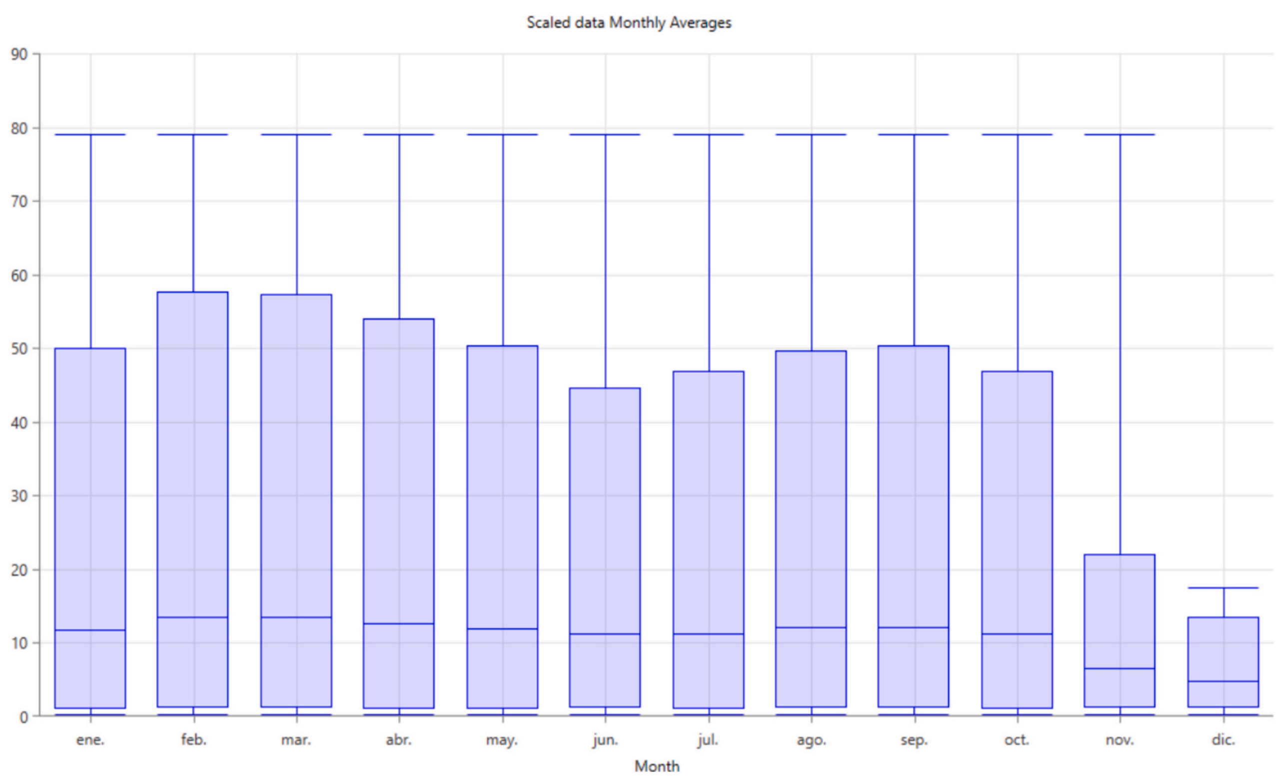

Fig. 8. Monthly averages for scenario 2.a.

Table 8
Scenarios characterization data.

Scenario	Total daily Load (Wh/ day)	Total yearly Load (kWh/ year)	Cooking yearly Load (kWh) (kWh/ year)	e-cooking factor (%)	Peak load (kW)	Load Factor (%)
0.a.	226.42	82,643	29,674	36 %	70.92	13 %
0.b.	145.12	52,969	0	0 %	28.89	21 %
1.a.	255.20	93,148	29,678	32 %	76.17	14 %
1.b.	173.89	63,469	0	0 %	34.82	21 %
2.a.	266.44	97,251	29,674	31 %	79.05	14 %
2.b.	185.14	67,576	0	0 %	36.70	21 %

Table 9 summarizes optimization results, including the sizes of key equipment and the electrical and economic data provided by HOMER Pro (CAPEX, OPEX, Net Present Cost, and LCOE).

It is verified that for all scenarios, the maximum capacity of the system remains below 200 kW and the CAPEX below 0.53 million euros. Table 9 also shows the load factor, e-cooking factor, and the difference between the LCOE of each scenario and the minimum LCOE (LCOE deviation). The minimum LCOE it is obtained for the scenario 0.b that considers 10 CIs without e-cooking needs.

Cooking solutions metrics

Baseline cooking metrics

At the time of data collection, only 59 % of Kobe ICs had access to

Table 9
Summary of results.

Scenario	0.a.	0.b.	1.a.	1.b.	2.a.	2.b.
Yearly Load (kWh/year)	82.643	52.969	93.148	63.470	97.251	67.576
Cooking Load (kWh) (kWh/year)	29.675	–	29.678	–	29.675	–
E-cooking factor (%)	36 %	0 %	32 %	0 %	31 %	0 %
Peak electric load (kW)	71	29	76	35	79	37
Load Factor (%)	13 %	21 %	14 %	21 %	14 %	21 %
PV AC (kWp)	108	52,2	103,7	57,6	96,6	66,4
PV DC (kWp)	30	30	30	30	30	30
Total PV (kWp)	138	82	134	88	127	96
Batteries (kWh)	101	54	134	76	166	71
Battery System Converter (kW)	75	30	90	45	90	45
Total Production (kWh)	237.740	142.067	230,949	173,766	220.540	168.456
Capacity Shortage (kWh/year)	4.197	2.694	4732	3.227	4.948	3.438
Capacity Shortage (%)	5 %	5 %	5 %	5 %	5 %	5 %
CAPEX (€)	314.966	199.780	369.676	255.023	385.916	278.219
OPEX (€)	164.096	87.524	186.998	104.434	199.450	111.926
Total Net Present Cost (€)	479.062	287.304	556.674	359.457	585.366	390.145
LCOE (€/kWh)	0,46	0,43	0,48	0,45	0,48	0,46
LCOE ($/kWh)	0,42	0,39	0,43	0,41	0,43	0,41
LCOE deviation (%)	7 %	0 %	10 %	4 %	11 %	7 %
GWP (Tn eq. CO2/year)	0	0	0	0	0	0

electricity, with most facing issues of reliability, affordability, and quality, resulting in an overall MTF Tier of 0, except for CS-KH-04, which had level 3. Educational facilities, the only CIs with cooking needs, had a very low energy and cooking MTF Tier 0, far below expectations for essential services (Table 10).

Baseline metrics are shown in Table 11.

Determined e-cooking metrics

With optimized PVMG and efficient EPCs, Kobe educational CIs will achieve Tier 5 for Capacity and Tier 4 for availability, with capacity shortages limited to 5 %. While reliability, quality, convenience, and security cannot be assessed pre-implementation, they are expected to reach Tier 4 with proper operation and maintenance, and during the equipment acquisition phase by compliance with IEC standards (e.g. 61,829) to ensure technical quality and efficient resource utilization (Solanki et al., 2024). The system complies with Ethiopian regulations, ensuring Tier 4 for legality, while solar energy, classified as BLEENS fuel, supports Tier 4 for Health. Affordability remains the key determinant of the overall MTF level, dependent on energy costs relative to national grid tariffs. Since the MG's CAPEX is donated and CIs cover only OPEX (about 20 % of LCOE), costs cannot exceed twice the grid tariff, ensuring at least Tier 4 across all MTF attributes, meeting clean and modern cooking standards. Taking in consideration the above, e-cooking metrics are shown in Table 12.

Table 11
Baseline cooking metrics.

Cooking metrics			Baseline	
Cooking and energy access tier	MTF Tier (based on Capacity, Availability, Reliability, Quality, Affordability, Legality, Convenience, Health and Safety)	n° (0–5)	0	
Economic impact	Levelized Cost of Cooking a Meal (LCCM)	$/meal	0.006[a]	0.010[b]
	Cost of Cooking a Meal (CCM)	$/meal		
Environmental impact	GWP	kg CO2eq/ year	0.07	

[a] For 12 % TSF efficiency.
[b] For 7 % TSF efficiency.

Results analysis and discussions

The estimated primary firewood energy needed is 0,17 kWh/single meal, 55 % of the calculated based on *per person per year wood or charcoal energy required for cooking purposes in Sub-Saharan Africa* literature data

Table 10
Educational CIs MTF Tiers.

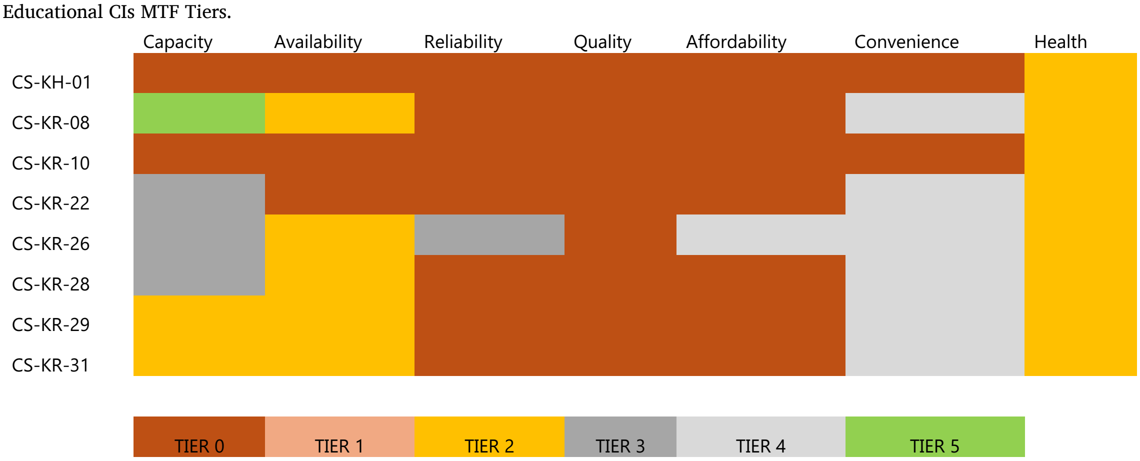

Table 12
Determined e-cooking metrics.

Cooking metrics			Optimized PVMG + EPC
Cooking and energy access tier	MTF Tier (based on capacity, availability, reliability, quality, affordability, legality, convenience, health and safety attributes)	n° (0–5)	4
Economic impact	Levelized Cost of Cooking a Meal (LCCM)	$/meal	0.010
	Cost of Cooking a Meal (CCM)	$/meal	0,008
Environmental impact	GWP	kg CO2eq/ year	0

(Jacobs & Couture, 2019). The estimated electricity required to cook a porridge single meal with EPC in the Kobe RC is 0.02 kWh/meal. This value is 50 %–66 % of the comparable data reported in the literature for households (Jacobs & Couture, 2019; Kweka et al., 2021), but it is two and a half times higher than the literature-reported values for cooking porridge meals on schools (Nsengiyaremye & Khalifa, 2023). Although direct scientific evidence comparing the efficiency of institutional versus domestic cooking is limited, in general, CIs cooking tends to be more energy-efficient due to economies of scale, optimized usage patterns, and better energy management practices in CIs. Nevertheless, for analytical purposes, the precise scale of cooking needs is less critical than the fact that it offers a standardized basis for comparing different technologies (Jacobs & Couture, 2019).

The daily aggregated load profile on working days presents two peaks, one in the morning and another in the afternoon, reflecting cooking activities in schools. On non-working days, load consumption decreases by about 95 %, and during school holidays, it drops by approximately 70 %, resulting in an energy surplus that could be utilized for other community needs in the future.

The metrics defined throughout the research (Table 13) allow to compare the impact of including e-cooking needs in the MG design, as well as to compare the baseline situation of access to energy and cooking with the proposed e-cooking solution (EPC with optimized PVMG). It results in a comprehensive approach to address two of the major concerns in displaced settlements, access to electricity and cooking services.

Table 13
Metrics.

Type of metrics		Metrics	Units
Scenarios metrics		Daily Demand	Wh
		Annual Demand	kWh
		Annual Cooking Demand	kWh
		Peak Load	kW
		Load Factor	%
		Cooking Factor	%
MG Optimization metrics		Levelized cost of electricity (LCOE)	€/kWh and $/kWh
		Capital expenditure (CAPEX)	€
		Operating expenditure (OPEX)	€
		Capacity Shortage	%
		GWP	tCO2eq
Cooking Solution Metrics	Energy and Cooking Access Tier	MTF Tier (based on capacity, availability, reliability, quality, affordability, legality, convenience, health and safety attributes)	n° (0–5)
	Economic impact	Levelized Cost of Cooking a Meal (LCCM)	$/meal
		Cost of Cooking a Meal (CCM)	$/meal
	Environmental impact	GWP	tCO2eq

Daily energy demand ranges from 174 Wh/day in the lowest-demand scenario to 266 Wh/day in the highest, with peak loads varying between 35 kW and 79 kW. In scenarios involving electric cooking, this load accounts for 31–36 % of total demand. Implementing Electric Cooking Pressures (EPCs) necessitates an increase of 31–68 % in photovoltaic (PV) capacity and a 39–58 % rise in CAPEX compared to the minimum investment of €199,780.

Fig. 9 illustrates the relationship between the cooking factor, load factor, and LCOE deviation. The LCOE deviation is inversely related to the load factor and directly related to the cooking factor. A e-cooking factor of 31–36 % results in a 7 % average reduction in load factor and only a 6 % increase in LCOE.

Table 14 presents the average LCOE for all optimized scenarios. This value is consistent with a Tanzanian hybrid MG case study (Kweka et al., 2021), which reported an LCOE only 7 % higher—likely attributable to fuel cost differences. Furthermore, the average LCOE is 47 % higher than figures observed in Ethiopian contexts with national grid access, yet 5 % lower than the recurrent cost of electricity generation using diesel generators in the Kobe RC.

The findings confirm, consistent with previous studies (Rosenberg-Jansen & Al-Kaddo, 2022), that high-efficiency EPCs, when CAPEX is donated and PVMG well-operated and properly maintained, can achieve a MTF Tier 4, qualifying them as Modern Energy Cooking Solution (MECS). Given that *reliability, quality, convenience, and safety* can only be thoroughly evaluated during the operational phase of the system, ensuring proper operation and maintenance is essential to minimize the risk of incidents requiring professional medical intervention, significant outages, and other high-impact safety, reliability, and quality challenges commonly associated with lower MTF-tier systems. Therefore, there is a need to ensure quality equipment acquisition by applying IEC standards as indicated above. Furthermore, a robust operation, maintenance, and management model was developed to address the unique challenges of the Kobe RC's MG project implementation, incorporating stakeholder capacity assessments, regulatory considerations, and donor requirements. It emphasizes the voluntary participation of the direct beneficiaries and their active engagement as stakeholders rather than passive clients. It also incorporates the establishment of formal documentation and agreements to define stakeholders' and communities' roles, rules, and obligations. In addition, the management model includes the implementation of fees to cover operational and maintenance costs, thereby ensuring the system's *convenience* and long-term sustainability (Pascual et al., 2024b).

The LCCM, which includes both upfront and recurrent costs, is comparable between the highest baseline value and the proposed e-cooking solution. However, when considering only recurrent costs (CCM), the optimized EPC + PVMG solution falls within the baseline range, unlike the Lesotho case study, where the CCM per student using EPCs is about one-sixth of firewood costs. Few recent studies have employed the CCM metric to assess cooking solutions (Lombardi et al., 2019; Nerini et al., 2017; Nsengiyaremye & Khalifa, 2023). In this case study, the LCCM for EPCs is only 11 % of Nerini's household study and 8 % of Lombardi's data for a single ICS and 33 households. These discrepancies stem from differences in load profiles, community versus household cooking efficiency, site-specific conditions, declines in MG costs since 2019, and due to the methodological approach and quality data. The latter, a contribution of this paper that introduces a novel addition to this scientific field. The calculated CCM is nearly seven times higher than that for cooking porridge with EPCs in Lesotho schools, where grid electricity is three times cheaper than the MG LCOE in this study. If electricity consumption measured during operational phase decreases by 2.5 times the estimated on the design phase (based on the data on firewood consumption and theoretical efficiency of the TSF), the LCCM could drop to 0.003 $/meal—half the LCCM of low-range firewood in the baseline scenario. However, limited benchmarking data, differing evaluation metrics, and variations in consumer typology and estimated cooking energy consumption constrain direct economic

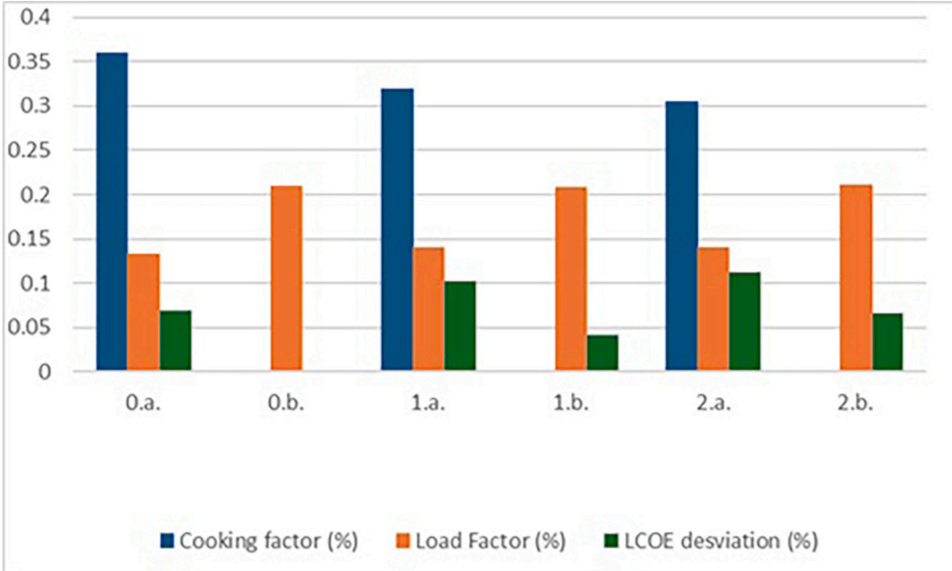

Fig. 9. LOOE deviation, load factor and cooking factor.

Table 14
LOOE summary.

	With cooking needs	Without cooking needs	Increase
Load Factor (%)	14 %	21 %	7 %
LCOE (€/kWh)	0.47	0.45	6 %
LCOE ($/kWh)	0.43	0.40	6 %
Total Net Present Cost (€)	540,367	345,635	56 %
Total PV Capacity (kWp)	133	89	50 %

comparisons of e-cooking across contexts.

While some scientists argue that biomass combustion is carbon neutral if harvested sustainably (Amin, 2016) this is not the case in the Kobe RC where -as in other refugee settlements (Njenga et al., 2024)- firewood is scarce, unsustainable, and combustion is incomplete, leading to emissions of CO_2, CH_4, and other pollutants. The GWP savings of a MG depend on its energy sources, with emissions from a PVMG being zero, allowing in Kobe case to save 7.76 kg of CO_2 equivalent per meal compared to the baseline data. Reducing reliance on traditional biomass and diesel mitigates both GWP and deforestation, preserving approximately 45 tons of firewood annually—an issue linked to conflicts over forest resources that affect women's well-being and increase their vulnerability when collection firewood. This comprehensive solution for access to clean cooking and electricity also eliminates harmful exposure to pollutants and improved educational and health opportunities due to reliable electricity.

Conclusions and policy implications

The Kobe case study provides in-depth, context-specific insights to address gaps in existing literature on electricity access and clean cooking solutions challenges for community infrastructures (CIs) (Ahmad et al., 2022; Byrne et al., 2020; Jeuland & Pattanayak, 2012; Odoi-Yorke, 2024), in particular the importance of techno-economic optimization, using realistic electricity demand forecasts and aggregated load profiles instead of simple energy total quantity and electricity prices, and considering budgetary and operational constraints of the context. This study suggests the use of scalable solutions like photovoltaic mini grids (PVMGs), which benefit from decreasing solar and battery costs as well as increasing reliability and quality of the technology, which is highly relevant for these contexts where financing shall be used efficiently while considering the economic limitations of communities. Furthermore, this research enhances the existing literature by further examining the benefits, challenges, and open questions surrounding the integration of CIs cooking needs into the sizing of electrical systems and the feasibility of using PVMGs to power electric pressure cookers (EPCs) in displacement settlements, considering metrics like energy access levels, cooking costs, and environmental impact.

The cooking energy demand depends on cooking practices, stove efficiency, and fuel type. To address research gaps, context-specific data were collected through surveys and literature. Cooking a single porridge meal with an EPC in the Kobe RC requires 0.02 kWh—50 %-66 % of household estimates but 2.5 times higher than school porridge cooking in Lesotho (Nsengiyaremye & Khalifa, 2023). While CI cooking is generally more efficient, verifying actual cooking needs during operation is important but less critical for standardized technology comparisons. HOMER Pro MG modelling shows that including the EPCs estimated demand increases PV capacity needs and CAPEX, but the levelized cost of energy (LCOE) rises only slightly by 6 %. This suggests that adding CIs e-cooking can help lower LCOE, aligning with previous research (Zubi et al., 2017). While CIs e-cooking improves affordability, it also creates financing challenges. The obtained LCOE is higher than Ethiopia's national grid but lower than diesel-generated energy, aligning with studies in Tanzania (Kweka et al., 2021). EPCs powered by well-maintained PVMGs and supported by donated capital, can meet the criteria for Modern Energy Cooking Services (MTF level 4). Since proper operation and maintenance are essential for long-term success, the Shire Alliance developed a management model for the Kobe RC MG, emphasizing beneficiary participation and fees to cover costs. The Levelized Cost of Cooking a Meal (LCCM) is more suitable metric for comparing community cooking solutions than daily or monthly costs, however, limited LCCM data restricts broader economic assessments. In this study, LCCM is lower than previous baseline figures for cooking with three-stone firewood stoves, possibly due to site-specific conditions and decreasing MG equipment costs. Comparisons with schools in Lesotho (Nsengiyaremye & Khalifa, 2023) suggest lower costs due to reduced grid prices. A predicted 28 % reduction in LCOE by 2035 (Come Zebra et al., 2021) could further lower LCCM for future e-cooking projects.

PVMGs eliminates greenhouse gas emissions and reduce deforestation, addressing a major issue in Sub-Saharan Africa's refugee camps (Gianvenuti et al., 2018), while improving educational and health opportunities. Unlike unsustainably sourced biomass, renewable-powered e-cooking offers a carbon- and air-polluting-free, conflict-reducing alternative while alleviating women's vulnerabilities in firewood collection. EPCs provide a safer, more efficient cooking solution, saving time and reducing health risks from harmful emissions. They align well with East African cooking practices, with over 90 % of typical meals being suitable. To overcome sociocultural barriers, ensure long-term adoption and local ownership of the solution, training on benefits, safe use and maintenance and community involvement in developing a robust operation and maintenance management model are recommended.

This study highlights e-cooking as a viable, sustainable, and scalable solution for community infrastructures like schools, particularly in regions with limited firewood availability. It aligns with Modern Energy Cooking Services criteria and supports Ethiopia's SDG 7 targets, challenging the perception that electricity is too costly for cooking in developing areas. While findings cannot be universally extrapolated due to limited benchmarking data and varying evaluation metrics, declining lithium-ion battery and solar PV costs, coupled with rising biomass fuel prices,—particularly in severely degraded or deforested areas (ESMAP, 2020a; Jacobs & Couture, 2019) — suggest that electric cooking is becoming an increasingly cost-effective alternative, especially for displacement institutions like schools, where millions of displaced students benefit from meal programs.

The proposed approach to comprehensive electricity and clean cooking access provides an integrated solution to climate, energy, and development challenges, especially in the humanitarian sector and supports the United Nations SDG 7 and SDG 13. Aid agencies and governments like Ethiopia's should integrate electricity and clean cooking access in refugee camps from the outset of crisis responses through a coordinated framework that ensures effective stakeholder collaboration.

Limitations, recommendations and further research

The study faced limitations in assessing key attributes such as reliability, quality, convenience, and safety, which require real-world system operation for a comprehensive evaluation. This underscores the need to examine the performance and stability of off-grid PVMGs, particularly in hot and tropical climates, to ensure reliable appliance use (Groen et al., 2022; Odoi-Yorke, 2024; Wassie & Ahlgren, 2023). Also, to validate environmental metrics, it is recommended to evaluate the GWP throughout the life cycle of the proposed solution.

Previous research (Jacobs & Couture, 2019) highlights the importance of understanding electricity consumption for cooking to enable cost comparisons and broader applicability. Accurate affordability assessments should incorporate smart meter data, detailed appliance analyses, and cultural acceptance factors. Refining Multi-Level Framework indicators and evaluating costs relative to grid tariffs and other solutions would improve assessments by integrating environmental and social considerations (Nerini et al., 2017). Additionally, further research on the LCCM metric across different institutional contexts would enhance benchmarking efforts.

Additionally, interdisciplinary collaboration among experts, practitioners, and policymakers, supported by increased funding and gender-inclusive approaches, is essential to overcoming sociocultural barriers (Byrne et al., 2020; Vianello, 2016). Further research should also investigate the benefits of modern cooking solutions in reducing vulnerabilities associated with firewood collection.

CRediT authorship contribution statement

Sonia Ramos-Galdo: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea A. Eras-Almeida:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization. **Javier Mazorra Aguiar:** Writing – review & editing, Visualization, Resources, Project administration, Methodology, Funding acquisition. **Miguel A. Egido-Aguilera:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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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Annex 1. Input data

Data objective	Data Input	Type of data	Data Source
CIs Characterization and Prioritizing and Daily Energy Demand estimation	Baseline Electricity supply access	Qualitative	SA surveys
	Type Electricity supply access	Qualitative	
	Type of Users	Qualitative	
	Average users per week	Quantitative	
	hourly energy profiles of each CI (daily demand, annual demand)	Quantitative	
	prioritizing criteria	Qualitative	Stakeholders' interviews
elaboration of the aggregate load profile for each optimization scenario	holidays and weekends	Quantitative	Local stakeholders' interviews
	Estimated hourly demand for holidays and weekends assumptions	Quantitative	
techno-economic e-cooking and MG optimization for the different baseline and optimization scenarios	energy resources like radiation profile	Quantitative	Reference databases
	technology market costs	Quantitative	SA reports and SA data on procurement phase

(*continued on next page*)

(*continued*)

Data objective	Data Input	Type of data	Data Source
	technology parameters	Quantitative and qualitative	Simulation software database and SA data on procurement phase
	economic constraints	Quantitative	SA data
	legal constraints	Quantitative and qualitative	Ethiopian Regulation
	environmental constraints	Quantitative and qualitative	SA data
	capacity data	Quantitative	
	availability data	Quantitative	
	reliability data	Quantitative	
	quality data	Quantitative	
Cooking Solution Metrics: Energy and Cooking Access MTF Tier	affordability data	Quantitative	SA surveys
	legality data	not available data	
	convenience data	Quantitative	
	health data	Quantitative	
	safety data	not available data	
	Fuel Price (LCOE for e-cooking)	Quantitative	SA surveys and modelling output for e-cooking
	cooking resources for cooking	Quantitative	SA surveys
Cooking Solution Metrics: Levelized Cost of Cooking a Meal (economic feasibility)	number of meals cooked	Quantitative	SA surveys
	stove efficiency	Quantitative	Literature
	stove operation and maintenance yearly costs	Quantitative	Local stakeholders' interviews and SA data on procurement phase
	number of meals cooked	Quantitative	Local stakeholders' interviews
	discount rate	Quantitative	Literature
Cooking Solution Metrics: GWP (environmental impact)	stove lifetime	quantitative	Literature
	emission factors	quantitative	Literature and modelling output for e-cooking
	Cooking Access Tier	Quantitative	Literature
Literature Cooking Solution Metrics	LCCM	quantitative	
	CCM	quantitative	
	GWP	quantitative	

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