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Techno-economic scenario analysis of containerized solar energy for use cases at the food/water/health nexus in Rwanda

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ABSTRACT

'Containerized' infrastructure solutions have the potential to power the needs of under-resourced communities at the Food/Water/Health nexus, particularly for off-grid, underserved, or remote populations. Drawing from a uniquely large sample of identical containerized solar photovoltaic energy deployments in Rwanda ("Boxes" from OffGridBox), we estimate the potential reach and impact that a massive scale-up of such a flexible, modular approach could entail for fast-growing yet resource-constrained communities around the world. This analysis combines modeled and in-the-field data to consider three use cases (water, food, and health), across optimistic and realistic scenarios. We estimate pollution externalities and compare this solution to incumbent technologies, incorporating uncertainties. In our optimistic scenarios, this containerized solution could provide for either 2083 individuals' daily drinking water needs, 1674 individuals' daily milk consumption, or 100% of a health clinic's energy demand. We then quantify the added benefit of providing these loads using solar energy instead of the incumbent non-renewable diesel generator in terms of cost and air quality, and incorporate the sensitivity of results to uncertainties using Monte Carlo Analysis simulations. For water purification and milk chilling uses, we find that solar has a lower lifecycle cost of energy; 0.39 and 0.38 USD/kWh respectively compared to 0.63 [range: 0.52, 0.80] USD/kWh and 0.59 [range: 0.48, 0.76] USD/kWh for diesel. Additionally, solar has lower cost variability and avoids pollutant and greenhouse emissions (e.g., 85,799.08 kgs [range: 66,830.49, 115,491.30] of carbon dioxide over the 20-year system lifetime). Moving beyond the standard energy modeling of previous literature, this analysis is uniquely able to inform future sustainable energy systems at the Food/Water/Health nexus.

1. Introduction

Innovations in the delivery of basic services through 'containerized' infrastructure solutions have gained interest among humanitarian organizations, development practitioners (Ossenbrink et al., 2017; Rocky Mountain Institute, 2020), and commercial providers of energy resiliency solutions. Here, we define containerized infrastructure solutions as "infrastructure in a box" that can be deployed rapidly as a "plug and play" solution. In the case of renewable electricity provision, the container is packed and shipped with solar photovoltaic generation assets inside, along with batteries, power converters, and a control system, all housed in standard or modified shipping containers which can be assembled centrally, deployed at scale through the globally connected freight transportation system, and easily installed at point-of-use.

Similar systems have been used for decades for rural telecommunications bases (Yoneoka and Millison, 2018), but this technology is only recently expanding into other applications. The benefits of such infrastructure service modalities over traditional utility models, like grid extension or diesel generators, include speed and ease of installation, cost-competitiveness (deeply sensitive to economies of scale) (Rocky Mountain Institute, 2020), semi-permanence (e.g., portable, yet rugged and durable enough to last for long periods and even withstand hurricanes), fuel security, and lastly, modular stack-ability, or the ability to easily increase service capacity through "daisy chain" expansion. The container form-factor is notably a key feature of these delivery modality advantages, not only from a design and operational efficiency perspective but also in terms of whole-of-system environmental accounting

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Glossary

Ah	ampere-hour
CO_2	carbon dioxide
CO	carbon monoxide
COVID-19	coronavirus
GHG	greenhouse gas
GSMA	Global Systems for Mobile Communications Association
kWh	kilowatt hour
kWp	peak kilowatt
L	liter
LCOE	levelized cost of electricity
MJ	megajoule
MPPT	maximum power point tracking
NO_X	Nitrogen oxides
NPV	net present value
OGB	OffGridBox
O&M	operations and maintenance
$PM_{2.5}$	Particulate matter under 2.5 microns in diameter
PV	photovoltaic
Rpm	rotations per minute
SO_x	Sulfur oxides
UV	ultraviolet
VAT	value added tax
W	watt
Wp	peak watt

(Mutingi et al., 2017).

This paper discusses the impact and potential for containerized infrastructure solutions to serve three productive use-cases of basic needs provision at the community level: (1) water filtration, (2) milk chilling, and (3) health facilities. We compare the monetary and non-monetary benefits added by serving these needs at the Food/Water/Health nexus using renewable energy as opposed to incumbent diesel generator technologies. Specifically, we ask.

1. What is the levelized cost of electricity (LCOE) from a solar-powered containerized energy system for these three use cases under optimistic and realistic scenarios?
2. How many individuals can be served under these three use cases under optimistic and realistic scenarios?
3. What is the range of LCOEs for providing the same amount of water treatment and milk chilling if powered by diesel generators instead of solar and batteries?
4. What are ranges of air quality and emissions gains from using solar over diesel?

The analysis is contextualized by the experiences of OffGridBox (OGB), a social enterprise that has deployed nearly twenty-five identical containerized infrastructure solutions in Rwanda and approximately eighty others around the world to date. We employ a variety of technical, market, and demographic data from Rwandan sites to provide further insight into containerized infrastructure approaches towards serving distinct community needs in a sustainable manner.

The key contributions of this paper lie in the: i) in-depth scenario analysis of a novel combination of containerized energy technology, remote context, and use-case application; ii) extensions beyond a standard techno-economic feasibility analysis via the use of field data and quantification of non-monetary benefits; and iii) the utilization of uncertainties in a Monte Carlo Analysis (MCA) that better characterize ranges of added benefits expected in the field. Such contributions are inscribed in the broader imperative to reach sustainable solutions to the challenges facing humanity at scale, from universal access to electricity and water, to the future of utility service provision, and to infrastructure deployment models in emerging markets.

While a rapid rise in interest in minigrid technology has resulted in hundreds of thousands of new proposed systems worldwide (Global Energy Alliance for People, 2022; ESMAP, 2020), there are few, if any, minigrids today that are financially profitable without the range of different subsidies. In that context, studies such as this one that examine actual community and business scenarios of system design and implementation to support productive uses and demonstrated community needs provide crucial insights into pathways towards system financial viability. OffGridBox, as a containerized, scale-able business model adds significantly to our knowledge base of 'business ready' minigrids.

The remainder of the paper is organized as follows: in Section 2 we describe the literature on containerized solutions and our contribution to the field. In Sections 3 and 4, we briefly characterize the OGB system ('Box') from a technical perspective and provide context on existing operations in Rwanda. In Section 5, we outline our methods and discuss three specific use cases of the OGB systems: (5.1) water treatment, (5.2) milk chilling, and (5.3) powering lighting, communication, and appliances at health clinics. In Section 6, we present key findings for each use case and quantified benefits of solar over a non-renewable solution in these cases. In Section 7, we draw from the analysis to offer reflections on the opportunity for massively scaled up containerized infrastructure approaches. Our conclusions are presented in Section 8.

2. Literature review

Thus far, the academic literature on containerized energy delivery principally proposes alternative hybrid energy systems designs and suggests the benefits of such an approach vis-a-vis decarbonization (relative to fossil-fuel generators) for short-term, urgent needs contexts. For instance, Nerini et al. proposes a design for a solar, wind, and biomass-powered containerized solution for water and energy needs in protracted displacement settings (Nerini et al., 2015); however, Nerini et al. neither includes data from these vulnerable settings nor provides an economic analysis considering field conditions. Meyer et al. describes design criteria for cold storage containerized solutions in South Africa (Meyer and von Solms, 2022), and Janko et al. describes a self-contained microgrid for disaster response situations such as after the 2010 earthquake in Haiti (Janko et al., 2016). Apart from van Hove et al. (van Hove et al., 2020) and Higier et al.'s containerized medical clinic (Higier et al., 2013), the use of in-context field data is extremely limited, and the majority of studies rely on simulations or were produced in laboratory settings.

Overall, this literature relies on high-level techno-economic analyses that focus on the system design rather than the community needs served. A few studies have addressed use cases but for mining and desalination in high income contexts (Paneri et al., 2021; Harrison et al., 1996; Tosi et al., 1997). Therefore, this study fills a key gap in the literature's understanding of the provision of basic infrastructure needs at the critical Food/Water/Health nexus for fast-growing or under-resourced communities over longer time periods. Refugee camps and other zones of humanitarian intervention serving displaced populations are among the hardest to plan for, given the operational complexities. We thus also build on the limited literature on these settings and discuss our results' implications for addressing multiple Food/Water/Health use-cases for possibly emergency or long-term infrastructure (Bradshaw et al., 2021). Further, the existing studies largely do not quantify the non-monetary benefits of their renewable energy solutions such as air quality, carbon emissions, and avoidance of fuel-price volatility. Paneri et al. simulates the reduction of carbon emissions by containerized renewable energy, but for a European mining application (Paneri et al., 2021). We are the first study to explore these co-benefits in a field context for use cases in a low-income setting. Consideration of these co-benefits is crucial as the global community simultaneously attempts to achieve Sustainable Development Goals on health, climate, poverty, and inequality.

3. Background on OffGridBox

OffGridBox's containerized energy system, i.e. a 'Box', is manufactured from a standard shipping container measuring approximately 2 × 2 × 2 meters. The lead time between commissioning and deployment from the central warehouse in Italy to a given location in sub-Saharan Africa is approximately 8–12 weeks. Inside the Box are 12 photovoltaic (PV) modules (each 280 peak watts (Wp) for a total of 3.36 peak kilowatts (kWp)), four 90-amp hour (Ah) Gel/absorbent glass mat lead-acid batteries, as well as a 3000-W (W) charge controller and inverter (Fig. 1). For water treatment, several configurations have been deployed, but most Boxes include an internal 600-L (L) food grade tank, a gravity-fed activated charcoal filter, a 5-μm filter, additional brush filters, a 20-L/minute self-priming pump, and ultraviolet (UV) lamp. Lastly, each Box is equipped with a wireless communication module - from the Global Systems of Mobile Communications Association (GSMA) - that serves a dual purpose: to provide monitoring of system performance (i.e., real-time power production, battery state-of-charge), and to provide a WIFI hotspot and data services locally. It takes approximately 4 h to set up the Box once on-site.

OffGridBox has been active in Rwanda across a diverse spectrum of communities since 2017. While some Boxes are in truly off-grid communities without national electricity grid connections, the majority serve urban or peri-urban markets (Figs. 2 and 3). The containerized solution can integrate into on- and off-grid areas well in Rwanda if there is close collaboration with district officials, particularly early in the development process, and if the use cases are in line with regional development targets. Although grid infrastructure is both available and relatively accessible in urban settings in Rwanda, the OGB currently performs best financially in high-density urban markets like Musanze and Rubavu, selling bulk packaged water to local shops. Further, six Boxes serve rural clinics in partnership with the Government of Rwanda's Ministry of Health (Fig. 2). However, this is not always the case. For example, a diesel-lamp replacement pilot for fishermen in the Rusizi district in the southwest of the country has been indefinitely stalled since running into regulatory barriers from local authorities concerned with overfishing. Close collaboration with policy makers and regulatory authorities is key to Box integration, regardless of the presence of the national grid.

Each Box is staffed with a local BoxKeeper agent and security guard, responsible for maintenance of equipment and liaison with headquarters around production and distribution of water and power banks (through a battery distribution/leasing model). In contrast to other markets where OGB operates on a 'build-transfer' model, the model in Rwanda entails developing revenue streams at each site that can improve system unit-economics. To date, this model has yet to sustainably yield high utilization rates of power or water relative to maximum output, indicating potential for the development of further productive uses of electricity at the Food/Water/Health nexus (Ferrall et al., 2021).

Fig. 1. Off grid box in Gasagara, Rwanda.

Financially, as USAID. Assessing the Effects of, 2020, each Box (hardware and shipping) costs roughly 25,500.00 USD (assuming six Boxes per 40-foot shipping container, including duties and VAT) and a 20-year lifetime. Replacement costs for the system total 3759.00 USD net-present-value (NPV) from the system converter (127.00 USD) and four battery replacements (908.00 USD each). Each box requires 646.00 USD in maintenance costs over the lifetime and 150.00 USD per year for remote monitoring (see SI for more economic details).

4. Rwandan context

Rwanda provides a particularly interesting case study for this productive use analysis given current efforts on (1) water purification, (2) dairy for nutrition, and (3) stable electricity in health facilities. Further, Rwanda has increasing rates of urbanization and separately high levels of displaced persons; all of which OGB is uniquely posed to address.

4.1. Water

Unsafe water remains a leading risk-factor for disease in Rwanda, where diarrheal diseases cause an estimated 10% of total child mortality (Bradshaw et al., 2021). Lack of access to safe water has additionally been linked to broader social outcomes such as stunting and wasting in infants, reductions in school attendance in children (particularly for girls who are menstruating), losses in economic productivity, and undue burden on women of time spent collecting water (Deshpande et al., 2020). Nearly half of Rwandan households spend over 30 min procuring water, with access rates that were aggravated through mobility restrictions due to coronavirus (COVID-19.) The national water utility has also reported significant losses through the pandemic on top of a systemic and widening chasm between its clean water production capacity and rising demand driven by rapid urbanization (Deshpande et al., 2020; USAID. Assessing the Effects of, 2020). OBG systems have the potential to reduce this crisis. Fig. 5 depicts a pilot design of a water purification system within the OGB system.

4.2. Food

Rwanda's dairy industry and associated value chain for milk present opportunities to reduce food insecurity and poverty by increasing household incomes and addressing nutritional needs. Several Government of Rwanda initiatives recognize the importance of the dairy industry in these roles, including the "One Cow per Poor Family" and "One Cup of Milk per Child" programs (Republic of Rwanda. Ministry of Agriculture and Animal Resources, 2009).

One way in which containerized solutions for energy access can help to facilitate improvements to the dairy value chain is by providing milk chilling points. Collection centers with milk chilling units form an important point in the value chain between production and processing — in areas of higher-volume milk production, producers can bring excess milk to such centers; upon reaching a certain capacity level, the collected milk is then transported for processing. Providing collection centers with adequate chilling can provide significant benefits by avoiding spoilage. In 2007, nearly 35% of the 160 million liters of fresh milk production in Rwanda was lost to spoilage (Republic of Rwanda. Ministry of Agriculture and Animal Resources, 2009). Importantly, in areas lacking grid electricity, renewably powered chilling units can

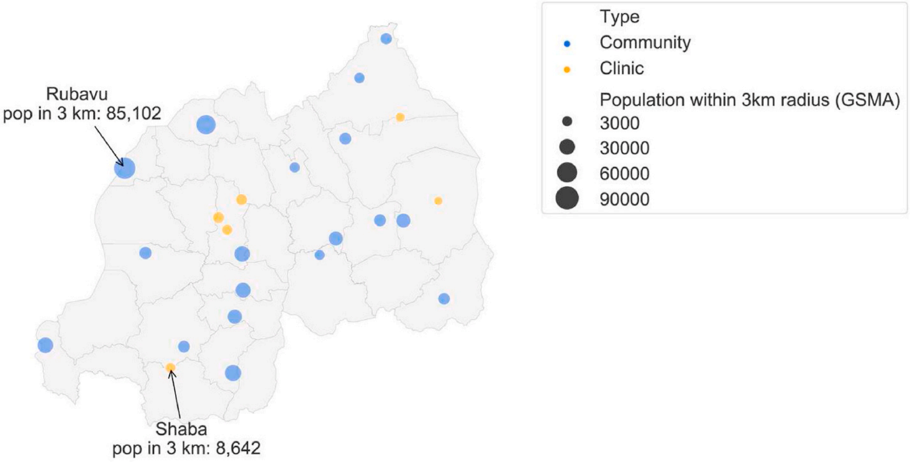

Fig. 2. Location of OffGridBoxes in Rwanda (sized by population within 3 km).

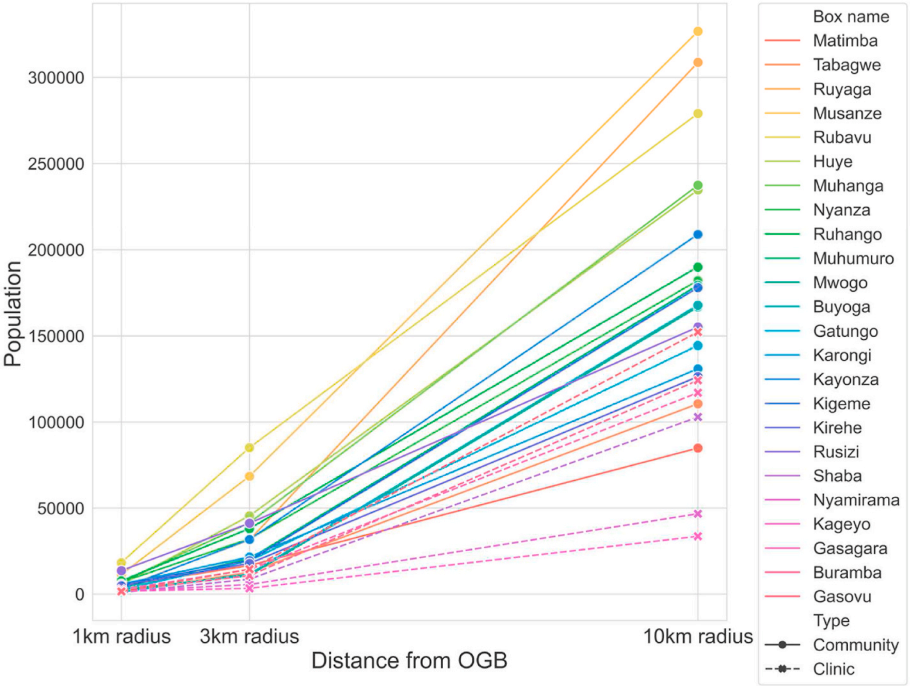

Fig. 3. Population within 1–10 km radii of deployed OffGridBoxes in Rwanda. Identical boxes are deployed across a wide spectrum of agglomeration sizes and morphologies, offering a unique perspective into the heterogeneity of infrastructural needs across the rural-urban spectrum. Data extracted from global positioning system locations using the GSMA's web tool (GSMA. Mobile Coverage Maps, 2021).

replace the generators that would otherwise be needed to sufficiently chill milk received at the collection center to the recommended 3–4 °C (Republic of Rwanda. Ministry of Agriculture and Animal Resources, 2009).

The majority (60%) of milk in Rwanda is sold informally, either at shops, along the street, from farmers, or delivered door-to-door, although Rwanda's government has attempted to formalize the sector. Informal sales pose a barrier to monitoring milk quality, while the formal sector provides pasteurized milk from vendors with legal licenses (Habiyaremye et al., 2021). Therefore, containerized solutions may be able to support the formal dairy industry to avoid spoilage, and simultaneously improve the quality of milk from informal dairy suppliers who provide the majority of dairy across the country.

4.3. *Health*

At least half of the healthcare facilities in Rwanda lacked stable electricity in 2017 (Franco et al., 2017). While grid electricity access for Rwandan health facilities has improved significantly in recent years, issues remain with maintenance of installed systems in areas designated for mini-grids or standalone solar PV. Clinics outgrow the capacity of existing solutions installed, driven by rapid urbanization and relocation that can rapidly double demand. Rural outpost clinics are particularly undersupplied; these facilities typically focus on the most common ailments like malaria or tuberculosis, but also provide services focusing on maternal or child health, as well as first aid. While rural clinic demand typically averages 10 kWh/day energy consumption, principally for lighting and lab equipment, vaccine refrigeration can also represent a significant load, a need which the World Health Organization expects to rise eightfold or more in the coming decades (Porcaro et al., 2017).

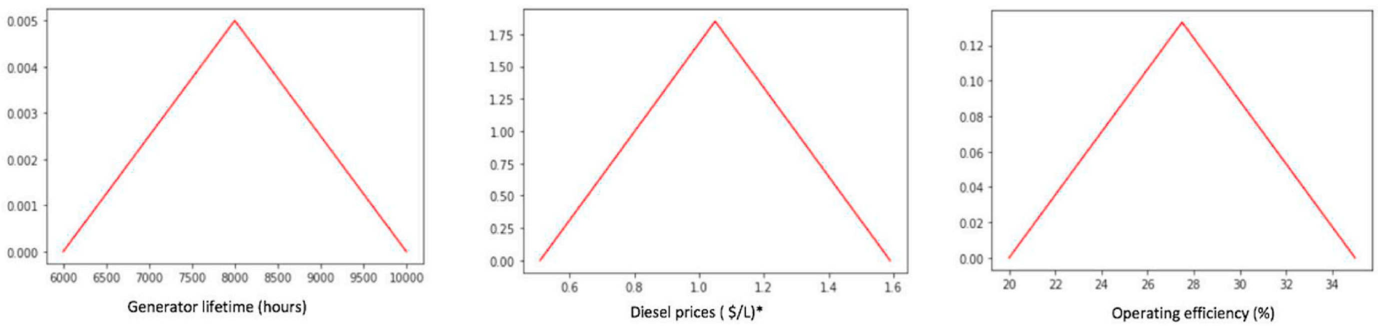

Fig. 4. Within the Monte Carlo simulation, we utilized triangle distributions for the generator lifetime, diesel prices, and operating efficiency for the analysis of the diesel generator. For each, we modeled a minimum and maximum, and the median as the mode. We estimated a minimum of 6000 h and maximum of 10,000 h as the generator lifetime, consistent with HOMER inputs for a 4–20 kW generator high speed (3600 rotations per minute (rpm)) air cooled diesel. We used a range of diesel prices in Africa that varied from 0.51 to 1.59 USD per liter (Lee and Callaway, 2018; International Renewable Energy Agency, 2016). We modeled 20% and 35% efficiency (equivalent to 3.6 MJ/kWh heat rate) as the minimum and maximum value for efficiency. *Subsequently, all distributions were scaled to fit the interval [0,1].

Fig. 5. Pilot design of the water purification system within the OGB system. It is composed of a 5-μm filter and an activated carbon/charcoal filter and an ultraviolet (UV) lamp. It also has a desalination option. The input sources can be rainwater, municipal water, groundwater, or freshwater. The clean water can then be distributed in jerrycans, sachets, a smart-tap, or packaged water.

We therefore investigate if an OGB could increase utilization of electrical and medical equipment at remote sites. These could include basic needs like lights for night-time activities to critical operations like infant warming machines, life support devices, and vaccine refrigeration.

4.4. *Displaced settings*

In Rwanda, the rate of urbanization is nearly double the global average and the urban population is ~18% and has been steadily increasing over the past decade (United Nations Population Division). Rwanda's Vision 2050 plans for 70% of their population to be in urban areas by 2050 (Republic of Rwanda, 2050). Separately, Rwanda also has influxes of displaced populations. The UNHCR estimates that Rwanda houses roughly 128 thousand displaced persons, including 77 thousand refugees from the Democratic Republic of the Congo and almost 50 thousand refugees from Burundi, up from around 80 thousand in 2014 (UNHCR, 2023). The majority (89%) of these individuals live in refugee camps, while 11% live in urban areas (UNHCR, 2023). The Government of Rwanda and the UNHCR have a strategic plan for 2020–2024 which outlines 2025 goals that all refugees will have access to facilities with energy, water, sanitation and hygiene services, and more refugees will have access to health and nutrition services. Often, these settings and needs are served by diesel generators (Nerini et al., 2015), and when solar is used, it is often only deployed to provide limited lighting. OGBsCo were recently installed across Rwanda's six refugee camps, which will shed further light into whether the existing form factor and delivery model will prove the right combination of size and performance for the dynamics of a population characterized by high density, constrained mobility, and limited access to permanent infrastructure. Given this context, we discuss our results in light of the potential of OBG systems to provide these productive uses and serve displaced settings.

4.5. *Beyond Rwanda*

Rwanda is a particularly interesting context; however, it is also representative of many East African and low-and middle-income countries with similar rates of unclean water use, interest in the use of dairy for nutritional programming (CGIAR, 2022), and need of further electricity supply for health clinics (Moner-Girona et al., 2021). Unclean water sources remain a top ten risk factor for attributable daily adjusted life years (DALYs) (Abbafati et al., 2020). There are active conversations in numerous countries regarding the best water filtration systems to deploy for both day-to-day access and emergency situations (Loo et al., 2012). Having found a positive correlation in increased milk consumption and improved child growth and reduced stunting, primarily from studies from East Africa, the Food and Agriculture Organization of the United Nations is promoting the expansion of the dairy sector globally (Food and Agriculture Organization of, 2020). Finally, in rural sub-Saharan Africa, 50,000 additional healthcare facilities require electricity (Moner-Girona et al., 2021).

This case study of OffGridBox in Rwanda is also representative of contexts that are rapidly urbanizing or accommodating displaced populations. Sub-Saharan Africa's rate of urbanization is over double that of the global average (The World Bank, 2018), and East Africa has tripled its number of refugees in the past decade (United Nations Humanitarian Aid, 2022). Globally, between 2013 and 2018, the number of refugees and other displaced people grew at a rate of 11.7% per year (Shell International, 2020). The underlying causes of this displacement have become more complex and interdependent over recent decades. The convergent impact of health crises, climatic changes, or civil unrest has increased the rates and duration of displacement. This culminated in approximately 16 million people having lived in temporary settlements for five or more years by 2018 (Shell International, 2020). Thus, our analysis has implications beyond Rwanda.

Fig. 6. The Promethean Rapid Milk Chiller is a modular system that cools milk from 35° to 4 °C with a capacity of 1000 Ls of milk per day. Such a system paired with a Box could significantly support Rwanda's dairy value chain as well as its aggressive childhood nutrition national strategy.

5. Methods

5.1. Use cases

We apply validated methods established in the literature to evaluate three specific, not yet explored, use cases of the OGB systems: water treatment, milk chilling, and powering lighting, communication, and appliances at health clinics. For each use case, we investigate both optimistic and realistic scenarios to describe the characteristics of a representative system in a Rwandan context. The realistic scenarios employ data from specific OGB sites and operations, representing case studies directly from the field that provide insight into opportunities and barriers which such service provision modalities entail. The optimistic scenarios address the total impact that a Box-like containerized solution may have for this use case given its theoretical maximum reach within existing design constraints.

In each optimistic scenario, we estimate that an OGB system can produce 12.48 kW h (kWh)/day using Equation (1). This estimate was calculated assuming 5 h of full sun hours per day, 32 °C, negligible temperature effects, maximum power point tracking (MPPT), a 0.8 derate factor, and assuming all energy generated is utilized within the day. The battery is available to time-shift 3.46 kWh of produced solar energy to align with electricity demanded at other times. The battery, therefore, is charged in times of excess PV and discharged in times of excess demand. The 3.46 kWh is the *useable* nominal capacity of 4 AGM batteries, indicating an 80% depth of discharge. In the baseline model, this assumption sufficiently holds for the majority of the battery lifetime. This assumption was confirmed via OGB's data, HOMER models, and conversations with OGB regarding how the Boxes can be oversized and underutilized. As productive uses, the below described use cases can be expected to predominantly draw power during the day when PV production occurs, therefore this straightforward modeling of the battery is more appropriate than for use cases occurring predominantly at night. The 0.8 rule-of-thumb derate factor accounts for all-of-system losses including efficiencies.

In Equations (2) and (3), we calculate an LCOE of 0.34 USD/kWh from the upfront cost and NPV of the replacement, maintenance, and remote monitoring costs (detailed in Section 3 and SI). The lead-acid batteries have a 5-year lifetime, and the inverter, charge regulator, and other electronics have 10-year lifetimes. These scenarios assume that all the energy from the Box is devoted fully to the specific use case considered.

$$Optimistic\ \frac{kWh}{day} = 3.12\ kWp\ solar\ * \ \frac{5\ hr\ sun}{day} * 0.8\ derate\ = 12.48\frac{kWh}{day} \quad [1]$$

$$\begin{aligned} &NPV\ of\ Costs\ (\$) = Upfront\ costs + NPV\ of\ Replacement\ costs \\ &\quad + NPV\ of\ Operation\ \&\ Maintenance\ (O\&M)\ costs \end{aligned} \quad [2]$$

$$LCOE\left(\frac{\$}{kWh}\right) = \frac{Net\ Pr\ esent\ Value\ of\ Costs\ (\$)}{Daily\ energy\ produced\ \left(\frac{kWh}{day}\right)} * \frac{year}{365\ days} * \frac{system\ lifetime}{20\ years} \quad [3]$$

Our optimistic scenario does not fully capture battery losses from discharge and charge inefficiencies or other localized effects. Therefore, we were further motivated to include a realistic scenario. Each realistic scenario uses the HOMER modeling simulation software to estimate that a Box's production is 8.14 kWh/day on average as shown in Equation (4). This decrease in production accounts for any losses from potentially heavier cycling of the battery, localized temperature effects, and incident solar radiation effects on PV power output over the year. We calculate the levelized cost of electricity to be 0.53 USD/kWh from the same financial estimation methods used in the optimistic scenario.

$$Realistic\ \frac{kWh}{day} = \frac{\sum_{0\ hrs}^{8760\ hrs} Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)\left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right]}{365\frac{d}{yr}} = 8.14\frac{kWh}{day}, where$$

$Y_{PV} = rated\ capacity\ of\ PV\ array\ [kW]$

$f_{PV} = the\ PV\ derating\ factor\ [\%]$

$G_T = incident\ solar\ radiation\ during\ timestep\ \left[kW / m^2\right]$

$\alpha_P = temperature\ coefficient\ of\ power\ [\% / ^\circ C]$

$T_C = PV\ cell\ temperature\ during\ timestep\ [^\circ C]$

$T_{C,STC} = PV\ cell\ temperature\ under\ standard\ conditions\ [25^\circ C]$ [4]

We acknowledge that these scenarios do not factor in several specificities relevant to the deployment of a Box such as additional transport costs or site-specific seasonal variation; we also note that shipping costs, including import duties and value added tax (VAT), may vary radically by country. However, they provide a baseline for assessing the impacts of perhaps the smallest containerized energy/water solution envisageable, as well as indicative costs and opportunities to scale up according to local demand. Additional details on the methods and equations used to arrive at each use case scenario estimate can be found in Supplementary Materials.

5.2. Comparison to non-renewable solution

To quantify the benefit added by serving these needs at the Food/Water/Health nexus using renewable energy, we pose a counterfactual question where the energy provided by the solar panel and batteries on the OGB system was instead provided by a diesel generator. Diesel generators are the incumbent primary source of power for many off-grid locations requiring electricity, and the incumbent back-up source of power for locations with poor quality transmission and distribution infrastructure. Other research documents the prevalence of unreliable grids across Sub-Saharan Africa (Ferrall et al., 2022), quantifies the implications of these outages on greenhouse gas (GHG) emissions, particulate matter emissions, consumer costs, and fossil energy consumption (Farquharson et al., 2018).

Building from the work of Farquharson et al., 2018) (Farquharson et al., 2018), we use an MCA framework to estimate changes in the levelized cost of energy when two of the three above OGB use cases are powered diesel generators instead of solar.

5.2.1. MCA framework

An MCA is a statistical framework which calculates possible outcomes when input parameters are randomly varied within a specified range (Fitzpatrick, 2018). A key difference between solar and diesel generators that is exploited to develop our model is the greater uncertainty in costs and diesel generator characteristics. While solar panels and batteries do have uncertainty, their variance is significantly less than those for diesel. For the OGB, we evaluate a very specific system with real data. Therefore, a probabilistic distribution approach would not be appropriate. We employ the MCA framework for the diesel generator given the higher variability and uncertainty because we model a typical system, rather than a specific technology like the OGB. We compare the optimistic scenario to the realistic scenario to model the uncertainty in the OGB, and use the MCA framework to model uncertainty for the diesel generator.

5.2.2. Implementing the MCA framework

We utilize the MCA framework to model the variance of three diesel characteristics - heat rate, diesel prices, and generator lifetime – using triangle distributions (Fig. 4). The Monte Carlo analysis thus generates values for heat rate, diesel prices and generator lifetime within our defined limits, following a defined distribution. We specified the simulation to run 1000 times, randomly generating new values for each of these characteristics and calculating an associated LCOE.

Following Farquharson. et al. (Farquharson et al., 2018) and informed by the research team's experience in the field, we modeled diesel generator efficiency to range between 20% and 35% (equivalent to 3.6 MJ (MJ)/kWh heat rate) as the minimum and maximum values of the triangle distribution, and the median as the mode. Similarly, we used Farquharson's range of diesel prices in Africa that varied from 0.51 to 1.59 USD per L.[1] However, recent global oil price spikes reveal these present-day numbers to be generally more conservative than future potentials. Finally, we estimated a minimum of 6000 h and maximum of 10,000 h as the generator lifetime, consistent with HOMER inputs for a 4–20 kW generator high speed (3600 rotations per minute (rpm)) air cooled diesel. We use a diesel fuel heating value of 38.7 MJ/L as used in Farquharson et al.

We model the diesel generator to produce the same energy output of our optimistic case of 12.48 kWh/day for both water treatment and milk chilling. We find the upfront cost by subtracting the solar and battery system value and adding the diesel system costs to the original OGB total shipped container upfront cost of 25,500.00 USD and calculate it to be 22,520.00 USD. We find Africa-specific estimates of small-scale solar and battery costs to be 1.00 USD/W, for the solar modules and direct-current balance of system costs, 0.30 USD/W for the inverter, and 2.00 USD/Ah for lead acid batteries (Lee and Callaway, 2018; International Renewable Energy Agency, 2016). The diesel generator costs 500.00 USD/kW, and we size the generator at 4 kW (to serve the 3.5 kW milk chiller and estimate a similar size as the solar peak capacity), as estimated by HOMER, resulting in a 2000.00 USD upfront cost. We find the system lifetime through Equation (5) given the range provided in HOMER.

$$System\ lifetime\ (yrs) = \frac{generation\ lifetime\ (hours)}{generation\ hours\ per\ day\ \left(\frac{hours}{day}\right)} * \frac{1\ year}{365\ days} \tag{5}$$

$$Diesel\ consumption\ (L\,/\,day) = \frac{daily\ energy\ consumption\ \left(\frac{kWh}{day}\right)}{Diesel's\ heating\ value\left(\frac{MJ}{L}\right) * efficiency * \frac{1kWh}{3.6\ MJ}} \tag{6}$$

$$Fuel\ Costs\ \left(\frac{\$}{years}\right) = Diesel\ consumption\ \left(\frac{L}{day}\right) * fuel\ costs\ \left(\frac{\$}{L}\right) * 365\ \left(\frac{days}{year}\right) \tag{7}$$

$$Operating\ \&\ Maintenance\ (O\&M)\ Costs\ \left(\frac{\$}{year}\right) = operation\ costs\ \left(\frac{\$}{hr}\right) * generator\ operation\ \left(\frac{hrs}{day}\right) * 365\ \left(\frac{days}{year}\right) \tag{8}$$

$$Total\ O\&M\ Costs\ \left(\frac{\$}{years}\right) = Fuel\ Costs\ \left(\frac{\$}{year}\right) + O\&M\ Costs\ \left(\frac{\$}{year}\right) + Remote\ Monitoring\ Costs\ \left(\frac{\$}{year}\right) \tag{9}$$

We then find the NPV of the total operations and maintenance (O&M) costs, the upfront cost of the diesel generator, and the replacement cost of the diesel generators. This total NPV, modeled from Equation (2) for solar, are the inputs for the LCOE formula (Equation (3)) in the optimistic scenarios for water filtration and milk chilling. All equations sourced from (Rubin and Chapter 13, 2000).

We additionally calculate the pollutant emissions associated with the use of a diesel generator as opposed to solar with the Box for the optimistic scenarios of water purification and milk chilling (US Environmental Protection Agency, 1950). We utilize the carbon dioxide estimation from the pollutant emissions to conduct the LCOE analysis

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[1] The price of diesel is highly variable and sensitive to geo-political context, and thus has been rapidly changing in Rwanda and across the continent (Iliza, 2023). In 2012, the Rwandan government increased their cap on diesel prices to 0.96 USD from 0.88USD. Therefore, the range from sub-Saharan Africa used is reasonable given the uncertainty, and still very applicable to Rwanda.

including the social cost of carbon at the price set by the Biden Administration (51.00 USD per ton) (Eilperin and Dennis, 2021). Although we utilize a cost of carbon recognized by the government of the United States, other research in sub-Saharan African countries has considered similar carbon taxes as well (Alton et al., 2014). The Rwandan government does not have a set social cost of carbon; however, the country has benefited and will continue to benefit from the carbon market, from which estimates suggest that Rwanda will benefit from an annual 82 billion USD, at 120 USD per tonne of carbon (Kagina, 2023). Further, recent research in Nature has estimated that the true cost of carbon is roughly 185 USD per ton (Rennert et al., 2022). Therefore, our estimates here are extremely conservative.

$$\begin{aligned} &\mathit{Pollutant\ Emission}\left(\frac{kg}{\mathit{generator\ lifetime}}\right)=\mathit{Emission\ factor}\left(\frac{kg}{MJ}\right)\\ &\quad *\mathit{Diesel's\ heating\ value}\left(\frac{MJ}{L}\right)*\mathit{Diesel\ consumption}\left(\frac{L}{day}\right)*365\left(\frac{days}{year}\right)\\ &\quad *\mathit{generator\ lifetime}\ (years) \end{aligned} \qquad [10]$$

We evaluate the annual carbon dioxide emissions from the diesel generator utilizing Equation (11) and the annual cost of that emitted carbon in Equation (12). We then include the annual social cost of carbon dioxide into the total annual O&M costs and find the NPV of the total O&M costs (Equation (2)). We conduct MCA simulations for the LCOE of the water purification and milk chilling uses, the associated pollution from the diesel generator for these uses, and finally the LCOEs including the social cost of carbon.

We also consider the LCA carbon dioxide equivalent emissions from the OGB, which has emissions beyond point of use. We assume 40 g of carbon dioxide equivalent per kWh, which is the median emission factor for solar mini-grid systems from the most recent IPCC report (IPCC, 2011). This inclusion had no meaningful impact on our initial results given the uncertainty in our estimates beyond two decimal places. However, we include the calculation in supplemental materials.

Full details on the methods, equations, and calculations used to calculate the comparison with diesel can be found in Supplementary Materials. All excel and python code for the Monte Carlo Simulations are available on GitHub *[link provided upon publication]*.

$$\begin{aligned} &CO_2\ \mathit{Emissions}\left(\frac{kg}{year}\right)=\mathit{Diesel's}CO_2\ \mathit{Emission\ factor}\left(\frac{kg}{MJ}\right)\\ &\quad *\mathit{Diesel's\ heating\ value}\left(\frac{MJ}{L}\right)*\mathit{Diesel\ consumption}\left(\frac{L}{day}\right)*365\left(\frac{days}{year}\right) \end{aligned} \qquad [11]$$

$$\begin{aligned} &\mathit{Social\ Cost\ of\ Carbon}\left(\frac{\$}{year}\right)=CO_2\ \mathit{Emissions}\left(\frac{kg}{year}\right)*51\left(\frac{\$}{ton}\right)\\ &\quad *\frac{1\ ton}{1000\ kg} \end{aligned} \qquad [12]$$

6. Results

6.1. Water treatment

Using an estimate of drinking water needs of 4 L/day per adult (WHO/UNICEF. Progress on Drinking Water, 2008), a Box at full utilization could fully serve 2083 individuals/day in our optimistic scenario, at a levelized cost of 0.20 USD/1000 Ls (Table 1). We draw on historical data from the Box at Musanze, a large metropolis in the northern part of the country. Between January and February of 2021, 28,000 Ls of water were produced for packaged drinking water sale – equivalent to satisfying the full safe drinking needs of 116 individuals/day. The levelized cost is the same as in the optimistic scenario, at 0.20 USD/1000 Ls. Fig. 5 depicts a pilot design of the water purification system within the OGB system.

Table 1
Optimistic and realistic scenarios for an OffGridBox.

	Scenario		*Units*
	Optimistic Scenario	Realistic Scenario	
Max kWh/day from one OGB system	12.48	8.14	kWh/day
Levelized cost of energy (LCOE)	0.34	0.53	USD/ kWh
USE CASES			
Water Treatment			
Power Consumed by Ultraviolet Light	21.00	21.00	W
Power Consumed by Pump	5.47	5.47	kWh/day
Potential # of Individuals Served Daily by one OGB system	2083	116	people
Liters sold per month	250,000	14,000	Liter (L)
Levelized cost per kilowatt hour (kWh)	0.39	0.59	USD/ kWh
Levelized cost of clean water	0.20	0.20	USD/ 1000 L
Milk Chilling			
Energy Consumed by Rapid Milk Chiller	12.48	8.14	kWh/day
Potential # of Individuals Served Daily by one OGB system	1674	1092	people
Liters sold per month	11,885	7752	L
Levelized cost per kWh	0.38	0.59	USD/ kWh
Levelized cost of chilled milk	12.10	18.55	USD/ 1000 L
Health Clinics[a]			
Average % of Load OGB can provide to a health clinic	100%+	100%	

[a] Boxes at health clinics are equipped with 4x the battery capacity as a 'standard' Box for which optimistic and realistic use-case scenarios are calculated. Therefore, the Box can meet demand for clinics whose daily consumption is < 8.14kWh/day, but additional capacity would need to be installed beyond this.

6.2. Milk chilling

If an OGB Box utilized all the energy produced towards milk chilling, it could serve the milk chilling needs of 1674 people with 0.24 L per day (Table 1). This is from the optimistic scenario in which we calculate the number of L per kWh from a Promethean System. A Promethean Rapid Milk Chiller System is a 1000-L milk chilling unit, which takes 4.5 h to charge on average, consumes 3.5 kW to charge the thermal storage system, and can store 500 L (Promethean Power Systems) (see Fig. 6). We calculate that optimistically the system could produce 396 L per day with 3.5 h available to charge. The system costs roughly 7300.00 USD, which indicates a levelized cost of 12.10 USD per 1000 Ls of chilled milk (Table 1).

However, in a more realistic scenario, a Box could serve the milk chilling needs of 1092 individuals and sell 7752 L per month with a levelized cost of 18.55 USD per 1000 Ls of milk (Table 1). This realistic scenario also requires an inverter upgrade.

6.3. Health clinic electrification

Currently, six upgraded OGB systems with sixteen 90 Ah batteries (4x the storage capacity of the standard Box) are deployed at separate health clinics across Rwanda. The health clinics require power for laptops, computers, monitors, printers, photocopy machines, vaccine refrigerators, infant warmers, aspirators, microscopes, hematology and chemical analysis equipment, lab rotators, centrifuge, sterilizers, autoclaves, mixers, and ultrasound equipment (Fig. 7). Each clinic's total daily consumption was estimated before connecting to the OBG system at 7.7, 16.7, 2.1, 9.0, 8.5, and 9.3 kWh respectively. The demand of the third health center is projected to reach 7.0 kWh when it receives its full

Fig. 7. Appliances powered by OffGridBox at health clinics in Rwanda. From left to right: Microscope, Vaccine Refrigerator, and Chemical Analyzer.

equipment.

These upgraded OGB systems are intended to supply the entirety of each health clinics' current demand for core operations, thanks to the additional battery storage deployed at these sites. While remote monitoring of systems indicates that clinics with the heaviest loads initially utilized 60% of the energy that the Box provides, such modifications demonstrate that the need or ability to use specific medical equipment at a given site can be met by scaling up or down specific components of the Box based on capacity or resilience requirements. This design choice reflects the ability to customize on top of a standardized solution, indicating a large potential for OGB to increase the number of individuals served by the health clinics, or to power additional equipment for the provision of health services.

6.4. *Quantifying benefit added by renewable energy*

If the energy produced by OGBs was instead produced by diesel generators, the LCOE for water purification would be 0.63 USD per kWh on average [range: 0.52, 0.80]. We estimate that the LCOE for the milk chiller would be 0.59 USD per kWh on average [range: 0.48, 0.76]. In terms of levelized cost per 1000 Ls of either purified water or chilled milk, solar is cheaper in both scenarios. For water purification, the diesel generator paired with the Box would cost on average 0.33 [range: 0.27, 0.42] USD per 1000 L of water, while solar is 0.20 USD per 1000 L of water (Table 2). For milk chilling, diesel paired with the Box would cost 18.59 [range: 15.12, 23.94] USD per 1000 L, while solar is 12.10 USD per 1000 L of chilled milk (Table 2).

These averages and ranges for the scenario in which diesel would replace solar for water purification or milk chilling are derived from MCA simulations that reveal the cost variability associated with the diesel generator (Fig. 8). In addition to the levelized cost of energy from solar being substantially lower than that from diesel, the lack of cost volatility associated with solar is particularly important as it shelters low-income customers from the uncertainty of higher prices.

However, diesel generators have additional social costs in addition to these direct monetary costs. Therefore, we also conduct an analysis to determine the air pollution associated with diesel generators in this case and how including the social cost of carbon affects the LCOEs. Diesel generators are major sources of local air pollution from the emission of particulate matter with a width of 2.5 μm or less ($PM_{2.5}$), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_X) and contribute to global carbon dioxide (CO_2) emissions. We find that the use of solar instead of a diesel generator in our optimistic scenarios avoids on average the emission of 164.47 kg (kgs) [range: 128.11, 221.39] of $PM_{2.5}$, 2291.20 kgs [range: 1784.66, 3084.11] of NO_x, 493.53 kgs [range: 384.42, 664.32] of CO, 139.86 kgs [range: 80.93, 139.86] of SO_X, and 85,799.08 kgs [range: 66,830.49, 115,491.30] of CO_2 (Fig. 9 & Table 3).

Table 2
Cost comparison table for solar or a diesel generator paired with the OGB in the optimistic scenarios of water filtration and milk chilling.

	Scenario without Cost of Carbon		Scenario with Cost of Carbon	
	USE CASES			
	Water Treatment			
	Optimistic Scenario with Solar	Optimistic Scenario With Diesel Generator	Optimistic Scenario With Diesel Generator & Cost of Carbon	Units
Levelized cost per kilowatt hour (kWh)	0.39	0.63 [0.52, 0.80]	0.65 [0.54, 0.83]	USD/kWh
Levelized cost of clean water	0.20	0.33 [0.27, 0.42]	0.34 [0.28, 0.43]	USD/1000 L (L)
Milk Chilling				
Levelized cost per kWh	0.38	0.59 [0.48, 0.76]	0.61 [0.50, 0.79]	kWh/day
Levelized cost of chilled milk	12.10	18.59 [15.12, 23.94]	19.22 [15.75, 24.89]	USD/1000 L

If we consider the social cost of carbon under the Biden Administration's 51.00 USD per ton of carbon dioxide and the carbon dioxide emitted from the diesel generator, the levelized cost per kWh and per 1000 Ls for both water treatment and milk chilling increase slightly. The LCOE for water purification with a diesel generator, including the social cost of carbon, becomes 0.65 USD per kWh on average [range: 0.54, 0.83]. We estimate that the LCOE for the milk chiller would be 0.61 USD per kWh on average [range: 0.50, 0.79] when a conservative estimate of the social cost of carbon is included (Fig. 10 & Table 2).

In terms of levelized cost per L of either purified water or chilled milk, solar is again slightly cheaper on average in both scenarios. For water purification, the diesel generator paired with the Box would cost on average 0.34 [range: 0.28, 0.43] USD per 1000 L, while solar is estimated at 0.20 USD per 1000 L (Table 2). For milk chilling, diesel paired with the Box would cost 19.22 [range: 15.75, 24.99] USD per 1000 L, while solar is 12.10 USD per 1000 L (Fig. 10 & Table 2).

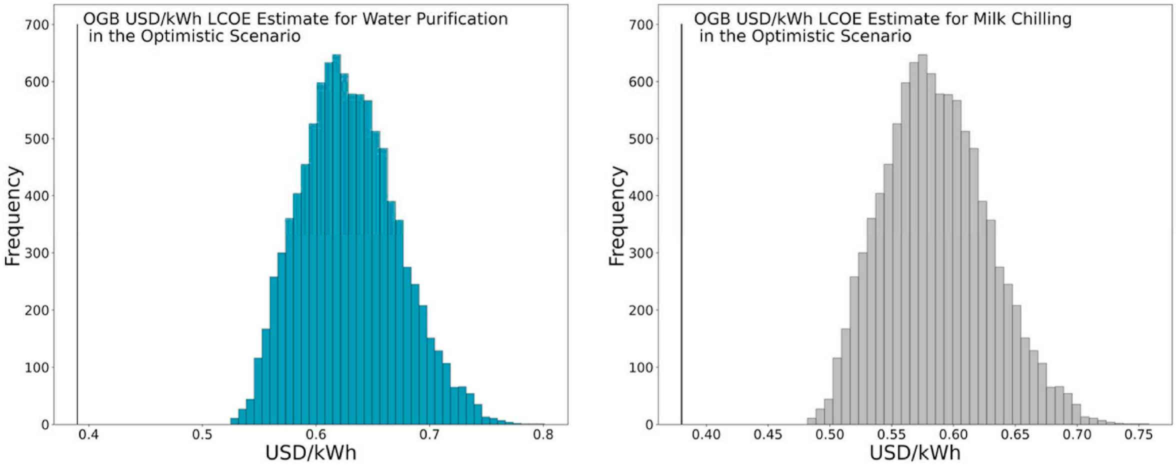

Fig. 8. The left column displays the results from the MCA simulation of the lifecycle cost of energy (LCOE) (USD/kilowatt hour (kWh)) from a diesel generator used with the OffGridBox (OGB) for the Optimistic scenario for water filtration as opposed to the LCOE found from solar panels paired with the OGB. The right column displays the results of the MCA simulation for the Optimistic scenario for milk chilling if a diesel generator replaced the solar panels paired with the OGB.

Overall, we find that the LCOE with solar as the fuel source paired with the OGB for water filtration and milk chilling is lower than the equivalent scenario with a diesel generator as the fuel source. We find that solar has benefits over diesel in terms of lower costs, lower cost variability, and the avoidance of local and global pollution including GHG such as carbon dioxide.

7. Discussions

We present an in-depth, techno-economic scenario analysis of a novel containerized energy technology for specific use cases, considering non-monetary benefits and uncertainty ranges. Overall, we find that this containerized solution could provide for either 2083 individuals' daily drinking water needs, 1674 individuals' daily milk consumption, or 100% of a health clinic's energy demand. Additionally, our results reveal that solar as the fuel for the containerized solution has benefits over diesel in terms of lower costs, lower cost variability, and the avoidance of pollution including GHGs such as carbon dioxide. Our scenario analysis allows us to discuss how this specific containerized solution could potentially serve settings beyond peri-urban and urban Rwanda as well as multiple development sectors. This discussion is particularly salient given the cost outlook and opportunities for further research.

7.1. Potential for containerized solutions for displaced settings and multiple development sectors

Our analysis reveals that Boxes can be cost-effective on a lifecycle cost analysis per-capita basis compared to other delivery modalities in humanitarian settings. The United Nations High Commissioner for Refugees (UNHCR) estimates an upfront cost of 50,000.00 USD and 3000.00 USD recurring maintenance cost including hand-pumps & piped water to serve 300–600 individuals (Deshpande et al., 2020). Containerized solutions offer the additional benefits of transportability or repurposing. The Box provides a level of service deemed acceptable for non-humanitarian settings (USAID. Assessing the Effects of, 2020), indicating that it could also provide additional electricity for poorly serviced agglomerations and cities. This offers a pathway for rethinking 'regular' service expansion, particularly in the context of struggling national utilities.

It remains challenging to identify 'universally' applicable use-cases at the Food/Energy nexus, given the importance of local context. Milk-chilling, for example, only makes sense in certain locations based on market needs. Additionally, proper value-chain assessments and government support are very important to limit the risk of a stranded asset. Our analysis is indicative, however, of how procurement of containerized solutions at scale could be allocated across several different government priorities. These include the Ministry of Education's early childhood nutrition strategy, power and water regulators/utilities' performance mandates, and Ministry of Health's extra-urban operations. Further work is necessary at the intersections of energy and other sections of development.

7.2. Cost outlook and implications

Overall, while costs of providing services at the Food/Water/Health nexus through containerized energy modalities are still quite high, most cost reductions are expected from scaled-up procurement. The Rocky Mountain Institute estimates that at scale, containerized solutions can reduce the LCOE by 0.11 USD/kWh. Although this estimate is not specific to OGB deployments, it does assume the bulk purchase of a standardized, containerized product like the OGB. Further work is needed to investigate the full spectrum of community impacts at sites for which Boxes have been in operation for multiple years.

In many African countries, the utility model for water and power delivery has not yet achieved cost-reflexivity in tariffs, nor eliminated quasi-fiscal deficits (Kojima, 2016; Banerjee et al., 2008). Sudden shocks like COVID-19, as well as chronic stresses from urbanization and climate change, further undermine the central grid. Future work should investigate scenarios in which OGB can rapidly serve needs in the short term, and in the medium-long term merge with a central network, adding capacity and resilience. Critically, however, the advantages conferred by containerization enable such infrastructure solutions to be redeployed once the 'main' network arrives. The Box can then be repurposed to another location or another strategic priority like food security or health.

8. Conclusion

We investigate a novel decentralized containerized energy infrastructure provider, OffGridBox, for three use cases at the Food/Water/Health nexus. This article moves beyond the standard energy modeling of previous literature to examine key use cases for low-income settings, using a combination of scenario analysis and in-the-field data. Our results are applicable within the Rwandan context, but also may have applications to other low-and middle income, rapidly urbanizing, or transient settings, particularly in sub-Saharan Africa. In optimistic scenarios, we find that this containerized solution could provide for either

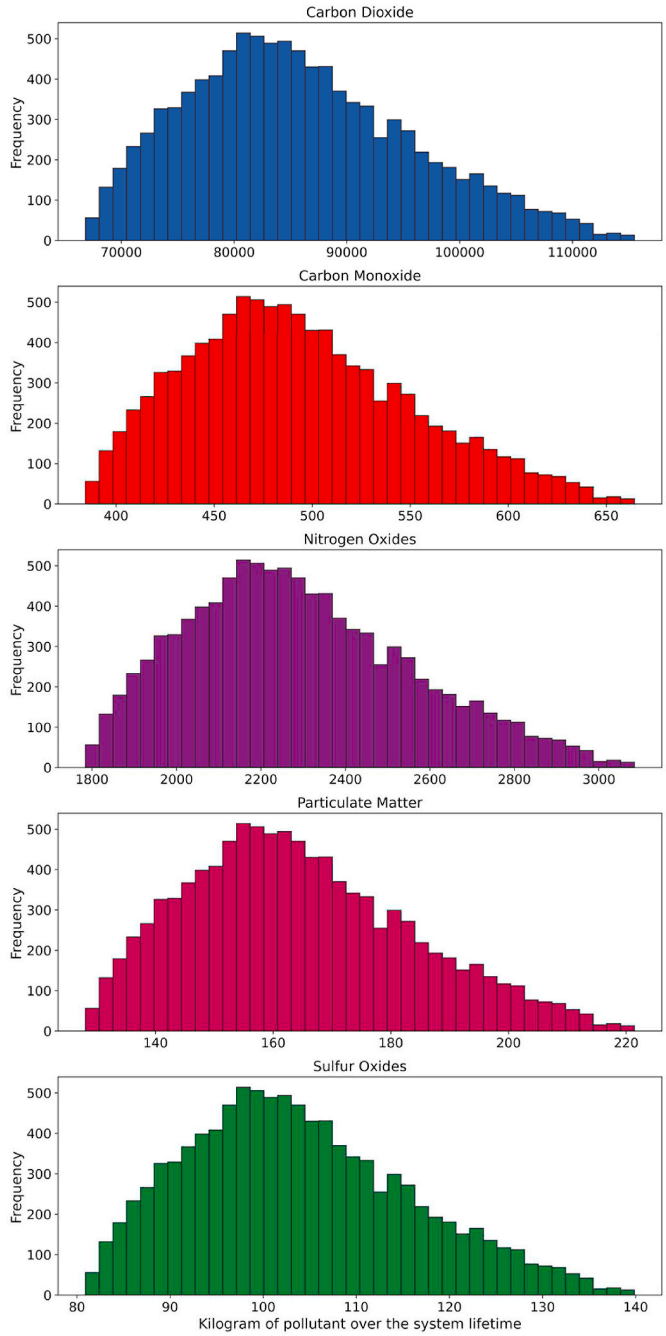

Fig. 9. MCA simulation results for the emissions of specific pollutants associated with the use of a diesel generator paired with the OffGridBox instead of solar. We model these for the Optimistic Scenario for the entire daily energy consumption of Box (12.48 kW h/day). In the MCA simulation, we vary the diesel generator's operating heat rate (efficiency), price of diesel, and the generator lifetime following triangle distributions.

Table 3
The average, min, and max for each pollutant's distribution from our MCA simulation results for the Optimistic Scenario.

	Optimistic Scenario *With Diesel Generator* $\left(\frac{kilograms\ (kgs)}{lifetime\ of\ generator}\right)$
Carbon Dioxide, CO_2	85,799.08 [range: 66,830.49, 115,491.30]
Carbon, Monoxide, CO	493.53 [range: 384.42, 664.32]
Nitrogen Oxides, NO_X	2291.20 [range: 1784.66, 3084.11]
Particulate Matter, $PM_{2.5}$	164.47 [range: 128.11, 221.39]
Sulfur Oxides, SO_x	103.90 [range: 80.93, 139.86]

2083 people's daily drinking water needs, 1674 people's daily milk consumption, or 100% of a health clinic's energy demand. We incorporate sensitivities and an MCA Framework to quantify the benefit of providing these loads using solar energy instead of an incumbent, non-renewable diesel generator in terms of both cost and air quality. For water purification and milk chilling uses, we find that solar has a lower lifecycle cost of energy 0.39 USD/kWh and 0.38 USD/kWh compared to 0.63 [0.52, 0.80] USD/kWh and 0.59 [0.48, 0.76] USD/kWh respectively for diesel. Additionally, solar has lower cost variability and avoids pollutant and GHG emissions (e.g., 85,799.08 kgs [range: 66,830.49, 115,491.30] of carbon dioxide over the system lifetime). Thereby we quantify that using solar has a meaningful mitigating effect in terms of cost and environmental pollutants for water purification and milk chilling.

We contribute to the literature on containerized infrastructure solutions in our findings that a solar powered OffGridBox is a realistic, cost competitive, and environmentally beneficial containerized solution to serve needs at the Food/Water/Health nexus. We offer scenario analysis, based partially on field data which is extremely lacking in the literature to date. Finally, we fill a gap in this literature by providing uncertainty ranges on both economic and environmental impact estimates. Our results are applicable within the Rwandan context, but also may have applications to other low-and middle income, rapidly urbanizing, or transient settings, particularly in sub-Saharan Africa. Our inclusion of a social cost of carbon and GHG pollution provides a more holistic social-environmental-technical-economic comparison of options. In particular, the additional burden of air pollution from diesel generators in protracted displacement settings is undervalued in traditional techno-economic technology comparisons that focus only on the production of energy, not its bi-products.

These results suggest that containerized, renewable energy systems such as OffGridBox have both cost and air quality advantages over a diesel generator. With a 20-year expected lifetime, over two dozen deployments in Rwanda and counting, OGB systems represent perhaps the best dataset for benchmarking a variety of community infrastructure needs and costs in existence. Although these systems are currently deployed in urban and peri-urban areas of Rwanda, we find that these systems may be well suited to serve displaced populations in refugee camps or other humanitarian zones. The deployment of such modular, containerized solutions could address electricity needs, change the landscape of utility service provision models, and provide productive uses of electricity at the Food/Water/Health nexus.

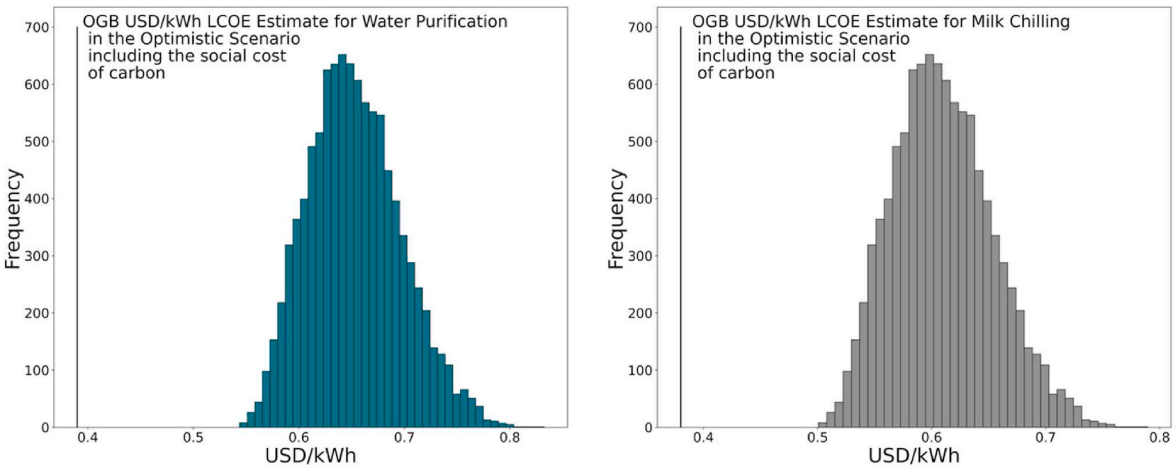

Fig. 10. The left panel displays the results from the MCA simulation of the lifecycle cost of energy (LCOE) (USD/kilowatt hour (kWh)) from a diesel generator used with the OffGridBox (OGB) for the Optimistic scenario for water filtration as opposed to the LCOE found from solar panels paired with the OGB—including the social cost of carbon. The right column displays the results of the MCA simulation for the Optimistic scenario for milk chilling if a diesel generator replaced the solar panels paired with the OGB.

Credit author statement

Annelise Gill-Wiehl: Conceptualization, Methodology, Formal Analysis, Writing- Original Draft, Review & Editing, **Isa Ferrall:** Conceptualization, Methodology, Formal Analysis, Writing- Original Draft, Review & Editing, **Serena Patel:** Methodology, Formal Analysis, **Samuel Miles:** Investigation, Writing-Original Draft, **Jodie Wu:** Resources, Writing-Review & Editing, **Alyssa Newman:** Funding acquisition, **Daniel Kammen:** Supervision, Funding acquisition, Writing-Review & Editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel Kammen reports financial support was provided by Google Inc. Jodie Wu reports a relationship with OffGridBox that includes: employment. Alyssa Newman reports a relationship with Google Inc that includes: employment.

Data availability

Explanation of all methods and calculations is available as a supplemental document, excel, and python code to ensure full reproducibility of results.

Acknowledgments

The short version of the paper won best paper at the Applied Energy Symposium: MIT A + B, August 11–13, 2021, Boston. This paper is a substantial extension of the short conference paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.deveng.2023.100110.

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