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Productive uses of electricity at the energy-health nexus: Financial, technical and social insights from a containerized power system in Rwanda

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ABSTRACT

We present a case study of successful uptake of a productive use of electricity (PUE) co-located at an off-grid clinic powered by OffGridBox in Rwanda. We develop a techno-economic analysis of the standardized, modular, and redeployable power supply technology, characterizing cost components, revenue considerations, and key challenges. We present a technical characterization of system utilization based on remote monitoring of electricity consumption, power reliability, and power quality at a PUE intervention site, estimating system reliability at 81% over the study period. Lastly, we characterize socio-economic costs and benefits from the productive user's perspective drawing on mixed-method interviews. We find that relatively low amounts of electricity consumption (10–30 kWh per month) command a high revealed willingness to pay (~\$3 per kWh) for the solar-powered displacement of diesel-based welding, significantly improving the unit economics of the deployed system. This analysis and data provides a resource model for the standardization of mini-grid hardware, performance and cost frameworks, and metrics to assess off-grid, under-grid and ultimately grid interactive distributed generation systems. These models are urgently needed to meet the UN Sustainable Development Goal SDG 7 commitment to achieve universal energy access by 2030.

1. Introduction

Alternatives to grid extension are gaining increasing strategic importance to African governments and their development partners in widening access to electricity, economic opportunity, and social welfare. Despite progress in recent years in both grid extension and off-grid supply modalities, about 940 million people will have to be connected by 2030 to reach universal access, or 85 million people each year in Africa alone (IEA, 2021). The COVID-19 pandemic has exacerbated the challenge for the continent's national utilities in particular, for whom each additional connection typically represents a significant capital expenditure to connect the lowest consuming customers, generally without any programmatic focus on demand stimulation in pursuit of eventual cost-recovery (Balabanyan et al., 2021; Butler et al., 2020).

Decentralized energy systems like standalone photovoltaic (PV) systems and mini-grid systems are expected to play a strategic role in bridging the access gap (IEA, 2019). Decentralized systems are particularly critical given the relative speed and flexibility with which they may be deployed across remote and dispersed locations — especially

important for the hundreds of thousands of health facilities across the continent requiring refrigeration and stable cold-chains for effective vaccine distribution (Moner-Girona et al., 2021).

Despite the maturation of various technologies and systems capable of powering such critical needs, the economic business models animating decentralized energy solutions remain several years from the scale suitable for commercial financing mechanisms (Soni and Kawahara, 2020). This motivates the need for a deeper accounting of the costs and benefits which different electrification modalities offer to inform decisions for the allocation of development finance and optimize impact return.

In line with these objectives, productive uses of electricity (PUE) have reemerged as a cornerstone for improving the utilization and unit economics of decentralized energy systems in academic and industry literature (Lukuyu et al., 2021; Hartvigsson et al., 2021; Besnard, 2019; ESMAP, 2019; Ngowi et al., 2019). In contrast to the generally inconclusive empirical literature aimed at quantifying if and how much electrification programs have economic development impact broadly defined (Attigah and Mayer-Tasch, 2013), research methods focusing on

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the uptake of PUEs call into question how distinct intervention design features — on-grid vs. off-grid supply, tariff considerations, or appliance financing, for example — translate into specific financial, technical, or social outcomes.

This paper contributes to the literature on integrated infrastructure planning through the lens of OffGridBox, a uniquely standardized off-grid technology provider aiming to scale up PUE interventions across its portfolio of technically identical deployments. Our work is guided by the following research questions: What are the technical and operational characteristics of a containerized power and water solution designed for remote and off-grid populations? How do such solutions perform in the field, from the perspective of the reliability and quality of electricity services offered? What are the challenges and opportunities developers face towards cost-recovery and profitability in deploying such systems? Finally, how do productive users of electricity experience the social and economic impacts of such interventions?

We employ a mixed methodological research design which seeks to: 1) provide technical, financial, and operational insight into the OffGridBox technology (“Box”) as a standardized electrification option; and 2) describe the site selection process and operational characteristics for a case study Box deployment in northeastern Rwanda, followed by a deep interrogation of the socio-economic impacts of the deployment from the perspective of a Box-powered productive user. Remote monitoring methodologies paired with a deep rendering of the end-user’s perspective helps to fill critical gaps in the empirical literature from both the supply and the demand side on the challenges and opportunities of implementing successful productive use interventions in remote, off-grid and low-income environments.

In Section 2, we provide background and context on the current literature on productive uses of electricity, the technology developer, and the study area. In Section 3, we discuss the methods which underpin the research. Section 4 provides a techno-financial characterization of OffGridBox as an electrification modality before describing a Box-powered case study site in northeastern Rwanda. For this case study deployment, we provide key operational indicators of electricity consumption, reliability, and quality at a productive use site, and a socio-economic characterization of the intervention from the perspective of the productive user at this site. Section 5 discusses strategic implications for targeting multiple Sustainable Development Goals at varying scales of energy access innovation in a pandemic-recovery regime, and Section 6 concludes.

2. Background

2.1. Productive uses of electricity

Productive uses of electricity are often defined narrowly as the provision of electricity as an improved input into income-generating activities (ESMAP, 2008). To assess the full socio-economic potential of PUE interventions, however, it is important to capture effects that are not explicitly market-oriented: the gendered aspects of time saved on household chores, for example (Kaygusuz, 2011), or the impacts of electrification on health and educational service delivery which, though linked to earning potential, are just as importantly ends in and of themselves (Cabraal et al., 2005).

Much work remains to be done in understanding and de-risking the simultaneous provision of broader definitions of productive uses of electricity (encompassing social benefits) with narrower income-generating ones. A recent review of nearly 80,000 published papers on energy access and transitions, for example, identified fewer than 20 that consider the impacts of energy on health facilities (Jeuland et al., 2021). Basic challenges remain in illuminating the current electrification status at health facilities across the continent, with an urgent need to move beyond simple binaries of connected/disconnected towards more multi-dimensional and contextual analyses of energy availability and reliability (Moner-Girona et al., 2021).

Similarly, significant gaps remain in the literature on the conditions which inhibit or contribute to the successful and sustained uptake of income-generating electricity interventions. While a niche literature has emerged documenting the economic impacts of PUE on mini-grid operations in particular, most studies still rely on synthetic or simulated demand, engendering significant under- or over-sizing of deployments, along with the associated negative financial impacts thereof (Hartvigsson et al., 2021; Hartvigsson and Algren, 2018; Booth et al., 2018; Blodgett et al., 2017; Mandelli et al., 2016). Furthermore, few studies delve into the specific use cases which generically reappear across productive use literature, revealing little of the economic lives and differentiating particularities of the artisans and entrepreneurs — welders, tailors, carpenters, barbers, shopkeepers, millers, fishermen, to name just a few — upon which successful PUE interventions fundamentally depend.

Cross-cutting through these demand-side challenges lies the basic challenge of technical comparability across systems; given the sensitivity of off-grid deployments to sizing challenges, projects capable of powering productive uses each tend to be custom-sized. Developing robust methods for assessing the multi-dimensional costs and impacts across electrification modalities thus remains a significant obstacle to developing truly integrated electrification strategies (Eeles, 2018) — particularly as technological, financial, and even regulatory innovation blurs the traditionally distinct categories of standalone systems, mini-grids, and utility-grid systems.

2.2. OffGridBox in Rwanda

OffGridBox (OGB) is a mission-oriented technology company founded in 2016 whose Africa operations are based in Kigali. Its principal offering is a containerized infrastructure solution. Each unit — a roughly $2 \times 2 \times 2$ m steel “Box” — is shipped with technology assets inside that, when installed, are capable of (a) generating, storing, and distributing photovoltaic (PV) electricity, (b) purifying local water, and (c) providing local data and connectivity services through cellular networks. There are to date over 80 Boxes deployed in 14 countries around the world.

OffGridBox operates in a liminal space between commercial providers of standalone home/single-structure energy solution vendors like BBOX or d.light, and operators of more traditionally understood mini-grid operators like PowerGen or Equatorial Power that act as ‘micro-utilities.’ This novel positioning, along with exceptional comparability across its technically identical deployments, provides a unique research perspective into the ‘thickening’ continuum of electricity access solutions (Miles et al., 2021; Alstone et al., 2015).

From a primarily sales-based business model, in which Boxes would be commissioned on behalf of humanitarian and aid organizations for deployment to infrastructure-poor locations around the world, the organization decided to develop an additional, more hands-on operational model; rather than simply manufacture, sell and ship Boxes, the company would retain management responsibilities for the Boxes in order to more clearly demonstrate how the technology assets can sustain themselves financially while supporting local communities.

Rwanda was selected as the most suitable country to test this new operational model, as it consistently ranks among the most stable countries in Africa politically, as well as across metrics of “doing business” (World Bank, 2020a). For these reasons, Rwanda also became the de facto Africa hub of the company’s operations, and today represents the nationally-defined territory with the most Boxes deployed as well as the most employees.

OffGridBox actively manages nearly 20 systems across its Rwanda portfolio through local commercial ventures — principally, sales of purified water and a portable power bank charging lease/distribution model. These activities are supported by co-financing schemes from international development stakeholders and strategic investors in the energy access domain as the organization refines its business model and product-market-fit. In 2020, for example, OffGridBox was commissioned

to electrify six off-grid clinics through a partnership between the Rwandan Ministry of Health and USAID's Power Africa, the first time the technology was applied to the challenges of the health sector. Fig. 1 shows Rwanda site deployments at the beginning of the study period.

2.3. Electricity and water access in Rwanda

Rwanda is a small country with a total population of approximately 13 million (World Bank, 2021). The capital city of Kigali (population >1 million, less than 10% of total population) consumes over 50% of total national electricity over evening peak (Ministry of Infrastructure, 2018) and holds about half of the country's urban population. The other million or so urbanites are distributed across six smaller cities and their peripheries.

Rwanda's existing generation capacity is below 300 MW, the bulk of which has historically come from hydropower. Pronounced drought crises in the late 2000s precipitated rapid and costly investments into thermal generation capacity, which in 2017 represented 27% of installed capacity and up to 45% of yearly energy production, largely driven by variability in rainfall and human-hydrological interfaces (Bimenyimana et al., 2018).

Despite an abundance of peat, lake gas methane, and geothermal resources with appreciable if uneven utilization, no raw petroleum resources have been identified in the territory. High costs of imported petroleum, a quarter of which is burnt for electricity generation, contributes to a high production cost relative to the regional average. The Ministry of Finance consequently disburses approximately \$40 million per year to the electricity sector to subsidize the cost of electricity for end-users, aiming at maintaining regional economic competitiveness (Bimenyimana et al., 2018).

Rwanda's electricity system is typical for its region in that transmission and distribution losses (22%) are significantly higher than international benchmarks (6–8%) (Ministry of Infrastructure, 2018). The transmission system runs principally through ~700 km of 110 and 220 kV lines, with distribution networks branching from 37 high and medium voltage substations throughout the country (Rwanda Energy Group, 2021). The lack of reactive power capabilities on the network introduces systemic voltage instability risks (World Bank, 2020b). Fig. 2 shows the transmission network overlaid on the population density map.

Demand-side dynamics reflect Rwanda's status as a low-income country. Comprehensive access to electricity metrics vary by study, but the World Bank's Energy Sector Management Assistance Program

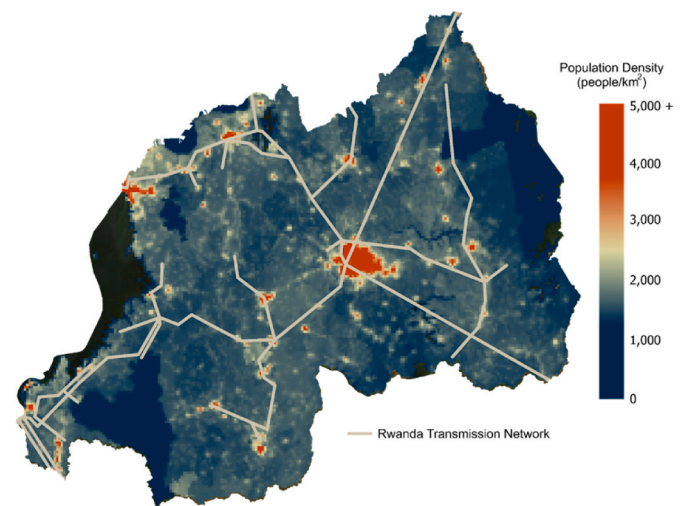


Fig. 2. Transmission network in Rwanda overlaid on 2020 population density data. Data from World Bank Data Catalog (2017) and WorldPop (2017).

(ESMAP) estimates that three quarters of the population consume little to no electricity (Bonsuk et al., 2018). 77% of urban households are estimated as connected to the grid, compared with 16% of rural households. For those with a formal grid connection, average energy consumption for residential connections is estimated between 10 and 30 kWh per month. The 2018 survey reveals 24% of grid-connected households had less than four disruptions a week with less than 2 h of total outage time. In contrast, 68% of grid-connected households experienced between 4 and 14 weekly disruptions.

Only 57% of the Rwandan population has access to safe drinking water within 30 min of their home. Diarrhea caused by untreated water and inadequate sanitation is the third leading cause of death in children under five (Umuhiza et al., 2021). The most recent data from WASAC (the Rwandan water and sanitation utility) indicates that the number of users per registered utility connection is 11 on average in Kigali, 36 per connection in the six secondary cities, and over 50 beyond these principal urban agglomerations. Water is provided through 15 urban water systems and over 850 rural piped systems (Frade, 2019).

In contrast to many African nations, Rwanda has taken an open and experimental approach to meeting its internal targets for improving access to basic infrastructure services. The 2019 National Electrification Plan allocated 48% of villages in the territory for off-grid electrification (as opposed to grid extension) (Ministry of Infrastructure, 2018), while private water vending services are also expected to play a significant role in expanding clean water access (Frade, 2019). For these reasons, along with explicit Rwandan marketing as Africa's innovation sandbox, private sector models for the delivery of infrastructure services like electricity and water — but also electric motorbikes and trucks, drone-based health clinic supply delivery, and one-stop-shop e-government portals — have attracted significant international capital to the country as a sandbox for innovation and learning in low-resource contexts.

3. Methodology

3.1. Techno-financial characterization of OffGridBox technology and operations

To develop a techno-financial characterization of the OffGridBox technology, we collected data on each component of the standardized systems. This data was collected through interviews with the technical and managerial cadre of the company, and included the technical specifications of each component, as well as their associated procurement and assembly costs. Costs were validated by referencing pricing

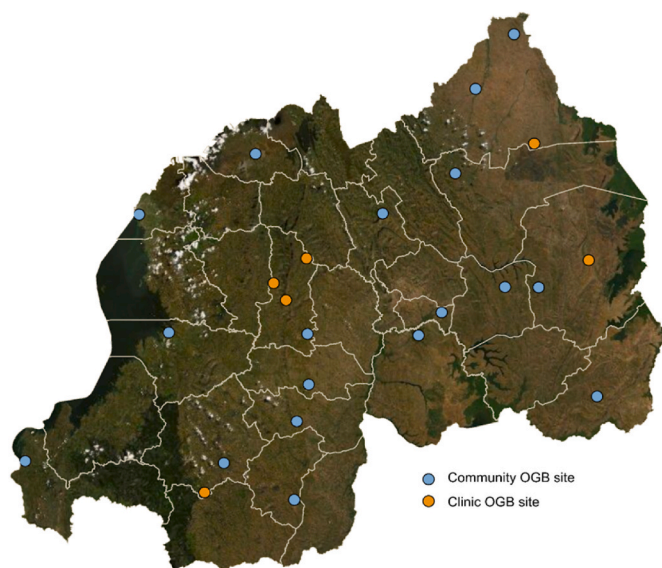


Fig. 1. Box deployments in Rwanda as of June 2020.

information of the original manufacturers' product catalogs where available, as well as interviews with OffGridBox funding partners.

Operational costs were similarly aggregated through interviews with OffGridBox staff, but specifically targeted the in-country team members responsible for the logistics of importing and deploying Boxes from OffGridBox's central manufacturing site in Italy to the various deployment sites across Rwanda. Detailed deployment costs were collected through participant-observation throughout in-country fieldwork between July and August 2020, during which we accompanied field staff in performing routine maintenance and resupply trips to Boxes around the country. Independent site visits, including direct interviews with end-users, were also performed to validate information collected through interviews with company staff. Fig. 3 shows site visits performed over the field research component.

To gain insight into the key operational indicators revealing the performance of deployed OffGridBox systems, we collected sales data from each Box via the company's internal sales dashboard. These dashboards were reviewed during weekly sales calls between OffGridBox Rwanda leadership and local field staff, and included both operational expenses as well as revenues generated from the sales of water and electricity at each Box.

To develop a clear sense of the output and utilization of the energy system in particular, we analyzed historical and live readings of energy production and consumption at each Box. We accessed this data through remote monitoring systems installed at each Box. These monitoring systems log information along specific components of a deployed system and relay the collected data to a cloud-based server via an internet modem housed inside the Box. We deployed additional sensors at the site of the PUE intervention to gain deeper visibility into the reliability and quality of the power supplied; these sensors sample power quality directly from any standard AC outlet and report voltage, frequency and outage data to a cloud platform through an integrated SIM chip. Further information on the sensor technology and deployment methodology is provided in Annex B. Table 1 summarizes the techno-financial data collected over the study period.

3.2. Nyamirama case study and productive user

To explore challenges and success factors surrounding the deployment of PUE interventions, we met for approximately 1 h every other week for research check-ins with OffGridBox leadership and operations

Table 1

Techno-financial data collected over the study period.

Data	Source	Description
Technical	Voltage, frequency, and outage frequency and duration of electricity supply	nLine PowerWatch sensor
	Consumption and demand of welding workshop powered by OffGridBox	Efergy
	Consumption and demand of off-grid clinics powered by OffGridBox	Efergy
	Solar panel power output and daily battery discharge	MorningStar/Tristar
Financial	Water sales data	OffGridBox data
	Power bank recharge sales	OffGridBox data

staff for approximately one year prior to commencing fieldwork. Through these consultations, we selected the northeast of the country as a focus site for particular attention within the study area, as the region hosts the organization's most developed productive use project — a workshop in Nyamirama powering the income generating activities of light construction work co-located with OffGridBox health clinic electrification, water treatment and sales, and power bank distribution. To gain deeper visibility into the reliability and quality of the power supplied by an OffGridBox system, we deployed additional sensors at this site.

In Nyamirama we obtained consent from a welder to participate in the study. Over the course of the next six months, we conducted unstructured and semi-structured interviews through Whatsapp, using text exchanges, voice messages, pictures, and video to develop an understanding of the dynamics contributing to a successful example of productive use uptake. Communications were conducted in English, supplemented by English-Kinyirwanda online translating tools and translations of voice messages by Kinyirwanda-English translators. We used the digital finance platform WorldRemit to send mobile airtime directly to the user's mobile account to cover the costs this flow of data, particularly video, engendered.

4. Results

In this section, we first describe the business model, cost structures, and dominant operational challenges of OffGridBox in Rwanda. We then present results from the case study deployment in Nyamirama, drawing on data collected through interviews and remote monitoring of the system deployed at the PUE site. Lastly, we represent the case study from the perspective of the end-user of the intervention.

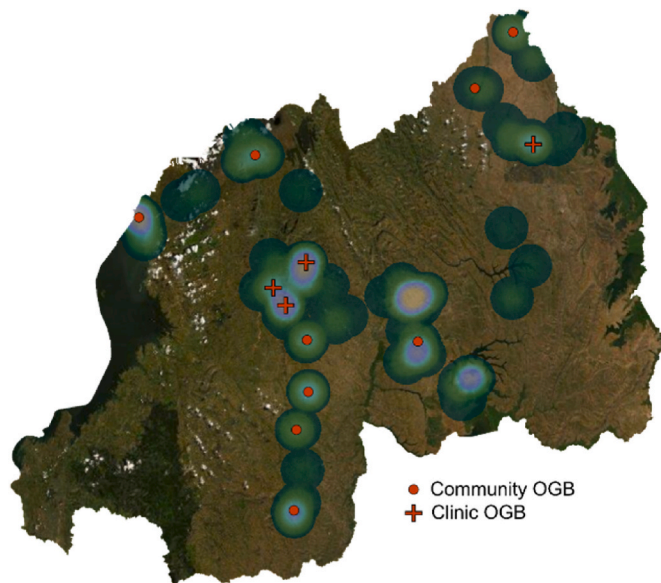


Fig. 3. Heat map of 1700+ photographs taken during field visits to eight Box and four clinic sites.

4.1. Technical, financial, and operational insight into OffGridBox

4.1.1. Technical specifications and capital costs

The Box is constituted of over 400 components which can be categorized into (i) power system for generation, storage, and distribution of electricity; (ii) water module for transforming raw water into high quality potable water; (iii) remote monitoring system for tracking system performance; (iv) a modified, miniaturized shipping container. Fig. 4 provides an illustrative breakdown of the respective cost of system components. These baseline manufacturing costs should be interpreted as representative as cost components change over time; while overall production costs generally decrease with increasing standardization both in the production of a Box and the global manufacturing industries that produce its components, exogenous events like the pandemic-induced supply chain disruption may impact in particular the shipping costs of a container, as well as base costs for the Box container itself. Table 2 provides a breakdown of Box components in deeper detail, and Fig. 5 shows a Box deployed on site.

The cost of deploying a Box can vary significantly across the specificities of the sites at which they are deployed, both across and within countries. Shipping costs for a 40 foot container transporting six Boxes from their assembly site in Italy to Mombasa, for example, typically costs \$3,000–4,000, after which they are shipped to Kigali overland, typically for equivalent cost (though frequently the overland component is slightly costlier than the shipping one). A small crane is used to transfer Boxes — each weighing approximately 1,500 kg — onto smaller deployment trucks, which can reach nearly any destination in Rwanda in less than 4 h for an approximate cost of \$500. It takes approximately 4 h to set up the Box once on-site.

Country-specific regulatory standards also introduce variability in

the capital expenditures associated with a Box deployment. In Rwanda, for example, the business model has focused on producing packaged water to the regulatory standards of the Rwanda Food and Drug Authority. These standards impose a host of requirements around health and safety, including that the Boxes are laid upon a concrete foundation (\$100–150), can be fully enclosed with fencing, and, during COVID-19, have automatic hand-washing and bottle washing stations available for employees and customers.

The Box's maximum output is 1,000 L of potable water per hour, and across the insolation range of installed sites in Rwanda, can generate approximately 10 kWh per day, or between 2 and 4 MWh per year.

4.1.2. Operational model and costs

Despite the relative standardization of Box capital costs and deployment, operational costs vary significantly both across countries, as well as within. In Rwanda, for example, the regulatory license for producing packaged water amounts to a yearly \$700 fee per Box. Once operational, a Box must then be resupplied with the materials it uses for the various business lines it engages in. Replacement filters and treatment materials for the water module, for example, average approximately \$400 per Box per year, but a given market may require materials unique to the specificities of that market or region, like a bicycle for shop deliveries or sachets for micro-water sales.

Standard supply runs (including, for example, the delivery of jerry cans for lease, packaging materials for retail sales, and labeling materials) from Kigali or from other Boxes also present significant variable operational costs principally contingent on proximity of the site to local transit hubs. These costs can be kept low if the Box is easily accessible through public transport (~\$10 round trip), but increase significantly if a dedicated vehicle must be dispatched (~\$30 per day plus fuel costs

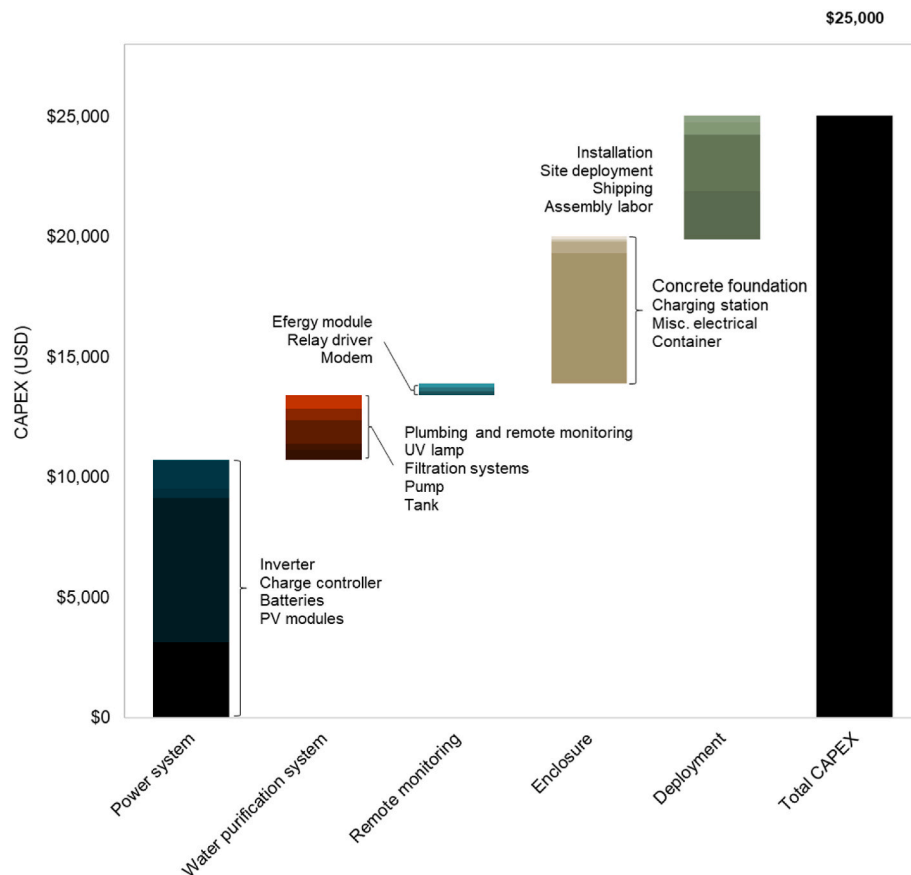


Fig. 4. CAPEX of a basic Box by principal components. Costs are presented for the typical case where six Boxes are packed in a single 40 foot shipping container. Battery cost sub-component in Power System are presented for Community (Power Bank/Water sales) and scale linearly by capacity. Shipping costs may vary significantly by shipping route and season. Boxes are generally purchased upfront by donor funding and thus do not incur additional costs from financing.

Table 2
OffGridBox system components.

Box Systems	System Components	Description
Power system	<ul style="list-style-type: none"> • Twelve 260–280 Wp PV modules (total rated capacity of 3.12–3.36 kWp) • Between 4 and 16 Gel/AGM lead-acid batteries (4–16 kWh) • 60 amp charge controller • 3kWp rated inverter 	Panels are mounted on Box roof, generate DC power stored in Box batteries or power banks for distribution, or converted to AC power through inverter to operate water module and power productive uses. Batteries have a 5-year estimated lifetime, charge controller, modules, and inverter have a 10-year estimated lifetime.
Water module	<ul style="list-style-type: none"> • 20 L/min self-priming pump • 600 L food grade tank • Gravity-fed activated charcoal filter • 5-μm filter and additional brush filters • UV lamp • Piping & fittings • Meters and tap fittings 	Water module uses 10–15% of power system's energy output and produces FDA-grade potable water from local raw water.
Remote monitoring	<ul style="list-style-type: none"> • Standard SIM-equipped internet modem • Solar charge controller remote monitoring platform • Efergy current transformer module (at clinics only) 	Remote monitoring hardware is powered by Box power system or internal batteries and transmit select readings through telecom networks. Modem also broadcasts wifi.
Container (including wiring, paneling, circuitry)	<ul style="list-style-type: none"> • 2 × 2 × 2 m steel shipping container with an approximate interior volume of 8 m³, dual-opening locking doors • Circuit panel • Mounted power strips • Grounding pole • Power Bank charging station (~40 microUSB cables) 	Box itself provides structural base and securitization against theft/weather for power system, water module, remote monitoring, as well as operations (supply storage, cash, manuals). Container has a useful lifetime of at least 20 years.

dependent on distance) or if staff need to stay at site for multiple days, for example for technical repairs.

Rental costs for the use of the land on which the Box is installed, negotiated with individuals or institutions based on the specific desirability of a location within a community, typically constitutes between \$20–40/month based on proximity to urban centers. Where Boxes are placed on homeowners' land with an existing tap from the utility, the Box may assume responsibility for the landowner's water bill in exchange for full access to municipal water for treatment and resale. This arrangement is particularly viable where municipal infrastructure is known to experience bacterial contamination in piping, requiring end-users to boil or otherwise disinfect municipal water prior to consuming it. The additional value-add of a storage tank mitigates the unpredictable cut-offs which plague municipal water service, particularly during dry months.

Data costs associated with managing both the remote monitoring of a Box as well as the costs associated with managing the flow of sales and inventory data varies based on how many sensors are actively being routed through the modem, the frequency of reporting, and whether the Box additionally offers wifi to the surrounding community as part of the local arrangement — a single Box's data needs can account for \$5–10 a month just for remote monitoring, but this fails to account for the time spent managing and refilling a fleet of SIM accounts across Boxes, which are predominantly pre-paid and must be recharged centrally.

Boxes are staffed by a BoxKeeper responsible for testing and recording the quality of each batch of water produced for regulatory auditing purposes, as well as collecting payment from customers and converting cash into mobile money for transfer to HQ. These positions

are exclusively offered to women from the host community in line with the organization's social mission.

4.1.3. Consumer pricing

There is a significant variety in pricing models across the services offered. Pricing schedules for water sales vary by location (based on local competitive dynamics and the demographic ability to pay) as well as by customer type (e.g. individuals, shopkeepers, or community entities like schools or clinics).

Pricing options are also offered to cater to customers' cash-flow constraints with respect to up-front fees, e.g. a down payment for leasing a jerry can for users who don't already have one or who need another (with subsequent charge by 5L refill), or the down payment for leasing a power bank (with a subsequent recharge fee). Pricing options are also offered as weekly or monthly subscription recharge/refill models.

Pricing schedules are iterative and adaptive, and designed to mediate product-market-fit at any given location and season, factoring in final delivery costs: shopkeepers may organize their own pickup of packaged water at a Box, for example, or pay for delivery through the organization's biker distribution system.

Most water is sold to customers for a standard unit of 5 L, corresponding to the jerry cans ubiquitously used among the population for procuring and transporting water from formal or informal sources. Packaged units (sealed plastic jugs) are also sold to local retailers where proximate and economical; RFID-enabled pay-as-you-go micropayments for water are also being piloted at several sites, enabling sales of units of water as small as a single cup of water for 50 Rwandan francs (\$0.05).

The electricity distribution capabilities of the Box take two forms - primarily, a power bank distribution model in which 40 Wh lithium-ion battery packs with QR codes and three lights are leased to customers for a down payment and a recharge fee. Customers may also pay a fee to have their phones charged directly at the Box. Secondly, Boxes are capable of powering community facilities like schools and clinics by running an electrical cable from the inverter to the facility's circuit breaker panel.

The model for electrifying schools and clinics falls under a distinct financing model, as these projects are typically funded up-front through grants or partnerships. The specific arrangements for these kinds of customers typically include in-kind water allocations or power service in exchange for land-use agreements or other specialized projects, for example a digital literacy program offered at a secondary school.

4.1.4. Revenue and profitability

Sales data over the past two years under observation reveal that the Boxes located in urban areas with high population densities and formal economic activity perform the best in terms of water sales, but proximity to grid infrastructure limits demand for power banks. Local labor dynamics are also observed to be a critical determining factor of sales growth for both power banks and water sales, particularly for regional sales managers responsible for developing local sales relationships and managing supply chains in their region.

Given the wide variety of operational expenditures categories across otherwise identical deployments, the cost centers associated with operating and managing the entire fleet are hard to disentangle, but from a unit economics perspective, several of the systems with higher sales are now covering their operating expenditures. An instructive metric for financial utilization can be found in a \$300/month sales target, which would recoup a Box's CAPEX in around five years, with the rest of its useful lifetime devoted to recouping operational expenditures and earning profit on a per Box basis.

4.1.5. Top challenges

4.1.5.1. Remote monitoring. Content analysis of meeting notes, internal communications, and project documentation with OffGridBox over the



Fig. 5. (A) A deployed Box. (B) View of water module inside Box. (C) View of internal power module elements. Photos by S. Miles.

study period reveal persistent challenges in developing and operationalizing a reliable remote monitoring system for assessing asset performance, utilization, and system health. Several solutions were tested over the study period, but none that simultaneously satisfied the technical and operational needs of the organization. These challenges were notable despite the generally high quality and wide coverage of telecommunications infrastructure in Rwanda, as displayed in Fig. 6.

The most basic remote monitoring system in use at the beginning of the study period was the reporting system that came with the installed solar charge controller. The controller comes with a remote monitoring option that allows users to access near real-time readings on the power generated by the solar array and the charging state and temperature of the battery. Historical data is also aggregated by the platform for the past 90 days with daily summary readings including energy produced as well as voltage and demand highs and lows for the day. These readings can be remotely accessed through a dedicated web address for each charge controller, but the usefulness of the system overall was limited. Some systems never managed to connect to the cloud server, others would do so only intermittently, or would cease reporting if the data package purchased for its dedicated modem expired early. Staff reported the user interface of this system to be both basic and inflexible, and managers deemed the data it produced unreliable for the cost and volume of data produced — roughly 200 MB/day/Box.

To circumvent these challenges, as well as gain further visibility into Box utilization, current transformer clamps were installed at the six

Boxes powering clinics. The Efergy clamp, powered by AA batteries, measures current passing through a wire around which it is clamped, sends granular data through bluetooth technology to its dedicated receiver nearby, which is itself connected by an ethernet cable to a modem, which uploads data to a proprietary cloud platform. A retail unit with a single receiver/hub and two clamps costs approximately \$150.

While these systems provided a significant improvement in terms of remote visibility into system performance and demand-side consumption dynamics, they are unwieldy at any level of scale as units are retailed individually, with a unique log-in required to access each unit's real-time and historical data. Lastly, the Efergy systems can be accidentally unplugged, the batteries must be monitored and replaced, and they are similarly reliant on the proper functioning and maintenance of modem devices and telecom packages to deliver accurate information on outages across distributed systems.

No off-the-shelf water monitoring system was identified for operations that suited the needs of the organization over the study period. As a backstop, BoxKeepers are responsible for manually submitting readings by text message and photos from water meters installed at the Box's water outlets, engendering additional BoxKeeper training and operations.

A US-based remote monitoring system marketed as an Internet of Things device for industrial and agricultural applications named Eze was procured and tested over the study period, but technical challenges with

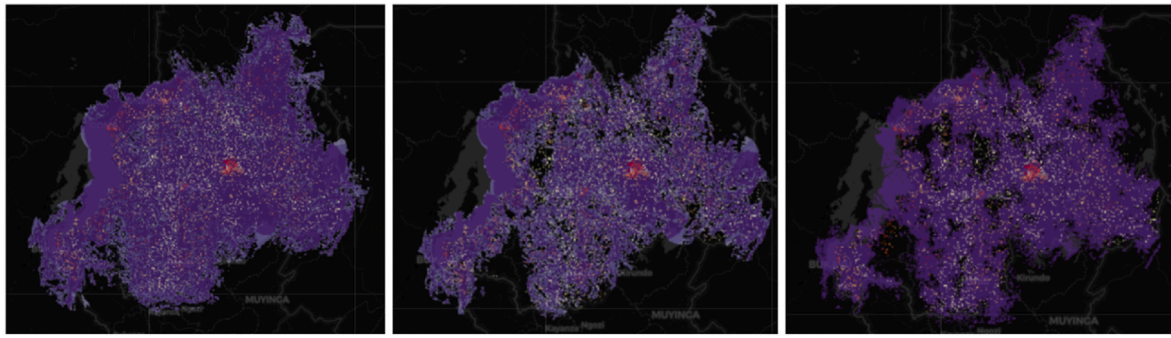


Fig. 6. 2G, 3G, and 4G coverage in Rwanda. GSMA Data from [GSMA, 2021](#).

respect to telecom band parameter compatibility at sites frustrated efforts at developing an integrated water and energy system monitoring solution.

In summary, multiple remote monitoring systems were tested with limited success, suggesting that off-the-shelf solutions designed for multiple and dispersed systems in low-resource environments remain a significant barrier to entry for digitizing and automating the remote monitoring and control of off-grid systems.

4.1.5.2. Market identification. Developing a deep understanding of potential deployment sites emerged as among the most significant operational challenges. When first broaching the Rwanda expansion, OffGridBox shortlisted 5–10 communities to investigate and surveyed 20–25 houses in the communities. These surveys were administered using a tablet-based data collection software package and consisted of approximately 30 questions per survey, aimed at surfacing local dynamics such as which shops sold the most candles, frequency of mobile phone use as a torch, and general poverty indicators. Ultimately, grant deadline pressures fast-tracked the selection of a number of sites for the commercial water business line, anticipated to be the most revenue-generating of all Box activities.

All major cities in Rwanda were targeted, with the specific locations within those communities determined as a function of water source availability, rental space availability, market centrality (i.e., proximity to a local covered market if available) and proximity to off-grid areas. Rural market selection undergoes a somewhat different process; a Rwandan ‘market scout’ is employed for a daily rate of \$14/day to explore a given region and compile a report on opportunities for the Box. These reports describe the local conditions of water access and electricity infrastructure, local economic activity, and qualitative assessments of wealth.

“We visited a village where you can see - it’s vibrant, people have money. There are flower farmers nearby that pay well. These folks travel 5 km to the next location for a barber shop.” -Market scout-Market scout

Published socioeconomic data from government and international bodies like the World Bank were initially considered, but these were considered insufficiently accurate or granular to serve the operational questions of site location, particularly given the dynamic nature of resettlement in Rwanda ([Nikuze et al., 2019](#)). A challenge emerged both in the truthful responses of participants (*“The clinic said we want power, we don’t have power, we show up but they have power from a nearby hydro plant. There is an incentive to ‘stretch the truth’”*) and respondents’ capacity to accurately predict their needs. This was particularly relevant to understanding a local population’s willingness to pay for electricity services, or even their ability to place a specific monetary value on a potential electricity service (*“Do you want lights?” “Yes.” “Do you want lights for 300 francs/day?” “...”*).

The market assessment and market identification strategy evolved over the study period towards more systematized processes in line with a general pivot towards being more revenue-driven than grant-driven.

Deeper “community-based design” in market assessment approaches aim to develop community buy-in from the onset, recognizing the critical role of properly understanding community dynamics before investing resources (and the risks inherent in failing to grasp community dynamics as ‘outsiders’).

4.1.5.3. Logistics and operations. Given the multiple product/service offerings, the heterogeneity of community sites, and the limitations on situational awareness imposed by low-reliability remote monitoring, the challenges around logistics and operations of the OffGridBox model are formidable. Internal documentation classify existing deployments as “urban”, “peri-urban”, (defined as within 3 km of a city) or “rural,” but significant variation in community dynamics exists even within these categories with respect to density and proximity to urban centers ([Fig. 7](#)).

Boxes placed in major secondary cities - Matimba, a trading town bordering Uganda; Musanze, Rwanda’s sprawling second-largest city at the foothills of the Volcanoes National Park; and Rubavu, bordering the rapidly expanding eastern Congolese provincial capital of Goma, all sustain sufficient water sales to cover Box operational costs. This is primarily thanks to high concentrations of local shopkeepers willing to retail packaged water — but these markets require additional resources in terms of the management and procurement of distribution systems, as well as competition not just with the national water utility supplier but also other packaged water wholesalers. The competitive dynamics of each market are unique to each and must be navigated accordingly.

Boxes in peri-urban zones are perhaps the most challenging to maintain, given the intermediate proximity to both national electricity and water infrastructure. In such spaces, traditional infrastructure service is available but unreliable; households may be connected to the grid but outages are frequent, or public water taps are nearby but are only available for several hours at a time, at unpredictable intervals, with long queues. In these spaces, Boxes must sustain themselves more as a ‘back-stop’ to traditional infrastructure, and their success is eked out in the cracks between improving and worsening public infrastructure performance.

Rural zones offer perhaps the clearest value proposition for a Box — here, improved water presents a clear differentiation from alternatives, which typically include several kilometers of walking or biking for untreated well water, swamp water, or manual pumping, all of which require boiling to become drinkable (along with the fuel costs and deforestation this entails). Power banks are also a compelling offering if grid infrastructure is absent, but the logistics of a power bank business are relatively time-consuming and low-margin: a \$20 power bank leased to a customer may take between 6 and 15 months to cover its cost, but theft, losses, failures, and other logistical challenges complicate cost-recovery without effective local execution.

These challenges are illustrative of the reality that in some sense, every Box has its own business model, and across a dispersed territory, this presents an enormous logistical challenge to wrangle for the organization’s managerial cadre.

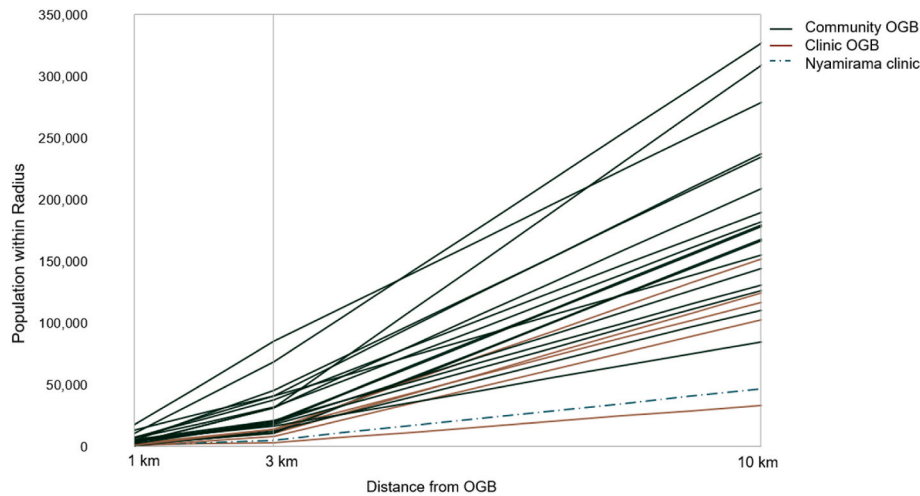


Fig. 7. Estimated population at 1, 3, and 10 km radius from OffGridBox locations. Data from GSMA, 2021.

4.2. Nyamirama case study of productive uses

OffGridBox launched a productive use workstream in 2020 for at least two reasons: firstly, to improve utilization and unit economics of Boxes, secondly, because they were awarded a grant by a donor for productive use pilot experimentation.

The company initially planned to pilot seven income-generating productive use applications: power tool equipment rental, refrigerator rental, milk chilling, horticulture chilling, agro-produce drying, barbershop equipment rental, and headlamp rentals for mining or coffee workers. A short business plan description accompanied each of these proposed ideas, including estimated equipment costs and anticipated revenues. Over the course of the following year, the productive use pilot grant money was used to procure power tools, sewing machines, electric hair cutters, and refrigerators.

In the following sections, we delve into the factors that led to the selection of the productive use pilot implemented around a single Box where a welding use-case was identified as particularly promising. While a more comprehensive analysis of the OffGridBox PUE model would consider the failures and successes across the wider set of interventions considered, we focus on the welding use-case in order to provide a fine-grained account of the unique context and challenges specific to a PUE intervention, both to reveal the idiosyncrasies inherent to successful uptake and to frame the perspective of the end-user in the following section. While we acknowledge the limitations this approach entails from a generalizability perspective, we argue that it offers a valuable method of characterizing the rich social context in which the successful uptake of a PUE can be more fully understood.

4.2.1. Nyamirama site selection and operational characteristics

The Nyamirama health clinic is located in the far north of the country approximately 30 km from the regional capital of Nyagatare, a town of 20,000–30,000 (GSMA, 2021). The area is designated for grid-extension according to the 2019 National Electrification Plan, but the clinic itself is 15–20 km from the nearest grid infrastructure, and for this reason OffGridBox chose to allocate PUE resources into a pilot.

Two other Boxes are in this region, including one of three urban boxes located in Matimba, the northernmost town bordering Uganda, and the other in the peri-urban outskirts of Nyagatare. Nyamirama clinic is itself approximately 1 h driving southeast from this regional capital; most of the time it takes to get to Nyamirama is spent driving slowly across unpaved roads, which are nevertheless passable by foot, moto, car, and even semi-truck. The population residing within 3 km of the clinic numbers approximately 5,000–6,000 (GSMA, 2021).

The clinic was constructed around the time of the Power Africa/

Ministry of Health clinic electrification award; its construction was in large part a result of the Rwandan government's efforts at centralizing dispersed and rural populations in what is known as 'model villages.' This community is thus young, with the majority of inhabitants having arrived within the last decade (Fig. 8).

In late 2020, OffGridBox market scouts arrived in the Nyamirama community to survey the land for the electrification of the health clinic, then still under construction. OffGridBox management, invested in rolling out productive use pilots, sought to develop a systematic approach to entrepreneur identification. After sending market scouts to identify all the potentially interested economic actors, a short list of two welders and two tailors were offered the opportunity to participate in the productive use electrification pilot.

Starting in May 2021, OffGridBox offered the two welders use of a welding machine and angle grinder, costing \$250 and \$170 respectively, for use in a workspace near the clinic. The machines had been imported from Italy, as none of the units available in Rwanda were energy efficient enough to be operated safely with the Box's inverter discharge capacity.

An initial charge of \$80/month was agreed upon for each welder, constituting more than 50% of the Nyamirama Box's monthly sales target, and \$50/month for the tailors. One of the welders dropped out of the pilot before paying the first monthly payment. Both tailors also dropped out, citing too many power cuts, and the electric sewing machines were repossessed for future pilot trials. Under these conditions, with just one active welder, the pilot costs would break even in approximately six months.

Five months of remotely monitored electricity consumption at the study area through the load consumption and power reliability/quality sensors, as well as interviews with the welder and clinicians, reveal that the Box is able to simultaneously power the clinic's energetic needs as well as supply most of the electricity needs at the workshop. For the month of August, during which the consumption sensor was functional for 28 days, the clinic consumed 94 kWh and the welder 27 kWh. A relatively low amount of electricity consumption for the welding PUE — approximately 1–2 kWh per day, consumed in short bursts during daylight hours — is thus revealed as quite high value over the study period, amounting to a willingness and ability to pay over \$3/kWh. Fig. 9 illustrates a typical 48 h period of welding and clinic usage.

After the month of September, the load consumption sensor failed, limiting both OffGridBox's ability to monitor clinic and welder electricity service as well as their situational awareness about Box uptime. The power quality/reliability sensor, however, remained functional and continues to provide high-resolution visibility on Box reliability, averaging 81% over the study period (Table 3).

We present these numbers as the most conservative estimate of

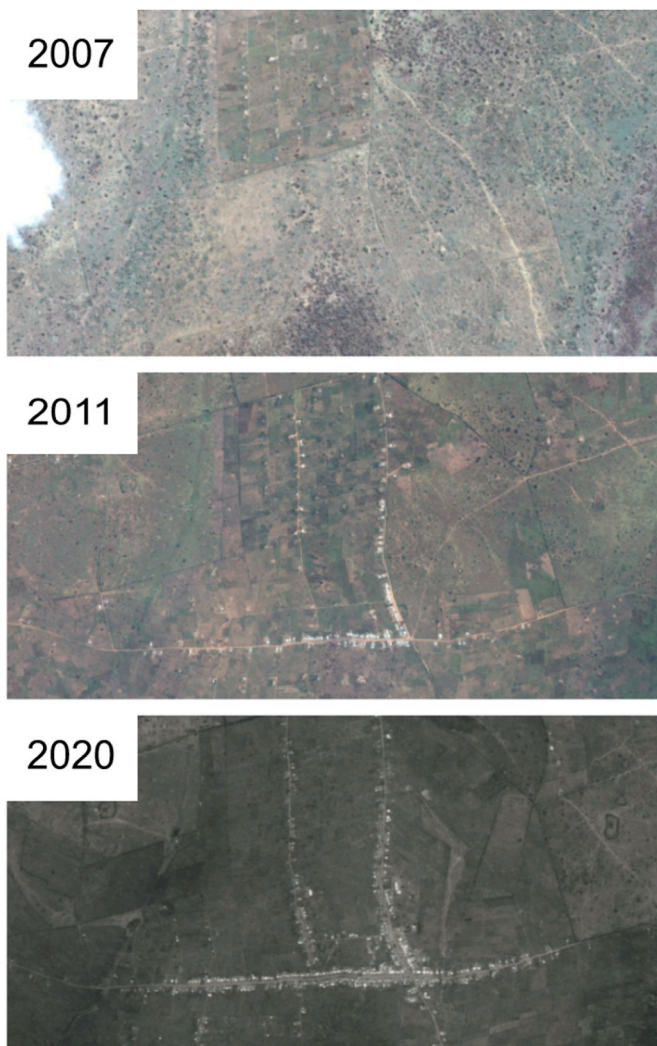


Fig. 8. Built up area at Nyamirama site in 2007, 2011, and 2020. Images from Google Earth.

uptime. Further analysis is needed to identify time of day trends and causes of power outages. One potential cause is the use of an autoclave sterilizer for disinfecting surgical tools in the clinic, typically once or twice a week for approximately 30 min; OffGridBox plans to replace the clinic's existing model with an energy efficient one with a lower instantaneous draw. It is possible that while such power cuts may not significantly impact the workflow of a welder, the reliability needs of tailors are much higher, with a low tolerance for a sewing machine to stop working even for a second mid-stitch.

No significant voltage deviations were detected over this period, revealing that the Box's power quality may be better than the grid, which in Rwanda is often characterized by over-voltage (World Bank, 2020b). Such voltage irregularities have implications not only for the integrity of machinery like the welding machine, but even more so for the sensitive equipment in clinics, including computers and other information and communication technology (ICT) equipment, as well as refrigerators, blood analyzers, and infant warmers. As of November 2021, the Nyamirama clinic has administered approximately 3,000 COVID vaccines to the local community, supported by the refrigeration capabilities powered by OffGridBox.

Outside of clinic electrification and the welding PUE, the Nyamirama Box has come to show fairly good utilization, with approximately 150 power bank customers bringing in an average of \$160 per month between January and November 2021 — over 50% of the Box's total revenue target. Nearly 100 customers generated on average \$32 of sales

at the site per month in water sales, or 11% of sales targets. Among Nyamirama's water customers is Gideon, the welder powered by OffGridBox's PUE pilot.

4.2.2. The solar welder

Gideon is a young man in his early 30s. He was born in the Southern provinces bordering Burundi, the fifth of 12 children. He was the only one of his siblings who managed to complete high school, which he did with an emphasis on accountancy in 2010. With the support of a family acquaintance he completed one year of university studies in Uganda, but when that benefactor died, he returned to Kamonyi district. Despite difficulties engendered by lack of stable employment, he married in 2012.

Soon thereafter, he got a job working in a local mining company focused on the extraction of the raw inputs for tin and coltan west of Kigali. He principally worked in human resources, organizing workers' schedules and supplies. During this time, he completed a series of vocational/technical trainings through an international NGO of Korean provenance, and in 2016 was awarded a certificate of completion for a six-month welding traineeship.

Gideon was always entrepreneurial, seeking additional work opportunities to start a family. His contacts through the mining industry led him to find work in Nyagatare, where he was employed by a local businessman in light construction work: welding doors and gates, fitting windows and affixing "modern" roofs¹, as well as making mechanical repairs to bicycles, motorcycles, and cars.

It was through these client networks that he wound up in the Nyamirama community. Between 2017 and 2019, a landowner he had worked for in Nyagatare contracted him to help with the construction of his house on the plot of land where members of the Akagera community had been relocated. That man later decided to move to Uganda, and sold the plot of land to Gideon for \$3,000.

Between 2019 and 2021, Gideon would continue most of his work as a self-employed or sub-contracted laborer in Nyagatare, seeking to expand his client list for mechanical repairs and welding — sometimes by renting specialized equipment from other artisanal metal-workers and laborers, other times by acquiring equipment and stock materials as he was able to afford them. He has long owned a small diesel generator which enables him to use electrical equipment like welding machines, angle grinders, and drills on the premises of his customers' work site (Fig. 10c).

Gideon's home is located 200 m from the Nyamirama clinic. When he observed the installation of underground lines from the Box to the clinic to power lights, a TV, fridge, and various medical equipment (infant warmers, equipment sterilizers, dental chairs), he approached the Box-Keeper to inquire as to the possibility of being electrified. He was attracted by the convenience of being able to work in the community rather than travel by bicycle each day an hour to the main road, where grid electricity made welding work for village construction needs possible.

The OffGridBox manager in charge of making the selection of pilot entrepreneurs attributed Gideon's selection largely to his certificate of welding traineeship — none of the other welders in the surrounding community could prove they had any formal training in their craft, which was of particular interest to the OffGridBox technical team, whose initial tests revealed that welding applications could be supported by the Box as long as the welder performed spot welds in adequately short bursts; too long an application of current could overload and damage the inverter irrevocably.

"Was paying 5000 francs [\$5] per day in town to use a welding machine, now getting it for half the price and close to customers."—Gideon

Gideon has so far paid for five months' service, and his workspace

¹ The government of Rwanda enforced a prohibition on 'traditional' roofs made of thatched grass in 2011

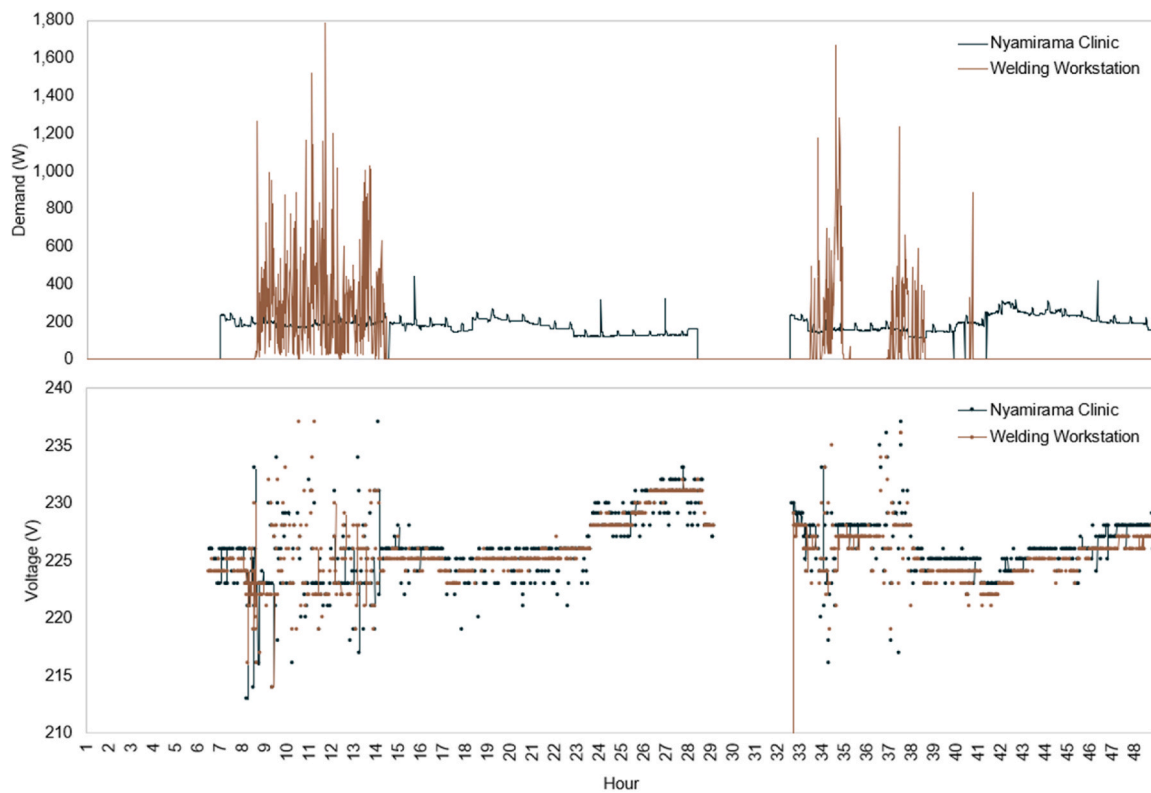


Fig. 9. Clinic and welding load profile in a typical 48-h period from August 13–14, 2021 (top). Voltage at clinic and welding workstation over the same period (bottom).

Table 3

OffGridBox reliability at Nyamirama site over period August 1–November 26, 2021.

Month	Outage Time (hours)	Reliability
August	162	78%
September	185	74%
October	103	86%
November	81	87%
Average		81%

has in that time doubled in size: an indoor room with an electrical outlet installed by OffGridBox where he keeps much of his material, and a connected courtyard space supplied by an extension cable from the indoor one with better light and aeration (Fig. 10b).

Gideon's work in the village is seasonal, and this can affect the prices he charges for his services by up to 50%. In a good week, he may have three or more clients, each commissioning the structural elements of a home that require specialized labor: doors, windows, roofs. He requests his clients pay him upfront so that he may acquire the materials needed — largely from his former employer in Nyagatare. He makes the 5 km trip by bicycle; laden with metal works, the trip takes 2.5 h.

- Gideon: *One of my first clients gave me an order of two doors of making and two windows, second order it was four windows and three doors, and the third order it was two double windows that I made, maximum I earned 34,000 francs [\$34] profit with those three clients.*
- Researcher: *How long did it take you to make all these?*
- Gideon: *It can take like one week and three days.*

Gideon typically charges \$60 for a single door, which typically takes 3 h using OffGridBox power — when using his diesel generator to power the welding machine, the work takes “perhaps 5 h” This is partly due to the fact that to conserve fuel, he must constantly turn the generator on

and off. Welding a single door exclusively with his generator consumes 5 L of fuel, costing him \$5.5 dollars — over 200% of what he pays to OffGridBox for a day of unlimited electricity (pro rata; he pays monthly).

His principal challenge is procuring stock of materials and equipment — though he maintains a competitive advantage in the immediate community as the only welder, he must still rent out tools from other laborers involved in construction, like cutting tools and power drills. This can eat into his take-home profit, which amounted to \$60 in October — but this was a difficult month. Rains had depressed economic activity throughout the community, and he also suffered a workplace accident, slashing his right hand while angle-grinding. Given that his workstation is 80 m from the clinic, he was able to receive medical attention quickly, getting the wound disinfected and stitched close within the hour. He was able to resume working after one week.

At the same time, Gideon doesn't feel that the electricity service he receives from OffGridBox is without room for improvement. He is able to identify different welding machines that he feels would improve the speed and quality of his work from Youtube videos on his phone, for instance, and wishes he did not have to rent other pieces of equipment from other laborers in the community. He believes his monthly pricing arrangement, while saving money on fuel costs, locks him into a payment obligation irrespective of how much use he is actually able to make of it; in his mental calculus, he pays for days of service even when he does not have work, which he anticipates will be particularly tenuous during the rainy seasons when there is less money in the predominantly agricultural village, and thus less client work.

Lastly, his client list is dispersed around the country and often requires him to travel several hours to a work site, and since he cannot take the Box with him, he is still reliant on his diesel generator. In November, for example, a client he met in the Southern province years back commissioned him to repair a water pump. The client sent him the pump by taxi so that he could repair it in his workshop, as it took several days' work, and he then traveled several hours with it by taxi to the site to ensure it worked properly when installed.



Fig. 10. (A) View of clinic (in blue) and welding workshop. (B) View of courtyard workspace. (C) A typical value-added roof, requiring power tools powered by a portable diesel generator. Photos A and B by S. Miles. Photo C by Gideon and used with permission. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

“OffGridBox has good power but the work is sometimes faraway from OffGridBox power.”-Gideon

Gideon is optimistic about his relationship with OffGridBox service delivery, particularly given the close attention he receives from headquarters around his pricing and seasonality challenges. Resettlement dynamics in the community imply a sustained need for construction for years to come, and he believes the presence of community infrastructure services like the clinic, power tools, and construction equipment will continue to attract further settlement to this specific part of the community, as well as demand for his services. He has taken on two youth from the community as apprentices, both to give back to the community as well as to grow his business.

5. Discussion

In this paper, we present a granular accounting of the OffGridBox technology and business model, key technical and financial performance indicators associated with achieving the successful uptake of a single productive use of electricity pilot in northeast Rwanda, and socio-economic impacts of the intervention as reported by the end-user of the intervention.

The standard community Boxes reviewed have a solar energy generation capacity of almost 3.5 kWp, 3 kWp discharge capacity, just over 4 kWh of battery storage, and a clean water output capacity of 1000 L/h. This configuration, when procured as the full set of six that can fit in a standard 40 foot container, costs approximately \$25,000 each to deploy to a given site in Rwanda. Technical specifications of components, most of which are widely available through well-established, global hardware manufacturers, are included in this review, and can be relatively easily replaced, downsized or upgraded to serve specific needs. These figures provide a useful benchmark for energy investors, humanitarian professionals, and development professionals in assessing the simultaneous

provision of power and water needs in remote and off-grid populations.

We also describe key operational characteristics, costs, and challenges around the ongoing delivery of power and water services through such a containerized solution. While the Boxes were observed to perform well from a technical perspective, the operational challenges around developing product-market-fit across a wide variety of target markets were observed to counteract the benefits of operating assets that were, on the product side, technically identical. Such challenges indicate that while the technology itself appears versatile across a spectrum of operating environments, this by itself does not guarantee its economic viability, and accentuates the need for rigorous market analysis and site selection processes prior to deployment.

The Nyamirama case study presents an example where the circumstances of the community matched the capabilities of the Box. Here, the host site included a newly constructed clinic with concentrated energy needs unserved by grid infrastructure, as well as high growth in community needs catalyzed by local population resettlement dynamics. Using established and novel remote monitoring methodologies, we find that the electricity services provided by an ‘upgraded’ Box (with four times the battery capacity) was able to not only serve the clinic’s energetic needs, but those of a local artisanal entrepreneur, with an average of 81% uptime. We observed the reliability of the system to increase over the study period, suggesting that a ‘learning’ process on both the Box operator side as well as the user side may contribute to improved reliability. No significant voltage deviations were observed over the study period, indicating that even sensitive or critical equipment like fridges for vaccine storage or oxygen respirators may be supported by the Box without the need for additional protection equipment.

We also find that under such conditions, the delivery model is highly competitive with the diesel-based welding use-case. Interviews with Gideon, the artisanal entrepreneur from the Nyamirama community that

largely displaced his generator usage for welding work with that of OffGridBox electricity, reveal a high willingness to pay of around \$3/kWh, along with a relatively high degree of overall reported satisfaction with the provision of electricity for the activities of the local enterprise — a productive use of electricity which in turn substantially improved the unit-economics of the Nyamirama Box. Such an account supports the finding that, for energy service providers, even a small number of productive uses of electricity can substantially reduce the payback period for distributed energy assets (Factor[e], 2019).

Overall, we find that with an investment of a single Box costing approximately \$25,000, appreciable social and economic impacts can be achieved for the artisanal welding use case in a young and rapidly growing off-grid community, even under conditions of relatively low energy consumption. Load consumption data over the five months observed was infrequently reported due to sensor inconsistency, but relatively high uptime over the month of August reveals a monthly consumption of around 100 kWh for the clinic and 30 kWh for the welder — this demand is likely constrained by an additional 15–20% from power cuts, however, as reported by the power reliability/quality sensor.

As real-world load consumption data is relatively rare in the literature, and is paired here with a qualitative account of usage, we believe this data can help modelers and project developers build more accurate load profiles with which to plan and size off-grid systems for productive uses of electricity in particular. We provide a link to sample data for the month of August in Annex C and the specifications for the welding device used in Annex D.

We hypothesize that further upgrading the battery storage of the Nyamirama OffGridBox could further improve uptime for the clinic/welder. This would also enable the system to supply the electrical demand of Nyamirama clinic as it grows to the size of some of the larger clinics OffGridBox serves, which register approximately two to four times the monthly energy consumption of Nyamirama over the study period. Transitioning from lead-acid based batteries to lithium battery chemistries would also increase the useable power and energy of the Box, given its greater depth of discharge capacity. Such upgrades might also facilitate the development of a portable battery-powered welding and power tool solution which could additionally replace the diesel consumption costs for off-site work needs.

The technical and operational characterization of OffGridBox's experience across Rwanda provided here offers further evidence that progress in ICT networking systems will continue to be critical in bridging the gap between headquarters and an inexorably growing fleet of remote and dispersed off-grid energy deployments (Engelmeier et al., 2020). Despite challenges surfaced through the case study, innovations in remote monitoring increasingly simplified remote operations for the monitoring and diagnosing of technical failures as they emerged. The PowerWatch reliability/quality sensor methodology deployed for the purpose of auditing the Nyamirama Box performance, for example, was demonstrated through the study process as low-complexity, durable, and reliable for monitoring AC-powered systems. The technical analyses of availability, reliability, and quality for both on-grid and off-grid systems through such methods provide a much-needed pathway for assessing and comparing the cost-benefit of various energy investments.

We note that the technical standardization of energy systems characterized here is not unique to OffGridBox. Mini-grid developers around Rwanda and the world are expected to witness dramatic cost reductions as manufacturing learning curves improve (most importantly for batteries) and operational models mature (Agenbroad et al., 2018). Such standardization will increasingly permit a critical density of case studies to emerge through which to compare various kinds of electrification models across demographic, topological, and regulatory environments: rapid and redeployable modalities for humanitarian interventions, low-cost “first access” models for towns crossing some important threshold of population density, “daisy-chain” mini-grids for rapidly expanding peri-urban or urban environments, and eventually, integration of megawatt-scale mini-grids with the macro-grid for ancillary

service provision and network resilience (Carvalho et al., 2019).

While the approach offered in this study focuses on a single use-case of a successful PUE intervention by OffGridBox, we suggest that such an analysis of technical performance indicators through remote monitoring methodologies, paired with the contextual framing undergirding the intervention's success, can help off-grid developers and development financiers gain a deeper understanding of how to evaluate, monitor and support scalable energy access models.

Further work is needed to characterize the social, technical, and economic particularities of distinct productive use cases. Load profiles for such use cases will in particular help energy modelers reduce the uncertainty gap associated with estimating demand as well as sizing generation and storage of energy deployments accordingly. We also argue that a deeper characterization of the idiosyncratic socio-political drivers underlying economic development at local or regional scales — such as the prohibition on thatched roofs driving a large part of Gideon's business, or the mandatory resettlement dynamics which catalyzed the Nyamirama community's genesis — is a critically under-examined facet of success for PUE uptake, calling for interdisciplinary methods in unpacking context-specific challenges at the intersection of energy and development.

6. Conclusion

We employ a mixed methods approach to characterizing the costs of delivering power at the health-PUE nexus through the lens of OffGridBox, a uniquely standardized off-grid infrastructure technology provider. We provide an in-depth overview of the technology and operational model, with a focus on the costs of deployment and delivery of services. We detail a case study deployment in Nyamirama, Rwanda through remote monitoring of load consumption on the demand-side as well as outlet-level sensors quantifying power reliability and quality on the supply-side. Lastly, to provide a more richly contextualized account of the successful uptake of a PUE intervention, we characterize the intervention from the welder's perspective.

We find that welding, despite the technical challenges associated with high instantaneous power draw paired with relatively low energy demand, is both technically compatible with a relatively small off-grid system simultaneously powering a small health clinic, as well as financially advantageous both to the developer and the productive user. This contributes to the literature on both “broad” and “narrow” definitions of the productive uses of electricity, as well as their simultaneous provision. We describe a novel power reliability and quality auditing methodology for analyzing the performance of decentralized power systems, and open-source a sample of high-resolution, real-world PUE consumption data.

The future of Rwanda's electricity and water sectors, as for many countries on the continent, is uncertain. While significant government and development assistance finance subsidizes the centralized infrastructure networks on a yearly basis, developed countries are leaning on technological innovations in decentralized generation, storage and distribution to enhance the reliability and resilience of their infrastructure services. It remains to be seen which models will prevail across the heterogeneous constellation of rapidly growing towns, cities, and agglomerations that increasingly constitute Africa's urbanizing landscape, particularly given the (political) power dynamics which in many cases pit traditional utilities in a defensive position against grid alternatives like mini-grid operators (Puig et al., 2021; Shirley and Attia, 2020).

To depart from previous waves of development pushes that have suffered from ill-conceived or inappropriately designed technologies, including solar systems with no maintenance contracts (UN Foundation and SeforAll, 2019) and children-powered well-pumps (Kreamer, 2016; Sindall and Barrington, 2020), more sophisticated incentive structures are still needed to ensure that widely dispersed, remote systems are sustainably provisioned from both an organizational perspective as well as a technical one.

We suggest that monitoring the evolution of this sector from the perspective of the impacts achievable from a single Box — in some sense, conceivable as the smallest building block of a community-scale micro-utility — can help build a more concrete vision for the pathways and financing strategies needed to scaffold distinct energy delivery modalities along the ladder of maturity and scale urgently needed to achieve SDG 7 and the development impacts it subsequently enables.

As the spectrum of energy technology models matures, in particular those solutions capable of powering the commercial and public service needs of rapidly growing communities, it is becoming increasingly critical to bring into focus what impacts one can expect for a given dollar invested. The OffGridBox analysis presented here is instructive for developing a framework for integrated resource planning that centers three critical community needs at once: the delivery of power for modern health services, the provision of clean water, and income-generating uses of electricity at the small and medium enterprise scale.

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.

Data availability

The data is made available in Annex in an open-access GitHub repository.

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Annex A: Boxes at Sites Visited

Muhanga



Buramba (Clinic)



Musanze



Rubavu



Ruhango



Huye



Mwogo



Matimba



Nyanza



Gasagara (Clinic)



Gasovu (Clinic)



Tabagwe



(continued).

Annex B: PowerWatch technical specifications and deployment methodology

The PowerWatch sensor is a fixed point device developed by nLine (nline.io) that samples the voltage and frequency of a power source directly at the outlet-level. Once plugged into a standard outlet, high resolution data is batched and transmitted via 2G telecom networks every 2 min to a data warehouse. A minimum of two PowerWatch sensors are installed to determine an outage; one at the power strips within the Box itself, the other at an outlet inside the clinic. Outages are calculated for report periods during which both sensors simultaneously report no power, reducing the possibility of interpreting single sensor failures or accidental unplugging as an outage.

PARAMETER	VALUE	PARAMETER	SUB-PARAMETER	VALUE
Weight	450 g	Power Consumption (Pd)	Sleep	0.075 W
			Nominal	0.5 W
			Maximum	10.4 W
		Voltage (Vdd)	Nominal	85 to 305 Vac _{rms}
			Maximum (pre-fuse)	3000 Vac _{rms}
		Frequency (fdd)	Nominal	47 to 63 Hz
		Temperature (TA)	Nominal	-10 to 40 C
			Maximum	-20 to 85 C

PARAMETER	SUB-PARAMETER	DESCRIPTION	VALUE
Power Quality Measurements	Voltage	Maximum voltage measurement error (E_{vrms})	0.5 V _{rms}
		Voltage spike measurement threshold (V_{spike})	400 V _{rms}
		Minimum time of voltage spike (T_{spike})	5 μ s
	Frequency	Maximum frequency measurement error (E_f)	50 μ s
		Outage detection time error (Assumes network connection within 2 days) (E_{t_out})	500 ms
Outage Measurements		Restoration detection time error (for outages less than 48 hours) ($E_{t_restore}$)	500 ms
		Restoration detection time error (for outages greater than 48 hours) ($E_{t_restore_l}$)	15 s

Annex C: Load profiles and voltage measurements

Welder and clinic load profile for month of August 2021 available at <https://github.com/jkkersey/OffGridBox>.

Annex D: Welding machine specifications

Single phase mains voltage	230V
Mains frequency	50/60 Hz
Current range	10–80 A
% Use (20 °C use)	50% @ 80 A
Max current	80 @ 5% A
Max no load voltage	72 V
Max absorbed current	15 A
Max absorbed power	2.3 kW
Motor generator minimum power	3 kW
Mains fuse	10 A
Efficiency	82%
Power factor	0.6
Useable electrodes in DC	1.6–2.5 mm
Protection degree	IP21
Dimensions	30 × 12.5 × 22.5 cm
Weight	3.53 kg

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