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Community energy infrastructure: Point-of-service clean energy to serve the food/water/health nexus

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Abstract—The COVID-19 pandemic has accelerated and deepened crises in many parts of the world, while also raising questions of global equity in the context of vaccine distribution. However, it is only one of many daunting challenges faced daily by those in protracted crises. Refugee camps and other zones of humanitarian intervention serving displaced populations are among the hardest to plan for, given the operational complexities — both immediate and protracted — associated with infrastructure deployment and the maintenance that such forms of distribution require. 'Containerized' infrastructure solutions have the potential to power the needs of under-resourced communities at the Food/Water/Health nexus and have gained interest in recent years as a way to mediate the temporal and political uncertainties associated with basic needs provision for off-grid, underserved, or remote populations. Drawing from a uniquely large sample of identical containerized infrastructure deployments in Rwanda, 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. We consider three separate use cases and find in optimistic scenarios that this containerized solution could provide for either 2,083 people's daily drinking water needs, 1,674 people's daily milk consumption, or 100% of a health clinic's energy demand.

Keywords—containerized, food/water/health nexus, energy access, modular, crisis, climate

I. Introduction

Between 2013 and 2018, the number of refugees and other displaced people around the world grew at a rate of 11.7% per year [1]. 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 had the additional effect of lengthening the time individuals remain displaced. This culminated in approximately 16 million people having lived in temporary settlements for five or more years by 2018 [1]. Beginning in late 2019, the COVID-19 pandemic has aggravated living conditions not just for these populations, but for all living under conditions of weak infrastructural provision, by disrupting supply chains not only for medical equipment but also for the provision of basic necessities like food, water, freedom of mobility, and communication.

In parallel to these developments, innovations in the delivery of basic services through 'containerized' infrastructure solutions have been gaining interest among humanitarian organizations and development practitioners [2][3], commercial providers of energy resiliency solutions, and even for military operations [4]. Here, we define containerized infrastructure solutions as "infrastructure in a box" that can be deployed rapidly as a "plug and play" solution in protracted crisis contexts. In the case of sustainable electricity provision, the container is packed and shipped with renewable 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 intermodal freight transportation system, and easily installed at point-of-use.

Such systems have been used for decades for various remote applications, particularly for rural telecommunications bases [5]. The benefits of such infrastructure service modalities over traditional utility models like grid extension include speed and ease of installation, cost-competitiveness (deeply sensitive to economies of scale) [3], semi-permanence (e.g. portable, yet rugged and durable enough to last for long periods and even withstand hurricanes), and lastly, modular "stackability," 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 from a whole-of-system environmental accounting one [6].

Thus far, the academic literature on the impacts and potential of containerization on energy delivery, however, principally examines the benefits of such an approach vis-a-vis decarbonization (relative to fossil-fuel generators) for short-term, urgent needs contexts [7]. Less has been analyzed comprehensively about the unique temporal and spatial degrees of freedom offered by containerization, particularly for the provision of basic infrastructure needs at the critical Food/Water/Health nexus for fast-growing or under-resourced communities over longer time periods.

This paper discusses the impact and potential for containerized infrastructure solutions to serve several use-cases of basic needs provision at the community level. The analysis is contextualized by the experiences of OffGridBox (OGB), a social enterprise that has deployed nearly 25 identical containerized infrastructure solutions in Rwanda and approximately 50 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 and sustained manner. The key contributions of this paper lie in the unique comparability such identical deployments offer in terms of techno-economic impact analysis, as well as novel insight into the rapid changes in settlement morphologies that characterize African urbanization. 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 writ large.

The rest of the paper is organized as follows: in Section II we briefly characterize the OGB system ('Box') from a technical perspective and provide context on existing operations in Rwanda. In Section III, we outline and discuss three specific use cases of the OGB systems: (3.1) water treatment, (3.2) milk chilling, and (3.3) powering lighting, communication, and appliances at health clinics. For each use case, we investigate both an optimistic and realistic scenario of impact. 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 an Box-like containerized solution may have for this use case given its theoretical maximum reach within existing design constraints. In Section IV, we discuss key findings and draw from the case studies to offer reflections on the opportunity for massively scaled up containerized infrastructure approaches.

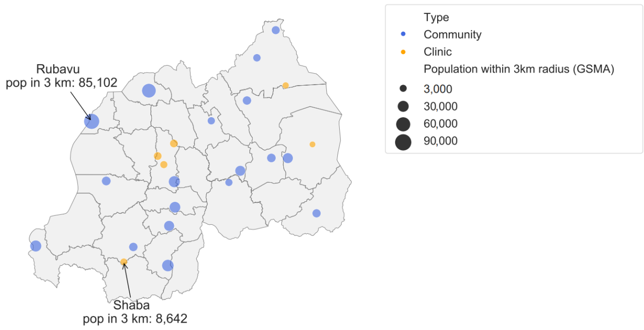

Fig. 1. Location of OffGridBoxes in Rwanda (sized by population within 3km).

II. Background on OffGridBox

A Box is approximately 2x2x2 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 PV modules of 280Wp (for a total of 3.36kWp), four 90Ah Gel/AGM lead-acid batteries, as well as 3000W charge controller and inverter. For water treatment, several configurations have been deployed, but most Boxes include an internal 600L food grade tank, a gravity-fed activated charcoal filter, a 5-micron filter, additional brush filters, a 20L/minute self-priming pump, and UV lamp. Lastly, each Box is equipped with a wireless communication module (GSM) that serves a dual purpose: firstly, to provide monitoring of system performance (i.e. real-time power production, battery state-of-charge, etc), and secondly to provide a wifi hotspot and data services locally. It takes approximately four hours to set up the Box once on-site.

OffGridBox has been active in Rwanda since 2017 across a diverse spectrum of communities; while some Boxes are in truly off-grid communities without national grid connections, the majority serve urban or peri-urban markets. Each Box is staffed with a local 'BoxKeeper' agent and security guard, responsible for maintenance of equipment and liaising with headquarters around production and distribution of water and power banks (through a battery distribution/leasing model). Six Boxes serve rural clinics in partnership with the Government of Rwanda's Ministry of Health. 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.

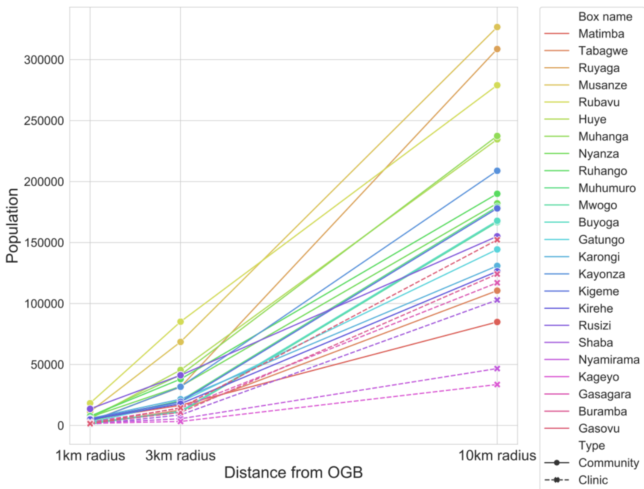

Fig. 2. Population within 1 to 10 km radii of deployed OffGridBoxes in Rwanda. Identical boxes are deployed across a wide spectrum of agglomeration sizes and morphologies, offering a unique perspective into

the heterogeneity of infrastructural needs across the rural-urban spectrum. Data extracted from GPS locations using GSMA web tool.

III. Use Cases

In each optimistic scenario, we estimate that an OGB system can produce 12.48 kWh/day. This estimate was calculated assuming 5 hours of full sun hours per day, 32 degrees Celsius, negligible temperature effects, maximum power point tracking (MPPT), a 0.8 derate factor, and assuming all energy produced is utilized within the day with a 3.46 kWh usable nominal battery. We calculate a levelized cost per kWh of 0.36 USD/kWh from the approximate estimation that each Box (hardware and shipping) costs roughly 25,500 USD (assuming six Boxes per 40-foot shipping container, including duties and VAT) and a 20-year lifetime. The lead gel batteries have a 5-year lifetime, and the inverter, charge regulator, and other electronics have 10-year lifetimes. These scenarios also assume that all the energy from the Box is devoted fully to the specific use case considered.

In each realistic scenario, we estimate that a Box actually produces 8.14 kWh/day on average. This estimate uses the HOMER modeling simulation to include localized temperature and incident solar radiation effects on PV power output over the year. We calculate the levelized cost of electricity to be 0.55 USD/kWh from the same estimation methods in the optimistic scenario.

We acknowledge that these scenarios do not factor in several specificities relevant to the deployment of a Box such as additional transport costs to island communities or site-specific seasonal variation; we also note that shipping costs, including import duties and 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.

A. Water Treatment

Unsafe water remains a leading risk-factor for disease in Rwanda, where diarrheal diseases cause an estimated 10% of total child mortality [8]. 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 [9]. Nearly half of Rwandan households spend over 30 minutes procuring water, with access rates aggravated through mobility restrictions due to COVID-19. WASAC, 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 [10].

Using an estimate of drinking water needs of 4 liters/day per adult, a Box at full utilization could fully serve 2,083 individuals/day in our optimistic scenario, at a levelized cost of 0.24 USD/1,000 liters (Table 1). For perspective on the challenges of achieving full-utilization through a for-profit distribution model, 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 liters 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 0.24 USD/1000 liters.

Fig. 3. Pilot design of the water purification system within the OGB system. It is composed of a 5-micron filter and an activated carbon/charcoal filter and a 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.

B. Milk Chilling

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" (Gira inka munyarwanda) and "One Cup of Milk per Child" programmes [11]. The latter, wherein children in school from Nursery to Primary Level 3 receive a cup of milk at least two times per week throughout the school term, is reported to have increased enrollment and attendance in nursery schools and to have improved students' health status [12], [13].

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 centres 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 centres; upon reaching a certain capacity level, the collected milk is then transported for processing. Providing collection centres with adequate chilling can provide significant benefits in avoided spoilage. In 2007, nearly 35% of the 160 million litres of fresh milk production in Rwanda was lost to spoilage [11]. Importantly, in areas lacking grid electricity, renewably-powered chilling units can replace the generators that would otherwise be needed to sufficiently chill milk received at the collection centre to the recommended 3 to 4 degrees Celsius [11].

If an OGB Box utilized all of the energy produced towards milk chilling, it could serve the milk chilling needs of 1,674 people with 8 oz per day (Table 1). This is from the optimistic scenario in which we calculate the number of

TABLE I. Optimistic and Realistic impact of an OffGridBox 'Box'

Scenario	*Optimistic Scenario*	*Realistic Scenario*	*Units*
Max kWh/day from one OGB system	12.48	8.14	kWh/day
Levelized cost	0.36	0.55	USD/kWh
Use Cases			
Water Treatment			
Energy Consumed by UV Light	21	21	W/day
Energy Consumed by Pump	228	228	W/day
Potential # of Individuals Served Daily by one OGB system	2,083	116	people
Liters sold per month	250,000	14,000	liters
Levelized cost	0.24	0.24	USD/1,000 liters
Milk Chilling			
Energy Consumed by Rapid Milk Chiller	12.48	8.14	kWh/day
Potential # of Individuals Served Daily by one OGB system	1,674	1,092	people
Liters sold per month	11,885	7,752	liters
Levelized cost per kWh	0.40	0.61	USD/kWh
Levelized cost per liter	0.01	0.02	USD/liter
Health Clinics*			
Average % of Load OGB can provide to a health clinic	100%+	100%	

* 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.

liters per kWh from the Promethean System. The Promethean Rapid Milk Chiller System is a 1,000 liter milk chilling unit, which takes 4.5 hours to charge on average, consumes 3.5 kW to charge the thermal storage system, and can store 500 liters [14]. We calculate that optimistically the system could produce 396 liters per day with 3.5 hours available to charge. The system costs roughly 7,300 USD, which indicates a levelized cost of 0.01 USD per liter of milk (Table 1).

However, in a more realistic scenario, a Box could serve the milk chilling needs of 1,092 individuals and sell 7,752 liters per month with a levelized cost of 0.02 USD per liter of milk (Table 1). This realistic scenario also requires an inverter upgrade.

C. Health Clinics

At least half of the healthcare facilities in Rwanda lacked stable electricity in 2017 [15]. While there are indications that this 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

Fig. 4. The Promethean Rapid Milk Chiller is a modular system that cools milk from 35 degrees to 4 degrees Celsius with a capacity of 1,000 liters of milk per day. Such a system, paired with a Box (pending real-world compatibility testing) could significantly support Rwanda's dairy value chain as well as its aggressive childhood nutrition national strategy.

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 significant load, a need which the WHO/PATH expects to rise eightfold or more in the coming decades [16].

Currently, six upgraded OGB systems with sixteen 90Ah 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 machines, chemical analysis equipment, lab rotators, centrifuge, sterilizers, autoclaves, mixers, and ecographines. Each clinic's total daily consumption was estimated before connecting to the OBG system at 7.699, 16.725, 2.100, 9.025, 8.524, and 9.293 kWh respectively. The demand of the third health center is projected to reach 7.000 kWh when it receives its full equipment.

These upgraded OGB systems are able 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 currently utilize 60% of the energy that the Box is able to provide, 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

Fig 5. Appliances powered by OffGridBox at health clinics in Rwanda. From left to right: Microscope, Chemical Analyzer, and Centrifuge.

power additional equipment for the provision of health services.

IV. Conclusions

We present preliminary impact results for OffGridBox, a decentralized, containerized energy infrastructure provider, for three use cases at the Food/Water/Health nexus.

With respect to refugee or displaced persons contexts, the potential for containerized solutions to address multiple Food/Water/Health use-cases over an asset's lifespan intersects meaningfully with the possibility for emergency infrastructure to become long-term infrastructure, particularly as the composition of energy demand at a site evolves over time [17]. This is particularly relevant in a country like Rwanda which is experiencing some of the most rapid rates of urbanization and displacement on the continent, in part catalyzed by the long-lingering effects of catastrophic droughts in the mid 20th century followed by several decades of political instability and violence, high natural population growth, topographical constraints to habitable land characterized by a preponderance of hills and massifs across the territory (hence 'the land of a thousand hills'), as well as contemporary politico-spatial constraints (i.e. a very high proportion of land designated as protected natural reserves).

In this context, assessing the cost of improved water services for refugee camps/displaced persons is particularly challenging, given the tradeoffs in CapEx and OpEx that different delivery modalities entail. Our analysis reveals that Boxes can be cost-effective on a lifecycle cost analysis per-refugee basis compared to other delivery modalities (one UNHCR estimate considers the case of 300-600 individuals served from a CapEx of 50,000 USD and 3,000 USD recurring maintenance cost) including hand-pumps & piped water [18] — but with the additional benefits of transportability or repurposing . While comparable metrics for water provision are challenging to assess, service levels are deemed acceptable for 'regular' settlements [19], indicating that such delivery modalities should be considered within the toolbox of planned urbanization 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 inherently locally-specific food and nutritional needs at the community, sub-national, and regional level. Milk-chilling, for example, though attractive in our analysis, only makes sense in certain locations based on market needs, and under a for-profit model, the risks of stranded assets are high without proper value-chain assessments or centralized coordination/government support. Our analysis is indicative, however, of how procurement of containerized solutions at scale could be allocated across a number of different government priorities, cutting across or providing linkages across ministries and strategies, for example the Ministry of Education's early childhood nutrition strategy, power and water regulators/utilities' performance mandates, and Ministry of Health's extra-urban operations.

There remains a lot of work to be done at the multiple intersections of energy and economic development; few studies, for example, explicitly look at the impact of electricity on health outcomes [20]. Given the poor electrification levels across rural or remote health facilities not only in Rwanda but across low-middle income countries, our results indicate that a single OGB can significantly improve utilization of medical equipment at remote sites, from basic needs like lights for night-time activities to critical operations like infant warming machines, life support devices, and vaccine refrigeration — particularly important in the context of the anticipated global COVID-19 vaccine roll-out through the COVAX program.

Overall, while costs of providing services at the Food/Water/Health nexus through containerized energy modalities are still quite high, the majority of cost reductions are expected from scaled-up procurement. RMI estimates that at scale, containerized solutions can bring down the levelized cost of electricity (LCOE) by 0.11 USD/kWh — yielding knock-on effects on use cases for which energy is the input, including each of the use cases considered here. Further work is needed to investigate the full spectrum of community impacts at sites for which Boxes have been in operation for multiple years, particularly through fieldwork, and particularly against the backdrop of COVID-19 stabilization and recovery.

Like in many countries in Africa, the utility model for water and power delivery in Rwanda has not yet achieved cost-reflexivity in tariffs, nor eliminated quasi-fiscal deficits [21][22]. Sudden shocks like COVID-19, as well as chronic stresses from urbanization and climate change, further undermine the workability (and solvency) of the centralized, traditional utility delivery modality. Future work should investigate network integration models for both power and water services, where decentralized infrastructure modalities like 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 to the next 'remote frontier,' and even be repurposed to other strategic priorities like food security or health.

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. At the terawatt scale, the deployment of such modular, containerized solutions could not only structurally address electricity needs, but also radically change the landscape of utility service provision models as well as possibilities for productive uses of electricity at the Food/Water/Health nexus.

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Supplementary Material

Supplementary materials and calculations available here. <https://drive.google.com/file/d/1mHKHDXgxMIjl8eWtAIjpMTxksDJ3z6Xt/view?usp=sharing>

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