Electrical Minigrids for Development: Lessons From the Field

This article describes and analyzes four identical capacity rural minigrid interventions undertaken in communities in Kenya and Uganda with differing socioeconomic characteristics and demographics.

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ABSTRACT | Energy services are crucial to human wellbeing and development, and without reliable energy, it is difficult to escape subsistence lifestyles and poverty. Here, we report on four identical capacity rural minigrid interventions undertaken in Kenya and Uganda with differing socioeconomic characteristics and demographics. The research outcomes presented briefly discuss the preparation stages of the interventions including community surveys that informed the technical design, deployment phases, and setup of the community cooperatives to manage the minigrid projects. The main focus here is on lessons learned, including system design and minigrid performance under various load profiles. The results show a clear and increasing uptake of power by the communities with intensities varying depending on the electricity tariff used. Across the four minigrids, daily electricity growth rates are seen to vary by a factor of 8. The Ugandan minigrids operated at close to utility grid tariff and reached the 28-kWh/day design limit within two years. By contrast, the Kenyan minigrids charged a higher cost recovery tariff, which capped the demand and systems operate below the design limit. These findings have implications not only to system design but also to system stability and longevity. The approach taken here, of community centered cooperatives running the delivered minigrids, is now embedded within the rural electrification authorities/agencies in both countries, with additional similar projects being planned in 2019/2020. The application, ramifications, and replication of such a minigrid concept as compared to other approaches are also discussed in this paper.

KEYWORDS | Community power; cooperatives energy services; electricity for remote villages; energy access; energy and development; minigrids; photovoltaics (PV) power systems; renewable energy.

I. INTRODUCTION

Access to energy, especially for rural communities, represents a central pillar of development. Around 1.1 billion people (14% of the world's population) have no access to electricity with approximately half of those living in rural areas of Sub-Saharan Africa (SSA) and a third in rural South Asia [1]. The lack of electricity access in rural communities in SSA locks these communities into living a subsistence lifestyle. Electricity access rates are also likely to be exacerbated by the ever-increasing population growth, lack of investments, and robust mandatory national targets for access. The United Nations (UN) Sustainable Development Goals (SDGs) now recognize energy access as a major challenge to the global society where SDG Goal 7 promises "to ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [2].

SSA countries suffer from the lack of electricity access; with Kenya and Uganda, such access in rural communities is 39% and 18%, respectively, in 2016 [3]. The extension of the national grid to remotely and sparsely dispersed rural populations is, however, very expensive and slow, delaying electricity access to small villages in SSA countries [4]. In addition, utility grid networks in most sub-Saharan countries are struggling to meet the power demands of their rapidly expanding cities let alone to increase their reach of electricity provision to rural communities. Most governments have ambitious plans for grid extension

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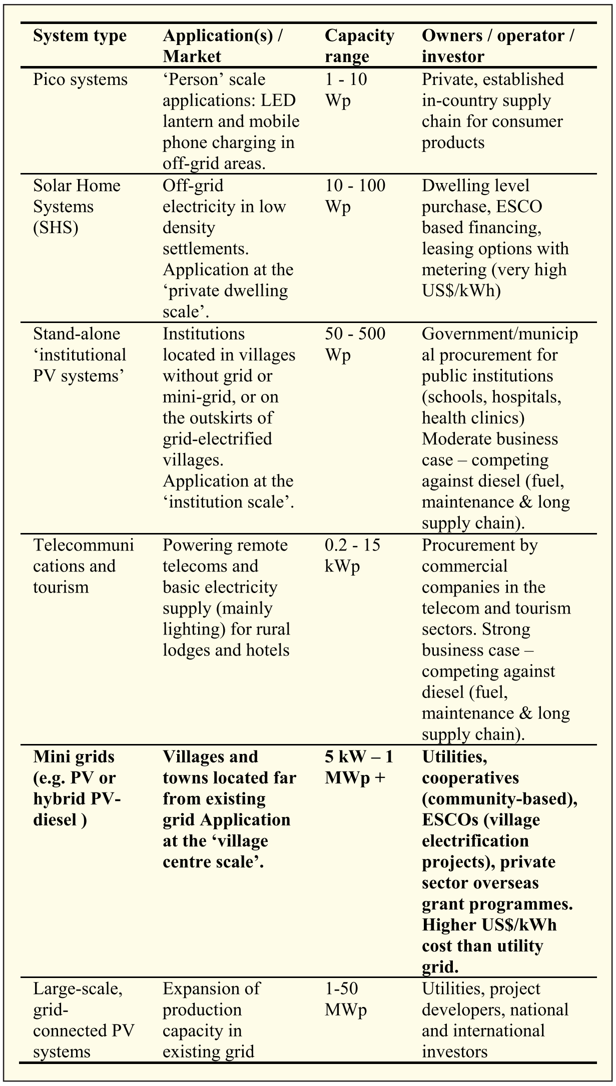
but past experience shows that delivery does not usually match the stated targets [5]. Therefore, small, decentralized clean energy technologies in developing countries can be a better option for a rapid and more economic approach to deliver on the electricity access challenge in remote communities. Appropriately designed, sustainable energy-driven minigrids systems can offer the solution; however, we need to understand how these can be deployed, how they are operated and used in isolated rural communities, what impacts they have and how minigrids can be integrated into national grids, and when they arrive. Minigrids and the utility network are potentially complimentary approaches. Minigrid clustering and integration with the utility grid can both avoid the minigrid becoming a stranded asset and support the utility network where it is at its weakest [6], [7]. In certain development scenarios, minigrids can be considered as bridging technologies to the ultimate arrival of the utility grid. In Uganda, in particular, the Rural Electrification Agency (REA) takes this view, where, from the customer perspective, a minigrid and the utility grid are essentially the same in terms of electricity supply. Upon the arrival of the utility grid to a village, the minigrid becomes integrated with no change from the village perspective. For future projects, the preference of the Ugandan REA appears to be the provision of three-phase power in minigrids to support large loads such as mills, water pumping, and welding activities.

The rapidly falling cost of photovoltaics (PV), the default renewable of choice for SSA due to wide solar resource availability, means that minigrids as an alternative to utility grid extension to provide electricity access are drawing increasing interest from major funders such as the World Bank [8], Africa Development Bank [9], Islamic Development Bank [10], and Abu Dhabi Fund administered by International Renewable Energy Agency (IRENA) [11]. The challenge is to put in place appropriate financing mechanisms and supply chains to support the transition from "one off" demonstrators to realistic options for roll out at scale in SSA.

The solar PV market can be considered to be made of differing capacity scales ranging from few watts to multiple megawatts, as shown in Table 1 [12]. These differing scales essentially relate to the transition from consumption for services (lighting and mobile phone charging) to productive use (agriculture and food processing), which has a greater electricity demand, but provides the needed economic growth. The IEEE defines a microgrid as a cluster of loads, distributed generation, and energy storage systems [7]. While the microgrids considered here are in the 5–50-kWp range, microgrid applications can exceed 1 MW in many cases [13]. In this paper, microgrids in this context are referred to as minigrids. The minigrid terminology reflects globally and generally accepted approach to the technology needed to provide electricity access as highlighted and used by international organizations such as the World Bank, the UN, Sustainable Energy for All, EU, and governments in both SSA and South East Asia.

Table 1 Characteristics of Different Scales of Solar PV Market Sectors (Adapted From [12])



System type	Application(s) / Market	Capacity range	Owners / operator / investor
Pico systems	'Person' scale applications: LED lantern and mobile phone charging in off-grid areas.	1 - 10 Wp	Private, established in-country supply chain for consumer products
Solar Home Systems (SHS)	Off-grid electricity in low density settlements. Application at the 'private dwelling scale'.	10 - 100 Wp	Dwelling level purchase, ESCO based financing, leasing options with metering (very high US$/kWh)
Stand-alone 'institutional PV systems'	Institutions located in villages without grid or mini-grid, or on the outskirts of grid-electrified villages. Application at the 'institution scale'.	50 - 500 Wp	Government/municipal procurement for public institutions (schools, hospitals, health clinics) Moderate business case – competing against diesel (fuel, maintenance & long supply chain).
Telecommunications and tourism	Powering remote telecoms and basic electricity supply (mainly lighting) for rural lodges and hotels	0.2 - 15 kWp	Procurement by commercial companies in the telecom and tourism sectors. Strong business case – competing against diesel (fuel, maintenance & long supply chain).
Mini grids (e.g. PV or hybrid PV-diesel)	**Villages and towns located far from existing grid Application at the 'village centre scale'.**	**5 kW – 1 MWp +**	**Utilities, cooperatives (community-based), ESCOs (village electrification projects), private sector overseas grant programmes. Higher US$/kWh cost than utility grid.**
Large-scale, grid-connected PV systems	Expansion of production capacity in existing grid	1-50 MWp	Utilities, project developers, national and international investors

Lee *et al.* [14] argued that even when people live close to the existing utility grid infrastructure, connection rates remain low. In their analysis of Kenya, for those "ideal" high-density populations living "under grid" where a low-voltage grid connection would be relatively low cost, electrification rates remain low (5% for rural households and 22% for rural businesses). Of course, a major barrier to addressing "under grid" connection rates is the extremely high electrical connection price, which had been fixed at KSh 34 980, or $412 [15]. In 2015, the government announced the Last Mile Connectivity Project, a plan to reduce the connection charges to KSh 15 000 for the poorest households and connect millions of new households. Despite this reduction, the rate of connection remains low as this is still unaffordable for most households [16].

Classified as a "lower middle income" country by The World Bank, the average Gross Domestic Product per capita (GDP) in Kenya is $1508 [17]. The longstanding KSh 34 980 connection charge ($412) represents 27% of annual per capita GDP and will clearly be a far higher percentage in rural areas in both Kenya and Uganda where incomes are lower and variable with less economic opportunities. By contrast, in the U.K., a high-income OECD country, the annual per capita GDP is $39 720 [17] with a typical domestic connection charge of $2511 [18], which corresponds to a level of 6%, a quarter of that of Kenya.

Technically, minigrids do not generally represent a particularly difficult design challenge—their success (or failure) is down to the level of understanding of the deployment context, the cost of electricity, and their operational management. This research and development program sits firmly in the minigrid sector (Table 1), targeting economically productive use from electricity provision. It has been conducted to address electricity access in rural Kenya and Uganda and provide evidence on how sustainable energy-driven minigrids can be utilized to support this goal in such regions in Africa. It is part of the Energy for Development (e4D) [19] program to address electricity access in this region, with learning to be extended to other parts of the world. The basic premise of e4D is that productive use of electricity alongside low-power appliances (LED lighting, radios, fans, hair dressing, tailoring, TV, information technology (ICT) and so on and the ubiquitous use of mobile phones) have the ability to transform the economics of off-grid electricity provision. Today, as a result of these low-power technologies, there is both a need and a willingness to pay for electricity supply among even the poorest of society. For example, smartphones are rapidly falling in price, with devices on the market in SSA at less than $50. This will further drive the demand for services (e.g., Wi-Fi hotspots and video) and appliance charging, especially in relation to the frequency of charging with smartphones rarely lasting more than a day before needing to be recharged. Here, we report on the experience of designing, deploying, and operating rural community minigrids in Kenya and Uganda under differing contexts.

II. ELECTRICITY ACCESS AND MINIGRIDS

Electricity access in rural communities is a complex issue and requires in-depth understating of the many salient issues necessary for its delivery. In Fig. 1, we capture some of these issues, providing a view of their intricacies and interdependencies. There is no one solution that fits all and interventions to provide electricity will always have to take into account the characteristic of the region considered.

Such complexity has rendered many electricity access projects to date ineffective [20]. Therefore, it is informative to consider first why some off-grid interventions in Africa often fail. A "typical" four-stage path to failure of a minigrid deployment might be as follows.

1) Renewable energy projects carry high up-front capital cost and may require additional support (grant aid/subsidy) to be deployed.

Fig. 1. ***Electricity access issues to be considered and where minigrid sits within the scope of other technologies, business models, regulations, sustainability, scalability, and tariffs. Here, SHS is solar home systems, PPA is power purchase agreements, and O & M is operations and maintenance.***

2) Renewable energy intervention is applied through a specific grant-based program, potentially with limited local engagement and skills training.
3) Intervention programs come to an end and no further support is given to support on-going projects.
4) Lack of local and in-country technical support and supply chain and local financing so that the systems fall into disrepair.

There are clear weaknesses at the onset of this process, in which there is no clear understanding of needs and what is already available within the communities that can be embedded within the intervention program. Postintervention of the system is not supported, and crucial learning opportunities are lost. For a system to be sustainable, the first requirement must be for it to operate for its entire design life. In the case of an ac PV-diesel-battery minigrid, this would be expected to be more than 20 years with two or more battery replacements, inverter, and generator exchange during this period. As a minimum, any system must be able to finance all of its costs postdeployment, including scheduled operation, unscheduled maintenance, security, payment collection, and management to name but a few. An "ideal system" would be able to charge an electricity tariff that would cover all up-front capital costs, operational costs, and financing charges. At present, that is not realistic for poor rural communities and some forms of initial capital cost (CAPEX) subsidy will be required from either the central government or a donor agency.

A. e4D Minigrid Approach

The e4D program has taken a community ownership approach to deliver a solution based on the above-mentioned principles. There are a range of issues, both technical and nontechnical, that need to be considered when developing such a minigrid intervention in communities who have had no access to electricity. In addition to community invigoration and development, the drivers for minigrid deployment include: low electrification rates and associated slow grid extension, health and education targets, and economic growth that is geared to reducing rural poverty and migration to urban areas. There are a number of technology innovations which have created the opportunity for minigrids, most notably: mobile phone use, low-power appliances, and, most importantly, the rapidly falling cost of PV systems. In terms of possible technical solutions, it is now widely accepted that electricity provision must be of a scale to enable economically productive activity to occur to be sustainable in the long term [21].

In contrast to private ownership, community ownership of minigrids has the potential to deliver a number of nontechnical benefits in hierarchical societies, particularly associated with enhanced sustainability and security of the project and the system, local pride, and enforcement of bill payment. That said, the structure also introduces risks associated with favoritism and the lack of transparency among village elders who may leverage the arrival of electricity to enhance their position. The principle of electricity provision scale is that there is a minimum level that is required to enable productive use (income generation) to be achieved. We believe that it is ultimately the economic growth (businesses) that determines the success or failure of a community and its infrastructure.

Remote off-grid African villages are often characterized by a central core of buildings (businesses, schools, health centers, places of worship, etc.) with a far lower density of dwellings in the surrounding area. It will only be economic to connect the central core of village buildings (businesses, etc.) in such a configuration, in all but the richest of settlements, thus reinforcing the business-led intervention approach. While there may be a desire among villagers for every adobe mud hut to have an electrical connection, in terms of economic viability (infrastructure cost), this is simply unrealistic. Provision of electricity at this level will be via either: 1) individual solar home systems (purchased, lease, or “pay as you” go options) or 2) batteries that may be recharged at businesses in the minigrid village center. Therefore, to select a site for an e4d intervention, a village should have the following characteristics.

1) A village center with an appropriate population density [22] and 2G/3G mobile phone coverage on the site.
2) No immediate plans (within ten years) for grid extension to the site as this risks creating a “stranded asset.”
3) Mix of existing business activities with the potential to grow following the provision of electricity. Typical uses include mobile phone charging, hairdressing, ICT, posho mill, lighting, refrigeration, tool sharpening, and welding.
4) Presence of “anchor tenants” within the village such as businesses, schools, health clinics, places of worship, water pumping, and so on.

B. Site Selection

The geographic scope of the e4D program was initially Kenya, but the scope has grown to include Uganda and Tanzania as the e4D network partners have shown interest through organized workshop events, visits to the initial project site, and other contacts [19]. In order for the projects to progress, a comprehensive assessment of the countries and the regions, in which interventions will be carried out, was undertaken. The assessment included: 1) the development of high-level preselection criteria to identify suitable administrative units using available data sets; 2) the development of a geographical information systems (GIS) database of Kenya and Uganda containing the necessary data for informing the program decision-making process; 3) initial reconnaissance visits to identify suitable candidate sublocations; and 4) willing communities who have the determination to progress and take ownership of the project. With the exception of Kitonyoni (see below), the other two projects in Kenya and two in Uganda were developed and deployed (on cost share basis) as a joint partnership with Rural Electrification Authority/Agency (REAs) in these countries.

Kitonyoni, a village of around 3000 people near Wote in Kenya (longitude: 37.654467, latitude: -1.954182), was selected as the first intervention site in the e4D program [19], [22], [23]. The village is around 130-km southeast of Nairobi of which all but the last 30 min of travel is on tarmacked roads. The project in Kitonyoni was wholly developed and incepted in 2012 by the e4D team as an exemplar installation to demonstrate what can be done in the minigrid electricity access space. After visits from the various REAs to Kitonyoni, in 2015, four similar systems have subsequently been deployed: two in Kenya and two in Uganda. Here, we compare the two systems in Kenya (Kitonyoni and Oloika) with those in Uganda (Kanyegaramire and Kyamugarura), all of which have the same battery, PV capacity, and overall infrastructure.

C. Standardized Systems Approach

The Kitonyoni project capacity and reticulation (designed for an initial 100+ connections) seem acceptable to both the perceived initial loads and REAs. Essentially, four identical systems in rural villages in Kenya and Uganda (with around 3000–5000 people each within the core and surrounding areas) have been operated under contrasting payment strategies for each kilowatt-hour of electricity provided to the consumers within the village centers. In Kenya, a per kilowatt-hour tariff has been set, which would enable future systems to be financed through a “soft” low-discount rate loan provider such as the Development Banks/World Bank. The tariff is set by the cooperatives and was informed by surveys undertaken for kerosene use and the need for income to support future inverter/battery replacements and contingencies. In Uganda, the schemes are operated such that electricity is charged at far lower but slightly higher than the subsidized utility grid price. This was a deliberate decision by the e4D team and Ugandan REA to understand and contrast between the four projects and the impact of close to grid tariff on consumption profiles in these villages.

Each of the four minigrids was sized to deliver 28 kWh/day across the year without the battery state of charge dropping below 30%. These four case studies highlight the challenge of tariff setting principles to the system design brief and the need for flexible approaches, in terms of supply and demand, to preserve the long-term viability of minigrids. In this paper, we provide an overview of the issues and findings across design, deployment, and operation and their wider implication for minigrids in a SSA context.

III. MINIGRID DESIGN CONSIDERATIONS

A baseline needs assessment was undertaken to determine the electricity requirements of the village as part of an extensive survey and consultation with all villagers concerning the intervention and the village energy cooperative structure.

This approach enabled a daily load profile to be generated, which is then used to model possible minigrid system solutions. The key challenge here is that the designer is trying to estimate electrical loads in a society for whom electricity provision and use are an almost alien concept. Demand will also be closely linked to electricity price. If the electricity price (tariff) is set too low, this will encourage wasteful usage such as low cost, inefficient incandescent lighting, and/or inefficient appliances. Demand on the minigrid will rapidly rise, exceeding its design limits and ultimately the minigrid will fall over. Conversely, if the tariff is set too high, demand will be very low and economic development will stagnate. The minigrid will not enable the village to flourish; the resulting limited income stream will mean the minigrid will fail. Demand elasticity in response to tariff price setting is, therefore, the key issue to consider. Too low and unconstrained, wasteful usage will lead to the minigrid struggling to provide the required demand, which could lead to system failures. Too high a tariff and development will essentially stall, meaning the minigrid cannot be sustained economically.

Lighting loads can be estimated by surveying the existing candle and paraffin use in a proposed location. The expenditure on these two items gives an indication of an electricity tariff for LED lanterns replacement, which would reduce household expenditure while also providing profit margins for businesses offering appliances charging service.

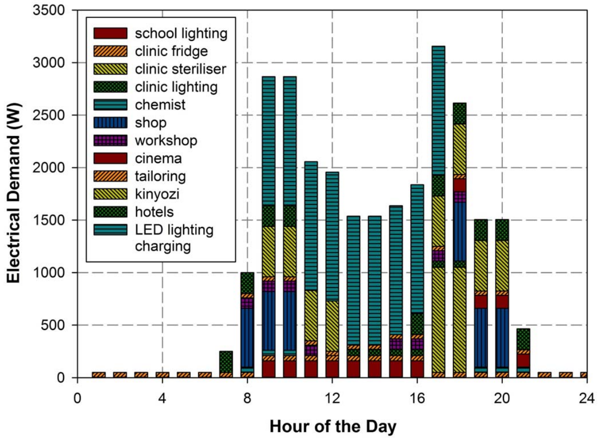


Fig. 2. ***Load profile for Kitonyoni based on needs of the assessment baseline survey. Peak electrical demand was estimated at around 3.2 kWp with a daily demand of 28 kWh. There was no seasonal variation in demand assumed.***

Fig. 2 shows the estimated load profile as a result of the needs assessment undertaken in 2011 for Kitonyoni. The estimated daily load is 28 kWh/day. LED lantern charging (a deferrable load) has been scheduled around the peak of the solar day to reduce overnight discharge of the battery bank.

HOMER, the minigrid design software [24], was used to size a PV-battery-diesel system for the Kitonyoni site. A number of constraints were placed on the HOMER model to reflect the engineering team's stated minimum performance standards as follows.

1) Twin-inverter system to provide redundancy in the event of an inverter failure. Option to reconfigure on site as a single-inverter system. The inverters are single phase and national grid connection ready.
2) Gel lead-acid battery technology to enable in-country supply chain.
3) Renewable energy supply >95% at the target load profile of 28 kWh/day, with no shortfall allowed. Autostart diesel with minimum 1-h runtime at the specified battery state-of-charge level (only in the Kitonyoni project). The minimum designed battery life is ten years.
4) No discharge of the battery below a 30% state of charge to maintain battery condition.

The HOMER modeling was set to allow a 10% intraday variation on the 28-kWh/day load. The system specification in Kitonyoni is as follows: 13.5-kWp monocrystalline PV array, 250-W Si modules, and four sub arrays each with a Flexmax80 charge controller. The system was configured to run at 48 V using 2-V lead-acid cells to provide an 800-Ah, 48-V battery bank. The ac side is supported by twin Victron 5-kW Quattro inverter-charger units. The diesel generator for Kitonyoni is 15-kW, 230-V ac single phase. The completed plant room is shown in Fig. 3. All subsequent projects considered here were standardized to this PV-battery system with no diesel generator as this was deemed unnecessary.

Fig. 3. *Kitonyoni plant room comprising four charge controllers, 48-V battery bank, and twin inverters. Data monitoring system is on the right-hand side below consumer units of twin distribution circuits. Diesel generator is located on the other side of central bulkhead added to the container.*

A. Principles for Implementation and Operation

The e4D approach is based around the delivery of the PV system in shipping containers to the intervention site, which contains all components of the community minigrid power plant. The two containers were converted to house the plant room and a community office. The PV canopy provides shading for a meeting place for the community and the containers and also collects rainwater if this is an issue for the intervention site [19], [23]. In Kitonyoni, the nearest water source is a river bed 2 km from the village; water is a valuable asset for the community outside of the rainy season. The canopy approach in addition to creating a shaded, focal point for the village has the other function of deterring theft and damage risk to the PV modules.

Different approaches were tried to collect revenues for consumed electricity. At the outset, our ethos was to have a project that would be robust, build on what was available in the village, and provide employment when that is deemed beneficial for the community but without compromising the efficient and economic operation of the minigrid. With this in mind and in addition to nonpaid management and steering committees of the cooperative, the structure allowed for a paid manager and security guard who also have the role of cleaning the solar PV modules. Initially, the income from power consumption was collected manually by the manager; however, after 12 months, it was clear that this was not working and a smart card system was employed for collection of consumption fees (see Section V for further details).

Technical support was at the heart of the thinking of the team. The community recruited four technicians to be trained on the project from installation, commissioning, and operation phases of the project. These technicians were paid per diem during their training, and two of these were selected to provide support on a negotiated day rate basis for the project. The project also provided a computer, a suite of appropriate software packages, and a digital camera to the cooperative. The manager and the technicians were also trained in using these as well as communication software. Link to the e4D team is available on a 24-h basis with further support from experienced technicians in Nairobi/Kampala for a negotiated daily fee. These approaches have worked well, with only minor issues arising in these projects which were dealt with quickly.

B. Design Standards

The e4D intervention is designed to U.K. design standards to reflect the design environment of the U.K. team. This poses a challenge in an African context where this approach will inevitably add significant up-front capital cost. The specification of structural calculations, wind loading and foundations requirements are all at a level that is beyond the norm in Africa. The PV canopy was designed by U.K. structural engineers Wernick Associates (now part of Engineers HRW) [25] in conjunction with Clarke Construction Essex Limited [26] and the e4D team at the University of Southampton.

The Kitonyoni system (with the exception of the batteries which were purchased locally) was procured in the U.K. and shipped to Mombasa from where it was delivered to site. Subsequent systems such as those in Oloika in Kenya and Kanyegaramire and Kyamugarura in Uganda have an entire in-country supply chain with the exception of electronic lightning protection (dc and ac), which were not readily available in the country. High-quality contractors in Kenya were selected with the brief to replicate the Kitonyoni system using local expertise and a very high local standard of engineering. This included the training of a steel fabricator in Kenya to manufacture the canopy. For the Uganda project, similar designs were commissioned by REA for the canopy and the purchase and adaptation of the containers [19]. Systems installed subsequent to Kitonyoni have all been finished to a high standard, which shows that high-quality in-country manufacture can be realized with careful choice of local partners.

C. Project Finance

The initiation of the e4D program and its projects stemmed from a grant awarded to the authors and their team from the Engineering and Physical Science Research Council (EPSRC) (https://epsrc.ukri.org/). The projects were undertaken in partnership with the REA in Kenya and Uganda with shared project cost. The power plant was funded from the grant, while the electrical distribution network was funded by the REA. The cost of the fully installed and commissioned power plant (PV system, balance of system, protection, and batteries) was around \$5000/kWp. The cost of the electrical network varies due to the length of the network and also competitive tenders. On average, the cost per kilometer was around $9000. All projects were managed through a cooperative responsible for selling electricity, maintenance, and expansion of the project [23]. Once commissioned, the functional operations for two-year ownership of the project were handed to the communities and REA.

D. Design Ethos and Lessons Learned

Electricity consumption at the premises level is measured using commercially available prepayment card meters (details at www.ytl-e.com/product/info/33). Consumers can purchase their electricity at multiples of kilowatt hours at the cooperative office through a special card reader. Once topped up, the card is inserted into the consumer meter, which allows access to the supply. The card reader and accompanying software record consumer information that is downloaded to the cooperative computer when the kilowatt-hour card is topped up. This system solved the problem of physical fees collection and avoidance of accumulated fees that can lead to debt as well as providing additional security to the power supply.

Management of consumption at each connection to the minigrid was achieved through two levels of circuit breakers; each having a different current rating, one installed in the consumer meter unit at the consumer premises, and the other mounted at the grid distribution pole away from the premises. This approach addressed two issues: 1) making sure no high-demand appliances such as old welding machines are connected to the grid that would cause the minigrid to fall over and 2) theft of electricity beyond the normal demand of the consumer.

For each connection, a 2-A-rated miniature circuit breaker (MCB) was installed in the electricity consumer unit at the consumer premises and a higher 6-A-rated MCB installed in a separate weather proof box mounted on the nearest distribution pole. The difference in the MCB current rating also allows appropriate margin in current addressing the risk of “false trips” at the pole level, which would create disruption and erode business confidence in the system. Within the design ethos, local installers have been trained to install replacement of such MCBs with higher tolerance rating (C or D compared to Type B used originally) when appropriate demand in a premises requires it. The design team was also concerned that consumers might bypass their 2-A MCB (embedded in the consumer meter unit) leading to unmetered electricity usage and potentially extreme loads, which would cause the minigrid to fall over. The two-circuit breaker approach meant consumers were unable to “hide” poor practices and required the system technician to reset their pole breaker (incurring a potentially significant inconvenience and cost for reconnection).

The minigrid is configured as two distinct circuits: 1) always on—health center, school, and plant room; and 2) other village buildings, including businesses. The system will automatically disconnect village circuit 2) in the event of low system battery voltage combined with the failure of the autostart of the diesel generator (Kitonyoni only).

IV. MINIGRID DEPLOYMENT

The “shipping container to site and convert” approach minimizes risk during the deployment phase providing a highly controlled plant room with ventilation, dust protection, and security. For Kitonyoni only, a physical separation between the diesel generator and PV electronics/battery is provided by a central bulkhead in the middle of one of the shipping containers (Fig. 3). For other projects, the dividing bulkhead is also used for the PV/battery system, while the diesel generator space was used for storage/office space. Using the walls of the shipping container for fixing of control panels ensures that all components are electrically earthed. There is a high level of design quality and control of the PV canopy and the converted container plant room.

During deployment, it is important to engage the villagers as fully as possible. Not only does this provide a source of work but it also helps foster local pride and community ownership of the system. The container conversion is a case in point, where, whenever possible, we use villagers’ welding skills to undertake this work and the wider general construction. Subsequent deployments in Uganda have iterated the design to structurally incorporate the shipping containers within the PV canopy to reduce material and installation costs (Fig. 4)

Engineering quality and level of workmanship quality are a potentially challenging issue. Contractor selection is critical as villagers have little or no understanding of electrical risk, and general electrical wiring standards are well below that of a developed country. Fig. 5 shows the two images that highlight this issue where the local reticulation contractor has connected consumers to the village ring main in Kitonyoni. Following a site inspection by e4D engineers prior to system commissioning, remediation work was undertaken (Fig. 5, bottom). For all other projects, the reticulation and connections to consumers were part of the REA support of the projects and hence adhered to a high standard.

V. MINIGRID OPERATION

In terms of technical operation, PV diesel minigrids are generally well understood. The biggest issue from our experience is the enforcement of bill paying by consumers and the objection to high tariffs relative to the utility grid price. Breaking out from a culture of “donation” to one of “paying for a service” is challenging even when affordability has been assessed in detail as is the case here. Enforcing payment for use of electricity has been one of the most challenging aspects of these minigrid deployments. In Kitonyoni, initially, the payment was collected monthly retrospectively (2012) and this was changed to weekly collection (2013) as a number of consumers ran up large

Fig. 4. *Top: two-container system under freestanding PV canopy, Kitonyoni, Kenya. Bottom: two containers integrated into the canopy system, Kyamugarura, Uganda (no water collection).*

usage debts, which they claimed were unable to pay. The payment system was switched to a prepayment pay-as-you-go card system (end 2013) to address the continued issue of late payment. All subsequent e4D projects have deployed a prepayment system from the onset, and this has worked well and no arrears occurred. Regardless of the business type or load (lighting, mill, phone charging, etc.), the billing system is now an identical prepayment meter.

The Kitonyoni system was commissioned in September 2012 and has operated continuously since this date with total downtime being less than 1 week. In comparison, the national utility grid will have had a downtime of around 30% during this period. In Kitonyoni, the most recent down period (two days in May 2018) was due to an electrical fault in the village bar following heavy rain, which was identified by the local electrician by systematically reconnecting business circuits under e4D team guidance.

The total daily village electrical load for both circuits and all metering (measured as apparent power (VA), delivered kilowatt hours by the inverters) has increased from around 10 kWh/day in 2012 to 18 kWh/day in 2018. The electricity tariff cost and payment collection method have changed four times over this period [22]. The “average daily consumption profile” is shown in Fig. 6 for years 2012–2018 inclusive (summary profile data is given in the Appendix). For every drop in tariff, there is a noticeable increase in consumption and this shows that income is highly dependent on affordability. It is interesting to note that during the highest income harvest months, consumption goes down as businesses shut their premises as food production becomes the priority and all workers spend their days in the fields. Electrical demand is, therefore, out of sync with income, which is counter to what a designer without local knowledge would assume.

By contrast, in Uganda, the kilowatt-hour tariffs for both projects are almost half that of Kitonyoni. This was deliberate as it will allow the project team to compare and contrast between projects but is also of interest to Uganda REA for future planning purposes. The consequence of this is that the demand has exceeded the design limit (Fig. 7), and remedial action was put in place to address this issue. As shown in Fig. 7, while the Kyamugarura evening peak is ∼1.5 times the Kitonyoni 2017 average, the night-time value is ∼2.5 times that of Kitonyoni. In the first instance,

Fig. 5. *Top: example of poor local contractor quality and poor understanding of electrical risk. Bottom: typical field remediation of poor-quality contractor deployment.*

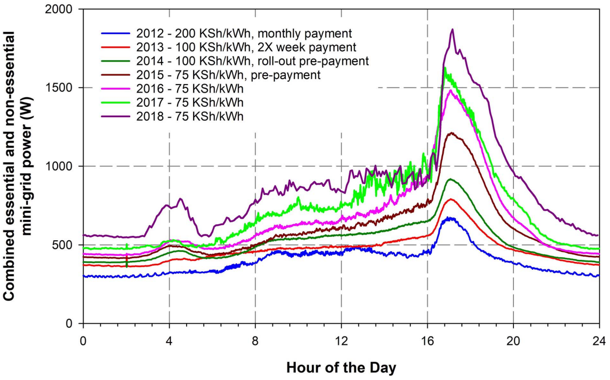


Fig. 6. ***Average daily profile for Kitonyoni, 2012–2018. Consumption Profile development is influenced by tariff price and charging mechanism ($1 = 101 KSh, August 2018).***

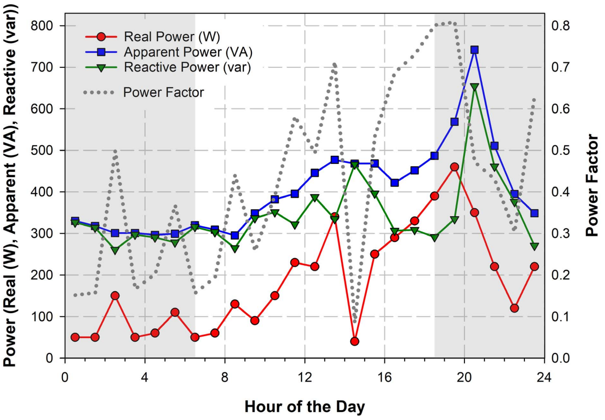


Fig. 8. ***Daily power factor variation for Kitonyoni minigrid, August 28, 2014. Daylight hours are shown in white.***

all lighting in Kyamugarura, especially those used for security, was converted from incandescent/compact fluorescent lamp (CFL) lighting to LED. This marginally reduced demand and was a short-term fix. A system upgrade for both the Ugandan projects was submitted to REA and will be out for tender in summer 2019. The lesson here is that REAs will need to be given the tools to address this eventuality and original systems design and deployment infrastructure must be upgradeable and be grid ready.

It is important to note that the real power (W) and the apparent power (instantaneous voltage x current, VA) may be significantly different in a minigrid. Real power/apparent power is known as the power factor and varies between 0 and 1. For electrical circuits dominated by resistive loads (incandescent lamps and heating elements), power factors of almost 1.0 can be achieved. For circuits with inductive or capacitive loads (electric motors, solenoid valves, transformers, and fluorescent lamp ballasts), power factors may be well below 1. A minigrid with a low power factor draws more current than a minigrid with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the minigrid distribution (I^2R losses that are not billable loads) and require larger wires and other equipment. In this analysis, we consider power factor losses as those associated with distribution, which are not directly billable to consumers.

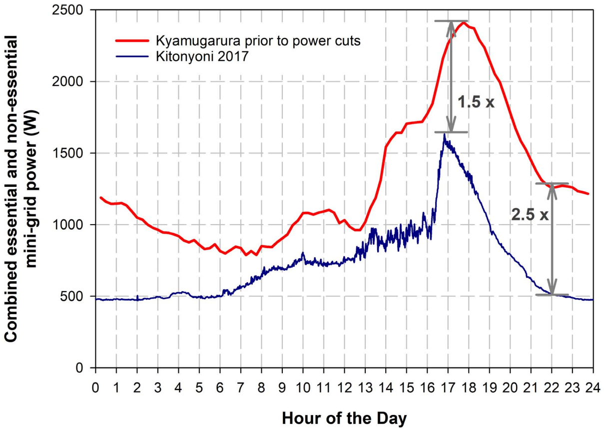


Fig. 7. ***Kyamugarura minigrid (July 2017, monthly average profile) reaching its daily capacity limit within 24 months of commissioning. Average July 2017, 31 kWh/day being delivered for a 28-kWh/day design load.***

The Kitonyoni system was designed to deliver up to 28 kWh/day without the need for diesel generator backup. This assumes a power factor of 1.0, i.e., the real and apparent powers are the same, which would require the minigrid load to behave as a perfect resistive load. This is unlikely to be the case and the scale of the power factor issue is an important unknown in the system design, especially for relatively small systems. To determine the impact of nonresistive loads on the minigrid, real power (watt-hour meter) and VA rms measurements were taken every 30 min for a 24-h period (August 28, 2014). The real power (W), apparent power (VA), and reactive power (var) are shown in Fig. 8 alongside the power factor.

The power factor analysis highlights that systems operating with extensive monitoring (individual metering) are likely to have poor power factors when operating at less than half the design load. While this should not cause an issue for a PV-based system (at this point, we have excess PV generation that is simply lost as PV arrays are disconnected to protect battery overcharging) in the case of a standalone diesel generator unit, more fuel will be consumed than that will be costed for at this point. In Fig. 8, across a 24-h period, a good power factor was observed (>0.7) during the core consumption hours (16:00–20:00). The power factor during periods of low demand is generally poor as a result of the high level of metering on the system. In particular, the research nature of the Kitonyoni system means that there is 50–100 W (real

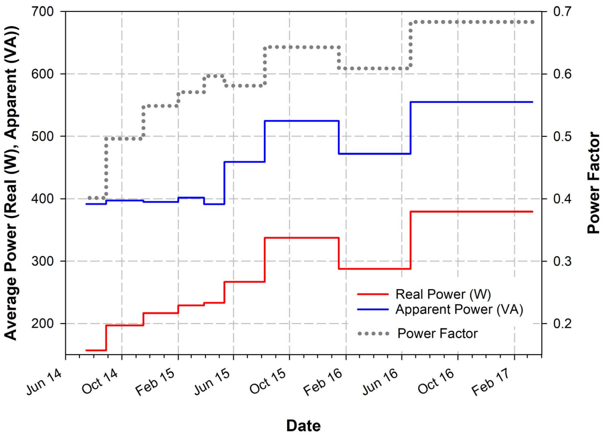


Fig. 9. *Power factor variation for Kitonyoni minigrid, 2014–2017.*

power) of monitoring additional to the normal base load of metering within businesses. When additional loads occur overnight (lighting/compressor operation), the power factor is actually seen to increase despite the fact that these are usually not purely resistive loads.

For the Kitonyoni minigrid, during 2014–2017, the minigrid average power factor has increased from 0.4 to more than 0.7, as shown in Fig. 9.

VI. DISCUSSION AND LESSONS LEARNED

The use of electricity in the Ugandan villages is observed to be quite different in the rate of development of demand over time. The enforcement of a high per kilowatt-hour tariff in Kenya relative to the grid is observed to regulate demand with electricity use being focused around economically productive activities or services. By contrast, the subsidized Ugandan minigrids enable secondary societal benefits to flourish such as street lighting provided by village businesses but this creates demand management and capacity limit challenges that were not envisaged at the project design stage.

In 2017, the two Kenya systems were operating at 18 and 23 kWh/day after 5 (Kitonyoni) and 2 (Oloika) years of operation, well below their daily limit. The Uganda systems have been operating for two years and have already exceeded their nominal 28-kWh/day limit. This has led to power cuts overnight as the system powers down to protect the battery bank from excessive discharge. While it is clear that the lower tariff in Uganda encourages greater usage and so acts as a spur to productive use, there are secondary effects detrimental to the minigrid. In particular, there is a very high overnight demand as consumers choose to leave lights on for security reasons. While this makes the village far safer and so has a strong social benefit, it has created a high demand profile, out of phase with the PV generation. Such a scenario was not envisaged and this has compromised the long-term sustainability of the system, most notably the battery lifetime. To minimize this impact and preserve the system battery life, the Uganda systems need to quickly change in terms of either installed PV capacity (to increase supply), tariff price, or lighting technology upgrade (to reduce demand). Here, we explore options and actions taken for immediate and longer term intervention to ensure the sustainability of the Uganda systems while preserving community goodwill and confidence in the minigrid. Supply chain (in terms of both engineering expertise and system components) remains a major weakness, especially in the Ugandan context where the off-grid infrastructure is comparatively underdeveloped in relation to Kenya.

The issue is further complicated by the very high-upfront capital cost (CAPEX) of the minigrid system, which provides the overall infrastructure for power generation and distribution, as well as the rapidly falling prices of the PV modules and (in the near future) batteries. Staging capital investments might be desirable but, in this context, it is particularly challenging due to: 1) the unpredictability of future finance; 2) the difficulty of upgrading battery banks midway through their life; and 3) general weaknesses in technical and equipment supply chains. PV is, of course, an inherently modular technology, which can make this possible provided the battery bank is carefully considered, i.e., as electrical demand on a minigrid grows, the PV array can be expanded to support this.

A similar approach may be taken for all other activities in the village. Extreme care must be taken with the claimed “electrical needs” of households/businesses, it is our experience that villagers tend to overstate these, predominantly due to the lack of understanding of use and cost. In addition, we observe that businesses have a tendency to overstate their income, wanting to appear successful to the assessment—self-reported data should always be treated with care.

Consumers electrical metering and general data logging loads can be significant—especially in the case of highly metered deployments such as Kitonyoni. Here, the level of metering is beyond what might be considered as typical of a deployment and has actually distorted the load profile of the minigrid. The load profile based on a needs assessment will almost certainly not reflect the reality of electricity consumption when high electricity tariffs are strictly enforced.

The Kitonyoni’s actual daily load in 2016 was around 10 kWh/day compared to a designed profile, informed by a needs assessment of 28 kWh/day. There is a fundamental difference between claimed and actual electricity used when a high price per kilowatt hour is charged. In particular, 1) villagers have no understanding of electricity prices in relation to equipment loads and 2) there is also a belief that, when power is provided, it will eventually be on the same tariff as the utility grid, even when it is clearly stated from the onset that this will not be the case.

When the true cost of electricity becomes apparent, users adapt their behavior to minimize cost and, therefore, electricity usage (elastic behavior). This has good and bad aspects; good, in that, in reality, a minigrid may be small and still have an impact by delivering the needed power; bad, in that, following a needs-based assessment, the risk of designing an oversized system (high CAPEX) is very high. The economics of minigrids are challenging, and having an oversized up-front capital cost investment will result in an electrically robust but financially loss-making intervention. Achieving the balance between promoting demand (and therefore economic activity) and setting a kilowatt-hour tariff, which is acceptable to all, is a real challenge and is further explored here through our field experience.

While we are observing these impacts across only four case study villages, we believe that the findings are widely applicable in a Kenya and Uganda context. The intervention villages were carefully selected to be representative of their regions across both demographic and financial metrics. In addition, the extended longitudinal nature of the observations makes these studies distinct from most of the previous works. Vernet *et al.* [27] assessed entrepreneurship in Kitonyoni with a nearby (but not competing) nonelectrified village to assess the impact of business growth and entrepreneurship following the minigrid deployment. This work showed that electrification benefited business growth and business creation but, at the time of measurement, this did not translate into increased profit for established businesses, which further strengthens the rationale for the observed elastic demand for electricity. Increased profits would be expected to occur several years later when their current investments costs had been paid off by businesses. More than 1000 household surveys were undertaken, assessing household wellbeing, perceived financial wellbeing, nutrition, electricity access, education, and healthcare, providing a range of widely applicable benchmarks for this study [22].

The observed price sensitivity in a Kenya context reflects the observations of other studies in an SSA context. Madubansi and Shackleton [28] studied the impact of electricity provision on fuel wood use over an 11-year period in villages in Bushbuckridge Lowveld, South Africa. Almost a decade after the introduction of electricity, 90% of households continued to use fuelwood, in part due to the far lower inflation rate for fuel wood compared to electricity [28]. Williams [29] modeled rural microgrids in Rwanda, demonstrating that price elasticity was the dominant variable in solar systems followed by mean daily consumption and exchange rates. Interestingly, Muller *et al.* [30] suggest that the level of elasticity in their study is small—due to the low levels of electricity consumption, which is, perhaps, at odds with the demand development that we wish to foster.

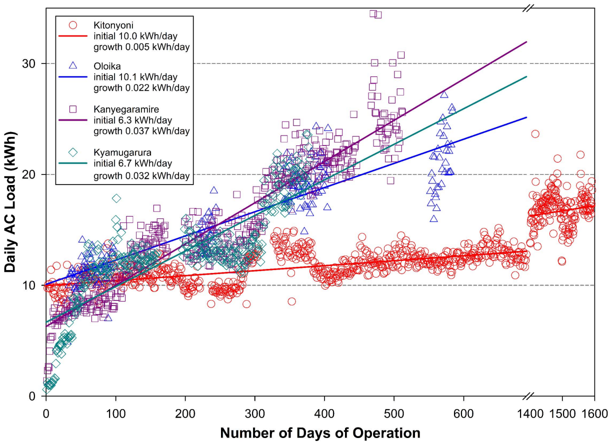


Fig. 10. ***Linear correlation of the measured daily demand growth with a number of days of operation. 28-kWh/day design load. Kitonyoni*** $y = 0.0045x + 10.0$, $r2 = 0.71$, ***Oloika*** $y = 0.022x + 10.1$, $r2 = 0.81$, ***Kanyegaramire*** $y = 0.037x + 6.3$, $r2 = 0.88$, ***and Kyamugarura*** $y = 0.032x + 6.7$, $r2 = 0.68$.

VII. CONCLUSION

We observe that businesses tend to overstate their level of turnover when surveyed in a village prior to deployment of a minigrid as they may wish to appear successful. In addition, despite making it clear that electricity prices for use will be much higher than the utility network, this is not really believed. High electricity price per kilowatt hour is a constant source of tension among consumers. Electricity demand is noted to be elastic in the village in response to price. In Kitonyoni, initially, billing was retrospective of usage and this led to problems of late payment and defaulting. The introduction of a prepayment system eliminated this issue. There have been three reductions in electricity price (from 200 to 100 and then to 75 and 70 KSh/kWh; note, 100 KSh = \$1.0), which have resulted in a rise in electricity usage [22].

The billable load (kWh) can be a small fraction of the daily load at low kilowatt per day operation. While, for renewable generators such as PV, this does not have any direct financing implication, it needs to be considered in relation to the costing of the battery and any diesel generators. In relation to the battery, in particular, the battery is being cycled and care needs to be taken to ensure this cost is being recovered. For highly monitored schemes such as the e4D scheme in Kitonyoni, the effect of power factor can be significant during the early years of operation when daily demand is low. The arrival of the utility grid remains the biggest threat to minigrid economics, the grid arrived in Kitonyoni in 2015, and this has placed further pressure to reduce the minigrid electricity price. The unreliability of the national grid is acknowledged to a certain extent by Kitonyoni consumers through their continued support for their minigrid.

The most notable difference between the four sites is the tariff setting per kilowatt hour of electricity, which has led to very different outcomes at the four sites. Across

Kenya and Uganda systems, we observe the effect of the full range of tariff options from subsidized to anticipated full economic recovery.

The Uganda minigrids (Kanyegaramire and Kyamugarura) have been operated on a different charging tariff to those in Kenya. It is interesting to compare the impact of this decision. All systems have been designed for a 28-kWh/day demand with only the original Kitonyoni system having a secondary diesel generator support. In Uganda, the 28-kWh/day limit was rapidly reached (within 30 months in both cases) due to the grid price equivalent electricity tariff that encouraged wasteful electricity use (Fig. 10). The growth in electrical demand is observed to be 0.032 and 0.037 kWh/day from the same initial level (6 kWh/day), compared to 0.005 kWh/day in Kitonyoni, which is approximately eight times slower. Oloika has developed more rapidly than Kitonyoni following electrification and has an electrical demand increase rate four times higher. At observed demand growth rates, the number of years until the design limit is reached in Oloika and Kitonyoni is 4 and 11, respectively. A 25-year lifetime system, delivering 28 kWh/day of operation, would represent 256 MWh of billable supply. Kitonyoni will take 11 years to reach its 28-kWh/day limit and will have a billable shortfall of 36 MWh (14%). Kanyegaramire and Kyamugarura reach capacity much quicker, having a shortfall of 6.4 and 7.1 MWh, respectively (2% and 3%).

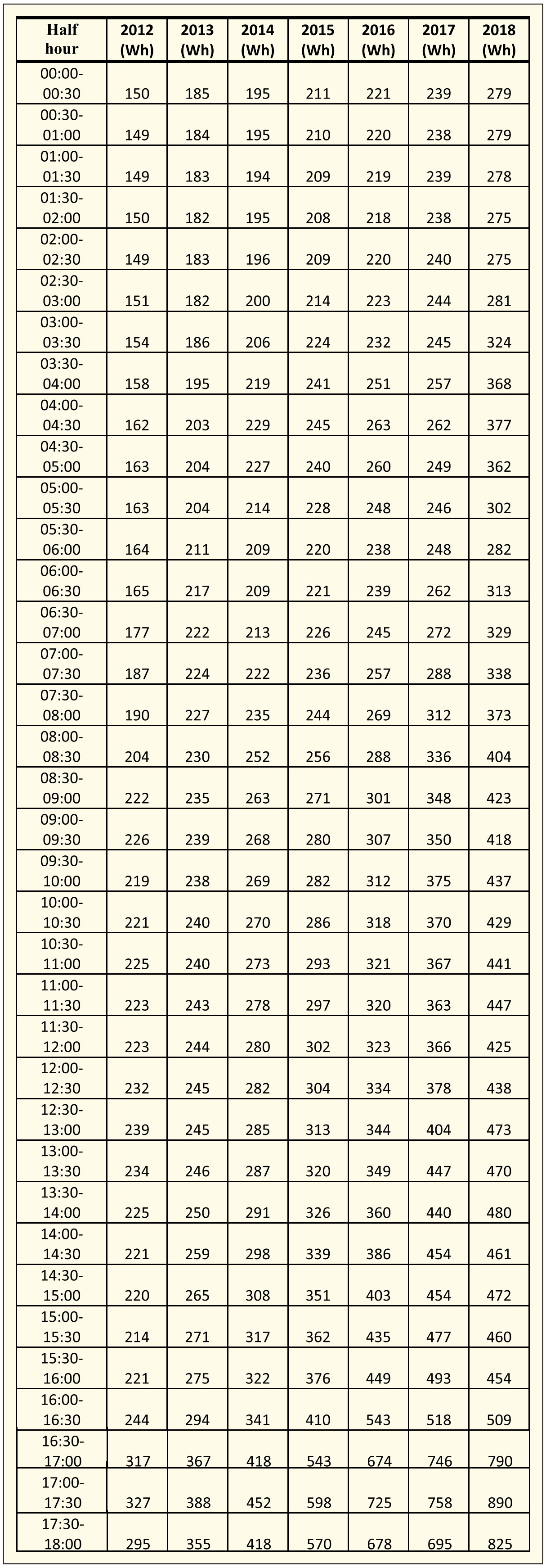
Lighting within the Uganda villages was operated throughout the night as consumers prioritized security over marginal electricity cost increases. There was no quick deployable solution to increase the capacity of the system (kWh/day limit), and hence, an alternative approach was taken to provide a free CFL to LED lighting upgrade throughout the village. These bridging approaches are critical to provide the time for engineers to deliver increased capacity to minigrids.

Affordability, in comparison to the subsidized utility grid, is perhaps the biggest barrier to minigrids combined with a political landscape, which creates significant investor risk concerning the rate and spread of utility grid electrification. The risk of a minigrid becoming a stranded asset due to sudden changes in grid policy is particularly high. Grid extension decisions may be made on short-term political rather than strong technical grounds that make investor risk hard to quantify and manage. Policy announcements governed by national politics creates uncertainty and can transform the energy landscape overnight. ■

APPENDIX

Table 2 gives the average half-hourly demand (Wh) for a 24-h profile in Kitonyoni by year. The corresponding load profiles are also shown graphically in Fig. 11.

Table 2 Kitonyoni Average Half-Hourly Load Profile (Watt-Hour per Half-Hour), 2012–2018



Half hour	2012 (Wh)	2013 (Wh)	2014 (Wh)	2015 (Wh)	2016 (Wh)	2017 (Wh)	2018 (Wh)
00:00-00:30	150	185	195	211	221	239	279
00:30-01:00	149	184	195	210	220	238	279
01:00-01:30	149	183	194	209	219	239	278
01:30-02:00	150	182	195	208	218	238	275
02:00-02:30	149	183	196	209	220	240	275
02:30-03:00	151	182	200	214	223	244	281
03:00-03:30	154	186	206	224	232	245	324
03:30-04:00	158	195	219	241	251	257	368
04:00-04:30	162	203	229	245	263	262	377
04:30-05:00	163	204	227	240	260	249	362
05:00-05:30	163	204	214	228	248	246	302
05:30-06:00	164	211	209	220	238	248	282
06:00-06:30	165	217	209	221	239	262	313
06:30-07:00	177	222	213	226	245	272	329
07:00-07:30	187	224	222	236	257	288	338
07:30-08:00	190	227	235	244	269	312	373
08:00-08:30	204	230	252	256	288	336	404
08:30-09:00	222	235	263	271	301	348	423
09:00-09:30	226	239	268	280	307	350	418
09:30-10:00	219	238	269	282	312	375	437
10:00-10:30	221	240	270	286	318	370	429
10:30-11:00	225	240	273	293	321	367	441
11:00-11:30	223	243	278	297	320	363	447
11:30-12:00	223	244	280	302	323	366	425
12:00-12:30	232	245	282	304	334	378	438
12:30-13:00	239	245	285	313	344	404	473
13:00-13:30	234	246	287	320	349	447	470
13:30-14:00	225	250	291	326	360	440	480
14:00-14:30	221	259	298	339	386	454	461
14:30-15:00	220	265	308	351	403	454	472
15:00-15:30	214	271	317	362	435	477	460
15:30-16:00	221	275	322	376	449	493	454
16:00-16:30	244	294	341	410	543	518	509
16:30-17:00	317	367	418	543	674	746	790
17:00-17:30	327	388	452	598	725	758	890
17:30-18:00	295	355	418	570	678	695	825

Table 2 *(Continued.)* Kitonyoni Average Half-Hourly Load Profile (Watt-Hour per Half-Hour), 2012–2018

18:00-18:30	248	316	365	509	606	632	761
18:30-19:00	223	282	316	431	507	548	697
19:00-19:30	208	256	277	360	416	464	578
19:30-20:00	197	239	251	315	356	412	504
20:00-20:30	188	230	237	292	322	376	461
20:30-21:00	179	222	229	274	294	333	421
21:00-21:30	172	216	220	259	262	291	374
21:30-22:00	167	209	213	244	244	266	350
22:00-22:30	162	201	208	231	235	254	329
22:30-23:00	160	195	204	222	228	248	311
23:00-23:30	155	191	199	216	225	241	295
23:30-24:00	153	187	197	213	223	238	283
TOTAL (Wh/day)	9,545	11,305	12,446	14,229	15,909	17,522	20,545

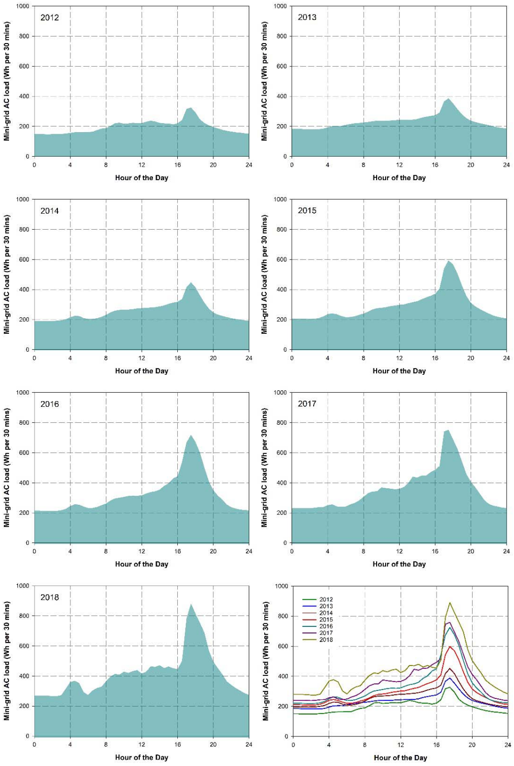


Fig. 11. ***Average daily profile for Kitonyoni, 2012–2018, half-hourly watt-hour average.***

Acknowledgments

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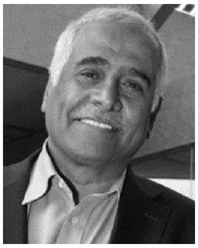

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