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PAPER

Service-based off-grid solar for productive use in poor urban settings: insights from an informal settlement in Cape Town, South Africa

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Abstract

The productive use of energy (PUE) is a critical pathway to development, as it enhances productivity and facilitates income-generating activities. However, PUE is little understood in low-resource urban settings in the context of off-grid energy. Drawing on two projects implemented between 2019 and 2022, this paper presents a case of off-grid solar for PUE in a young, unelectrified informal settlement in Cape Town, South Africa. The projects investigated the state of energy access in the settlement using household surveys and interviews, and installed solar microgrids in partnership with a local off-grid solar provider who deployed a 'service-based' provision model. We find that limited energy options in the settlement commensurately limited energy usage mainly to domestic applications. The microgrids provided reliable refrigeration and lighting for small businesses which improved their operations, delivered energy autonomy, and stimulated aspirations for growth. Energy consumption from the microgrids revealed seasonal and temporal variations which requires flexible demand-responsive energy systems, and holds implications for sizing, storage, and scaling. Although targeted, the 'service-based' model limited productive uses to only those that fit within the remit of the model and high costs particularly for appliances prohibited wider PUE adoption. These challenges impact the scalability of off-grid solar in informal settlements which calls for innovative financing approaches and increased policy support for off-grid providers operating in these communities. Off-grid solar has the potential to stimulate PUE and alleviate energy poverty in informal settlements, but more case studies are required to widen the evidence-base, thereby advancing South Africa's energy transitions agenda.

1. Introduction

This paper demonstrates that service-based off-grid solar (i.e. providing tailored energy services rather than electricity) is a potential way of electrifying poor urban communities and stimulating productive uses of energy (PUE). We build onto similar work and efforts that have explored different electrification approaches for poor urban communities (ESMAP 2012, World Bank 2015, de Bercegol and Monstadt 2018, Runsten *et al* 2018, Slum Dwellers International 2018a, 2018b, Conway *et al* 2019, Smit *et al* 2019). The case considered is a relatively young, unelectrified[5] and unelectrifiable[6] informal settlement in Cape Town, South Africa, and we show how bespoke 'service packages' offered through solar microgrids are meeting the energy needs of

[5] We use the term 'unelectrified' to mean not formally connected to the grid.
[6] By 'unelectrifiable' we mean settlements that will not be formally connected to the grid in the foreseeable future either because they occupy disputed land, wetlands, or gazetted land reserves.

women-led small businesses in the settlement. By working with women-led businesses, the paper also contributes to understanding of the gendered aspects of energy access in poor urban settings (Parikh *et al* 2012, 2015, Musango *et al* 2020, Petrulaityte *et al* 2022, Anditi 2023). The paper contributes to literature on off-grid infrastructure in African cities, specifically furthering our understanding of off-grid energy for productive uses in informal settlements which is an even less understood area of inquiry. We argue that 'service-based' off-grid solar models can electrify poor urban communities, overcome the barriers to grid access, and stimulate PUE. This case study is not intended to be normative, and neither do we prescribe it as the panacea for all off-grid solar electrification of informal settlements in Cape Town or elsewhere.

There is growing recognition of PUE, but little rigorous evidence links off-grid electrification, let alone off-grid solar, to productivity, poverty alleviation and sustainable development in poor urban settings (Doumbia *et al* 2013, GOGLA 2018, Dagnachew *et al* 2023). Given the high incidence and growing number of informal settlements in African cities, there is a need to consider what role off-grid solar can play in electrifying these communities, and how best electrification can be delivered for productive uses. Across its many configurations of scale, capacity and application, off-grid solar is revolutionizing energy service delivery to the most deprived populations in sub-Saharan Africa (International Energy Agency 2022). Even with disruptions from the Covid-19 pandemic, the off-grid solar sector remained resilient, is steadily recovering to pre-pandemic levels and solar energy kits were on track to meet the energy needs of nearly half a billion people by 2021 (GOGLA *et al* 2022, p 12). In fact, the pandemic occasioned a relatively new trend for off-grid solar companies to serve urban and weak-grid markets which were easier to reach and typically have higher energy needs (Advisors 2022, p 13). The cost of solar PV has also rapidly declined over the last decades; by as much as 85%, 80% and 90% for utility-scale solar, residential rooftop solar, and solar PV modules respectively between 2010 and 2019 (International Renewable Energy Agency 2020, p 61). Declining costs, buttressed by innovative financing and business models have attempted to make solar more accessible. As such, increasingly, solar kits provide the primary energy source and first-time access to electricity for urban households in countries like Liberia, Rwanda, Uganda, Nepal, and Myanmar (Advisors 2022, p 52). However, the upfront cost of acquiring solar systems and devices remains prohibitive for many low-income households. Further, off-grid solar has largely been framed as a solution to address energy poverty in rural areas (Jaglin 2019b), therefore most off-grid solar companies have primarily targeted markets in rural and remote areas where there is no grid or the grid is yet to arrive. However, urban areas are a nascent, promising market segment for off-grid solar (Le Picard and Toulemont 2022), for reasons such as a weak or unreliable grid and urban dwellers' growing aspirations for 'energy autonomy' (Jaglin 2019a).

Electricity access in sub-Saharan Africa is highly unequal at the subnational level (World Bank 2016), with stark inequalities in urban areas which have enclaves with a weak grid or no grid, communities living in multidimensional poverty, and unelectrifiable areas like informal settlements (Yaguma *et al* 2024). Despite these gaps in urban grid coverage and access, there is little knowledge and evidence of the role that off-grid energy could play in filling them. With this growing untapped potential and an increasingly heterogeneous energy landscape in cities, off-grid solar is poised to play a critical role in advancing urban energy access and energy transitions either alongside the grid or as the sole energy source for the urban unelectrified (Runsten *et al* 2018, Koepke *et al* 2021, Pilo' 2022, Smith *et al* 2022). Indeed, we are starting to see increased solar presence in urban areas. Evidence of this is all over many African cities—in retail shops selling solar kits and devices, solar streetlighting, PayGo solar advertising through mobile telecom operators, rooftop solar on private residences in the affluent neighborhoods, and community solar in low-income housing blocks (Slum Dwellers International 2017, 2018a, Conway *et al* 2019, Munro 2020, Koepke *et al* 2021, Munro and Samarakoon 2023).

The technical, social and material geographies of solar uptake across Africa and even within countries are manifold (Ockwell *et al* 2018, Kirshner *et al* 2019). In South Africa for instance, solar deployment has largely been grid-tied and utility-scale oriented, while lower-income African countries with limited grid coverage and low electricity access rates have off-grid solar as the main configuration (Kirshner *et al* 2019). These variations are a product of different phenomena, including policies and (dis)incentives for renewable energy, energy resource endowments, grid coverage, socioeconomic trends, cultural and historical contexts, among others (Ockwell and Byrne 2016, Baker and Sovacool 2017). The diffusion of off-grid solar in urban Africa reveals multi-scalar socio-technical energy geographies, which calls for nuanced understanding of off-grid solar in low-resource settings like informal settlements. Heeding this call, in this paper we 1) investigate the energy gaps in 'young' informal settlements; 2) explore the role of off-grid solar in filling these energy gaps, and 3) consider the utilization of off-grid solar for productive uses in these communities. We start by discussing the concept of energy for productive use with respect to off-grid energy, then present a case study of solar microgrids deployed in an informal settlement, and finally offer implications based on our learnings from this unique case.

2. Off-grid electrification for productive uses

The productive use of energy (PUE) and productive use of renewable energy—broadly referring to the application of energy and electricity for production rather than simply consumption—has gained traction over the last decade, fuelled by a recognition of the causal linkages between energy and development outcomes of poverty reduction and economic growth (Meadows *et al* 2003, Kooijman-van Dijk 2012, Practical Action 2012, Doumbia *et al* 2013, EnDev 2020). There is no official definition of 'productive uses' in the context of energy, but commonly these are applications of energy that increase incomes and productivity by facilitating income generating activities or improving the business climate (de Groot *et al* 2017, EnDev 2020, p 49). The general premise is that energy is a service, so it is not an end in itself but is a means to different ends, some of them productive. Initiatives like the PUE (PRODUSE)—a joint initiative between the Energy Sector Management Assistance Program (ESMAP), the Africa Electrification Initiative, the EU Energy Initiative Partnership Dialogue Facility and Deutsche Gesellschaft für Internationale Zusammenarbeit—advocate for the active promotion of productive energy usage in energy access programs, arguing that PUE substantially increases the impact of electrification and energy access programs on poverty alleviation and economic development (Doumbia *et al* 2013).

Other initiatives include the Efficiency for Access Coalition and Access to Energy Institute which focus on appliances (Access to Energy Institute n.d., Efficiency for Access n.d.), the Powering Agriculture and Water and Energy for Food which focus on the agricultural sector (USAID n.d., Water and Energy for Food Grand n.d.). Notably, many of these initiatives largely focus on PUE in rural settings. In this paper, we demonstrate that similar approaches for stimulating PUE can be extended to low-income urban communities, particularly those which are largely unelectrified and unelectrifiable. Some studies have investigated PUE in urban informal settlements (King *et al* 2012, Matinga *et al* 2018, Mohlakoana *et al* 2019), but these studies have been conducted in established settlements with substantial grid presence, taken a broad view of all energy forms (both grid-based and off-grid), or they only focused on a sub-sector in informal settings like street food vendors. Further, although the paper is PUE-focused, one of the projects on which it is based worked with women-run small businesses, which implicitly adds a gender dimension and a novel intersectionality to the topic of PUE in informal settlements.

Pro-poor electrification solutions range from lower tier energy sources like pico-solar lamps, lead acid batteries and SHSs to the highest energy access tiers that involve some form of grid-based service, and everything in-between. Typically, the lower energy access tiers feature energy sources of capacity between 3 W and 2 kW, while higher tiers offer larger capacity energy access and longer duration of service (ESMAP 2015). While each tier has its merits, PUE can only be realistically achieved with larger capacity energy sources that can power productive-use equipment and appliances, thus lower tier energy sources like pico-solar home systems are limited in their ability to stimulate PUE (Bharadwaj *et al* 2023). Therefore, in moving from energy-for-basic-services to energy-for-productive-uses, off-grid energy providers are expanding their product ranges to meet PUE applications and innovating to widen their service offerings to accommodate larger capacity applications and higher-wattage electrical appliances like refrigeration units, televisions and entertainment sets, or appliances tailored to specific businesses like hairdressing kits and sewing machines (Rocky Mountain Institute 2015, EnDev 2020). Subsequently, off-grid solar has found emerging productive uses in smallholder agriculture, small business enterprises and health facilities (Miles *et al* 2022). This expansion in service offerings is particularly well suited to the urban market where customers have relatively high incomes and considerable energy demand. Despite this, little is known of how higher-tier off-grid solar can be successfully deployed at scale in urban settings, and particularly in weak-grid or unelectrified communities like informal settlements.

In addition to facilitating economic empowerment for end users, PUE is one way of de-risking off-grid energy projects, as it increases the demand for energy, increases end users' incomes and revenue and consequently, their ability to pay for the service (Dagnachew *et al* 2023). PUE renders off-grid energy projects scalable and financially viable for developers, investors and financiers, especially if targeted at groups for whom demand can be stimulated (International Solar Alliance 2022). When considerations for PUE are embedded in off-grid energy initiatives, households and communities prospectively become fertile ground for stimulating entrepreneurial ventures, growing businesses and creating local employment opportunities (GOGLA 2018). Thus, electrification efforts in low-resource settings are urged to pragmatically plan for PUE if they are to deliver the envisaged socio-economic benefits (Dagnachew *et al* 2023). In the project on which this paper is based, solar microgrids were installed in an informal settlement and targeted at women-run small businesses, although households close to the microgrids were also connected. This was achieved by aggregating energy provision from the microgrids into distinct 'service packages' each offering a specific energy application (or combination of applications) to consumers as will be detailed later.

3. Methods and study design

3.1. Context and case study

The study took place in Qandu-Qandu informal settlement in Cape Town, South Africa. South Africa has suffered energy supply shortfalls and loadshedding since the late 2000's, resulting in nationwide rolling blackouts and recently, a rapidly deteriorating energy crisis. The 2022 national census puts the electricity access rate at 94.7%, with variations between regions and provinces. Disparities also exist in electricity applications at household-level. For instance, 96.7% of households in Cape Town use grid electricity as their main source of lighting while 64.2% use electricity for cooking (Department of Statistics South Africa 2023). Cape Town also has the highest proportion of inequality and slum incidence in South Africa, with 12.5% of households currently living in informal dwellings compared to the national average of 8.1% (Cinnamon and Noth 2023). In their 2050 Energy Strategy, the City of Cape Town municipality recognizes alleviating energy poverty as one of its main priorities, which includes electrification and public streetlighting for informal settlements and extending subsidies to unelectrified households (City of Cape Town 2024). Despite high grid electricity access in the city and subsidy schemes like the Free Basic Electricity allocation and Lifeline tariff, energy poverty in low-income households remains pervasive. These households are primarily in informal settlements or so-called 'backyard dwellings'. By 2021, an estimated 10 000 informal households in Cape Town were unelectrifiable; that is, they cannot be connected to the grid owing to their location on disputed or reserved land, or wetlands (City of Cape Town n.d.). Qandu-Qandu is one such settlement; located in the quasi-formal Khayelitsha settlement, it sits on a wetland (see figure 1) and under high voltage transmission lines so it is not formally connected to the grid and there are no known plans to electrify it. It is also one of Cape Town's youngest informal settlements, first inhabited in 2018. At the time of writing, it was home to roughly 3500 households. For these reasons, we selected Qandu-Qandu as the case study.

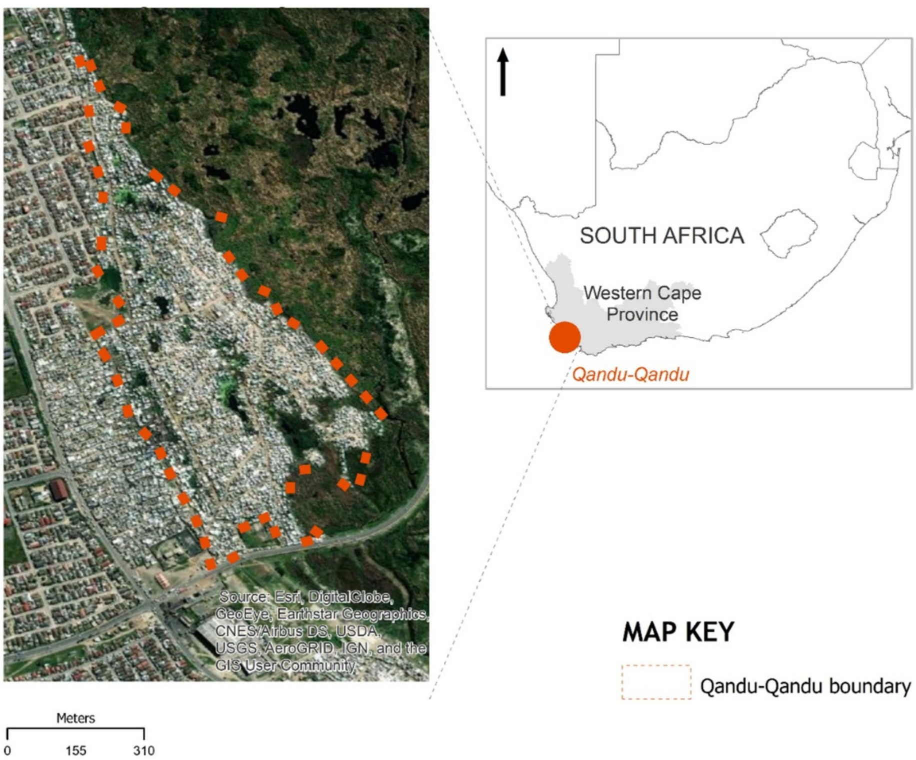

Figure 1. Location of Qandu-Qandu informal settlement, Cape Town, South Africa. Reproduced from Bobbins *et al* 2023. CC BY 4.0.

3.2. Data collection and analysis

The study followed a mixed-methods approach, with data collected through two projects that run between 2019 and 2022 which culminated in the installation of solar microgrids in the settlement. In the first project, household surveys ($n = 331$) were conducted, and 30 interviews held with purposively selected participants. This phase investigated energy and wellbeing in the settlement, and asked participants about their experiences of accessing energy, water and other social services, their energy aspirations, and linkages between energy and their wellbeing. The second project installed microgrids in the settlement and worked with 21 women business owners to investigate their energy needs and run business training workshops. Ten exit interviews were conducted with some businesses which were connected to the microgrids to understand their experiences and benefits. We worked with women-run businesses because commonly, women are excluded from participating in innovative energy projects, lack access to capital and business skills, they dominate the informal and micro-business sector, and women tend to make most of the energy decisions at household-level (de Groot *et al* 2017, Mohlakoana *et al* 2019, Anditi 2023). The survey data (a comma separated values (.csv) file) were imported into Microsoft Excel and R, where basic statistical analyses were done to extract frequency tables of the energy sources used, energy applications, and the sufficiency of the available energy sources. The interviews, some conducted in IsiXhosa (one of the local languages), were translated into English where necessary and transcribed. Each transcript was anonymized with a unique code representing the interview participant and then imported into the NVivo software for coding (primarily deductive) and thematic analysis. Forty codes emerged from the coding process and were grouped into themes related to solar energy usage and experiences and business aspirations. These themes related to the broad question of microgrid-stimulated PUE in the settlement. Finally, energy consumption data from the microgrids were imported into Microsoft Excel, where they were analyzed and visualized. More details on the microgrids are presented next.

3.3. Solar microgrid installation

With support from the project, 11 solar microgrids were installed and are operated by Zonke Energy, a local solar energy company based in Cape Town. The microgrids consisted of 1.2 kWp solar panels mounted on a tower (see figure 2) and 5 kWh battery storage. Each served up to 16 households within a 40 m radius, and consumption was digitally metered under four 'service packages' offering a set of applications and appliances with a daily runtime limit, consumption cap, and tariff as shown in table 1. Early observations from the first few connections showed that running the fridges for 24 hours constrained supply and storage, therefore the fridge and business packages were limited to three consumers per microgrid. Each microgrid also featured a streetlight that provided night-time lighting to surrounding areas. Consumers who signed up for fridges were required to make a down payment of at least R500 ($26) towards the total cost of R3500 ($184), and pay off the rest in interest-free monthly installments of R500 ($26) over six months. The paper is partly informed by time-use energy consumption data from the microgrids collected over a period of six months (from August 2021 to February 2022).

3.4. Study limitations

The time-use data analyzed for this study is for a limited period of six months and from the microgrids that were operating at the time. The number of microgrids, consumers and service packages connected, and energy consumption have most likely changed since the data were captured. The paper focuses on the initial phases of the project; that is from installing the solar microgrids, connecting households and businesses, and monitoring energy consumption over a limited period. Coupled with Covid-19 restrictions which interrupted parts of the field data collection, we are not able to evaluate the longer-term causal linkages between energy consumption from the microgrids and socio-economic impact. We also acknowledge that some energy-productivity linkages can be indirect (de Groot *et al* 2017, Dagnachew *et al* 2023), but these aspects are beyond the scope of this paper and are not considered at length. At the time of writing, Qandu-Qandu is only about six years old, is still largely unelectrified, and borders an electrified settlement. Therefore, the results and observations made cannot be assumed generalizable to other informal settlements in Cape Town or elsewhere.

4. Results

4.1. Energy mix and usage in the settlement

At the time of conducting the survey, the household energy mix consisted of three main energy sources: paraffin, liquefied petroleum gas (LPG), and electricity. Correspondingly, the main energy applications included cooking, lighting, and heating bathwater. This reveals a linkage between the energy sources available to households and the applications they can achieve with those sources. All the respondents who used grid

Figure 2. Some of the solar microgrids installed in the settlement (Photos: Authors).

Table 1. The different service packages offered from each microgrid (Source: Zonke Energy marketing brochure).

Service package	Consumption cap[a]	Cost	Appliances and daily runtime				Number of connections
			Lights	Radio	Television	Fridge	
Lights	0.15 kWh per day	R150 per month [$8]	7 h	5 h	N/A	N/A	130
TV	0.275 kWh per day	R310 per month [$16]	8 h	4 h	3–8 h	N/A	13
Fridge	1.2 kWh per day	R14 per day [$0.7]	4 h	N/A	2 h	24 h	2
Business	1 kWh per day	R12 per day [$0.6]	4 h	N/A	N/A	24 h	19

[a] Occasionally, the caps were slightly adjusted to account for discrepancies caused by operational issues like supply and storage constraints resulting from 24 h fridge operation for the fridge/business consumers.

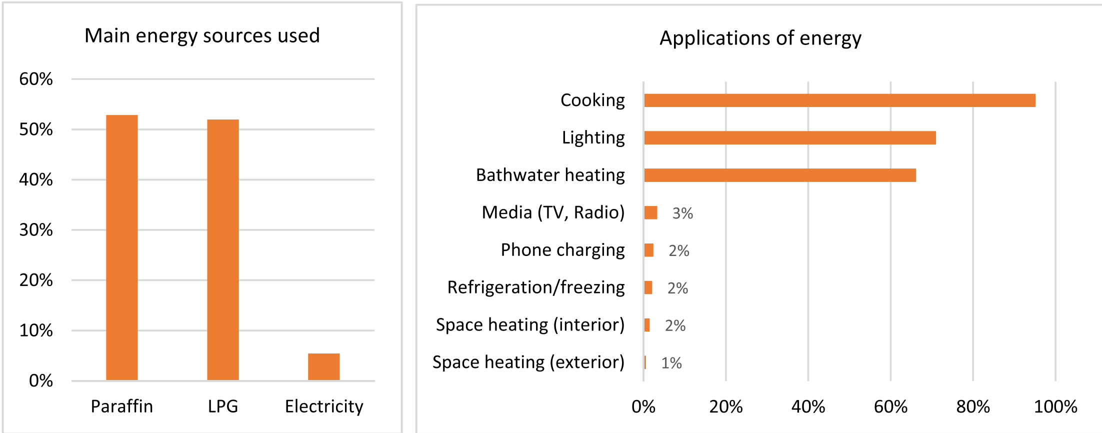

Figure 3. Household energy mix and applications of energy in the settlement ($n = 331$).

electricity acquired it through an illegal connection—64% of them had only had the connection for one year, and 36% had had it for three years which was roughly how long the settlement had been inhabited. Illegal connections are tapped from the nearby Greenpoint settlement often at a fee, and monthly electric bills are paid to informal providers. The settlement's unelectrified status is evident in the very limited usage of electricity for phone charging (2%), refrigeration (2%), and media (3%) as shown in figure 3. LPG, firewood, paraffin and electricity were commonly used for cooking and water heating; candles, paraffin and electricity were used for lighting; and paraffin heaters were used for space heating.

4.2. Sufficiency of the energy options in the settlement

To understand the sufficiency of energy in Qandu-Qandu, we made inquiry into the level of satisfaction with the energy sources used by households. Specifically, we asked respondents if they considered the energy they used for lighting, cooking, and water heating adequate and for all three applications, most respondents thought that the energy sources insufficient—see figure 4. Households using candles for lighting noted that candlelight only lit a small portion of the home and was not bright enough: '*Candle is the only thing I use but it does not light properly like electricity, it does not light the whole house*' (**Respondent QQT19**). Another respondent relayed insufficient lighting in terms of children's ability to read by candlelight: '*…they [children] cannot do homework at night because the candle is too small to light … it does not provide enough light to the whole house…So they [children] are struggling*' (**Respondent QQT4**). Insufficient lighting in informal settlements is widely known to adversely impact activities like children's reading, security, and night-time movements (Caprotti *et al* 2021, Borofsky 2022).

For some households, paraffin for cooking usually run out faster than they expected, compared to when they used it solely for lighting. When using paraffin for space heating or cooking, a participant noted that: '*It does not even last a day, one liter of paraffin…if you cook something like samp [dried corn kernels] it takes long…or modgudu [tripe or offal] it is gonna take a long time to be right [get ready]. So everyday you must buy paraffin, you must have a lot of money, maybe R50 [$2.50] for five liters. And that five liters is not gonna last even a week, more especially if you have a heater which by itself takes five liters of paraffin to be full*' (**Respondent QQT6**). Similarly, LPG intended to last the month ran out before month-end and had to be supplemented with other less desirable fuels like paraffin: '*I use gas [for cooking], but sometimes it finishes before the end of the month, and I do not have money so I must go and buy paraffin*' (**Respondent QQT6**). Expectations for how long LPG will last may come from previous experiences, monthly household expense budgets, or comparisons with cooking with illegal grid electricity for which users typically pay a low flat fee or no fee at all. Grid electricity (all illegal) was unreliable and weak, and could only power light bulbs and phone charging: '*I am using the illegal connection…for TV but sometimes it is not working. Sometimes it works, sometimes it is not working. The problem may be that they stole the cable or maybe the power is weak if someone is cooking or boiling water in their kettle. Even me here, if I am boiling water the TV is not working. I must not boil, I must not use the heavy stuff [electrical appliances]*' (**Respondent QQT6**). All these shortcomings had most households aspiring for better energy services. Asked what they would change in their community if they could, most respondents named 'bringing electricity, housing, water and sanitation facilities' to the settlement. Aspirations for energy could also be deduced from people's preferences for certain energy sources for specific applications. For 64% of respondents, electricity was the preferred lighting source, while the preferred energy for cooking was electricity (75%), LPG (4%), and paraffin (2%). These results indicate widespread energy poverty and energy insecurity in the settlement.

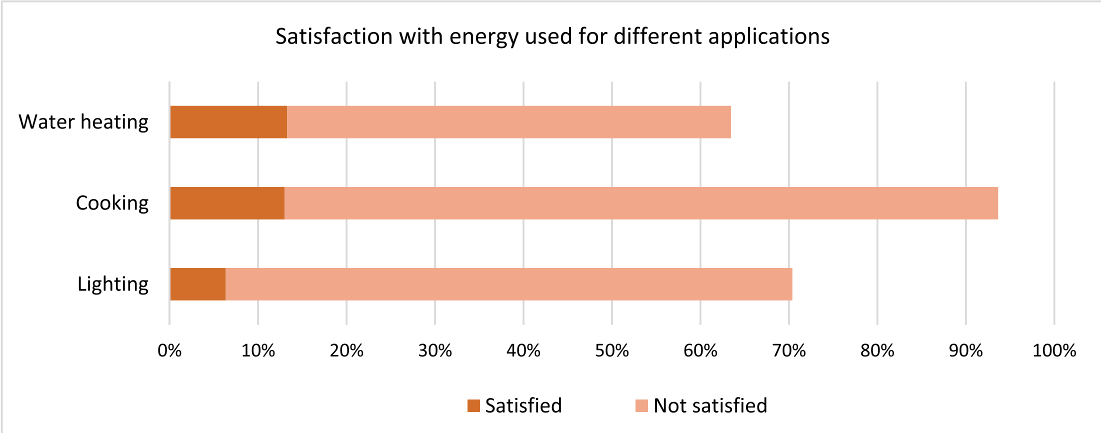

Figure 4. Energy gaps in the settlement, measured as households' satisfaction with the energy they use for water heating, cooking, and lighting ($n = 331$).

4.3. Solar energy usage in businesses

By the end of 2022, about 160 small businesses and households in Qandu-Qandu had been connected to a solar microgrid. We held interviews with some of the business proprietors—focusing on how they were using the solar energy in the business, what changes it had brought thus far, and how they envisaged solar would further benefit the business and advance their livelihood goals. These findings are detailed in this section, substantiated by respondents' remarks.

4.3.1. Lighting

Given that 64% of the households surveyed were not satisfied with their lighting (see figure 4), the lighting delivered by the microgrids was a welcome benefit to neighborhoods and businesses alike. With solar lighting, businesses are now able to remain open for extended hours in the evening, a trend that was observed in the energy usage patterns as will be later shown in figure 5 where consumption on the Lighting package steadily increased between 6:00PM and 10:30PM. Lighting also creates a secure environment where women feel safe running their businesses late into the night, and it facilitates safe nighttime movements, allowing customers to purchase goods which increases business revenues:

> '*…now that I have solar, there is no dark moment because you cannot do business in the dark. The minute it becomes dark and you have no way of lighting, you will only work up to a certain time. For example, my braai [meat-grilling] business, I do it outside and so I need light. And most customers come in the evening after work so I need light outside and inside my house. In the refreshment business, customers stay till late at night.*'—**Respondent P110413**

It is important to clarify that all the *braai* (meat grilling) businesses we came across were using charcoal or wood to *braai* including those that had access to electricity. In this project, the businesses only used the solar microgrids to support the *braaing* i.e. for lighting or refrigerating raw meat products (more details later). The reasons for this were not explored in this study but they likely align with other studies which have found that preferences for cooking with charcoal or wood are informed by factors like cost, food flavor, suitability, and cultural reasons (EnDev 2021). In supporting businesses to run at night, solar lighting also brought safety from fire outbreaks which are notoriously caused by open-flame lighting and cooking sources (Arup 2018), also noted by a respondent:

> '*In business, it helps me a lot, because I am able to light, I am not afraid of getting burnt, I do not use candles, I do not use a paraffin lamp. Even if I am not there and it is late, my children are able to light. Previously this was not possible because the candle is dangerous. I have seen a big difference; I can charge, I can light, I can listen to the radio.*'—**Respondent P110415**

The above quote also reveals the safe lighting removes the hypervigilance and mental stress that comes with using certain energy forms (Li *et al* 2022, Caprotti *et al* 2024); in this case it allowed respondent P110415 above to leave the home and attend to their business at night.

4.3.2. Refrigeration

Two main kinds of businesses signed-up for solar fridge/freezers—those who sold refreshments like cold drinks, and those who sold fresh produce like raw meat, dairy, fruit and vegetables. The direct benefits from refrigeration were an increase in sales for beverages which customers preferred cold; '*…I sell drinks, so they are more enjoyable when they are cold. In the beginning I was not making much profit because people did not want warm drinks but now, I am able to compete with my competitors*' (**Respondent P1111435**). The benefits of refrigeration reported by businesses (specifically for cold beverages) correspond to the energy consumption profiles (see figure 5), where during any season, energy consumption on the Fridge package peaked in the evening when people are more likely to congregate and have a drink. The fridges also preserved perishable goods thus, '*This fridge helps me a lot because when I buy food, I am able to store it in the fridge…*' (**Respondent P1100720**). Before acquiring the fridges, some businesses had to limit how much stock they bought or make multiple shopping trips to re-stock. With the fridges, businesses were able to better plan their restocking purchases, save on transport costs by purchasing bulk stock at reduced prices which they could now safely store: '*I am also able to buy and store my business stock in this fridge which helps me to avoid going to purchase stock all the time*' (**Respondent P1100720**), and '*…in terms of transport as I will be able to buy in bulk and get the stuff cheaper because I will be able to store it [in the fridge]…to sell continuously to my customers with the solar fridge*' (**Respondent P110415**). For others, the fridges offered an opportunity to grow and expand their businesses as discussed next.

4.3.3. Business growth, expansion, and diversification

Many proprietors planned to leverage the solar microgrids to grow and diversify their businesses. While the microgrids had only been recently installed (at the time of colleting the data), some businesses had already started to see an increase in the number of customers and revenue: '*What I have noticed is that since I started this business, I have joined a lot of stokvels [savings groups] because of this business. I am able to get R2500 [$130] for stokvel from this business, I am able to pay myself, buy solar and pay for the fridge…I am able to cover my household budget and also stokvel money. I get close to R7000 [$370] from this business*' (**Respondent P1111424**). Other businesses held visions for growth, such as selling larger volumes of products, adding new business lines and employing people; '*My plan is to grow my business…I would like to sell meat because I have cold drinks…my business can grow bigger than it is now, so that I can also be able to hire someone to work for me…I will be very far in five years' time*' (**Respondent P1111424**) and, '*I would like to expand my products and not just sell one thing…I have been selling refreshments, hard and soft drinks. Now I have added chicken, I am able to braai [grill]*' (**Respondent P1111435).** For others, the microgrids spurred aspirations to diversify into investing in *stokvels* (savings groups) and different products '*…I am now also selling ice cream and popsicles now that I have a fridge*' (**Respondent P110413).** Some proprietors who were employed outside the settlement and only run their businesses part-time held visions to focus solely on self-employment, '*I do not see myself working [being employed] but fully focusing on my own business and extending it to other things, for example… have an internet café … then also add a printing machine for when people want to print or photocopy*' (**Respondent P1111412).** Most of the businesses served customers within their local neighborhood, with only one holding aspirations to grow the business beyond their neighborhood and serve the entire settlement and even neighboring settlements. A notable observation based on the businesses we interacted with in this study is that there seemed to be limited ideas of what to do with the energy since most businesses and business ideas were food-related (e.g. *braai* and fresh meat, pubs/taverns, fruit and vegetable stalls, tuck shops/grocery kiosks). This may be because of the relatively young age of Qandu-Qandu settlement, limitations of the bespoke 'service packages' offered, or because we only worked with women-led businesses which are predominantly informal, survivalist ventures like street food businesses (Knox *et al* 2019). Limited business ideas have implications for business competition in the settlement, revenues, and business growth, and consequently the ability to pay for energy services. This can impact PUE-based energy provision models and opportunities for scaling these models beyond lighting and refrigeration, and therefore warrants further interrogation.

4.3.4. Energy use autonomy and reliability

One aspect that some businesses appreciated about the microgrids was their reliability and agency over energy usage compared to the illegal grid connections which were prone to loadshedding, cable theft or disconnection without notice; '*Currently the problem is if the landlord wants to switch off the [illegal] electricity, they can switch it off even if you have just purchased electricity…there is a huge difference between the [illegal] electricity we are using and solar electricity*' (**Respondent P1100419).** Notwithstanding the consumption caps (see table 1), autonomy over energy usage was enabled by Zonke Energy (the microgrid provider) interfacing directly with consumers which eliminated middlemen like landlords and informal electricity providers. Battery storage provided reliable electricity which enabled businesses to equally operate reliably; '*When we first settled here, we depended on illegal connections, and it is not reliable. One day there is electricity, the next there is not electricity, so I could not make it in the business I first started…the solar has helped me a lot because there is no dark moment, there is no load shedding, it is always here, because it is natural* *[renewable]*' (**Respondent P1111435**). To keep consumers within a 40 m radius of a microgrid, shorter wiring was used which was cost-effective and less prone to theft, therefore cables did not need to be replaced as often as the grid-connection cables. This minimized cases of microgrid power outages caused by infrastructure vandalism. This foregrounds the importance of a robust repair and maintenance ecosystem for off-grid solar infrastructure, which is usually offered under the auspices of aftersales services from the developer/utility or sourced by consumers from local electricians (Harrington and Wambugu 2021). Off-grid infrastructure repair is challenging in the Global South, worse still for users in remote areas or the urban poor who may be disenfranchised from accessing repair centers or skilled technicians (Harrington and Wambugu 2021, Munro *et al* 2023a). Cognizant of these issues and the short lifespan of most solar products marketed and used in the Global South (Munro *et al* 2023b, p 15), a growing body of work is investigating the repairability of solar systems in the context of tackling solar e-waste, increasing the life span of solar systems, and fostering a political economy that eases solar repair and maintenance for remote or vulnerable users (Harrington and Wambugu 2021, Kinally *et al* 2022, Munro *et al* 2022, 2023a, 2023b). Thus, solar systems should be built to forestall infrastructure breakdowns and local challenges like cable theft, as was the case in Qandu-Qandu where the short cables minimized these risks, reduced repair and maintenance needs, and increased microgrid reliability.

4.4. Energy consumption from the solar microgrids

Time-use data were collected for six months (11 August 2021 to 11 February 2022) from the 11 microgrids which were operational at the time. Given this limited-period data set (six months rather than a full year), we only consider the three seasons that straddle this period that is from the end of the winter, through the

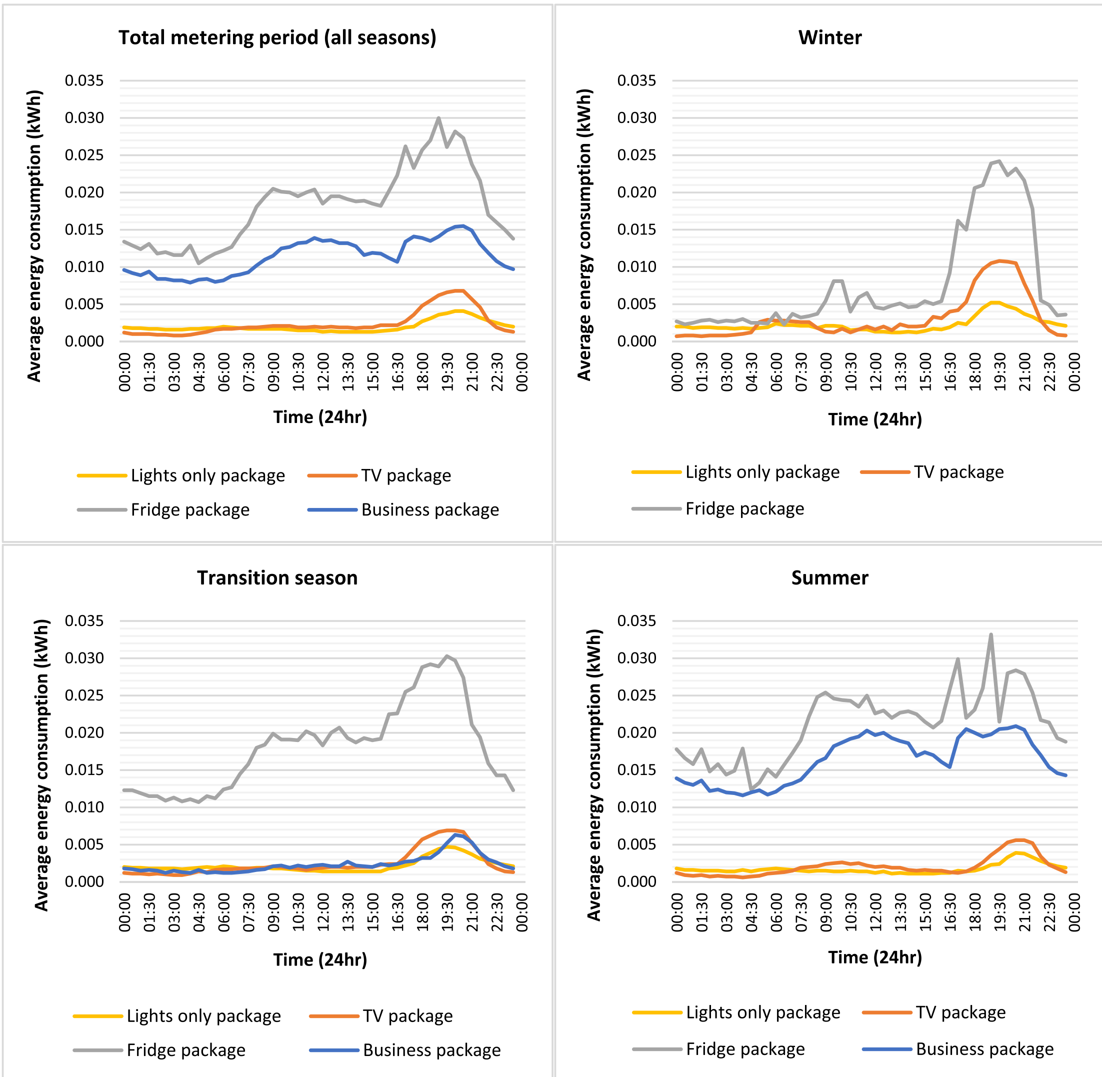

Figure 5. Average half-hourly energy consumption in a 24 h period during different seasons for the different service packages. *Business packages were connected starting in October 2021, during the transition season.

transition season, and into the summer. The average half-hourly energy consumption from the microgrids in different seasons is illustrated in figure 5. For all the service packages, consumption peaked in the early evening hours (between 7:00PM and 10:00PM) in all seasons. There were also noticeable differences in energy consumption across seasons and service packages. Consumption for the Lights package and TV package was highest in the winter and lowest in the summer, while for the Fridge package consumption was lowest in the winter and highest in the summer. The summer also saw fluctuating consumption for the Fridge package and Business package, constituting two high-consumption windows—one in the early morning hours and the another in the early evening hours. For the Lights package and TV package, consumption was lowest in the summer, although the consumption patterns closely mirrored each other except in the winter evening hours where consumption on the TV package outstripped the Lights package by a larger margin.

5. Discussion

5.1. Off-grid solar for small businesses

Considering the insufficiency of energy in the settlement and aspirations for starting or expanding businesses, the energy demanded from the microgrids was likely to increase before long. An expected outcome of PUE in businesses is increased revenues that boost the ability to pay for energy and facilitate business growth (de Groot *et al* 2017, Dagnachew *et al* 2023). For Qandu-Qandu, a shift in energy demanded from the microgrids could come from consumers using electricity for longer hours, using more electrical appliances, or more businesses and households getting connected. Experiences shared by consumers who were already bridged the knowledge and information gaps regarding solar energy, which sparked increased interest in getting connected. This aligns with concepts from *diffusion of innovations* theory, such that early adopters of off-grid solar in newly electrified settlements play the role of appraising, trendsetting and paving the way for others to get connected and derive the same benefits (Dearing and Cox 2018). Wide evidence also shows that whenever a community is first electrified, their energy needs evolve and grow before stabilizing, and requests for energy system upgrades with higher-capacity energy sources soon emerge (Parikh *et al* 2012, Richmond and Urpelainen 2019, Opiyo 2020). Scalable energy solutions are then required to match and meet these growing energy needs.

Although the energy consumption data and narrations point to people's desires to run businesses and put electricity to different productive uses, the service packages that can be considered productive-use (Fridge package and Business package) were cautiously adopted likely because of their higher cost. At the time of collecting the data, 79% of the service packages installed were Lights (cost R5 or $0.3 per day), about 12% were Business packages (cost R14 or $0.8 per day) and just over 1% were Fridge packages (cost R12 or $0.6 per day). High costs are prohibitive, therefore closing the last-mile access gap through off-grid solar or other sources can only be meaningfully achieved in an enabling environment that economically empowers people and bolsters their ability to pay for social services. This will require a whole-systems approach to off-grid solar in informal settlements, whereby energy provision is aligned with social protection and poverty eradication policies and integrated into existing energy policies, subsidies and tariffs. One such policy in South Africa is the Free Basic Alternative Energy Policy 2007 (FBAE) (Department of Mineral Resources and Energy 2007), which is targeted at unelectrified poor households and implemented at the discretion of municipalities and city councils. Beneficiaries of the FBAE must be connected to the 'official non-grid systems' provided by either the municipality or service providers appointed and supervised by the municipality (Department of Mineral Resources and Energy n.d.). Widening the policy to young informal settlements like Qandu-Qandu and working with local off-grid solar providers like Zonke Energy would alleviate the cost-burden from households and widen the productive-use consumer base.

5.2. Variable energy consumption patterns

The energy consumption patterns observed in this study underscore the following: (1) the importance of reliable battery storage in off-grid solar for productive use initiatives, (2) that seasonal and temporal variations in energy consumption are dependent on the type of productive use/business, (3) that the structure of energy service offerings elicits specific energy usage patterns from consumers, and (4) that there is sizeable energy demand for productive uses in informal settlements. Across all the service packages, energy consumption from the microgrids peaked in the evening, more so for the Fridge package and Business package. Therefore, off-grid solar for productive uses in informal settlements should feature sizeable battery storage to meet the high nighttime demand, and to power sizeable appliances and equipment. Seasonal and temporal variations in energy consumption followed typical behavioral patterns in households and businesses and are crucial considerations for off-grid solar provision (Adeoye and Spataru 2019, Conevska and Urpelainen 2020). In the winter, people are more likely to stay indoors using lighting and television, and the cooler temperatures warrant less usage of fridge/freezers. The converse applies during the summer season. Similar relationships between electricity consumption and household activities have been observed in domestic settings (Satre-Meloy *et al* 2020). Most businesses also dealt in beverages or fresh produce, therefore consumption on the business package correspondingly increased in the summer and in the evening hours when alcoholic beverages are typically consumed. This was substantiated by several business owners whose customers preferred chilled beverages. Variable seasonal and temporal energy consumption also depends on the operating cycles and type of business or productive activity, for example a tavern/pub selling cold beverages would have a different consumption profile from a hair salon. Regarding the structure of the service packages, the consumption caps (see table 1) likely elicit self-limiting behavior in energy usage, which also shapes energy consumption trends.

Despite these variations, these findings demonstrate appreciable energy demand for domestic and productive uses in informal settlements which cannot be met by low-capacity solar kits like solar lamps and solar home systems. Indeed, some energy demand was likely suppressed for different reasons like cost or limited physical space for appliances as noted by one respondent who said, '*Although I am looking to grow my business and get all the appliances so I can watch TV and do other things, currently my space is limiting me*' (**Respondent P110415**). This response aligns with observations that problematize approaches which assume that providing energy access will necessarily lead to development outcomes. Fingleton-Smith (2020) urges that we temper our expectations of how, at what scale and to what extent energy access spurs development and Bharadwaj *et al* (2023) show that low-capacity energy systems although 'clean', limit appliance usage and curtail the productive use of electricity. While clean energy has the potential to unlock numerous benefits for businesses and business owners may be willing to adopt clean energy sources, the reality is that often, realizing these benefits is complex and nuanced (Fingleton-Smith 2020). As such, maximizing energy access benefits especially in complex settings like informal settlements will require a comprehensive consideration of factors that encompass socio-economic, environmental, material conditions (as in the case of the limited physical space to use appliances), and others. Overall, the energy consumption patterns observed in this study offer useful lessons for off-grid energy provision in informal settlements, and can inform solar system sizing and appropriate business and infrastructure models, all of which determines the acceptability and practicality of off-grid energy solutions for these communities.

5.3. Suitability of off-grid solar for unelectrified informal settlements

This project demonstrated service-based energy provision as a viable electrification model for informal settlements that have considerable energy needs but not the means to own or operate energy infrastructure. Among other things, the value proposition of the microgrids installed in Qandu-Qandu lay in aggregating energy provision into 'service packages' tailored to specific energy needs of both domestic consumers and small businesses. This improved consumers' willingness and ability to pay for their desired service package. Scaling up the solar microgrids to meet growing demand could offer Zonke Energy (the provider) favorable economies of scale and cost competitiveness whilst also delivering appreciable energy quantities to consumers (International Renewable Energy Agency 2019, p 8). Further, the service packages and piecemeal payments for appliances were well suited to Qandu-Qandu as a young settlement where incomes are low and irregular as in most informal settlements. There was also an appreciation for the autonomy that the solar microgrids offered compared to illegal grid connections, which aligns with postulations that off-grid solar by private developers like Zonke Energy enables citizen autonomy from state-led processes. The perceived merits of autonomy imply that under favorable conditions, informal settlement dwellers may be willing to (co)own off-grid energy systems and this could be explored as a long-term strategy in Qandu-Qandu, especially if grid electrification or resettlement to a new area remains unlikely. Earlier on, we alluded to aspects of scalability, where the unmet energy needs for cooking, space heating, space cooling, water heating, and other applications could be met by sufficiently sized off-grid solar. This would present possibilities to feed into the grid given the safety of DC power in settlements like Qandu-Qandu which is in a wetland. The policy environment in which off-grid energy is provided is also relevant, as it shapes technological and business model innovation (Trotter and Brophy 2022). For instance, synergy between poverty eradication policies and (renewable) energy policies can be harnessed to support off-grid energy specifically for productive uses in informal settlements.

While the focus of this paper is on PUE, the suitability of off-grid solar for informal settlements requires an appreciation of the challenges associated with operating microgrids in these complex settings. One challenge that is widely known in the literature is financing (EnDev 2020). In this case study, the capital costs of the microgrids were funded by grants from international research funds through local and international partner universities, with operating costs met by revenue from consumer payments. However, informal settlement dwellers typically earn low and irregular incomes therefore affordability was a challenge, specifically the down payment and monthly installment payments for appliances (especially the fridge). This impacted cashflows and the operation and maintenance of the microgrids. Zonke Energy (the provider) is a socially-oriented private enterprise, but the success and continuity of the company still requires sustainable funding streams and realistic financial projections, which can be difficult to construct given the complexity, temporariness, and variable conditions in informal settlements. Such complexities manifested in the irregularity or non-payment of consumers, local micropolitics like solar tower placement in the settlement and the ensuing land disputes, and delays in addressing technical faults eroded trust which necessitated strong and continued community engagement (Bobbins *et al* 2023). Although the service-based model met specific energy needs, it also limited the range of productive uses to only those which could be supported by the service packages and appliances offered. Another challenge was in the earlier stages of the project when there was a mismatch between the planned consumption caps and actual appliance consumption (specifically the fridges), which created supply and storage constraints that necessitated adjustments in the business model. These challenges are common in off-grid energy provision in low-resource settings, and cognizance of them can inform realistic and impactful provision models.

6. Conclusions

Using the case of solar microgrids installed in a young 'unelectrified' informal settlement in Cape Town, this paper aimed to demonstrate the potential of service-based off-grid solar for stimulating productive uses in such settings. It contributes to knowledge on productive uses of (renewable) energy, informal settlement electrification approaches, and it is a timely contribution to discussions and solutions for South Africa's (urban) energy transition given the country's current energy crisis. We find that unelectrified informal settlements like Qandu-Qandu have very limited energy options which in turn severely limits energy applications to mostly domestic and non-productive applications that can be achieved with the narrow range of energy sources available. Innovative off-grid solar can be deployed to fill these vast energy gaps, stimulate productive uses and economically empower people. In the project on which this paper is based, a service-based off-grid solar model fulfilled specific energy needs for businesses, inspired new business ideas and precipitated aspirations for business growth. The model also limited the number and type of PUEs to which the microgrids could be put, which calls for scalable off-grid solutions beyond bespoke service offerings in the medium-long term. An examination of energy consumption from the microgrids reveals variable seasonal and temporal consumption patterns depending on the type of productive use or business, which warrants flexible but reliable battery storage to meet these variations. We contend that such energy demand variations may be heightened by climate extremes like heat waves or colder winters, and this should inform microgrid sizing and scaling. Further, while the value proposition of service-based off-grid solar is in meeting specific energy needs, such models should also hold considerations for shifting demand and a wider range of PUE in the long term. In this case, the focus on lighting, media and refrigeration limited the range of productive uses to mostly food-related businesses. This was informed by the microgrid financing mechanism (grant funding) and affordability for consumers, both important considerations for off-grid solar provision in low-income communities.

Our analysis is based on a limited data set collected soon after the microgrids were installed, and further work could investigate the longer-term impacts on the community, the energy demand with respect to population growth, business expansions, climate extremes, and changes in the socio-economic status of residents. We reiterate that the unique case presented in this paper should not be assumed generalizable across all informal settlements and urge context-specificity in drawing lessons from the study. Therefore, there is a need for more case studies employing different provision models to broaden our understanding of off-grid solar for PUE in low-resource urban settings. In Cape Town, such an evidence-base could then galvanize increased support for off-grid energy initiatives in informal settlements through existing policy frameworks like the Free Basic Alternative Energy Subsidy and feed-in tariffs for grid-tied distributed generators, and would be in line with the City of Cape Town's 2050 Energy Strategy. For the foreseeable future, Qandu-Qandu will remain unelectrified and for such settlements, off-grid solar offers a viable sustainable energy option that can afford residents a comfortable life and prospects for engaging in productive activities for their livelihoods.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

Conceptualization—P Y; Data analysis—P Y; Methodology—P Y, F C, P P; Validation; Visualization; Writing (original draft)—P Y; Writing (review & editing)—P Y, F C, P P; Funding acquisition—F C; Project administration—F C; Project administration—F C; Data curation and validation—F C.

Conflict of interest

The authors have no known competing interests to declare.

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