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Beyond the Grid: The Micropolitics of Off-Grid Energy in Qandu-Qandu, South Africa

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Abstract: In this paper, we argue using smart technologies beyond the grid disrupts the access and use of existing energy sources, with profound impacts on everyday social life. We show how off-grid smart energy solutions constitute their own politics when considering existing conceptualisations of urban infrastructures in geography and the social sciences. To expose its politics, or "micropolitics", we consider how tensions occur at the interface between infrastructures, where there are additions and modifications. We draw on an empirical example of Qandu-Qandu, an informal settlement in South Africa, to highlight how the *placement*, *technical capabilities*, and *flexible financing options* associated with off-grid solar energy create micropolitics with profound implications for everyday life. To conclude, we reflect on the value of using disruptions for understanding and enhancing equity in off-grid settings, contributing to the broader sustainability transitions narrative, and its "liveliness".

Ushwankathelo: Kweliphepha, sibhala ingxoxo ethi ukusebenzisa ubuxhakaxhaka balamaxesha kufutshane negridi, kuphazamisa ukufikelela kunye nokusetyenziswa kwamandla akuvimba, nto leyo enefuthe elibi kwimpilo yemihla ngemihla ngenxa yendlela izakhiwo zegridi ezichaphazeleka ngayo. Indawo yase Qandu-Qandu, imbacu yase Ntshona Koloni, eMzantsi Africa ingumzekelo ophilileyo esisekela ngawo lengxoxo, siqaqambisa igalelo lokubekwa, ukusebenza kunye nochitho mali olunxulumene nezi gridi zisebenzisa amandla ombane kwaye nembambano ezithi zivele zibenegalelo kwindlela lamandla elanga asebenza ngayo imihla ngemihla. Sibuya siveze imbambano ezizalwa zezi gridi xa sijonga imbono ezikhoyo zokulondolozwa kwezakhiwo zophuhlisa kwiJiyografi kunye nenzululwazi zokuhlala. Ukudandalazisa ezipolitiki zincinane, sijonga ubudlelwane phakathi koxinizelelo kwizakhiwo zophuhliso siqwalasele ekongezweni nasekuphuculweni kwazo. Xa sishwankathela, sibonakalisa ukuxabiseka kokuba sisebenzise impazamisa buxhakaxhaka ngenjongo yokufuna ukuqonda kunye nokuphucula utyalo mandla kwindawo zegridi zabucala.

Keywords: South Africa, off-grid energy, informality, renewable energy, socio-economic outcomes, infrastructures

Introduction

In this paper, we draw on the empirical example of Qandu-Qandu, an informal settlement in South Africa, to analyse the lively aspects of infrastructures in off-grid urban settings. We focus on the example of the installation of ten solar mini-grids in the settlement. These were implemented, costed, and managed by a small-scale utility to provide clean and safe energy to community members. The Qandu-Qandu off-grid case can be situated within the remit of research on the complexity of infrastructural lives "beyond the grid" (Bobbins et al. 2023; Caprotti et al. 2022; Guma and Wiig 2022; Truelove 2019; Truelove and Cornea 2021). This has included work on off-grid adaptation (Silver 2014), and how infrastructural lives in off-grid spaces actually straddle grid, off-grid, and other contexts (see Jaglin 2014; Silver and McFarlane 2019).

The paper is also situated within the broad remit of work on energy landscapes (Castán Broto 2017; Castán Broto and Sudhira 2019) and energy services (Castán Broto 2017; Monstadt et al. 2022; Silver 2014; Smith 2019; Truelove and Cornea 2021). In our focus on energy services "beyond the grid", we draw on interdisciplinary research on the fragmented and uncertain characteristics of infrastructures (and the grid) (Cantoni et al. 2022; Furlong 2014; Guma and Wiig 2022; Truelove and Cornea 2021).

While off-grid spaces and their infrastructural configurations are often classified as being "failed" or "broken" (Guma 2020:729), we place the spotlight on their very real liveliness and dynamicity. By liveliness we mean the socio-economic, technical, and cultural practices and networks that help to co-produce dynamic off-grid infrastructural lives in informality. Here, we draw on Amin's (2014) conceptualisations of "lively" infrastructures as comprised of visual and non-visual alignments of social interests, regulatory standards, expectations, and histories. Approaches to exploring these aspects have typically involved going "behind the scenes", acknowledging that infrastructure "narrates" social life (Amin 2014) and co-constitutes it in deeply political ways (Loftus 2006; Monstadt et al. 2022; Phillips and Petrova 2021; Silver 2014; Silver and McFarlane 2019; Smith 2019). In analysing the development of off-grid solar infrastructures in Qandu-Qandu, we build on existing conceptualisations of "lively" and "beyond-the-grid" infrastructures in the following ways.

First, we build on Amin's (2014) work by considering the many ways local energy infrastructures can be lively and what this means as part of a broader network of energy options. The "liveliness" of infrastructures is already understood to form part of the complex and diverse ways in which infrastructures are made and re-made, highlighting the actors, politics, and power associated with place-based infrastructures and individual lives (Lawhon et al. 2014, 2017; Truelove and Cornea 2021). To build on this, we focus on how infrastructures "shift" and "adapt" (Silver 2014:789) by considering how additions, modifications, new interventions, and other (re)configurations are part and parcel of the shifting and dynamic energy landscape in Qandu-Qandu.

Second, we specifically focus on the politics of infrastructure as it emerges. We focus specifically on "infrastructures-in-the-making", underlining the political implications of different kinds of infrastructures "in-use" and how they create politics. While much contemporary research on smart cities is critical of the governance-corporate nexus, off-grid and informal settlement spaces are largely ignored, especially outside the global North (Datta and Odendaal 2019; Guma 2020). Building on the notions of a "living experiment", we draw on how material participation manifests (Marres 2012), opening up lines of inquiry about *how* they influence everyday life. Additionally, our work builds on research on the smart city, where "smart" signifies the use of digital technologies, sensor networks, Big Data, and other approaches to govern and "steer" the city now come into play into areas that have previously been overlooked in the urban (Caprotti et al. 2022). Indeed, as Odendaal (2021) has underlined, there is a crucial need to provincialise research on the smart city, to ground it more carefully both in terms of granular context, and everyday lives and livelihoods. In the following, we extend and decentre the notion of smart urbanism as high-tech, capital-intensive, and formal, understanding the deployment of solar mini-grids as incremental and socio-technical forms of infrastructure (Kumar 2019) rather than as standalone technological "innovations" constructed as "solutions" to be parachuted into these contexts.

Identifying the micropolitics of off-grid infrastructures builds on a growing trajectory of infrastructure-led development and energy transitions scholarship in geography and the social sciences. We challenge existing orthodoxies by: (i) providing a more nuanced perspective on high-level accounts of the power struggles around infrastructure-led development (see Ahmad 2022); (ii) identifying the spatiality and locality of infrastructures, where technologies support and develop infrastructures in new ways (see Akhter et al. 2022); (iii) considering actions taken by residents in relation to the shifting and adapting configurations of urban infrastructures revealing their interests, needs, and identities (see Allan et al. 2022); and (iv) providing a more balanced account of the energy sources used, supporting just perspectives in the social sciences (see Bouzarovski 2022). Through these contributions, we illuminate the real complexities associated with hybrid energy access, where we show it cannot be pinned down to one technology, governing structure, or one set of users. This provides essential outcomes for providing critical knowledge for guiding and supporting sustainable energy transitions in off-grid places.

The following focuses, firstly, on a conceptual approach to the micropolitics of off-grid energy infrastructures. We then present the Qandu-Qandu empirical example, including the mixed methods approach we used to gather data on the disruptive aspects of solar energy. Last, we reflect on the micropolitics of off-grid energy access and use, including its value for enhancing sustainability transitions and equity in off-grid settings.

The Micropolitics of Off-Grid Energy Infrastructures

Heterogeneous Infrastructures and the Politics of Everyday Life

The diversity of energy infrastructures in the global South has sparked debate on the disparate ways actors access energy via the formal grid, off-grid approaches, or other means. Energy infrastructures have lively aspects, with a diverse range of energy options that provide various benefits, such as improved well-being (Mathebula et al. 2022), affordability (Pailman et al. 2018), and safety (Wiig 2018). An established body of work exists on the heterogeneity of off-grid and other forms of infrastructure, where heterogeneous infrastructural configurations are seen as part of the constantly changing and evolving energy landscape (Silver 2014; Silver and McFarlane 2019; Smith 2019, 2023). The splintered and fractured ways in which energy transitions take place have also been seen as entrypoints to explore overriding logics involving both power and politics (Caprotti et al. 2020; Graham and Marvin 2001, 2022; Lemanski 2020). For example, public infrastructure has been used to identifying state-society relationships and citizenship in Cape Town, South Africa (Lemanski 2020), power and knowledge asymmetries affect the ways citizens participate (Haque et al. 2021b) as well as identity, as seen in Moroccan-occupied Western Sahara (Allan et al. 2022).

In global South urban settings, the formal grid tends to be associated with formal and usually more wealthy parts of the city, while informality is linked to off-grid energy infrastructures. However, exploring the heterogeneity of off-grid energy infrastructures reveals a range of interventions that fall across formality-informality spectrum (see Banks et al. 2020). A consideration of heterogeneity is, therefore, essential for considering the full extent of infrastructures as part of an interconnected set of overlapping, incremental (Silver 2014), iterative (Haque et al. 2021a), and constantly changing infrastructural options (Jaglin 2014; Lawhon et al. 2014) along the formality-informality spectrum. For example, Amankwaa and Gough (2022) show how residents "make do" concerning their energy needs in Accra, Ghana, including how they take advantage of self-help and state energy options; Smith's (2019) exploration of the hybrid energy networks of Kisumu and Kitale, Kenya, demonstrates where the mediation of land tenure relations played an influential role in energy infrastructure (access and use); and Koepke et al. (2021) identify and analyse the multiple modes of infrastructure in Dar es Salaam, Tanzania, and their evolution toward supporting sustainable urban transitions. In all cases, conceptualisations of heterogeneity illuminate many "conditions of possibility" (Loftus 2012:56) where one or more options, or actions, could be taken at any time. Exploring the use of multiple energy options in situ requires a reading of the many ways actors use and draw on them to meet their needs, including considering the complexity of actor participation and use (de Groot et al. 2021; Mukama et al. 2022; Musango 2022). It is in this relational, emergent, and constantly reshaping complexity that we situate our understanding of the micropolitics of off-grid energy infrastructures. Building on this, a key issue that emerges from research on heterogeneous infrastructures is that infrastructures "do not fit neatly into inherited concepts" of infrastructure, development, and power (Truelove and Cornea 2021:236). It is in this sense that we can start to talk about off-grid infrastructures as awkward, tricky, difficult to define and deal with.

Disruptive Off-Grid Energy Infrastructures

Studies of the use of energy beyond-the-grid in the global South often start considering state failure in the provision of energy (see Amin and Cirolia 2018). However, it can be tempting to consider the development of off-grid energy solutions in informal settlement contexts as the making of new infrastructures that come to being in a stateless vacuum, and in contexts with no prior energy services. This, however, is far from the truth when considering heterogeneity with regards to off-grid energy infrastructure. The introduction of disruptive energy sources, such as off-grid solar, can be seen not as a *replacement* of existing forms of energy in informal settlements, but as *additions* to the existing energy mix. This, in turn, forms part and parcel of the often uneasy and rapidly shifting landscape of energy use, which is in turn related to issues such as affordability, changing market prices for specific sources of energy, maintenance and its costs, and the uses of energy (for example, solar cannot be used for cooking, but can be used instead of candles for lighting).

In this vein, recent work has pointed to the need for a more dynamic approach to understanding energy infrastructures. Smith (2023) explores the quality and dynamism of informal energy services in Maputo, Mozambique, highlighting the need to consider "alternative configurations" of energy and how they "materialise dynamically", including how more "traditional" interface with "modern" ones. Smith's (2019:1257) above-mentioned research on energy access in Kenya similarly concludes that the boundaries between "networked" and "non-networked" energy access are "somewhat blurry and shifting".

To study the disruptive aspects of energy beyond the grid, we acknowledge the need to consider the relationship between more "traditional" options along-side more "contemporary" ones (Smith 2023), especially where they come to be accessed as part of the sociality of infrastructure. This forms a new and relatively under-explored aspect of heterogeneous infrastructures, and necessitates critical engagement with solutionist and technologically-celebratory narratives (Bobbins et al. 2023; Guma 2020), usually built on discursive constructions of informality as characterised by imperfection and inadequacy (Caprotti et al. 2022) that need to be "solved" by technological interventions. Building on this, it is key to note here that disruptive "solutions" such as off-grid solar are deeply political in their development, deployment, and operation, as seen in our analysis below. At the same time, the micropolitics of energy infrastructures in situ in informality are linked to power relations involving the state and other institutions whose remit impinges, directly or indirectly, on the informal landscape. In this vein, Baker et al. (2021) highlighted the power struggles associated with the deployment of renewable energy alongside other energy options in South Africa. Their work underlined power struggles between the state and state-funded utility Eskom in relation to governance and administration of the push for renewables (see Baker et al. 2021). While a consideration of the power relations and politics involved in the South African energy landscape lies outside the scope of this paper (but see Baker and Phillips 2019; Caprotti et al. 2020), we acknowledge the situatedness of our micropolitical analysis within this broader and multi-scalar context.

Smart and Disruptive Energy Infrastructures in Qandu-Qandu, South Africa

Solar Energy in Qandu-Qandu

Qandu-Qandu is an informal settlement part of Khayelitsha in the Western Cape Province of South Africa. We use Qandu-Qandu as an example to highlight how the introduction of new energy infrastructures creates its own politics (Figure 1). Established in 2018, the settlement currently has over 4,000 households, which do not have access to formal "grid" infrastructure access (electricity, water, or sanitation). The settlement is built partly on a wetland, and located on a site currently owned by the city. The South African government is yet to retrofit these spaces with energy as part of the national government programmes for informal settlement upgrading.[1]

Between 2019 and 2022, two UK-funded projects were awarded to implement ten solar mini-grids in Qandu-Qandu. The solar technology used was based around solar towers, situated within the Qandu-Qandu community. Each steel tower included a 1.2 kWp solar panel, a 5 kWh lithium-iron phosphate (lithium ferrophosphate, or LFP) battery unit, and was connected to multiple households through direct current (DC).[2] Each household was able to subscribe to a different level of energy service, ranging from basic lighting to more intense energy usage able to support televisions and other small appliances, and (from 2022) also

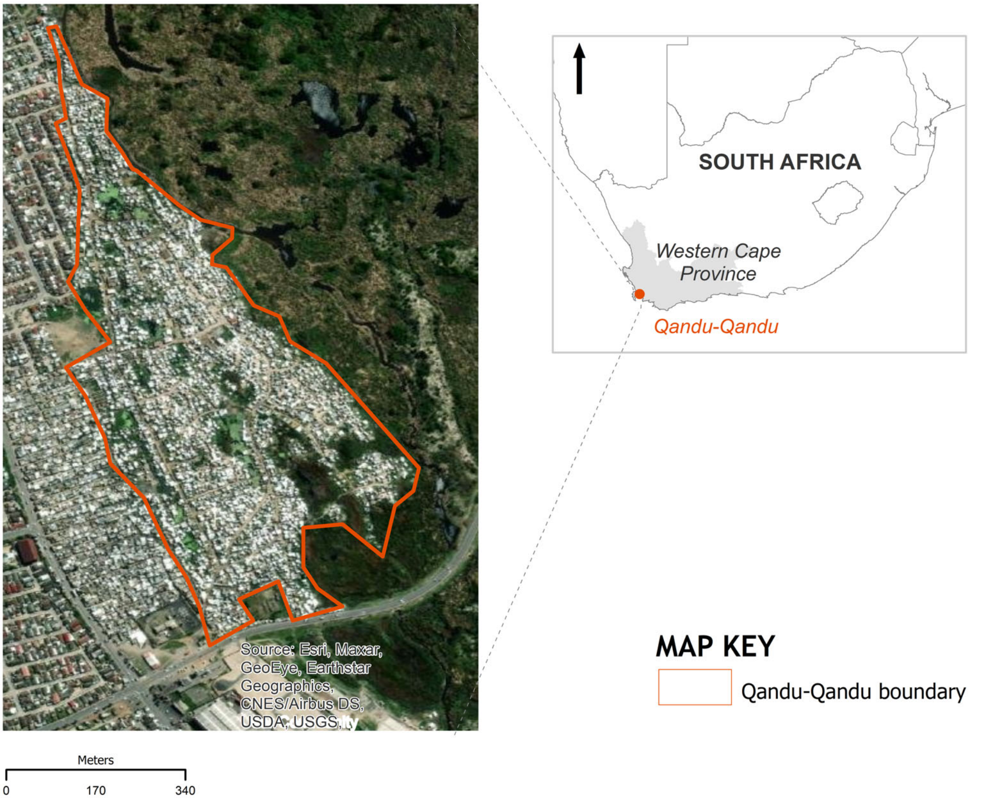

Figure 1: Location of Qandu-Qandu, South Africa (map created by authors) [Color figure can be viewed at wileyonlinelibrary.com]

fridges and fridge-freezers (although the number of households who could power refrigeration was limited by each tower's capacity).

Subscription and payment for energy services was carried out digitally, and the utility was able to access payment through third-party payment platform processing; additionally, each householder could access their own energy usage data, and the utility could access this data as well as other data related to the use of energy from each tower. It is in this sense that the mini-grids are described as smart: through the networked, and digitally-mediated delivery and management of specific types of energy service and associated data and financial flows. A key benefit of the solar mini-grid technology used was that it could easily be implemented in densely populated urban areas such as informal settings. After installation, each mini-grid serves up to 16 households within a 40 m radius and the energy provided can be used for lighting, charging devices, fridges, and entertainment (TV and radio). The location of each mini-grid was determined by the suitability of land (including for laying foundations for each solar tower), access to the tower site (cranes mounted on the back of trucks needed to be used to lift each tower in place), and community acceptance.

Project team members included universities in South Africa and the UK, and non-academic partners such as the Qandu-Qandu community, a solar utility, and an energy consultancy in Cape Town. The solar utility had been involved in a prior, and much smaller, solar energy mini-grid programme focused on rooftop-based solar panels in a neighbouring informal settlement of Jabula.[3] The Qandu-Qandu community were integral to the development and use of solar energy services (see Appendix 1 for more information on the project partners and their specific roles). The project partners worked together to troubleshoot the technical, social, and financial aspects of the project. The community was consulted throughout the implementation of the solar mini-grids.

Qandu-Qandu Off-Grid Infrastructures in Flux

To grasp the disruptive aspects of solar energy in relation to other off-grid infrastructures, we used an applied research methodology working with members of the Qandu-Qandu community to define their energy needs and determine the location of towers. We collected data between 2019 and 2022. Community information sessions were run by the local utility, ahead of this the research team approached the leaders of the community to explain the programme, granting residents to have the freedom to directly approach the utility should they be interested in solar energy.[4] In addition to these, a set of in-depth interviews, a client affordability survey, and solar mini-grid tower data analysis enabled key variables of the applied approach to be drawn out and analysed as part of a robust research process (see Appendix 2).

The Micropolitics of Smart Infrastructures in Qandu-Qandu, South Africa

Placement and Proximity

The material placement of solar mini-grid towers disrupted the use of existing energy services in Qandu-Qandu (candles, paraffin, diesel generators, and illegal connections). The type of solar mini-grid technology used was ideal for use in densely populated off-grid settings, while also being nimble enough to serve a relatively low density of households (within a higher total density area) interested in solar power. Indeed, for each tower site there needed to be at least 14–16 households interested in accessing solar services. As a member of the solar utility remarked, these parameters enabled them to "quickly come in and serve a lot of clients in a small region" (UPT001), which is atypical of traditional grid-based energy that is subject to long planning and deployment processes. That said, even though towers could be placed using a flexible approach, they would ultimately become semi-permanent features as foundations would need to be laid to install the tower base and column. For these reasons, the utility needed to work carefully to balance factors influencing the long-term placement of the towers (e.g. ground stability, no overhanging structures including overhead high-tension power lines) with the financial viability of the mini-grids themselves. Thus, while community consultations and information delivery took place in Qandu-Qandu to gauge desirability, the operation of the utility as a business meant that part of the consultation process had to not only gauge interest, but willingness to sign up as a customer. This related, in part, to the financial risk taken on by the utility when serving areas of a settlement that may not have had enough client households to make the placing of a tower in a specific location financially viable. While this meant that the power relation between consultative processes and the utility was not symmetrical, it must be recognised that the utility, without access to standard sources of finance, had to rely on making its business work from the start in order to ensure longevity and continue serving the community.

To explain the micropolitics of solar mini-grids, we must first highlight a moment in the placement of the towers and associated mini-grids. At the start of the project, the small-scale utility used existing informal boundaries between sections of Qandu-Qandu to identify sub-areas for installation. These were identified using community knowledge of the settlement (see sections labelled A–J in Figure 2). The community were involved in co-design sessions set up by the local utility company; at these sessions, community members indicated they felt they wanted to be more involved in the implementation of solar energy. To include the community more centrally in decision-making about the placement of towers, the solar utility set up community engagement sessions in each settlement area. During the discussion process, hotspots of residents' interest in accessing solar power sprung up across the settlement. These were mapped (Figure 2), and the utility used the final map to plan and prioritise areas for the placement of solar towers.

An outcome of the community sessions was that it became clear that initial interest in solar was based on affordability: one resident remarked that solar energy "costs less than Eskom's power" (UPT004). Eskom is the South African electricity public utility responsible for the generation, transmission, and distribution of energy in South Africa, but in this case, as residents do not have a formal connection, they used the term "Eskom's power" to describe their illegal connection and the cost they pay for the setup and maintenance of this form of energy.[5] As we show below in greater detail, while illegal connections are less expensive than most of the solar utility's packages (that start in the region of R150 for lights-only service, for example),[6] the ability to use digital vouchers to "top up" energy use mean that mini-grid access payments are both more flexible and more affordable than illegal connections, taking into account the dynamic infrastructural lives in Qandu-Qandu (BP003D and BBP004D).

It can be seen that while community interests and preferences formed part of the planning and placement process for the towers, the final location selection decisions were considered alongside other factors such as distance from overhead infrastructure such as pylons and cables (indicated by the brown polygons in Figure 2), and ground stability (not on a wetland and/or land prone to seasonal flooding). Therefore, while there were "a lot of people who want the electricity", many were "still waiting" (BBP004D). It became, therefore, a waiting game as to whether or not certain parts of the community received power, and a critical mass of energy service demand, willingness and ability to pay, and physical site conditions were key factors in the roll-out of further towers.

Another micropolitical aspect of tower placement was the issue of access to paraffin, usually used to cook food and provide light in Qandu-Qandu households

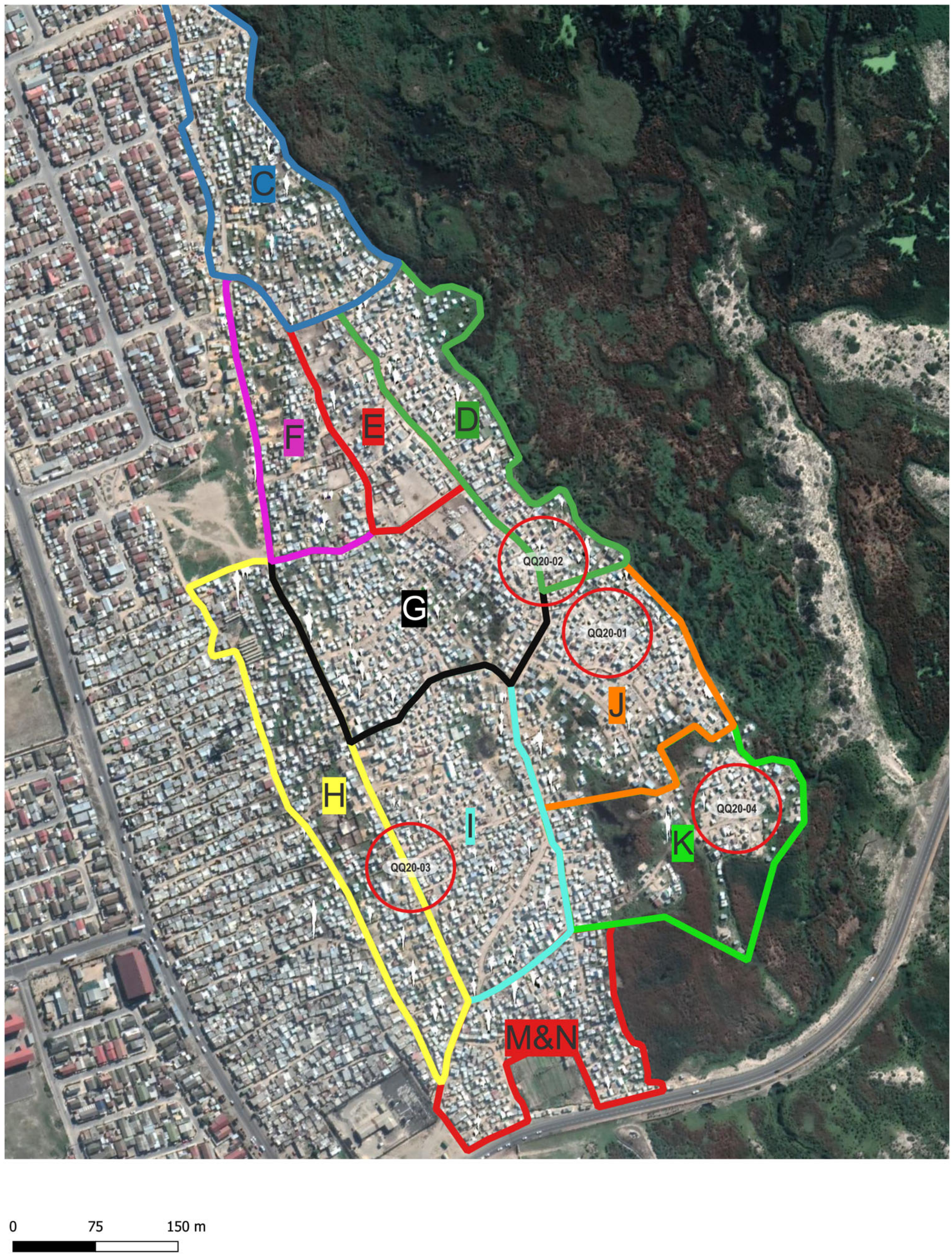

Figure 2: Resident interest in solar energy per region (regions labelled A–J) (source: Zonke Energy) [Color figure can be viewed at wileyonlinelibrary.com]

with no or unstable electricity access. As the settlement grew after its foundation in 2018, demand for paraffin grew apace. A local economy of small informal enterprises selling paraffin and gas for cooking also emerged in the settlement: this was seen as a "promising" business prospect as residents "saw that there is a need" (BBP002B), a demand to be fulfilled and which could generate livelihoods in the settlement. The use of paraffin in cooking, and as a business opportunity, is key in the unequal and gendered context of energy access and socio-economic opportunity in informal settlements, where the burden of obtaining energy for cooking mostly falls on women, as does the need to secure suitable lighting for uses such as indoor illumination and children's homework. At the same time, and underlining both gendered and racialised facets of energy inequalities in South Africa, Black/African and female-headed households are the most vulnerable to energy insecurity (Ngarava et al. 2022). The provision of solar affected the demand for paraffin: mini-grid clients no longer used paraffin lamps due to their fire risk and the relative safety of solar. This was described as "a big difference" (BBP002B). Access to clean and safe solar energy also enabled other appliances to be used: as the same resident noted, "I can charge, I can light, I can listen to the radio" (BBP002B). The shift away from paraffin across all homes connected to solar impacted the spatial demand for paraffin in these areas, and were part and parcel of the micropolitics of tower placement, which partially involved a direct implication for the livelihoods of paraffin and gas sellers. A related shift, and tension, emerged in the move from illegal connections to solar. Illegal connections are often involved in serious damage to appliances, and fire and electrocution risks. Two residents previously using illegal connections explained that there were "things" that "would get damaged" (BBP002B), and "fridges [were] burnt" (BBP001B). A preference for solar, therefore, directly influences the economics around illegal power access and use, including impacts on the networks selling access to illegal connections.

The impact of mini-grids on the everyday lives of Qandu-Qandu residents is, therefore, mixed. On the one hand, solar constitutes a much safer form of energy for certain parts of the settlement, in its replacement of gas, paraffin, and illegal connections. Clear benefits emerged: households drawing on solar energy could choose to overcome the "dangers of using informal electricity" in a context where illegal connections were "not sustainable, and it's not safe", and where sometimes people's "house burn[ed] up" (UPT004). Solar energy, therefore, provided an energy source that is "safer, it's reliable, it's cheaper … and [residents] … don't have to worry about what could go wrong" (UPT002), and thus positively affects wellbeing (Mathebula et al. 2022). On the other, the availability of these benefits was geographically uneven, and had impacts on other socio-economic facets of life in Qandu-Qandu. The most profound impact experienced by residents living outside the solar mini-grid availability radius were around the fewer households regularly buying candles, paraffin, and diesel.

Technical Capabilities and Limitations

Solar energy also disrupted the access and use of existing energy services due to the technical limitations of the mini-grids themselves. While a key benefit of the solar mini-grids was that they could provide enough power to serve between 14 and 16 households to power low-rated appliances including lights, TVs, and radios, not all households can access these services equally. This was due to the technical limitations of the towers. For example, high energy appliances such as fridges require more power. Furthermore, the towers were not able to provide enough power for cooking and heating appliances. By implications, not all 14-16 households can access enough energy (per tower) to power a fridge and while the towers themselves presented an energy access point, the number of existing households that signed up influenced how subsequent sign-ups could draw on and use energy from the tower. Therefore, being located next to a tower was not necessarily a positive indicator of the availability and use of solar energy and households could not always change their requisite package due to the technical limitations of the tower. This is a point that we will revisit below, but it speaks to the production of new or changed forms of marginalisation that are part and parcel of infrastructural interventions in off-grid (and formal) spaces (Ngarava et al. 2022).

Another feature of the technical capacities of the towers meant energy use could be recorded regularly (every 30 minutes). The granular data gathered by each tower included the detailed monitoring of energy usage to support a voucher scheme for enabling the user to access lights, TVs, and fridges. A member of the small-scale utility system explained that residents "can go to spaza shops[7] and purchase a voucher", and "the voucher has a code on it" that can be redeemed (UPT001). Thus, household-level granular data allowed energy tracking and the application of vouchers seamlessly to enable energy access (including monitoring which users are accessing energy for low- and high-demand appliances). This kind of real-time digital monitoring of energy use challenged existing notions of infrastructure service management where larger grid-based systems gather data at a regional or neighbourhood level. Available solar mini-grid data indicates households draw on electricity more readily at different times of the day. The graph below demonstrates such fluctuations in energy use throughout the day during the summer months (start of December 2021 until the end of February 2022), where the use of lighting, TV, and fridges peaked in the evening, while limited usage was observed at other times of the day (Figure 3). This means that while general patterns can be determined, other factors such as seasonality, extreme weather events, or finances formed part of energy rhythms of access remain somewhat obscure. This kind of granular data gathered by the tower helped the utility to plan and manage the use of solar energy users and needs per tower, driving the development of flexible packages and payment options. This data was also used to manage the development of more flexible energy packages and payment options (such as vouchers) when compared to grid-based energy.

The micropolitics of technical limitations is significant for understanding social life for two key reasons. First, it enabled some end users to manage and use their energy in such a way as to support knock-on benefits. For example, one client mentioned that it reduced the number of trips they needed to buy products outside the settlement. As one local business owner explained when talking about the ability to plan and manage energy use, "it helped me a lot", by "avoid[ing] going to purchase stock all the time" (BBP002D). Not travelling as much meant local businesses could buy in bulk or travel further when they did travel for better

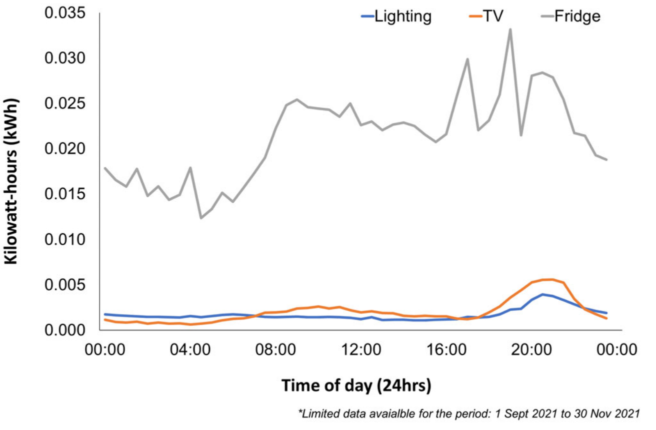

Figure 3: Average energy use per solar mini-grid tower during a 24hr period. Data are shown for one tower only during the summer months (December 2021–February 2022) (source: Zonke Energy) [Color figure can be viewed at wileyonlinelibrary.com]

prices: another local business owner indicated that "to stock up, I will stock up once and store in the fridge" (powered by the mini-grid). This enabled them to "stock up a few things … and if you stock up in bulk, you get a discount" (BBP008D). There are knock-on implications for nearby stores, which tend to be run by women in the community: access to tower-based services means a lessening of the time and safety issues related to the need to travel outside the settlement (see also Wiig 2018). Enhancing the business opportunities of local residents, in turn, helps to tackle the link between energy poverty and employment precarity in a South African context, an issue that is both gendered and racialised (Koomson and Awaworyi Churchill 2022).

On the other hand, however, technical capabilities and limitations also influence how users access energy. A mismatch was found between client expectations of the capabilities of the solar service, and the actual capability that can be delivered by the solar utility. Expectations are mostly focused on reliability. As a representative from the small-scale utility remarked, solar services "increases expectations and the demand on us to be reliable … [and] delivering what they expect … [and it is] really important to us that we're reaching that reliability" (UPT001). One way reliability concerns manifested was through the inability, at times, to utilise solar electricity for more than one use at the same time. A client indicated that daily limits presented a concern, especially where there was more than one use for energy. As they explain, "I bought the TV so that I can stay and watch whilst serving my customers", but if they used energy for more than one purpose, they run a risk of it running out, so "once I watch this TV during the day, the following day, I won't have electricity" (BBP007D). While it could be argued that this is inherently part of the solar package and that the client would need to pay for a "top-up" voucher when needed, it also means that clients need to make choices around their use of energy and available financial resources. As the same client remarked, "once I use the TV, the following day I won't have electricity, as a result, my cool drinks are warm. Even if I store meat in there it gets bad [referring to a solar-powered fridge]" (BBP007D). The daily capacities of energy, then, affect client behaviours and expectations, and dictate the need for other or add-on sources of energy. As the client explained, the "electricity only comes back late at 5 because you have exceeded your daily limit. Sometimes it switches off at 9 in the morning and comes back in the evening" (BBP007D). Not being able to effectively gauge usage, or the time of available electricity when running close to or over the daily limit, makes it difficult to rely on solar energy.

Flexible Financing and Multiple Uses

Flexible payment options offered by the small-scale utility disrupted existing notions of fixed payments for services delivered through energy infrastructures. While formal, grid-based options in grid-connected parts of Cape Town can only be accessed via a fixed metered connection or a prepaid meter,[8] solar mini-grid customers can pay monthly, weekly, or via pay-as-you-go top up (starting at R15 upward).[9] In turn, an energy purchase can be actioned via a voucher that could be purchased from spaza shops. This meant there was a more flexible payment option, but also the ability to buy vouchers that were located within the settlement rather than via mainstream retailers such as supermarkets (where grid-based prepaid meters can be recharged). The relative flexibility of solar mini-grid payment options, therefore, disrupted existing notions of energy access and use: the utility worked with the community to develop payment options around end-user needs, giving clients more than one way in which they could pay for solar energy.

Granular usage data gathered through the towers enabled the modification of solar energy packages to meet user needs. This led to pronounced shifts to the use of solar as a safer means of accessing energy in instances where residents had funds available, where they may have relied on illegal connections or combustible energy sources previously. These adaptations were far nimbler than what could be achieved for larger utilities given their size and scale, where modifications could be developed using feedback and data gathered on energy use, rather than focused on a baseline value for ensuring revenue generation as would be common for larger utilities. By implication, the development of more flexible payment options forms part of a careful balancing act, where despite being reduced to a fixed package or top up value, how end users accessed energy brought their lively way of accessing energy into the fray, where access to energy was supported by a range of different means that required financing, but also where preferences toward solar demonstrated a clear shift away from other sources.

An example of how flexibility was factored in using granular data was when the small-scale utility introduced a "shop package" (in the region of R430pm for fridge and lights only). The package was developed based on feedback from community members, after initial engagement with the project's business training partners. This is indicative of the utility's ability to be more flexible around the development and use of energy in the community. However, making the package available also presented a challenge for the utility, since if clients signed up to this package (due to the power draw-down of fridges), fewer clients would be able to sign up to solar services from the same tower. Furthermore, the shop package was priced only slightly lower than the Fridge Package (which powered a fridge, TV, and lights for R490pm).

Out of 18 residents using solar energy who participated in our affordability survey, six indicated that they were willing to pay for a Shop Package, while only two said they could afford it.[10] While this is not an absolute gauge of interest and willingness to spend on energy, it does indicate that while community members are willing to pay for solar electricity, they are not always able to afford it. That said, in-depth interviews revealed the concept of affordability was highly nuanced, and not necessarily confined to individual affordability. As one resident explained, an illegal grid connection was arranged as part of a "group", where "we divide the cost amongst ourselves" (BBP0010D). It was highlighted that the cost of illegal energy could be higher when compared to the packages offered by the solar utility. For example, the lights-only package is in the region of R150pm, and R250pm for TV and lights, in addition to R425pm for the shop package and R490 for the fridge package. It was also pointed out that an unpredictable, hidden cost of illegal connections was their propensity to damage appliances supplied. Both the affordability survey and in-depth interviews indicated that residents preferred solar rather than illegal connections, and that they were theoretically willing to pay for safety even if they did not have the actual financial means to do so. This replicates the findings of other studies, for example work on cookstoves in a sub-Saharan African setting which showed that affordability was one of the key determinants to adoption of these systems (Pailman et al. 2018).

Notwithstanding the flexibility and responsiveness to end-user needs of the solar utility, the financial implications of solar electricity access for clients constituted a micropolitical interaction between clients, the solar utility, and suppliers of other forms of energy. This is because it influenced how and why clients drew on solar, and on other energy options considering solar's technical limitations. These constraints created their own micropolitics through their financial implications for clients. In addition, technological, practical, and other factors (i.e. the capacity of each tower, daily capacities, and other practical limitations imposed by the physical location/setting) constituted micropolitics where there was an expectation for continuous or uncapped use of energy. We have already remarked on the clients using a TV and also wanting to run a business who noted that engaging in one form of energy use decreased the ability to use solar electricity for other uses: "we pay a lot of money … so that we can be able to watch TV, where you … have to watch TV for only three or four hours a day, so it's unfair" (BP007D). Therefore, to engage in a multiplicity of energy uses, there was a need to buy a more expensive monthly or weekly package, and top up via a pay-as-you-go voucher more regularly. Topping up or shifting to a more expensive package was not always possible, thus meaning clients almost always relied on solar energy combined with other self-help options.

One client explained that while they enjoyed the use of solar energy, they still relied on other energy sources: "I am using a gas stove and I am also using a paraffin stove and solar" (BBP002D). In some cases, the use of solar for some uses enabled cost savings that gave clients the freedom to purchase other forms of energy. As a resident remarked, "I am able to buy paraffin, I am able to buy gas without asking for assistance from my parents" (BBP003D). Despite providing an affordable option for lighting, TV, recharging of mobile phones, and refrigeration, a core technological limitation of solar electricity as experienced by the utility's clients was around the need to power appliances that needed more power than could be provided through solar: these uses (mostly around cooking and heating) therefore necessitated the stacking of multiple forms of energy to fulfil their varied energy demands.

Energy usage and purchase patterns are impacted by affordability, employment opportunities, and seasonal income, including technical limitations affecting the financial planning and use of energy services. That said, while the original solar energy package options were not developed with multiple uses in mind, clients indicated they balanced their energy use using the payment options available. For example, some clients said they paid for energy monthly using the voucher system. Others explained they "only load in small amounts", where one client mentioned they "have never loaded … the whole month … I only load in small amounts" (BBP002D). Another client also outlined this process: "you top it up according to your financial strength … you don't have to pay all of it". They further explained: "if you have R50, you can top up, and you can try again and top up with R30" (BBP001D). Factoring variability in use, therefore, formed the crux of the solar utility's approach.

For the appliances that could be powered via solar electricity, there was a clear preference for solar over other energy sources. As one resident explained, "we were dependent on illegal connections", and their unreliability meant that "the one day there is electricity, the next there isn't" (BBP001D). Another client underlined the safety of the solar mini-grids versus illegal connections: "solar is safe, it doesn't cause me stress associated with stolen cables and wires" (BBP009D). Before using solar, self-help options such as illegal connection, candles, paraffin, and the like "create[d] enormous risks for not only the individual … and risk of death, but also for the community as a whole where it can often result in fire" (UPT003). This is because a fire starting in one shack can quickly spread in the context of very dense settlements comprising structures that use a lot of combustible materials. Additionally, the cost to replace such items would often be far greater than only a monetary investment. As the client whose two fridges "were burnt" explained further, "in May this year my business shut down because I did not have a fridge" (BBP001B). As a result, their livelihoods were affected, and their business was "not doing well because my competitors sold cold drinks and I didn't" (BBP001B).

Access to solar energy has a marked impact on the social lives of those who could subscribe to it. The financial value of reducing the risk of damaging their appliances and the risk of death associated with illegal connections meant solar energy was a service they were willing to pay for even if they did not always have the financial means to do so every week or every month. The accessible and end-user-orientated ways packages and payment options were developed left a door open for clients to manage their energy access, where they could dip into or out of solar as and when needed. It also enabled them to make different choices around energy stacking practices. Therefore, the sheer liveliness of how residents draw on energy means that rather than solar directly replacing other, combustible or illegal forms of energy, the energy landscape in Qandu-Qandu is far more nuanced, and the energy system can be described as having reached a new state of flux that includes solar.

Conclusion

In this paper, we have argued for the need to explore the micropolitics associated with using smart infrastructures in off-grid settings, where solar energy disrupted existing energy configurations and created its own politics. Building on work by Amin (2014), Silver and McFarlane (2019), Smith (2023), and Truelove and Cornea (2021), among others, we have showed how the use of solar energy in Qandu-Qandu is constituted by interactions articulated through the placement of towers, technical capabilities, and flexible financing modes. The introduction of solar mini-grids into the solar energy landscape in Qandu-Qandu did not replace the overlapping set of grid-based illegal connections and self-help energy options (candles, paraffin, and diesel generators) already in use. Instead, access to solar electricity enabled households to self-regulate energy access, shift consumption patterns, and move towards a more reliable connection. This shows that one of the critical characteristics of heterogeneous infrastructures in off-grid, informal urban settings is not only its disruptive nature, but also its awkwardness. In underlining this, we refer to awkwardness to denote a set of infrastructural configurations and energy access challenges that are not easy to deal with, and that are complex and subject to unexpected shifts and changes in configuration. While disruptive infrastructures can go some way towards providing new ways of configuring existing infrastructural geometries, the off-grid context remains awkward in its complex and tricky energy landscape. Thus, awkwardness can be seen as a critical constituent of off-grid infrastructures, rather than simply as a set of points of friction or obstacles to idealised notions of access.

Rethinking heterogeneous infrastructures as disruptive, awkward, and in flux helps move towards understanding off-grid energy landscapes as highly context-specific and fluid in nature. In so doing, an analytical approach that is deeply engaged with the different ways in which energy landscapes are configured in different off-grid sites opens up possibilities for policy and practice engagement which moves past generalised, top-down, and prescriptive strategies and "solutions" and towards re-engaging with communities and their specific energy needs and the dynamic price, affordability, technical and socio-cultural contexts within which these needs exist.

Our study is limited by our granular focus on and engagement with a single informal settlement community, and by the relatively short period (three years) in which the shaping of off-grid solar infrastructure was studied. While continued assessment of how off-grid solar is developing in the community will be crucial to long-term learning, our work shows that deep engagement with lived infrastructural experiences and sensitivity towards granular context is essential to inform learning that can be applied in informal contexts. Furthermore, a fundamental limitation and ethical issue is that engaging in infrastructural service provision is always political and fraught with issues of access and spatial distribution. As seen above, introducing solar towers in specific parts of the settlement meant that other areas could not be served. This presented an unequal landscape of off-grid infrastructural access. Within this project's scope, this unequal distribution was determined, among other things, by the amount of funding available for infrastructural installations, funder requirements around capital spending, and the need to find appropriate locations and gain community approval for the siting of solar towers. To some extent, this is tempered by the fact that the project enabled the solar utility to begin operations in Qandu-Qandu, and to scale over time. It is vital to recognise that utilities operating in the off-grid space often do not benefit from easy access to venture and other forms of capital, which in turn means that scaling is less rapid than for other businesses operating in more "formal" environments and with access to finance. At the same time, it is essential to acknowledge the inequalities involved in delivering a service that in formal urban areas could be provided for free (see Tarasova and Rohracher 2023), at least in part, by the municipal government, under South Africa's guarantee of 50 kWh of Free Basic Electricity (FBE). While this is a limitation and element of inequality that transpired during the short project lifetime, an area for further exploration and practice-focused work should involve linking FBE vouchers to the usage of the microgrids.

Our findings contribute toward understanding the nuances of infrastructure-led development, which has emerged as a critical theme in the provision and access of energy in off-grid settings, with profound implications for residents' infrastructural lives. The many complex ways new or novel technologies are used in off-grid locations reveal critical learnings for energy transitions. We have shown that introducing new forms of energy can constitute new and lively avenues around preferences and the ways infrastructures are accessible and used as part of an energy system in flux. In this context, we have also shown how disruption can be used in nuanced ways to understand how new technical systems and approaches can be part and parcel of the process of shifting infrastructural landscapes. This moves away from understanding disruption as existing "apart from" existing socio-technical systems, cultural dynamics, and approaches. Indeed, our study has underscored how disruption cannot be achieved without considering community dynamics and the lively experiences of infrastructures by members of the community.

Understanding the liveliness of infrastructures in this way is crucial for three separate but linked reasons. First, analysing infrastructural liveliness enables shaping critical perspectives on lived infrastructures, and not just on the politics, economy, injustices, or other distinct aspects of these socio-technical systems. Liveliness shows how infrastructure is constantly negotiated, lived, performed, and resisted and how it can, in turn, exhibit agency (via liveliness) through its engagement with individuals, households, and the worlds of politics, policy, and finance. Secondly, the micropolitical is mediated and played out through infrastructural liveliness. At the level of communities' and households' engagement with and performance of infrastructures, the specific micropolitics of energy landscapes, and their intricacies, become visible. Third, and building on these two points, a key issue is how liveliness plays out in practice, on the ground, and in people's lives: hence the need for deep engagement with the granular context of infrastructural lives. Both aspects contribute to leading debates and discussions around infrastructure-led development (Ahmad 2022; Akhter et al. 2022; Allan et al. 2022; Bouzarovski 2022) and the need for renewable energy options to "stand on their own two feet", by contributing critical nuances on the setting and use of such services in informal settings (building on Christophers 2022), where the use of one or more approaches constitute the energy transition.

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Endnotes

[1] The South African Department of Energy classified informal settlements into three categories. Qandu-Qandu is part of the third category that will not be electrified (see de Groot et al. 2021).
[2] The supply of alternating or direct current in the QQ installation is 26V DC.
[3] The Jabula project was much smaller comprising of three solar mini-grid towers. The technology used was developed by the technical team. Learnings from this work, although not discussed in detail in this paper, did form an entry point to the technical work carried out at Qanu-Qandu. Due to the focus on the situated nature of energy transitions as conceptualised by this paper, they will not be considered it length.
[4] The Qandu-Qandu community is governed by leaders who live adjacent to the settlement. Members of research team met with leaders to explain the programme ahead of formal works taking place on site. The leaders agreed to the work taking place.
[5] Eskom works closely with Metropolitan Municipalities such as Cape Town Municipality to ensure grid-based energy provision in the larger metropolitan areas. Metropolitan Municipalities such as Cape Town Municipality can also produce their own electricity through municipal projects and programmes.
[6] All costings in this section are applicable for May 2022 only.
[7] Informal tuck shops.
[8] Options supported by the state-owned utility, Eskom, including metropolitan municipality initiatives to deliver energy as part of the grid. These options are generally not available in Qandu-Qandu.
[9] Follows service-oriented approaches found in rural Tanzania (see Bandi et al. 2022).
[10] Although 18 completed the survey in total, only 16 and 15 respondents opted to answers these questions respectively.
[11] Packages were developed by the local utility who designed them with a five-year timeline in place. Due to the commercial integrity of the utility, they have not disclosed detailed financing information on how the packages were calculated.
[12] The functionality and use of energy may differ at each tower due to its location, number of users, choice of solar energy package, and actual use of energy throughout the day, season, or over an annual period.

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Appendix 1

The 10 solar mini-grids were implanted by a project team, including the following:

• *Two universities* (one based in the United Kingdom and the other based in South Africa). Integral for defining the overall research approach and scope for the implementation and operation of solar mini-grids and coordinated the research activities (data gathering, writing up of outputs). Local partners included the following.
• *Small scale utility*. A leading private sector company involved with the development and use of solar mini-grids in informal settings and is responsible for the refinement of technical parameters and ensuring the long-term management and maintenance of the solar systems.
• *International data consultancy*. Data consultancy specialising in the innovative use of quantitative data on energy access and use in informal setting. Their role on the project involved project management and the co-ordination of data management on the ground.
• *Social enterprise*. A local social enterprise initiative specialising in business education, mentorship and support. Their role included the setting up of a 4-month training programme on how to set up a small-scale business using productive use appliances.
• *Qandu-Qandu community*. The Qandu-Qandu community were integral to the development and use of solar energy services. At all stages the community was engaged in the development of the project, together with refinements to the technical, financial, and monitoring of solar energy.

Appendix 2

• *In-depth interviews*. We conducted 21 in-depth interviews with residents in Qandu-Qandu. Respondents were those residents interested in using solar, including residents who had received access. Interview respondents, recruited via snowballing, had already worked with the researchers over the duration of the project, and were asked about their interests and preferences for solar, including what they felt they benefitted the most from. In-depth interviews were analysed using thematic analysis (Attride-Stirling 2001), using NVivo.

• *Client affordability survey (willingness to pay and affordability)*. 18 prospective and existing clients of the solar utility were asked to complete a survey about their average household income, as part of a broader business skills and knowledge sharing training programme, their willingness to pay for solar energy, and how they would go about paying for their packages.[11]

• *Data analysis of solar mini-grid tower data*. Solar tower data was downloaded from each tower[12] and statistically analysed to identify patterns in energy usage, including seasonal variability (summer and winter). Data provided the numerical means to study patterns and trends observed while working with the community.