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# Urban innovation in the informal city: overlapping infrastructures, co-production and sector coupling in a South African informal settlement

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Informal settlements face significant infrastructural challenges, exemplified by limited electricity access in sub-Saharan Africa. We present insights from a 2020–23 research program in a South African informal settlement that highlighted the importance of systems thinking and sector coupling for integrating infrastructural and economic interventions to address the needs of informal settlement populations sustainably. In the program, this was done through solar off-grid electricity innovations and entrepreneurship training. This study's novelty lies in its expansion of 'sector coupling' beyond its conventional technical definition, applying it to socio-technical integration across energy, entrepreneurship, and digital services in an informal urban context. It provides one of the first empirical demonstrations of how systems thinking and co-production can reframe energy provision as a foundation for multidimensional development in the informal city.

KEYWORDS

**sector coupling, infrastructure, informal settlements, global south, off-grid city, co-production**

## 1 Introduction

We outline a recent set of interlinked, multi-infrastructural research projects and asks: how can the key concept of sector coupling be reconceptualized and applied to co-produced energy and economic interventions in informal settlements to overcome infrastructural and socio-political barriers? In doing so, we contribute to the literature on infrastructure transitions, urban informality, and development innovation by showcasing the integrative potential of socio-technical approaches grounded in lived realities.

The 'informal city' refers to urban development and associated processes beyond formal systems of regulation, governance, and planning (Banks et al., 2020). Informality is tied to poverty, inadequate access to essential services, resulting in long-term, limited social mobility (Rains and Krishna, 2020). Addressing infrastructural challenges in informal areas faces barriers such as technocratic delivery models, financing gaps, siloed governance, and slow policy innovation adoption (Haque et al., 2021). In this paper, we discuss our research in an informal settlement in Cape Town, South Africa, where the project team co-developed a sector coupling approach. Traditionally understood as integrating different energy systems, our program of research expanded sector coupling to link solar energy infrastructure with socio-economic services such as entrepreneurship, refrigeration, lighting, and internet connectivity. The aim of this was to sustainably address infrastructure inequalities through an integrated perspective on infrastructural configurations. In so doing, our research both builds on and contributes to existing literature that has sought to understand the nature of socio-technical transitions in energy systems (Essex et al., 2024; Verbong and Geels, 2010), including through multi-sectoral (Andersen et al., 2024) and multi-scalar perspectives (Caprotti et al., 2020) and through analysis of different types of energy regimes (Baker, 2023; Branch et al., 2023). In particular, we link our focus on sector coupling to recent research on hybrid infrastructures (Andersson et al., 2022) that has shown how hybridity in infrastructural configurations can be part and parcel of just and sustainable processes of socio-technical transformation (Schmid, 2021).

Informal settlements housed an estimated 1.2bn people in 20,201 (Zerbo et al., 2020). Sub-Saharan Africa (SSA) has the highest proportion of urban residents in informality (51%) (World Bank, n.d.). Since 2010, the number of people in SSA without grid access has risen by 5 million, as grid connection rates fall behind population growth (IEA, IRENA, UNSD, World Bank, and WHO, 2024). In Cape Town, South Africa, 16.5% of residents live in informality, with 40% of informal households lacking electricity (Runsten et al., 2018). Often, in informal urban settings, it is policy, political and legal obstacles rather than technical and financial feasibility that are key challenges to grid electrification (Caprotti et al., 2022). Despite these challenges, informal settlements are hubs of innovation, including for off-grid energy solutions (Pailman et al., 2024).

# 2 Method

## 2.1 Case area

The project was undertaken in the Qandu-Qandu informal settlement, on the eastern side of the partially informal Khayelitsha area of Cape Town (Figure 1). Qandu-Qandu dates from c.2018. At the time of the project (2020–23), there were around 3,500 households in the growing settlement. There were no formal electricity connections, but the settlement lies below high-voltage pylons

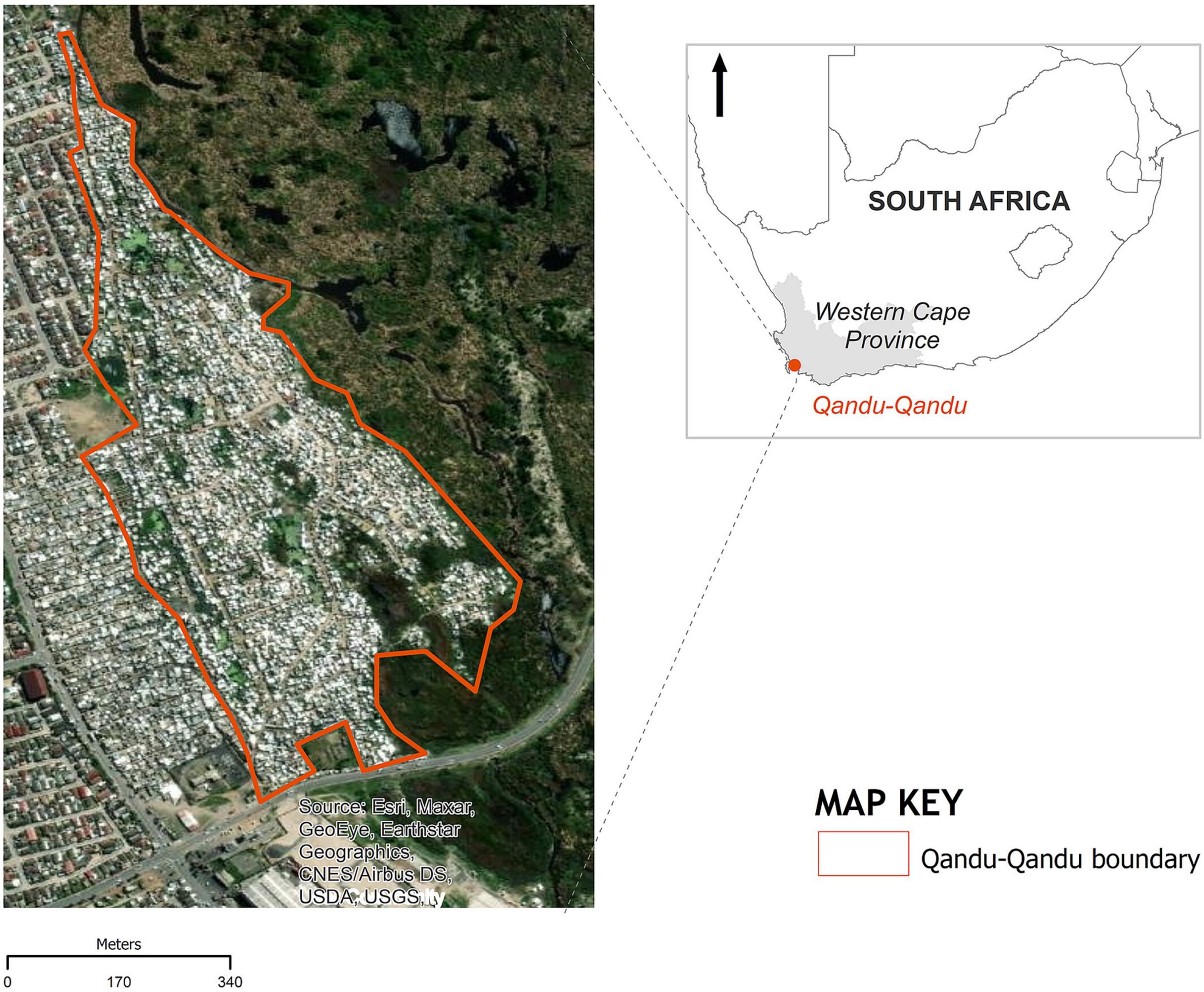


FIGURE 1
Location of Qandu-Qandu, Cape Town [reproduced with permission from Bobbins et al. (2024)].

carrying power lines from the national electricity grid managed by the State utility company Eskom, and as such Qandu-Qandu can be said to exist both below and beyond the grid (Munro, 2020). There were multiple iterative design and implementation phases, with data collected throughout the project. An extensive number of co-production meetings, ranging in frequency from monthly (for the initial project) to weekly (for the energy subsidy project) were held. Since some projects' implementation ended during the program timeline, data was also collected post-project to assess the impact and viability of the project after its formal end date. For the surveys and interviews, we used a non-probability sampling approach, based on convenience sampling, given the research context.

## 2.2 Co-production

The project was based on a co-production approach informed by Community-Based Participatory Research (CBPR) principles (Igwe et al., 2022). This was central to the overall design of the project: academic, private sector and community stakeholders (including community leadership and Qandu-Qandu residents) were involved through various project stages: design, debate, data collection, implementation and evaluation. Although resource- and time-intensive, co-production enabled the project to be highly attuned to community granularity, ensuring inclusivity while attempting to avoid the potentially extractive nature of development-focused research. As part of this process, community members were included in face-to-face discussions including around solar tower siting, solar lighting mapping, leadership meetings, and community information and discussion sessions. Examples of how community members were involved in decision-making, for example, include the organisation of meetings, held in Qandu-Qandu, with the overall community leadership group and the leaders of all of the settlement's sections, to discuss potential project activities and community responses and potential support, as well as to negotiate the role of each partner (including community leadership). These meetings served not only to gauge community responses to off-grid infrastructure development, but also to give specific directions to the project and the project team, informed by feedback from community members.

## 2.3 Surveys

Quantitative survey data collection was undertaken to examine how the installation and operation of solar microgrids had implications for participants. This was carried out via: (a) a baseline survey ($n$ = 52, 2020) with Qandu-Qandu residents through DataHuddle, a data-free app developed by the Thrie Energy Collective and that can be used on entry-level cell phones commonly used in Qandu-Qandu. The survey work focused on forming a basic understanding of energy use and access to different forms of energy by settlement residents. It included: (a) a survey of affordability and willingness to pay ($n$ = 17, 2021–22); (b) a survey of household energy stacking, choices and aspirations ($n$ = 223, 2021–22); (c) solar tower energy usage data (half-hourly energy usage readings, per household and per energy package, 2021–22).

## 2.4 Interviews

The project undertook in-depth qualitative interviews ($n$ = 21, 2020–21) collecting detailed information through discussion with residents and developing an understanding of their energy service challenges and needs. These were analyzed using well-established thematic analysis techniques whereby data are coded and then iteratively analyzed by using themes from the contemporary research literature, as well as grounded analytical themes derived from the data.

## 2.5 Ethnographic methods

Use was made of ethnographic methods of observation, documentation, and interviews as part of entrepreneurship training sessions. These involved a cohort of 100 residents in weekly sessions delivered by training partner Story Room (October–December 2021). The data comprised: (a) documented entrepreneurship mentoring for 19 bootcamp participants who stated an intention to develop a refrigeration-enhanced business (January–March 2022); and (b) exit interviews with entrepreneurship programme participants ($n$ = 7, 2022).

# 3 Results

This paper presents findings from a 2020–23 research program on off-grid, solar-based innovations for key services like lighting and refrigeration, that was coupled with entrepreneurship training to help informal settlement residents generate income and afford energy services. The program comprised US$1.2 m of multiple externally-funded sub-projects across four phases. External funding enabled time and space required to co-produce bottom-up energy interventions with the local community that have potential for future scaling (albeit with full cognizance of the political, community dynamic, financial and other constraints that may inhibit this). Part of this was an aim to ensure long-term financial sustainability for the energy services we introduced: this was achieved by designing the interventions to be operational without continued external funding long after the initial design and installation. At the time of writing, the projects are financially self-sustaining, albeit with difficulties (such as access to scaling finance) inherent in enterprise operation in informality. This highlights insights from the project regarding the importance of integrating electricity infrastructure with other infrastructural services and income-focused interventions to meet informal settlement needs sustainably. Using systems thinking combined with a focus on energy services rather than electricity access, we conceptualize this as operationalizing sector coupling for energy infrastructures and services (Acuña-Coll and Sánchez-Silva, 2023).

Sector coupling typically refers to the integration of energy consumption and demand systems (e.g., solar PV with heat pumps) (Fridgen et al., 2020). However, we suggest it has potential to neatly characterize connections between other important social dimensions of energy infrastructure systems, which ultimately make technical interventions viable and sustainable. We therefore build on and expand the concept of sector coupling to denote the integration of solar electricity with services, such as refrigeration (including freezing), as well as with entrepreneurship and policy innovation. This approach moves beyond isolated energy or other infrastructural interventions, as often found in development-focused projects, and draws on research that understands socio-technical systems as integrated, enabling multi-sectoral urban development strategies that effectively address the techno-economic and social challenges of off-grid infrastructures (Rateau and Jaglin, 2022; Lawhon et al., 2023; Kasper and Schramm, 2023; Caprotti et al., 2024).

In the following, we use examples from the research program to argue that sector coupling can be broadened beyond its traditional technical focus to encompass linked social interventions that support desired outcomes from energy system transformations. While prior literature has focused on technical interconnection within energy systems, this paper proposes an expanded framing where sector coupling captures the institutional and social linkages necessary for the sustainability of off-grid systems. This bridges theoretical debates in urban transitions with practical experimentation in underserved contexts. It also provides some key elements of an approach for addressing issues such as energy justice and just energy transitions. These are key themes that fall outside the scope of this paper, but which can be addressed through a granular, multi-scalar and sector coupling-focused approach we developed and deployed in Qandu-Qandu.

## 3.1 Phase I: solar microgrids

Our solar microgrid focus was informed by the results of survey work with 223 residents of Qandu-Qandu, conducted between November 2020 and March 2021. This indicated that the great majority of households reported energy stacking practices, with no access to formal electricity connections and continued reliance on paraffin, candles and informal electricity connections. Further survey work on affordability revealed that even though residents could not necessarily afford solar electricity, they were nonetheless willing to pay for it (had they been able to afford it) due to its safety over paraffin and candles (Bobbins et al., 2024). As a resident stated in an interview, candles, paraffin and illegal connections '*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.*'

The research program used co-production principles that recognize co-production as an iterative and collaborative process. Our approach was driven by an understanding of co-production as context-based, pluralistic, goal-oriented and interactive (Norström et al., 2020). The program's initial project was a solar microgrid infrastructural intervention used as a basis for learning about the possibilities for further change arising from energy interventions. The project consciously avoided the representation of microgrids as one-shot solutions (Bobbins et al., 2024). Working in Qandu-Qandu in Cape Town, South Africa, 11 solar microgrids were installed between 2020 and 2022 by program partner Zonke Energy, a solar utility. Each microgrid consisted of a solar tower, with panels with a peak rating of 1.2kWp, underslung 5kWh lithium-ion battery, and power cables connecting up to 16 households to each tower (Figure 2). Unlike many co-production studies that remain limited to consultation or project design, this research embedded co-production throughout all phases—including technological deployment, business training, and subsidy policy shaping—marking a significant advance in participatory infrastructure research in informal settlements. A further example of co-production was the involvement of community leaders in the process of choosing sites for microgrid installation (Figure 3).

FIGURE 2
Installing a solar tower-based microgrid in Qandu Qandu, Cape Town, 2021.

The co-production approach to microgrid siting was also useful for the project team, since community engagement was necessary due to technical needs: each microgrid's effective radius was 40 metres from each tower, so clients needed to be situated nearby. Microgrid-based electricity was provided as Direct Current (DC) and was charged and metered digitally, with Zonke Energy operating a digital payment system for this purpose. Analysis of half-hourly microgrid telemetry across towers from August 2021 to February 2022 shows clear daily and seasonal demand variation, consistent specific electricity usage loads, although peak load was always concentrated between 7-10 p.m. across all seasons (Yaguma et al., 2024). Observed profiles suggest the need for demand-responsive sizing and storage, with winter peaks and evening clusters shaping feasible service packages. These quantitative patterns corroborate resident reports of improved reliability and autonomy relative to their prior energy sources.

In the microgrid project, household clients selected different service packages on a 'pay as you go' basis, ranging from the cheapest ('lights and charging', US$8.10 p.m. for up to 7 h of usage per day) to

FIGURE 3
Solar microgrids being installed in Qandu Qandu, Cape Town.

the most expensive package that enabled a fridge or chest freezer to operate (US$26.45 p.m.). Again, co-production was key here in that community members took part in discussions on affordability and 'willingness to pay.' At the same time, it is important to note that follow-on survey work revealed that, even after signing on to a microgrid-based solar electricity service, illegal connections, paraffin and candles continued to be used in cases where affordability became a concern, or where the daily allowance of solar electricity had been used. As Bobbins et al. (2023) note in their analysis of project data, solar microgrid-based electricity use was determined by a dynamic mix of preferences, affordability, seasonality, and meteorological events (mainly intense rainfall). It is therefore key to consider contexts such as Qandu Qandu as sites where testing (of approaches to solar electricity service delivery) and experimentation (with different approaches and technologies aimed at decreasing the use of unsafe energy sources) needs to proceed and be refined over the long term.

## 3.2 Phase II: solar refrigeration and entrepreneurship training

Following installation, the co-production approach enabled emergence of residents' need for refrigeration as a key energy service: this occurred as a result of iterative feedback from community members to the project team. At the same time, our research indicated a significant challenge: the gap between willingness to pay for solar services, and their actual affordability. Indeed, 16 out of the 18 solar clients surveyed on the topic of affordability indicated that they would be willing to pay a monthly fee of ZAR 430 (US$24.86) for access to a solar service package enabling refrigerator and lights use. However, our research also introduced a nuanced distinction between willingness to pay and actual affordability: of the 18 clients surveyed, only two stated that they would be able to afford a solar refrigerator and lights package.

The solution that was implemented by the project was based in overlapping electricity service provision with refrigeration-enhanced entrepreneurship. As is the case in most informal settlements, a significant small business sector exists in Qandu-Qandu: several business owners expressed interest in refrigeration. However, residents faced challenges relating to affordability of fridges and chest freezers, as emerged from our survey of 223 respondents conducted between December 2020 and March 2021 (Cantoni et al., 2022). Previous research has highlighted the need for Efficient Productive Uses of Electricity (EPUE) (Xhafa et al., 2024), and for more field testing of high efficiency productive use-linked solar appliances (Abagi et al., 2020), since high efficiency appliances are needed for the utilization of the lower power capacity of solar electricity compared to grid connections. A key obstacle to EPUE in informal settlements was the high cost of these efficient appliances. This highlighted the need for coupling of technical systems with other social system elements to achieve improved outcomes for residents, and led to an entrepreneurship-based project aimed at enabling microgrid-connected clients to use refrigeration as part of their businesses.

This second project, therefore, delivered an entrepreneurship 'bootcamp' to a total of 100 informal settlement residents, including training in financial literacy skills. The project team developed a two-month program of training. This included the design of bespoke training materials on a range of entrepreneurship-focused topics. The core aim was to enable participants to operationalize EPUE through their own refrigeration businesses, to enhance livelihoods and ensure viability. Of 19 businesses that started using refrigeration appliances as part of their business offering following the bootcamp intervention, 17 are still operational. By integrating off-grid solar electricity with services (refrigeration) and entrepreneurship initiatives, the program not only expanded service delivery potential but also challenged entrenched infrastructural and technical silos. At the same time, as our EPUE-focused thematic analysis showed (Yaguma et al., 2024), there remained key barriers affordability, which in turn was a potential constraint on scalability. Nonetheless, as one training program attendee told us in end-of-training feedback in November 2021: '*This program has helped me a lot [.] I now know how to do a business plan, business strategy, marketing, business finance also budgeting coz its very important. [I] also have an action plan to follow my business*.' Therefore, while thematic analysis revealed that micro-political factors such as siting, technology type, safety, affordability and type and scale of financing were key determinants of microgrid access and EPUE applications.

### 3.3 Phase III: public solar lighting

A further notable intervention, in addition to combining refrigeration and entrepreneurship schemes, involved introducing solar tower-powered public lighting, paired with standalone (community-owned, maintained, and operated) solar lights to illuminate public spaces and thoroughfares. It was found, through survey work, that 64% of residents were not satisfied with the (non-solar powered) lighting in their homes (Yaguma et al., 2024).

Through co-produced mapping sessions with residents, the intervention questioned assumptions about lighting needs, which often focus narrowly on individual households. Four participatory design workshops were held in February–March 2023, with a focus on community mapping. Additionally, 18 separate meetings were held with community leadership and other community members, in order to progress the project. The workshops were designed so that all 13 settlement sections were represented: two participants from each section were present at the sessions (26 in total per session, with a total of 38 unique individuals across all four sessions). The mapping sessions were intensive, mediated and *in situ*, and were central to the process of understanding exactly where each public solar light should be sited. The workshops produced 13 maps, identifying locations for the installation of 460 solar lights, each comprising a 15 W solar panel LED floodlight, and lithium-ion phosphate battery (3.2 V / 10A). The community ownership, maintenance and repair model further underscored the critical socio-technical interconnectedness of technical solutions and social dynamics. At the same time, our results, and comparative research between our intervention in Qandu Qandu and other solar lighting projects in informal settlements in Cape Town (Borofsky and Caprotti, 2025) show that a complex dynamic between ownership models, the involvement of non-state actors, local community political arrangements, and the characteristics and temporalities of project financing determine the eventual long-term sustainability and potential scalability of similar projects.

Nonetheless, at the level of the community the results of introducing solar lighting were significant, in that solar lighting was seen as a significant improvement to wellbeing and safety. For example, a resident who also ran a business out of a home reported in Yaguma et al. (2024, 8) that:

> '*[I]t 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*.'

Taken together, our integrated survey, solar tower usage and qualitative, thematic data show that service-based solar microgrids can reliably deliver lighting and refrigeration, enable targeted PUE among selected micro-enterprises, and reduce exposure to hazardous energy practices. However, affordability, appliance availability, and the fit between packaged services and heterogeneous livelihoods currently limit broader PUE adoption and scaling. These results directly inform the themes that have to be taken into account in designing potential future financing and policy supports required for equitable, scalable off-grid services in peri-urban informal settlements.

### 3.4 Phase IV: digital access through solar Wi-Fi

A final program project concerns electricity-data coupling, which arose through residents describing challenges linked to the necessity of and limited access to internet services. Residents relied on expensive pay-as-you-go data or travelled long distances for free Wi-Fi, and 2022 solar microgrid-focused interviews highlighted community need for Wi-Fi infrastructure. This is crucial in a context where digital data access is increasingly crucial for socioeconomic purposes, including job seeking, welfare information, service access, banking, communication, including with kinship networks across South Africa, and information and education, including online schoolwork. In response to these challenges, the project supported entry into the settlement of a Wi-Fi internet provider. The provider installed mesh repeaters on the solar towers, using their power. The network enabled settlement residents access to high-speed data, the first hour per day of which was free (a one-day Wi-Fi package was US$0.27, one month was US$4.87).

## 4 Discussion

The research outlined above enabled electricity-focused services to be linked to further sectors (lighting and data), using a range of delivery models, from community ownership to private service delivery with limited free daily use, which crucially emerged from giving attention to the social dimensions of infrastructural provisioning. In existing literature and practice, debates have centred around problems with situating electricity provision as a single isolated service or product (Yaguma et al., 2022). Building on the call for stronger links between and across energy sectors that are found in these debates, we show how understanding energy as nested within a network of linked infrastructures and livelihood development opportunities enables urban transition agendas to move past silos that militate against socio-technical system interconnections and multi-sectoral ways of working. In this way, the project contributes to a deepened understanding of challenges involving multiple services and infrastructures, particularly in electricity-refrigeration-entrepreneurship, electricity-lighting, and electricity-data connectivity, by adopting a co-production approach centered on residents' voices and needs.

The research program's outcomes in terms of sector coupling and cross sectoral thinking has further important implications for debates about policy innovation and how to overcome persistent challenges of structural inequality engendered by living in informal contexts.

Research has demonstrated how a lack of recognition (from authorities) of rights to the city for those living in informal contexts creates enduring issues in energy (and wider) infrastructure provisioning (Huchzermeyer et al., 2019). This often means that even where settlements have become long-standing parts of the city, they are likely to never receive benefits (such as energy subsidies) enjoyed by other inhabitants of the 'formal' city.

By demonstrating the viability of off-grid solar service delivery, and community demand for it, the program was able to develop policy interventions that overcome the formal/informal divide. A 2024–26 pilot, funded by InnovateUK's Energy Catalyst Round 10 program, will test the provision of a solar electricity subsidy to Qandu-Qandu residents. This was partly the result of a policy testing interest from the City of Cape Town based on the research program's work on solar-based interventions. The subsidy, known as Free Basic Electricity (FBE), was previously only available to formally grid-connected city residents. The pilot will help to address inequalities linked to the availability of subsidies to formal households, but largely not available to informal settlement residents. This shows the significant potential that exists for linking private sector off-grid energy utilities to policymaking priorities and resources, and overcoming structural conditions that reproduce inequalities by adopting approaches that foreground socio-technical infrastructural change processes.

At the same time, the scalability and replicability of the program and its sub-projects need to be tempered with acknowledgement of significant potential constraints. These include barriers and bottlenecks linked to municipal and local politics, governance and planning systems, and the impact of external policy frameworks around such things as social housing provision. Furthermore, there are significant and enduring scalability challenges with approaches that are based on resource-intensive, on-the-ground engagement with specific local communities (Borofsky et al., 2025), although such granular work has, in our case, yielded thematic results that have a claim to generalisability in terms of design and approach principles and themes [see, for example, Bobbins et al. (2024)]. At the same time, community dynamics, community relations, and the cost and affordability profile of off-grid technical systems such as off-grid solar can be key determinants and/or obstacles to scalability and replicability. All of these factors form part and parcel of a risk profile that needs to be assessed across project lifetimes and within the broader urban and regional contexts in which replication or scaling is targeted.

On the other hand, the program's results chime with arguments for systems thinking in evolving infrastructural energy service delivery models. Systems thinking involves understanding infrastructure not as isolated components, but as interconnected networks where technical elements, social contexts, economic factors, and policies dynamically influence one another. Our work offers clear insight into the value and importance of socio-technical aspects, including co-production, for system change. The program highlights how technical infrastructural interventions can be brought together with understanding of the wider social, political and policy contexts to create successful energy transitions within the informal city. Crucial to this was the external finance made available through the research program as a necessary enabling condition for pilot testing innovative approaches: this can then attract interest and investment from municipal authorities and thus lead to long-lasting socio-technical and policy change. The approach embodied in this project offers potential for wider scaling and citywide application within and beyond South Africa.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by the Department of Geography Ethics Committee at the University of Exeter. The studies referenced in this article were conducted in accordance with local legislation and institutional requirements. Written informed consent for participation in this study was provided. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

FC: Validation, Project administration, Conceptualization, Methodology, Supervision, Writing – review & editing, Data curation, Investigation, Writing – original draft, Funding acquisition, Resources, Formal Analysis. JG: Investigation, Supervision, Funding acquisition, Conceptualization, Formal analysis, Project administration, Writing – review & editing, Resources, Data curation, Writing – original draft, Methodology, Validation. CB: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization, Supervision, Data curation, Methodology. WP: Writing – review & editing, Writing – original draft. NM: Writing – original draft, Data curation, Investigation, Writing – review & editing. HS: Validation, Investigation, Writing – review & editing, Funding acquisition, Project administration, Writing – original draft, Methodology. AD: Writing – original draft, Validation, Writing – review & editing, Project administration, Investigation, Funding acquisition, Methodology.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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