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The informality-energy innovation-finance nexus: Sustainable business models for microgrid-based off-grid urban energy access

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ABSTRACT

This paper proposes the concept of the *informality- energy innovation- finance* nexus, as a theoretical framework to analyse micro-grid based urban off-grid energy access. The provision of energy access in urban informal settlements has received increased attention by scholars working on informality and energy in recent years. Recently, scholars have looked at the off-grid-urban informality nexus and have argued for the integration of off-grid electrification technologies in South Africa's informal settlements. Concurrently scholars have argued for more user centric business models for off-grid contexts. Off-grid technologies like micro-grids and stand-alone solar home systems have become an integral part of the energy landscape of energy access in Sub-Saharan Africa and can fill a key gap for unelectrified urban informal settlements. However, there remains a gap in the literature linking user-centric off-grid business, financing models and urban informality. This paper fills this gap and argues for greater contextual embeddedness and attention to the local context when implementing off-grid business models in settings of urban informality. This paper draws on the findings of the Umbane project, a pilot study on solar powered refrigeration for women owned enterprises connected a micro-grid in an informal settlement Qandu-Qandu in Cape Town, Khayelitsha. This paper uses mixed research methods, including semi-structured interviews with entrepreneurship project participants and a survey. This paper offers key insights from our practice-based work on implementing solar micro-grids in settings of informality and the contextual factors and drivers that shape the informality, energy-innovation and finance nexus.

1. Introduction

Energy access in informal settlements increasingly includes off-grid 'solutions' such as solar microgrids, Solar Home Systems (SHSs) and other forms of non-grid electricity access. While these systems often contain innovative technical elements and rely on significant community engagement for their deployment and operation, their success or failure is often contingent on how well business models are tailored to local contextual factors such as affordability, willingness to pay, and user experiences. In light of this, this paper proposes the concept of the *informality- energy innovation- finance* nexus, as a theoretical framework to analyse the provision of micro-grid based off-grid urban energy access. We base our analysis on the study of a rollout of solar microgrids and microgrid-linked productive use appliances in Qandu-Qandu, an African informal settlement in Cape Town, South Africa. The *informality-energy innovation- finance* nexus emerged as a culmination of our practice-based work on solar micro-grids in informal settlements in Cape Town South Africa. This framework was informed by pilot projects including Energy for Wellbeing and UMBANE (2019–2022) co-led by the Universities of Exeter and Cape Town, focused on micro-grid tower based solar innovation, wellbeing and refrigeration for productive uses. Through these pilots, *affordability* and *finance* were emphasised as salient aspects of business model sustainability. Furthermore, by drawing linkages between practice based observations and theoretical insights on implementing solar micro-grid innovation pilots in contexts of urban informality, see e.g. [1–3], practical insights emerged, which necessitates rethinking how we conceptualise the interlinkages between *finance* (particularly end-user finance), *innovation* and *informality*.

The provision of energy access in urban informal settlements has received increased attention by scholars working on informality and

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energy in recent years [1–5]. Urban informality continues to be the lived reality for many urban dwellers with urban informal settlements rising to 1bn residents in 2018; 230 m informal settlement residents are Sub-Saharan Africa [6]. Informal settlements are often characterised by critical infrastructural gaps, including inadequate housing, sanitation, water supply and access to electricity [5]. Despite their proximity to centralised grid infrastructure, many households and businesses in informal settlements remain unconnected to the main grid [7]. Reasons include prohibitively high connection costs, technical constraints due to locality, contestations over land tenure and a failure to effectively integrate informal settlements into city planning. The physical or material aspects of urban informality continue to be intrinsically linked to the broader social, economic and historical context that shapes the structural and spatial inequalities in Qandu-Qandu and South African cities at large. Indeed, as Haque, Lemanski and de Groot et al. [8] contend, infrastructure delivery (or lack thereof) is often not just an issue of physical access but encompasses socio-technical and socio-political processes involved in the governance of urban infrastructures. These dynamics all impact the development, refinement and likelihood of success of an off-grid business model.

In lieu of access to formal grid infrastructure, off-grid innovations, which are often used to serve remote rural communities, are increasingly considered as a tangible, immediate, and potentially lasting solution to energy access challenges in growing and sprawling cities [1,2]. It is thus important to consider off-grid options as households, businesses or home-based enterprises in a settlement like Qandu-Qandu, are unlikely to receive a formal grid connection[1] and would thus not be electrified if not for off-grid alternatives. Off-grid technologies like micro-grids and stand-alone solar home systems have become an integral part of the energy landscape of energy access in Sub-Saharan Africa [9] and can fill a key gap for unelectrified urban informal settlements [1–4]. Recently, scholars have looked at the off-grid- urban informality nexus and have argued for the integration of off-grid electrification technologies in South Africa's informal settlements [1–3]. While off-grid stand-alone solar systems provide an entry level of service for basic energy services including lighting and powering basic appliances, micro-grids (i.e., decentralised distributed grids) can provide energy access to several households simultaneously with higher levels of service (tiers 2–5 in the Energy Sector Management Assistance Programme (ESMAP) Multi-tier framework[2]). Micro-grids can enable productive uses of electricity but in practice sometimes fall between solar home systems and mini-grids in terms of the level of service offered. In contrast, larger rooftop solar systems and small-scale embedded generation units often used by more affluent households, can offer higher tiers of access, but at a substantially higher cost.[3] Among more affluent households in Cape Town and other South African cities, these systems could either be entirely privately funded or through commercial debt finance for rooftop solar.

[1] While formalisation might be an option for some informal settlements in South Africa, Qandu-Qandu, has been catergorised as a Type 3 settlement that is unlikely to receive formal grid connection due to several encumbrances. These include among other being partially constructed on wetland and under a transmission line which poses, safety and practical constraints. It furthermore links to broader issues and contestations around informal housing settlements, like tenure and mandates for service delivery. This creates a particular gap and need for solar electricity and niche innovation pilots like the Energy for Well-being and Umbane pilots.

[2] The framework has been developed by ESMAP, part of the World Bank, to categorise levels of off-grid energy access according to pre-defined tiers that range from lower levels of access providing only basic lighting and other basic levels of access.

[3] In South Africa, depending on the size of the system and storage, this could range between 100,000 ZAR to 150,000 ZAR, which significantly above what businesses or households in informal settlements like Qandu-Qandu could afford.

Considering the above context, this paper analyses off-grid micro-grid business model development in the 'informal city' with a focus on affordability and end-user finance for developing sustainable off-grid models for urban energy provision. Drawing on findings from the Qandu-Qandu case study, the sections below first contextualise off-grid solar innovation, informality and finance within existing literature and theoretical paradigms, and introduce the key elements of the *informality-energy innovation- finance* nexus as a lens through which off-grid solar business model innovation in the 'informal city' can be analysed.

2. Affordability, local contexts and user-centric business models

Although off-grid technologies and business models can offer significant advantages for electrifying urban informal settlements, as listed above, these models need to be critically assessed, and continuously improved to enable low-income customers to afford energy services. The affordability gap, which is especially pronounced in low income and income constrained environments like off-grid informal settlements, makes affordability and frequent payments for energy services particularly challenging, and adds complexity to the challenge of energy service provision [10,11]. This has given rise to innovative payment technologies including mobile based payment systems (used by companies like MKOPA, BBOXX and several others) and business models for the diffusion of off-grid stand-alone solar and micro-grids [12,13].

Affordability and the ability to pay for energy services are key considerations as many settlement residents earn low or irregular incomes [14]. In addition, it is important to consider how these off-grid electrification projects are financed. Off-grid electrification projects are often funded by a combination of international development/ donor finance, mostly in the form of grants as well as private equity and debt finance [15]. These include large innovation grant funding programmes, including international government and foundation funding through e. g. the Transforming Energy Access Platform, the Shell Foundation, Rockefeller Foundation and other development funds that competitively award innovators with funding to pilot and test off-grid innovations. The extent of the energy access gap necessitates suitable and innovative of financing models, from a range of funding avenues, and leveraging blended finance to multiply limited public funding and 'crowd in' private capital to fund energy innovations, projects and initiatives [11]. This requires innovative financing mechanisms and models to address the affordability gap and price sensitivity of customers. The funding models and sources of financing are thus an integral part of developing business models to provide services that are tailored to filling this notable electrification gap. While innovative energy access 'solutions' may be framed as a response to global imperatives, such as SDG 7, these are also direct responses to local energy access deficits and infrastructure challenges, where niche innovations fill the gap left by national utilities or municipal authorities. These approaches not only fill an important energy access gap on the ground, but also provide fertile ground for testing innovation.

Importantly, the implementation of off-grid solutions in informal settlements should be contextually grounded [16,17]. Given the focus on SDG 7, critical reflection is needed on what it means to develop sustainable, innovative and scalable models for energy technologies [10,18], including in informal settings. It is therefore important to ensure that energy access technologies and business models are locally appropriate and suitable for the contexts for which they are being developed. Informality is a key dimension in which there are few locally appropriate and scalable business models developed to date. While off-grid innovations like solar micro-grids in the case study of Qandu-Qandu and elsewhere, are often framed as 'solutions' to persistent energy access challenges, these systems also come with layers of complexity, regarding the effective functioning of a technology, the suitability or appropriateness of the business model and responsiveness to community needs [5].

The idea of user centric business models for electrification or energy

services has been well acknowledged in the literature [see e.g. 19, 20, 21]. Suitability for local context and user centricity are crucial for our analysis of off-grid business models in informal contexts. However, there remains a gap in the literature linking user-centric off-grid business models, financing and urban informality. This paper fills this gap and argues for greater contextual embeddedness and attention to the local context when implementing off-grid business models in contexts of urban informality. This requires an understanding of how end-users experience technologies and to incorporate this understanding into the design of business models. This paper draws on the findings of the Umbane project, a pilot study on solar powered refrigeration for women owned enterprises connected a micro-grid[4] in an informal settlement Qandu-Qandu in Cape Town, Khayelitsha. This paper uses mixed research methods, including semi-structured interviews with entrepreneurship project participants and a survey (elaborated in the methods section). The Umbane project specifically focused on supporting livelihood opportunities for women-owned businesses in Qandu-Qandu, addressing a need identified[5] for solar refrigeration.

Our inquiry into the co-production of innovative business models for off-grid energy access is set against the backdrop of growing discourse promoting productive uses of energy. International development organisations including Sustainable Energy for All, the World Bank, Energising Development (EnDev) and others advocated for off-grid productive use of energy appliances placing a spotlight on the need for innovative business models. Solar powered productive use appliances, like solar refrigeration, are considered the 'next frontier' of off-grid solar for their promise to facilitate income generating activities [22]. While the off-grid productive use literature largely discusses the logical drivers and rationale for higher tiers of energy access, the case study of Qandu-Qandu, nuances these arguments. Importantly it shows the disjuncture between theory and praxis that can often occur when deploying off-grid appliances like solar fridges in settings of urban informality.

3. Informality, energy innovation, and finance

The perspective on off-grid solar innovation projects proposed here, is based on two interrelated conceptual approaches. First, we develop an understanding of the informal context as needing granular and contextual engagement. At the same time, we argue for a critical engagement with often-celebratory discourses that elevate off-grid 'solutions', 'innovations', and 'disruptive technologies' as panaceas for long-running, embedded, structural inequalities around basic service provision, infrastructural disruption and heterogeneity in informal settlements. Second, we argue for a need to engage with the nexus through which informality, energy innovation, and finance are intertwined.

3.1. Provincialising urban knowledge production and problematising informality and off-grid 'solutions'

The paper's focus on solar energy-based infrastructural interventions in off-grid urban spaces is contextualised within broad research trends on the provincialisation of urban knowledge production [16,17]. Grid-based initiatives, and some off-grid energy projects, are often set within worlding discourses linked to the state's policies, the global market, and the international circulation of development targets [23] such as the UN's SDGs, or global agendas such as the New Urban Agenda [24]. These development-focused narratives of political modernity [25] are all too often based in notions that prioritise the global over the local, and that reproduce notions of development trajectories that emerge from the Global North, or at least from the circuits of international economic and development elites [26]. While the global impetus for the focus on the SDGs speak to some of the challenges faced by informal settlement residents, these international drivers should not be 'leading the charge' to develop solutions for local communities. In contrast, recent work linking energy and off-grid cities has underlined the importance of engaging with granular local contexts [1,2].

The focus on off-grid infrastructural interventions as rooted in place and bounded within specific sites and actor-networks is also rooted to an understanding of the off-grid as not just a spatial construct (although the spatial dimension is crucial), but as something that is produced, performed, and constantly relationally reworked. It is in this sense, through viewing off-grid infrastructures and the 'off-grid city' as the product of dynamic relationships, that it can be seen through a lens that takes granularity seriously, while at the same time acknowledging the relationships that extend and stretch beyond the purely spatial [27]. This also sets our understanding of off-grid solar energy within the panorama of energyscapes, a 'moving landscape of suppliers, consumers, technologies, ideas, components and production techniques' [28,16].

With regards to off-grid solar, recent work has highlighted the existence of off-grid urban solar 'solutions' within a bricolage of multiple, dynamic and persistent energy practices [29]. While some recent work has sought to chart the link between off-grid solar and global circuits of capital investment and policy support for the solar industry in a Global South context [30], the link between granular urban contexts and the broader notion of off-grid solar as innovation (in terms of technology, service offering, and as an enabler of innovative energy practices) has been underexplored. The move towards more innovation funding and private funding for off-grid systems is also given impetus by global shifts more generally towards private sector involvement in energy provision, which itself raises questions around complexity of 'shifting' state responsibility in energy provision towards the private sector and some of the potential benefits and challenges involved in that move.

Likewise, there has been a lack of focus on the financing dimensions of deploying off-grid energy solutions, specifically within the contexts of urban informality. Notwithstanding studies exploring global and international circuits of investment into off-grid solar [30] and off-grid energy access development finance projects [see 31,32,33], there is paucity in the literature exploring dynamics of finance, including end-user finance for micro-grids in urban informal settlements. Both aspects are crucial to understanding and engaging with the dynamic energy landscapes around off-grid solar in off-grid urban areas and has a bearing on the affordability of off-grid solutions/proposed models. Engaging critically with energy innovation processes and how they play out at the local and community level is key to conceptualising the relational and shifting nature of off-grid energy. Furthermore, this needs to take place in tandem with unpacking the multiple financial ramifications of off-grid projects: from affordability to long-term financial viability and availability of capital. This will aid in understanding their multiple iterations and materializations across different urban contexts in the Global South. Iterations include the multiple configurations and forms of off-grid energy (and their dependencies on grid access), including how this interrelationship changes over time in relation to affordability and financing options.

To engage with off-grid solar energy landscapes in the Global South city, the paper is also grounded in a critical recognition of the complex nature of informal settlement urban contexts. This is crucial to contextualizing off-grid energy: firstly, many off-grid solar projects in low-income areas in cities in the Global South are in informal settlements. In this paper, urban informality is treated not as part of a formal/informal binary that risks reproducing colonial hierarchies [34,35], but as a set of processes, strategies, and power relations [36]. At the same time, in underlining our commitment to granular context, we also

[4] The micro-grid (or nano-grid) in Qandu-Qandu comprises a solar tower with 1.4kWp solar PV and 5kWhs of lithium-ion battery storage. Each solar tower consists of low voltage distribution (i.e.,24 V). This system provides lower-tier energy access (ESMAP 1–2/3), closer to what a solar home system could provide but with the capability to power a DC solar fridge.

[5] Through data collected in the Energy4Wellbeing project, preceding the Umbane project, refrigeration was identified as a key gap among sample respondents (community members) in Qandu-Qandu.

understand informality as a material reality with key physical and morphological characteristics [37]. Furthermore, our conceptualisation of informality relates to situated practices around energy, and the production of precarious infrastructures (of which off-grid solar can be considered one) [38] can be seen as nested within the morphologically identifiable and yet dynamic and shifting informal urban context.

Secondly it is necessary to consider user-centricity in the design and application of off-grid business models [19,21,39]. Schiellebeeckx. et al. [19] advocated for a user centric approach for business models for rural electrification in Global South contexts, while Tolkam et al. [21] researched the context of energy service business model design in the Netherlands. Castan Broto et al. [20]'s focus on a people centred approach to energy access in Global South, urban contexts extend to business models as well. Different off-grid business models cater to different markets, and the business and financing models used to cater to more affluent households within the same city are often vastly different to low-income innovation models being piloted, especially regarding affordability barriers which often times serve as a significant millstones to the sustainability of a business model in an off-grid context. In more recent scholarship, authors have argued for integrating an end-user perspective into the design of micro-grid projects [e.g. 39]. Oyeya, Muhoza & Johnson [39], who studied six micro-grid projects in Tanzania, contend that user centricity is a key aspect of designing micro-grid services and needs to incorporate an understanding of end-user needs and expectations while also considering socio-cultural aspects of energy transitions.

Thirdly, it is key to problematise off-grid technologies, services and approaches which are constructed as 'solutions' to the infrastructural and other inequalities of informality. Off-grid solar is often constructed as a panacea for the lack of formal energy services in informal contexts described, more or less openly, as somehow deficient or inadequate [4]. This, however, does not reflect the results of social science-informed research and experiences of companies on the ground regarding the implementation and operation of off-grid solar in cities in the Global South. It is therefore key to critically engage with emerging, persistent constructions of off-grid 'solutions' as inherently progressive and as leading to positive outcomes in most cases. Cross and Neumark [30: 903] have highlighted how policymakers and practitioners 'appear to have largely accepted the role of privately owned, off-grid energy companies as essential for meeting the United Nations' Sustainable Development Goals' and that there are key concerns around affordability, e-waste, reliability, and the achievability of the oft-touted mantra that off-grid solar will necessarily deliver energy access results for the poorest. This further relates to the 'morality' and justice-related view of delivering energy services, and whether the responsibility for electrifying off-grid communities should rest in the public or private domain [3].

3.2. The informality- energy innovation-finance nexus

Off-grid solar represents an innovative technology *and* approach to energy access in informal settlements, and the 'silent technological revolution' [40: 915]. In the broader African context this technological revolution has been defined by the diffusion of new technologies (such as mobile phones, drones, and solar energy), and by indigenous innovation linked to these, for example Rwandan based social enterprise ARED who developed the 'solar smart kiosks' which also serve as a mobile phone charging stations in Kigali [41].

In this paper we propose an *informality-energy innovation-finance nexus* (see Fig. 1 below). We argue that a nexus perspective is needed to analyse the development of off-grid business models in informal settlements. The above sections have highlighted gaps in the understanding of the complex interface between urban informality, finance, off-grid business model development and innovation. Particularly it highlighted the need for understanding the granular urban contexts and 'co-development' of off-grid solar innovation through processes of refinement and iteration. It also emphasised the paucity in the literature specifically looking at finance for off-grid innovations in the informal city in urban studies literature.

Informality is the key context and interface through which innovation and scaling can (and often cannot or does not) occur [42]. Recent scholarship on urban informality has furthermore signalled a shift from characterising urban informality through a lens of deprivation, but rather acknowledging the legitimacy of the informal city as well as off-grid modalities for energy provision [1,43–45]. For example, Bobbins et al. [45] reconceptualise the traditional notions of 'formality and informality' for energy provision in the informal city, recognising the need to 'reposition' these notions for energy access and energy transitions. Kovacic et al. [44] emphasise the need to acknowledge and legitimise the informal city and livelihoods within informal communities, pointing to the critical need for appropriate urban governance for shaping energy transitions.

Off-grid informal settlements are characterised by a range of facets that make them highly diverse, and at the same time render engagement with this granularity important for business sustainability, affordability, community acceptance, and long-term viability. The market for off-grid energy in informal settlement contexts is nevertheless significant: Sub-Saharan Africa currently accounts for c.70 % of global sales of SHSs, for example [46], with an expected growth rate of 80–90 % globally to 2025 with an overall market of 310 million people [47]. Mini-grids are also considered to have a significant market penetration potential in Sub-Saharan Africa, if supported by favourable financing and regulatory conditions [48]. Of the total market penetration for off-grid solar products, the opportunity for the deployment of variation of these systems is considerable and still largely untapped [49], except for disparate initiatives deploying off-grid solutions in informal settlements or slums.

We viewed *innovation* through the lens of informality: not as a technocratic, top-down process, but as an *adaptive* practice. This perspective recognises that obstacles to infrastructural, business and service delivery innovations in informal contexts is largely rooted in the misalignment between innovation on the one hand, and the informal context on the other [50]. Thus, we consider *innovation* and *informality* as both being constantly changing. According to this perspective, innovation is not a single technical service or product occurring at a single point in time. This reflects the everyday practices of informal settlement residents' lives, and the constant need to adapt and change to a dynamic context which does not lend itself well to one-size-fits-all infrastructure or service delivery options designed 'outside' the settlement [51]. The dynamic nature of innovation in contexts of urban informality, requires business models that are a commensurately dynamic and flexible.

Due to the paper's focus on analysing sustainable business models for off-grid solar, we base our understanding of off-grid solar innovations in work that sought to understand features such as scaling[6] in a sub-Saharan African context. Amankwah-Moah [52] has proposed multiple models through which scaling can be understood in an African solar context, such as: a.) those led by NGOs and international agencies; b.) models based on Chinese multinational investment via exports and/or manufacturing; c.) the 'Avon' model of person-to-person sales, such as the Solar Sister enterprise; d.) pay-as-you-go (PAYG) models based on incremental payments for specific service levels. In the context of off-grid solar in a South African context, the models that are most relevant are those led by NGOs and international agencies, and fee-for-service models whereby solar utilities charge a fee for a pre-determined level of service. The use of the latter model is a response to two of the key barriers to technological adoption and development in informal settlements: affordability (for consumers), and access to

[6] Here scaling refers to reaching more customers in a given market segment or expanding the geographic reach of off-grid solar in new unreached or underserved markets.

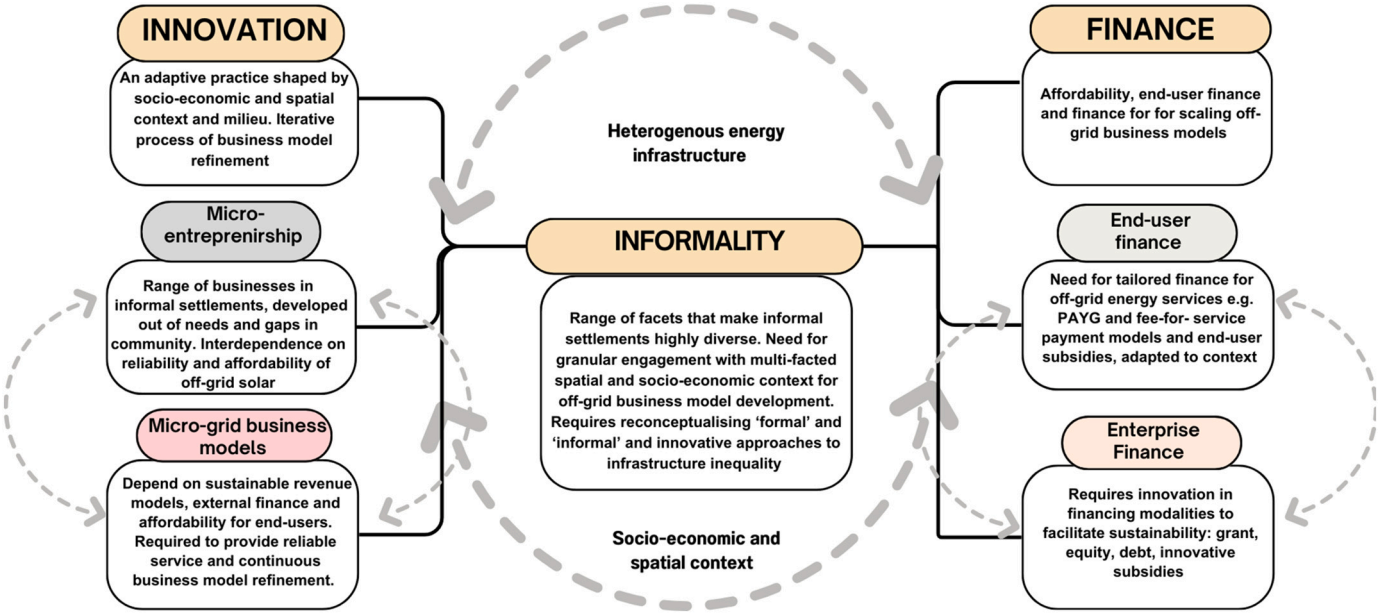

Fig. 1. Informality-energy innovation-finance nexus (Source: Authors).

finance (for solar utilities). Indeed, in 2012 PAYG systems accounted for c.85 % of all investment into the off-grid SHS sector [46].

Finance is a crucial link between innovation, informality, and multiple aspects of sustainable and just development and transitions, such as energy. While finance has been acknowledged as critical aspect for deploying off-grid solar innovations and advancing SDG 7 [31–33], it is often not included in mainstream urban and energy studies literatures on informality and energy service delivery. Yet, access to finance is key for the successful scaling and long-term sustainability of off-grid solar energy projects [33]. Several market-based, public and donor pathways to financing off-grid projects exist. Market-based avenues include venture capital and impact funders, alongside banks and other forms of investors. However, the risk profile of firms operating in informal settlements is compounded by the risk of operating in informal settlements and the lack of experience of mainstream finance actors with informal settlement contexts, means that access to market-based finance is in most cases a significant barrier. Public pathways include funding from municipal, state, or other usually government-based sources. There are difficulties, however, in directing public funds towards solar utilities, which are usually private firms; and the landscape of innovative public financing of off-grid solar (through, for example, voucher schemes given directly to settlement residents) is relatively new at the time of writing [53]. Donor finance is generally grant-based, and time-constrained. While donor finance can be seen as the least risky option for off-grid utilities, a clear implicit risk to reliance on donor funding is the impossibility of planning beyond the short term. This is because there is no guarantee that one grant will follow another, and therefore, donor finance has to be seen as part and parcel of initial project development, or of funding of spin-offs or additional activities for which one-off funding can be suitable.

Much of the literature on informality and energy focuses on the role of the state and its constituent bodies (including government departments, but also municipalities, local political systems, regulators, and energy authorities), and on international governance actors as enablers or inhibitors of sustainable development [54]. A significant body of literature also exists on the role of the state in providing loans and credit schemes for technologies such as SHSs [47]. Nonetheless, while the state is a key stakeholder in development, finance is often underrepresented in studies of the link between informality and energy [1]. In the context of informality, finance needs to be treated as a multifaceted construct, which considers end user affordability and finance with consideration to how innovation finance is being used to deploy innovative projects and its ability to leverage additional forms of funding. Elements of finance which impact on innovation and energy include financial constraints and opportunities at the following scales:

a.) *the household* and home-based enterprise scale: affordability of off-grid energy services both in a standalone manner, and in relation to energy stacking (the practice of using multiple forms of energy such as paraffin, kerosene, charcoal, candles, and others to respond to shifting energy availability and costs); financial resilience of individuals and households in terms of being able to continuously access and pay for PAYG services and products [12,14]; access to finance for upgrading, maintenance and replacing home energy systems, their components, and linked appliances; financial records and mechanisms that enable access to loans, microcredit, and other financial services. This further considers irregular income patterns and seasonal employment. It should be further noted that non- GOGLA affiliated sales of off-grid solar products also constitute a considerable 'informal market' for off-grid solar products. In the case of rural micro-grids in India, Bandi et al. [55] find that if social enterprises are not able to manage the complexities of the socio-technical systems like mini-grids, the customer affordability and business model viability paradox remains unsolved. Although the tension between end-user affordability and micro-grid viability is well documented in the literature [see e.g., 55,14,5], there are several nuances and contextual factors that make creating viable off-grid business models challenging in the context of off-grid urban informality (including seasonality of income and how business is conducted in the community).

b.) *the community* scale: the availability and existence of sectors of the community that can function as a customer base for off-grid energy utilities; representation of the local community within and by governance structures to enable communities to access public subsidies that make off-grid energy services affordable.

c.) *the firm* scale: the accessibility of private, venture capital (VC), impact funding, donor or other funding streams that enable off-grid firms to function in informal settings; and the availability of finance for scaling and replication of innovative off-grid services in informal settings.

d.) *the off-grid financing industry* scale: the suite of finance-linked firms and agencies that can supply financing streams specifically to the off-grid sector, whether to households, communities, firms or other relevant bodies. This financing universe is taking shape in many off-grid geographies, embryonic in others, and non-existent in some. Obstacles to the development of off-grid financing industries include elements such as financial risk profiles, risk perception, finance aims, financing timelines, and communication and interaction between off-grid finance and actors as the firm and community levels.

This paper primarily focused on end-user finance and affordability at the household/ home-based enterprise scale dimension of the informality- energy innovation-finance nexus, while acknowledging how this level or dimension impacts and is impacted by other dimensions of finance.

4. Solar micro-grids in Qandu-Qandu, South Africa

4.1. Context

Qandu-Qandu is part of an existing informal settlement in Khayelitsha in the Western Cape Province of South Africa (see Fig. 2). Established in 2018, the settlement has over 4835 households, which lack access to formal 'grid' infrastructure access (electricity, water, or sanitation) [56]. The settlement is located on a site owned by the council that is designated for the implementation and management of grid-based energy infrastructures.[7] Furthermore, the settlement is built partly on a wetland resulting in periodic and seasonal flooding. The latter makes it an unlikely site for infrastructure retrofitting and upgrading as part of Department of Energy's programme on the *Electrification of Unproclaimed Areas* [57].[8]

4.2. Implementing solar micro-grids

Two UK-funded research projects implemented 10 solar micro-grids in the settlement, supplying up to 160 clients with renewable energy. The projects included the 2019–23 British Academy funded Energy for Wellbeing project (3 solar micro-grids), and the 2020–23 Newton Fund-sponsored Umbane project (7 solar micro-grids), which is the focus of our case study. While solar micro-grid technologies have already been developed and used in other off-grid contexts, particularly within rural areas, and have gained traction in parts of East and West Africa, there are limited examples of micro-grids being implemented in urban informal settlements such as Qandu-Qandu,[9] with exceptions of a few studies like for example, Ampulolo et al. [58] who explored the techno-economic feasibility of micro-grids in in an informal settlement in Namibia. A key benefit of the solar micro-grid technology for use in informal settings is that it could easily be implemented in densely populated urban areas such as Qandu-Qandu. Each micro-grid serves up to 16 households[10] within a 40 m radius and the energy provided can be used for lighting, changing devices, fridges, and entertainment (TV and radio).

5. Research methods

The Umbane project was delivered by academic and implementation partners, comprising two universities (The Universities of Exeter and Cape Town), a local utility provider (Zonke Energy), an energy consultancy (Thrie Energy Collective), a social enterprise (Story Room) and the Qandu-Qandu community. The team engaged in action research in Qandu-Qandu to co-produce knowledge on solar micro-grids and their implementation in urban informal settlements. During this time, data was gathered to support the embedded understanding of energy use in terms of informality, innovation, and finance and their interrelationships. The community was engaged to understand their interests in solar energy and how the project could best accommodate their needs.[11] The overall aim of the Umbane project was to explore how the addition of solar refrigeration could facilitate income-generation and livelihood opportunities for women owned enterprises in Qandu-Qandu. Drawing from the findings of the Umbane project, this paper uses the *informality-energy innovation- finance nexus* as a framework and lens through which the 'co-production' of off-grid energy business models can be analysed. It emphasises affordability context, as well as broader socio-economic and spatial context co- shaping both micro-entrepreneurship and off-grid energy business model refinement.

The use of mixed methods including in-depth interviews, data collection during business training sessions and an affordability survey enabled the research team to gather embedded accounts as well as triangulate our research findings, where data could be verified. Where necessary, all data was translated into English from isiXhosa. The data analysed in this paper includes:

- *In-depth interviews (December 2021 – June 2022):* We conducted 40 in-depth interviews residents in Qandu-Qandu and project team members. Interviews were analysed using thematic analysis using Nvivo.
- Business training 'bootcamp' (October 2021 – April 2022): Twelve engagements were set up between the social enterprise and women living in Qandu-Qandu that were interested in starting a business using solar-powered energy. Notes were taken at each session. Participants also provided weekly reflections on the impact of solar refrigeration and energy on their businesses, business goals, business plan development and financing. Both sets of notes and data gathered on participant forms were coded in Nvivo along with transcribed in-depth interviews.
- Client willingness to pay affordability survey (December 2021): A mix of 18 prospective and existing clients were asked to complete a survey about their average household income and willingness/ability to pay for packages.

6. End-user experiences, affordability and business model viability in Qandu-Qandu: Informality, energy innovation and business model development

As highlighted above, *informality,* the departure point of the nexus framework, is the context in which energy innovation and scaling of business models occurs. Energy innovation in our case study is furthermore intrinsically linked with local entrepreneurship in Qandu-Qandu and the broader milieu shaping the 'informal city'. In Qandu-Qandu, spatial and socio-economic disparities and inequalities are enmeshed with infrastructure and service delivery gaps in the settlement, which further impacts entrepreneurship and solar innovation opportunities in the settlement [1,3]. One of the emerging themes from the interview data is how the context of the informal settlement (i.e.

[7] Referred to as servitudes in the South African context.

[8] To guide efforts to retrofit and upgrade informal settlements in South Africa, such as Qandu-Qandu, the Department of Energy has identified three core informal settlement types. The first category recognises informal settlements that can be retrofitted with electricity; the second, settlements that could be retrofitted or relocated; and, last, settlements that are not able to be retrofitted with grid-based energy As outlined by de Groot et al. [3], Qandu-Qandu is listed as a category 3 settlement.

[9] The solar micro-grid technology used included four solar grids and a battery positioned on a vertical tower that was positioned next to existing dwellings in the community.

[10] To service up to 160 clients with 16 clients signed up to each tower, but can only support up to 3 fridges per tower. More appliances added restricts the number of customers that can be connected.

[11] This included their financial and social needs.

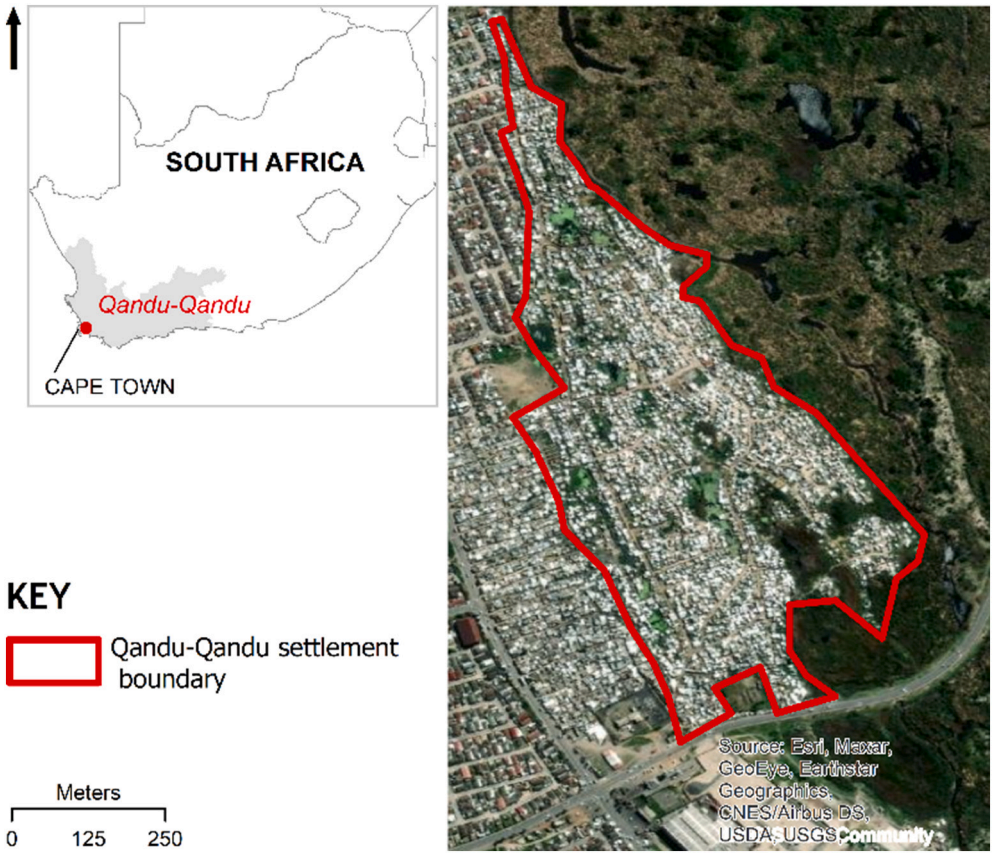

Fig. 2. Location of Qandu-Qandu, South Africa (Source: Authors).

socio-economic, infrastructural and spatial) shaped and influenced the types of businesses started within the settlement. One of the entrepreneurs participating in the Umbane training programme reflected on the early days of starting her business and first moving to Qandu-Qandu:

> When I moved to QQ I had to think of what I could sell, because there was no electricity and I had electricity in the area I had moved from. I thought of first selling sausages and chicken chunks, and I would quickly sell and loan them to people so that I wouldn't need to store them (S3G3D2).

Similarly, another entrepreneur commented on a business developed around a key need and gap identified within Qandu-Qandu:

> When I first arrived in QQ in 2019, I had a fishery business, but I had to stop because I did not have a place at the time…. My wish is to move forwards with my business, I see my business being of very high standard. The fishery business is […] needed in QQ [S4G4D3Y].

The above quotes further illustrate how the lack of formal electricity gave impetus to some of the micro-businesses arising within the community, and concurrently created a niche for suitable off-grid solar appliances and business models to support micro-enterprises. It further shows how micro-entrepreneurs in Qandu-Qandu needed to innovatively work around not having access to electricity or refrigeration.

Other contextual factors specific to Qandu-Qandu include the settlement being precluded from formal grid connection due to being partly located on a wetland among other local municipal planning and governance considerations (and contestations) [1,3], as well as economic socio-economic disparities like a lack of access to formal employment opportunities. These factors continue to influence uncertainty around operating micro-enterprises in the community, as illustrated in the quotation below.

> They say the people in the flooded areas will be moved to occupy areas not flooded. So, it would be unfair for me to place a stand in the area where people are likely to be placed in. After some has moved maybe I can then place my stand where they were (S3G3D2).

Engagement with community members in Qandu-Qandu and entrepreneurs in the programme revealed a range of businesses in the community all requiring access to alternative reliable and safe energy and refrigeration particularly. Local businesses participating in the Umbane entrepreneurship training ranged from tuck shops, meat selling enterprises, businesses selling beverages, a local creche and a gym. Further challenges around poverty and basic access to food and nutrition was noted by one of the entrepreneurs running a day-care centre at the time.

> Because I see the need for people of QQ, they are living in poverty, and the small children are very hungry when coming from school, some their parents are not home, so they need bread (S2G2D1P).

The development of a 'context appropriate'[12] business model and value proposition for micro-grids in Qandu-Qandu therefore needed to be acutely sensitive to the spatial and socio-economic context and dynamism of the settlement. The value proposition of the solar fridge package was partly informed by the lack of access to refrigeration through the formal grid for businesses and home-based enterprises. A key theme from the interview data is the need for accessible and reliable energy for businesses and households. A lack of access to safe, reliable and affordable energy can have a tangible negative impact on the operations of a business, notwithstanding micro-entrepreneurs finding ways to conduct business in the absence of 'formal' electricity or clean

[12] The term context appropriate recognises that off-grid 'solutions' can be fluid and evolving, and that informal settlements in South Africa and the Global South are highly heterogenous

and affordable alternatives. As one interviewee commented:

> In my struggle for electricity — I did not have electricity for four months— so I stopped the business. I would occasionally sell. So, I heard that there was solar, I asked people 'does this solar fridge work?' (P114017).

The above quote elucidates how accessing electricity informal settlements is often a struggle, which has a notable tangible impact on the ability of businesses to continue trading. Therefore, off-grid solar alternatives have an important place and tangible gap to fill in these settings. However, as seen from the above quote, the presence of new solar towers and addition of solar refrigeration also created an expectation around the prospect of using solar. This required tailoring energy services to business needs and developing business models that could offer energy services in a sustainable way. This was found to be an iterative and continuous process throughout the duration of the Umbane project (and post pilot), and relates back to the idea that innovation when viewed through the lens of the *informality-energy innovation-finance* nexus should not be construed as a once-off technical service or offering, but rather an ongoing set of processes and interactions shaped by end-users and the community at large.

In the Umbane project the addition of solar refrigeration was a distinct add-on from the previous monthly energy packages offered by the micro-utility.[13] The lack of formal grid electricity, and the need to power appliances safely, created a niche for Direct Current (DC) solar appliances to ensure compatibility with DC micro-grid solutions being piloted in Qandu-Qandu.

One of the entrepreneurs explained;

> It [the fridge] will help a lot, because I would like to sell meat, drinks …..and popsicles for the kids' (P110417). The entrepreneur further explained 'I will take everything and store it there and my business will function properly, I won't be out of stock' (P110417).

Another entrepreneur in the programme commented:

> When you stock up without a fridge, if people do not buy your product you have to cook and eat it, because it will spoil. So having a fridge has been very beneficial because I am now able to stock up in bulk and so I minimise the time of going back and forth (S3G3D2S).

From the above quotes it is evident that refrigeration was a particular need for businesses in the community to support and facilitate the effective functioning of their enterprises. Interview data collected after entrepreneurs completed the entrepreneurship training programme, revealed several positive benefits for solar refrigeration and businesses. These included improved revenues and more consistent business for some of the businesses.

Some of the benefits of access to solar electricity extended beyond the business and impacted the household level. For example, one of the entrepreneurs expressed a sense of empowerment as a mother, as her home has lighting that does not depend on paraffin or candles which is safer for her children.

> That is when people also started to see that this thing works, and they expressed interest. It has helped me a lot as I have children and shack houses can easily burn (S3G3D2S).

Considering that many of the enterprises in Qandu-Qandu are home-based enterprises or a hybrid between a home-based enterprise and having a stall in the community, the benefits of solar electricity extend to the household level.

While there was an overall 'positive energy' around business creation and refrigeration, the reliability of electricity connections made running a successful business more complex. Introducing a solar fridge package for local businesses needed to consider the variability of off-grid solar appliances and how they perform in real life contexts. Furthermore, as with any energy service delivery model, its success (or failure) is dependent on how end-users experience a technology and derive value from the attendant business model, as well as affordability and willingness to pay. These factors are all contextually bound and specific to the 'lived realities' of businesses, including home-based enterprises connected to the micro-grid. Testing solar fridges in businesses in Qandu-Qandu revealed discrepancies in the expected performance and basic functionality, with technical interventions needed to understand and resolve technical problems with the fridges. For example, the solar fridges used in the Umbane project were particularly sensitive to thermostat settings, with slight variations significantly altering the ability of the fridge to cool food or beverages as desired. This also relates to the moral challenges of testing technologies in more 'vulnerable' settings. This observation is supported by Lai, Muir & Ruff [59], who argued that fridge performance may differ in lab and field settings and may be affected by how the fridge is used daily.

Another key emerging theme in the data is the interconnectedness of micro-enterprises using solar based refrigeration to the technology (i.e. solar towers and fridges) and business models, and dependence on their effective working and reliability. Reflecting on the capacity constraints of each solar tower, as highlighted by Bobbins et al. [1], an interviewee explained,

> The fridge is working well. The only challenge we had was when our tower would switch off [S1G1D1].

Similarly, other interviewees explained:

> We have one of the new towers, in the beginning it was functioning very well, up until we added the fridge, because there were five of us that had fridges, it started having tendencies of switching off at 6pm. That period affected me a lot, because that is the time that people get back from work and I must be doing my business and the electricity only comes back around 4 am in the morning [S1G1D2].

> When it did that thing of switching on and off, it affected my business because my things that were in the fridge went bad. So, I had to start all over again….so I'm still afraid of stocking up in bulk. Because what if the products go bad again [S3G3 D2].

The above quotes demonstrate that off-grid appliances, like solar fridges, are not only impacted by variations from manufacturing defaults in 'real life' settings, but also depend on the capacity of the micro-grid to support higher productive loads. Disruptions or inadequacy of electricity supply have immediate, and potentially lasting impacts on business operations. Thus, while off-grid solutions can fill an energy access gap, continuous improvements are needed to ensure the technologies and business models are effectively providing a reliable service and levels of access. Communication in the delivery of energy services, and effective troubleshooting to resolve technical issues in a timely manner, is necessary to bridge the gap between technology underperformance and create trust in an environment where gaps in communication and expectations could create distrust between end-users and utilities and/or energy service providers. Thus, communication should be prioritised to ensure that the anticipated value is delivered to end-users and that technological challenges are mitigated and resolved timeously.

In addition, the practical constraints that often hinder the growth and sustainability of local enterprises in the community must be considered. It is also important to acknowledge that although a solar fridge could offer some immediate tangible benefits, as highlighted above, these off-grid solar appliances are not a panacea for all the business needs. One of the entrepreneurs in the programme explained the trade-offs and sacrifices needed to make a business succeed and

[13] The micro-utility Zonke Energy offered different monthly energy packages ranging from a Lighting package as their lowest entry level option to a Fridge and TV package as their higher priced offering and would-be option selected by Umbane entrepreneurship programme clients

challenges contributing to business 'failure':

> After we finished the project, I tried doing some business using what I had. But that business did not do so well. I thought this was because I started the business whilst not having much. But I tried again but still the business failed. So, I'm not doing business now [S4G4D1Y].

> Firstly, it's not having money and sacrificing the little that we have for the business. And secondly there's no one that works in my household, so we use the money made by the business to buy food.. That is why I thought we should pause for now and see if there's another way [S4G4D1Y].

The above also links back to the argument of the importance of affordability and the opportunity costs entrepreneurs are faced with when running micro-enterprises and using money to run their businesses and support their families. Thus, while off-grid solar productive use appliances may be a useful tool for enhancing the offerings of local micro-enterprises, there are still other challenges that continue to persist within the broader environment in which the entrepreneurs operate.

7. Financing off-grid energy innovations – affordability and end-user financing

Financing is a crucial link in the *informality-energy innovation-finance nexus*. At a household and micro-enterprise scale (which often is a home-based enterprise in the context of Qandu-Qandu), affordability is important to consider. Financing off-grid systems requires balancing between the amount end-users can afford, how they can afford it, and how to sustainably finance off-grid technologies. As highlighted in Bobbins et al. [1], a flexible finance model was used by the micro-utility in Qandu-Qandu. This model is in essence a variation of PAYG models (previously discussed) and allows micro-grid customers to make incremental payments and 'top-up' on a monthly or weekly basis, or via PAYG top ups (starting at R15). The micro-utility offers energy packages, ranging from lighting, television and more recently (through the Umbane project) solar refrigeration packages for businesses and households. An integral part of the development of a sustainable revenue and business model for solar micro-grid energy and solar refrigeration is affordability. We furthermore recognise that affordability is dynamic and influenced by multiple factors including seasonal variation in income, employment opportunities and income micro-entrepreneurs derived from their businesses.

Developing a sustainable micro-grid model in Qandu-Qandu, around solar refrigeration, thus required specific attention to the affordability of end-users [1]. An affordability survey was conducted with 18 participants who were present during one of the entrepreneurship bootcamp training sessions. While noting that this small survey is not representative of affordability in the whole of Qandu-Qandu, it does provide an indication of willingness and ability to pay within the Umbane entrepreneurship programme sample (i.e. 21 women-owned micro-businesses). When asking entrepreneurship training participants, which of the energy packages offered by the micro-utility they felt they were able to afford, 6 out of 16[14] or 37.5 % said they could afford the Shop Package (R425 per month) while only 2 indicated that they could afford the original Fridge package (R490 per month). Furthermore, half of the participants indicated they could afford packages priced under R250 (i.e., Lights and TV packages). Interestingly more respondents (5 out of 15[15]) were willing to pay for a Fridge Package, which could indicate a higher willingness to pay despite lower affordability. While this is indicative of willingness to pay for alternative energy services, the long-term sustainability of a revenue model is contingent on how households can pay for energy services in the longer term and if they would have sources of income to sustain the monthly payments or tops ups. However, when comparing responses based on average monthly income (as reported by the respondents), some respondents would be paying up to 25 % of their monthly income on the Fridge Package.

According to the literature on affordability and energy poverty [see e.g. 60,61], the higher tier energy packages (particularly the fridge packages) are not considered affordable for all users and could risk unintendedly contributing to energy poverty, if ability to pay is not carefully considered. It is furthermore important to consider the wider factors that could hinder the uptake or adoption of off-grid solar fridges including sociocultural and socio-political factors. Smit, Musango and Brent [43] have highlighted a myriad of sociotechnical and governance considerations that are necessary to consider when exploring fuel choices and adoption among informal settlement residents in pursuit of access to affordable, modern, reliable, sustainable energy for all. This can extend to energy technologies and off-grid appliances. While studies have shown that low-income households in South Africa often pay disproportionately higher percentages of their household income on energy [60,61], off-grid models serving low-income communities need to develop mechanisms to reduce and address the affordability gap to be sustainable and achieve desired positive impacts. Affordability is a key aspect of achieving universal and meaningful access and the availability of clean off-grid energy alternatives alone is not enough to deliver energy access in a meaningful way. One interviewee commented that initially she tried to figure out how she would be able to afford any pay for the fridge:

> They had mentioned that there are also fridges, but I did not know how I would go about paying for the fridge. And at that time, I had used up my business money… So, when the fridge arrived, I didn't have money…[S3G3D2].

Furthermore, one of the participants who completed the survey during the training session expressed that the monthly difference between the Fridge package (R490) and entry level Lighting package (R150) is what she would rather use for food or other necessities (UETAS 1). This illustrates that there are opportunity costs associated with acquiring a fridge at the price it was offered, as this needed to be considered in relation to other key necessities. This further shows the very real trade-off of delivering higher tiered energy services in income-constrained environments. While the focus of the Umbane project was on solar fridge businesses, some of the participants who attended the training sessions could not necessarily afford the fridges and needed to consider other households expenses and necessities before considering signing up to a Fridge Package. Furthermore, while a 'productive use' appliance should also enable income generation to recover the cost of the fridge, this would vary from business to business. This should also be weighed up against the cost on the fridge itself, its payment period, and whether sustainable revenue can be generated to cover the costs and make a profit [22]. Thus, the fridge payment expenses (either upfront or spread over time), when viewed in relation to business income and other expenses, may impact whether entrepreneurs can effectively make a profit using the fridge or simply have to use a significant part of their profits or income to pay back the fridge.

The value proposition of the solar fridge further relates to the micro-utility revenue and how this was affected by technological constraints. For example, each tower (1.4kWp with 5kWh of battery storage) could only support up to three fridge customers per tower. This over time, invariably led to trade-offs for the micro-utility to support more domestic customers on TV and lights packages versus a few productive-use customers, which goes against the grain and the popular narrative that productive uses of energy would automatically result in a better business case for micro-grids or off-grid utilities. In this case study, technological constraints regarding the capacity of each tower and low distribution

[14] 16 respondents of the 18 respondents who participated in the survey answered this question

[15] 15 respondents of the 18 who participated in the survey answered this question

voltage lines (i.e. 24 V), limits the number of households per tower and the amount of revenue per customer for the utility. It may thus be more financially viable for the mini-utility using the system to connect more customers on the entry level lights and TV packages than connecting more fridge customers. While this may be more financially viable for the utility, it is a lower level of energy access for households (providing an equivalent to tiers, 1 and 2 on the ESMAP multi-tier framework), which hinders additional income generating opportunities and the types of energy services that can have any substantial impact on addressing energy poverty. However, it serves as an entry point for providing alternative energy access at a cost that is more affordable to community residents/households. This links to the above point of the complex interface between technology and end-users, but also adds a layer of technological complexity where financial viability is affected by the technology itself. A further emerging trade-off is that some customers needed to choose which appliances could be used simultaneously. For example, one client on a Fridge Package (fridge and TV) was limited with the number of hours the TV could run, to ensure that the fridge would be running for the full 24 h, which ideally should not be a trade-off which households or home-based enterprises should need to make. Challenges encountered should become a starting point for the refinement of business models, payment models and technologies.

In addition to considering affordability and end-user financing, it is also important to consider the financing model and sources of finance off-grid companies use for their projects [33]. Within a range of financing options from equity, debt and grant finance, private sector off-grid solar companies need to navigate this landscape to bring in forms of finance that are appropriate for the stage and growth of the business on terms that are favourable. Grant finance is usually a key part of financing, innovative off-grid technologies and models that need to prove the concept and are considered risky investments for traditional commercial lenders [15]. The Umbane project was supported and largely funded by UK government research and innovation funding. However, as noted while development finance, including grant finance, is an important piece of the financing puzzle, grants cannot be relied on in perpetuity to create sustainable revenue models. This paper shows that there is still a need for innovative sources of financing, combined with tested approaches to reduce the viability gap for models in such contexts. This necessitates a role for municipal funding and finding ways to effectively channel municipal funding (e.g. South Africa's Free Basic Alternative Energy) subsidy into off-grid projects like these, which is often vary rarely successfully applied to off-grid solar projects. As noted above the reliance on grant/ donor finance would have significant implications on the longevity of the energy service, and how long the utility would be able to provide the off-grid service. This necessitates critical thought into the long-term sustainability and design of urban energy services and remains an area where more research and practical 'best practices' are needed for financing, sustaining and scaling off-grid innovation pilots.

8. Conclusion

The *informality-energy innovation-finance* nexus proposed here is an entry point into analysing the complex interactions between informal settlement communities, relational and heterogeneous energy infrastructures, new ways of thinking about infrastructural provision and the financial constraints and opportunities that can help shape the nexus. We present four key areas of learning emerging from our practice-based work on solar microgrids.

Firstly, the paper's focus on solar microgrid-focused innovations in the Qandu-Qandu informal settlement was based on a co-production approach that involved multiple (community, technology, finance and other) actors. The relational engagement between these actors constituted the assemblage that envisioned, planned, resourced, built, operated and used the solar tower-based microgrids. Engagement with the community highlighted the key importance, for provincialising urban knowledge production, of working with and at the level of communities when dealing with challenges such as infrastructural service provision. These challenges are usually considered at municipal scales and by actors (policymakers, private firms) that often (and perhaps unwittingly) preclude valorising the granular context of informality itself, while aiming to speak for it and serve the needs of informal settlement communities.

Secondly, and in keeping with our focus on co-producing urban knowledge with informal settlement communities, innovation can be seen as adaptive and responsive to local context, rather than as technocratic and top-down. This is in part due to the pragmatic need for infrastructural innovations to be sensitive to informal settlement residents' need to adapt to constantly changing infrastructural contexts, as is the case with energy stacking practices. It is also part and parcel of the need to take local granularity seriously, for example in being sensitive to the varying infrastructural and energy needs of the diverse range of households and usage patterns within each informal settlement community.

Thirdly, we make the case for the importance of considering finance as a key aspect within the informality-innovation-finance nexus. We have shown how finance is both multi-scalar and multi-faceted, and can be both a constraint and an opportunity, for private sector actors as well as community members in terms of enabling specific technological innovations, product offerings, and services. Our research has shown that while finance is clearly crucial for financing private sector technology firms who develop, install, operate and maintain solar microgrids, this is not the only key facet to finance in the informal context. Rather, the community and household scales are also important, since affordability, willingness to pay, and end-user financing approaches can determine whether infrastructural offerings are acceptable by the community, and sustainable in the long term. This underscores the need for finance innovation at multiple levels including the municipal level where energy subsidies or energy tokens can help to reduce the cost and burden of energy services for low income households using alternative energy sources, including off-grid solar. At the private sector actor scale, being able to access appropriate levels of financing is key to scaling, replicability, and sustainable business models. This is key in a landscape currently constituted by a large selection of niche actors (solar utilities working in informal settlements in sub-Saharan Africa) that are, at the time of writing, not showing significant scaling activity.

Finally, working on solar microgrid business models in informal settlement contexts raises ethical questions that centre on urban knowledge production. While the development of off-grid infrastructures in informal urban contexts is key to addressing communities' needs, there remains a gap between the right to infrastructural access and the services available in informal settlements. This is an ethical issue since off-grid innovations provide a service level that is, in this project context, far below that offered by the grid (with the level of service being closer to that of a solar home system). At the same time community members are charged for basic energy services that could (depending on national context) be available as part of basic energy service rights for urban dwellers in formal settings. While we recognise that solar microgrid services do not necessarily mean that informal settlements residents pay more for energy as a result of being connected to microgrids (because connection means a reduction in the need to purchase other forms of energy), at the same time it entails a de facto situation whereby residents pay for a level of service that is free in formal contexts. Additionally, economic and spatial inequalities are potentially generated at the community level, between households who can afford to pay for microgrid-based energy services, and who are located close enough to solar towers to be connected, and households who may be located in range of a microgrid but cannot afford a connection. We suggest that a focus on financing is key, as is our underlining of the adaptive characteristic of innovation. In this context, we call for more adaptive, and hence innovative, policymaking that is based in valorising the experience and granularity of informal

settlements and can be adapted and respond to the needs that emerge from co-productive relationships with these communities.

CRediT authorship contribution statement

Whitney Pailman: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization, Funding acquisition. **Federico Caprotti:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Kerry Bobbins:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Jiska de Groot:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data has been gathered anonymously through interviews and focus groups and thematically analysed to maintain anonymity. Examples of data has been presented through relevant selected quotes.

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References

[1] K. Bobbins, F. Caprotti, J. de Groot, W. Pailman, M. Moorlach, H. Schloemann, A. Densmore, K. Finlay, E. Fischat, S. Siwali, Beyond the grid: The micropolitics of off-grid energy in Qandu-Qandu, South Africa, Antipode 56 (2024) 49–71, https://doi.org/10.1111/anti.12963.
[2] F. Caprotti, J. de Groot, N. Mathebula, C. Butler, M. Moorlach, H. Schloemann, A. Densmore, K. Finlay, Rethinking the off-grid city, Urban Geogr. (2022), https://doi.org/10.1080/02723638.2022.2036928.
[3] J. de Groot, M. Moorlach, F. Caprotti, W. Pailman, N. Mathebula, H. Schoelmann, A. Densmore, K.Butler.C. Pillay, Dealing with informality, in: Integrating off-Grid Electrification Modes for Achieving Universal Access to Electricity in South Africa. SASEC Conference, Stellenbosch University, Cape Town, 2021.
[4] D. Conway, B. Robinson, P. Mudimu, T. Chitekwe, K. Koranteng, M. Swilling, Exploring hybrid models for universal access to basic solar energy services in informal settlements: case studies from South Africa and Zimbabwe, Energy Res. Soc. Sci. 56 (2019), https://doi.org/10.1016/j.erss.2019.05.012.
[5] Z. Kovacic, J.K. Musango, L.A. Ambole, K. Buyana, S. Smit, C. Anditi, B. Mwau, M. Ogot, et al., Interrogating differences: a comparative analysis of Africa's informal settlements, World Dev. 122 (2019) 614–627, https://doi.org/10.1016/j.worlddev.2019.06.026.
[6] United Nations, Make cities and human settlements inclusive, safe, resilient and sustainable. Available. https://unstats.un.org/sdgs/report/2019/goal-11/, 2019 [2024, January 25].
[7] S. Graber, O. Adesua, C. Agbaegbu, I. Malo, J. Sherwood, Electrifying the Underserved: Collaborative Business Models for Developing Minigrids under the Grid, Rocky Mountain Institute, Basalt, 2019.
[8] A.N. Haque, C. Lemanski, J. de Groot, Is (in)access to infrastructure driven by physical delivery or weak governance? Power and knowledge asymmetries in Cape Town, South Africa, Geoforum 126 (2021) 48–58, https://doi.org/10.1016/j.geoforum.2021.07.013.
[9] IEA, IRENA, UNSD, World Bank & WHO, Tracking SDG 7 the Energy Progress Report 2022, World Bank, Washington DC, 2022.
[10] R. Rahnama, Essays on the attitudes, behavior, and decision-making of income-constrained electricity consumers: Implications for integrative grid and off-grid business model planning. Masters Thesis. MIT. Available. https://dspace.mit.edu/bitstream/handle/1721.1/117795/1051222914-MIT.pdf?sequence=1, 2018 [2023, October 20].
[11] W. Pailman, Towards Integrated Business and Partnership Models for Universal Energy Access in Kenya and Rwanda, PhD thesis., University of Cape Town, 2024.
[12] W. Pailman, J.L. Kruger, G. Prasad, Mobile payment innovation for sustainable energy access. Domestic use of energy (DUE), 2015 international conference, Cape Town: Cape Peninsula University of Technology 2015 (2015) 39–44.
[13] P. Reichert, U. Trivella, Increasing energy access: the rise of pay-as-you-go solar and innovative financing partnerships, Enterprise Development and Microfinance 26 (2015) 248–261, https://doi.org/10.3362/1755-1986.2015.022.
[14] S. Ketelaars, S. Wheeldon, Discussion paper: how end-user subsidies can help achieve universal energy access. Amsterdam: global off-grid lighting association. Available. https://www.wame2030.org/files/catalogue/2021/2/gogla_discussion_paper_subsidies_def_2_Amaw6wB.pdf, 2021.
[15] BloombergNEF & SEforAll, State of the Global Mini-grids Market Report 2020. New York: BloomBergNEF. Available. http://dergipark.gov.tr/cumusosbil/issue/4345/59412, 2020 [2023, Sept 12].
[16] E. Pieterse, A.M. Simone, New Urban Worlds, Cambridge, Polity Press, Inhabiting Dissonant Times, 2017.
[17] E. Sheppard, H. Leitner, Provincializing critical urban theory: extending the ecosystem of possibilities, Int. J. Urban Reg. Res. 40 (2015) 228–235.
[18] W. Pailman, J. de Groot, Rethinking education for SDG 7: a framework for embedding gender and critical skills in energy access masters Programmes in Africa, Energy Res. Soc. Sci. 90 (2022) (2022) 102615, https://doi.org/10.1016/j.erss.2022.102615.
[19] S.J. Schillebeeckx, P. Parikh, R. Bansal, G. George, An integrated framework for rural electrification: adopting a user-centric approach to business model development, Energy Policy 48 (2012) 687–697.
[20] V. Castán Broto, L. Stevens, E. Ackom, J. Tomei, P. Parikh, I. Bisaga, To, L.S, J. Kirshner, Y. Mulugetta, A research agenda for a people-centred approach to energy access in the urbanizing global south, Nat. Energy 2 (10) (2017) 776–779.
[21] J.C.C.M. Tolkam, J.C.C.M. Huijben, R.M. Mourik, G.P.J. Verbong, R. Bouwknegt, User centred sustainable business model design: the case of energy efficiency services in the Netherlands, J. Clean. Prod. 182 (2018) 755–764.
[22] L. Labruto, J. Stottlemyer, Waiting game: where is all the Investment in Solar-Powered Productive use Appliances? Available. https://nextbillion.net/waiting-for-investment-in-solar-appliances/, 2019.
[23] R. Horner, Towards a new paradigm of global development? Beyond the limits of international development, Prog. Hum. Geogr. 44 (3) (2020) 415–436.
[24] F. Caprotti, R. Cowley, A. Datta, V. Castán Broto, E. Gao, L. Georgeson, C. Herrick, N. Odendaal, S. Joss, The new urban agenda: key opportunities and challenges for policy and practice, Urban Res. Pract. 10 (3) (2017) 367–378.
[25] D. Chakrabarty, Provincializing Europe: Postcolonial Thought and Historical Difference, Princeton University Press, Princeton, NJ, 2000.
[26] U. Kothari, Authority and expertise: the professionalisation of international development and the ordering of dissent, Antipode 37 (3) (2005) 425–446.
[27] C. Barnett, The strange case of urban theory, Camb. J. Reg. Econ. Soc. 13 (3) (2020) 443–459.
[28] S. Samarakoon, A. Bartlett, P. Munro, Somewhat original: energy ethics in Malawi's offgrid solar market, Environ. Sociol. 7 (3) (2021) 164–175.
[29] P. Munro, On, off, below and beyond the urban electrical grid the energy bricoleurs of Gulu town, Urban Geogr. 41 (3) (2020) 428–447.
[30] J. Cross, T. Neumark, Solar power and its discontents: critiquing off-grid infrastructures of inclusion in East Africa, Dev. Chang. 52 (4) (2021) 902–926.
[31] ESMAP, Funding the Sun: New Paradigms for Financing off-Grid Solar Companies, World Bank, Washington, DC, 2020.
[32] Shell Foundation & Catalyst Off-grid Advisors. 2018. Achieving SDG 7: The Need to Disrupt Off-Grid Electricity Financing in Africa.
[33] G. Falchetta, B. Michoud, M. Hafner, M. Rother, Harnessing finance for a new era of decentralised electricity access: a review of private investment patterns and emerging business models, Energy Res. Soc. Sci. 90 (2022) 102587.
[34] N. Banks, M. Lombard, D. Mitlin, Urban informality as a site of critical analysis, J. Dev. Stud. 56 (2) (2019) 223–238.
[35] A. Varley, Postcolonialising informality, Environ. Plan. D Soc. Space 31 (1) (2013) 4–22.
[36] C. Marx, E. Kelling, Knowing urban informalities, Urban Stud. 56 (3) (2018) 494–509.
[37] K. Dovey, R. King, Forms of informality: morphology and visibility of informal settlements, Built Environ. 37 (1) (2011) 11–29.
[38] I. Baptista, Electricity services always in the making: informality and the work of infrastructure maintenance and repair in an African city, Urban Stud. 56 (3) (2018) 510–525.
[39] M. Ogeya, C. Muhoza, O. Johnson, Integrating user experiences into micro-grid business model design in rural Tanzania, Energy Sustain. Dev. 62 (03) (2021) 011, https://doi.org/10.1016/j.esd.2021.03.011.
[40] J. Amankwah-Amoah, Technological revolution, sustainability, and development in Africa: overview, emerging issues, and challenges, Sustain. Dev. 27 (2019) 910–922.
[41] W. Pailman, An explorative study of the synergy between social enterprises and local micro-entrepreneurs in the provision of off-grid clean energy access, University of Cape Town. (2016) 1–160. http://hdl.handle.net/11427/20577.
[42] M.J. van Welie, B. Truffer, H. Gebauer, Innovation challenges of utilities in informal settlements: combining a capabilities and regime perspective, Environ. Innov. Soc. Trans. 33 (November 2019) (2019) 84–101.
[43] S. Smit, J.K. Musango, A.C. Brent, Understanding electricity legitimacy dynamics in an urban informal settlement in South Africa: a community based system dynamics approach, Energy Sustain. Dev. (2019), https://doi.org/10.1016/j.esd.2019.01.004.
[44] Z. Kovacic, et al., Building capacity towards what? Proposing a framework for the analysis of energy transition governance in the context of urban informality in Sub-Saharan Africa, Local Environ. 26 (3) (2020) 364–378, https://doi.org/10.1080/13549839.2020.1849075.

[45] K. Bobbins, F. Caprotti, J. de Groot, W. Pailman, M. Moorlach, H. Schloemann, A. Densmore, K. Finlay, E. Fischat, S. Siwali, J. Links, Smart and disruptive infrastructures: Re-building knowledge on the informal city, Urban Stud. 61 (1) (2024) 165–179, https://doi.org/10.1177/00420980231172582.
[46] N. Mukisa, M.S. Manitisa, P. Nduhuura, E. Tugume, C.K. Chalwe, Solar home systems adoption in Sub-Saharan African countries: household economic and environmental benefits assessment, Renew. Energy 189 (April 2022) (2022) 836–852.
[47] V. Kizilcec, P. Parikh, Solar home systems: a comprehensive literature review for sub-Saharan Africa, Energy Sustain. Dev. 58 (October 2020) (2020) 78–89.
[48] ESMAP, MINI GRIDS FOR HALF a BILLION PEOPLE Market Market Outlook and Handbook for Decision Makers, The World Bank, Washington DC, 2022.
[49] A. Bajpai, S. Stratton-Short, I. Adelekan, Scaling up Essential Services in African Cities, African Development Bank, Cities Alliance/UNOPS, 2022.
[50] P. Blomkvist, D. Nilsson, B. Juma, L. Sitoki, Bridging the critical interface: ambidextrous innovation for water provision in Nairobi's informal settlements, Technol. Soc. 60 (February 2020) (2020), https://doi.org/10.1016/j.techsoc.2019.101221.
[51] P.C. Cherunya, H. Ahlborg, B. Truffer, Anchoring innovations in oscillating domestic spaces: why sanitation service offerings fail in informal settlements, Res. Policy 49 (1) (2020), https://doi.org/10.1016/j.respol.2019.103841 np.
[52] J. Amankwah-Amoah, Solar energy in sub-Saharan Africa: the challenges and opportunities of technological leapfrogging thunderbird, Int. Bus. Rev. 57 (1) (2015) 15–31.
[53] S. Smit, J.K. Musango, A.C. Brent, Understanding electricity legitimacy dynamics in an urban informal settlement in South Africa: a community based system dynamics approach, Energy Sustain. Dev. 49 (2019) 39–52. April 2019.
[54] J.C. Steckel, M. Jakob, C. Flachsland, U. Kornek, K. Lessman, O. Edenhofer, From climate finance toward sustainable development finance, WIREs Clim. Change 8 (1) (2017) 1–8, https://doi.org/10.1002/wcc.437.
[55] V. Bandi, T. Sahrakorpi, J. Paatero, R. Lahdelma, The paradox of mini-grid business models: a conflict between business viability and customer affordability in rural India, Energy Res. Soc. Sci. 89 (2022) 102535, https://doi.org/10.1016/j.erss.2022.102535.
[56] Social Justice Coalition, Qandu-Qandu. Available. https://ehwoza.com/qandu-qandu, 2020 [2024, March 20].
[57] Department of Energy, Policy guidelines for the electrification of unproclaimed areas. Department of Energy South Africa. Available, in: https://www.energy.gov.za/files/policies/Policy-Guidelines-for-the-Electrification-of-Unproclaimed-Areas-2015.pdf, 2015.
[58] A. Amupolo, S. Nambundunga, D.S.P. Chowdhury, G. Grün, Techno-economic feasibility of off-grid renewable energy electrification schemes: a case study of an informal settlement in Namibia, Energies (2022), https://doi.org/10.3390/en15124235.
[59] E. Lai, S. Muir, Y. Erboy Ruff, Off-grid appliance performance testing: results and trends for early-stage market development, Energ. Effic. 13 (2020) 323–347, https://doi.org/10.1007/s12053-019-09793-z.
[60] Omowunmi Longe, Khmaies Ouahada, Mitigating household energy poverty through energy expenditure affordability algorithm in a smart grid, Energies 11 (2018) 947, https://doi.org/10.3390/en11040947.
[61] B. Masuku, Rethinking South Africa's household energy poverty through the lens of off-grid energy transition, Dev. South. Afr. (2024) 1–24, https://doi.org/10.1080/0376835X.2023.2300411.